

# Exploring Ichnofacies Distribution in Ancient Seaways: The Late Miocene Rifian Corridor as a Natural Laboratory

**Wouter de Weger**

Royal Holloway University of London

**Francisco Rodríguez-Tovar**

University of Granada

**Olmo Miguez-Salas** (✉ [olmoms@ugr.es](mailto:olmoms@ugr.es))

Departamento de Estratigrafía y Paleontología, Universidad de Granada, Avd. Fuentenueva s/n, 18002, Granada, Spain

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# Abstract

Oceanic gateways have modulated ocean circulation and have influenced climatic variations throughout the Earth's history. During the Late Miocene (7.8 - 7.35 Ma), the Atlantic Ocean and the Mediterranean Sea were connected through the Rifian Corridor (Morocco). This gateway is one of the few examples of deep ancient seaways with a semi-continuous sedimentary record. Deposits comprise turbidites intercalated between deep-sea fine grain sediments (i.e., hemipelagites and drift deposits), channelized sandstone contourite facies, and shallow marine sandstones. Herein an ichnological analysis was conducted in these upper Miocene sediments to improve characterisation of palaeoenvironmental conditions. In addition, ichnofacies were analysed to elucidate how bottom currents control ichnofacies distribution and can modified their attributes. Turbidite deposits are typified by vertical trace fossils (i.e., *Ophiomorpha*), conforming the *Ophiomorpha rudis* ichnosubfacies. Contouritic sandstones exhibit high density and low diverse trace fossil assemblage, with predominant *Macaronichnus* and *Scolicia*, resembling a proximal expression of *Cruziana* ichnofacies. Shallow marine environments are dominated by vertical trace fossils (e.g., *Conichnus*, *Ophiomorpha* and *Skolithos*), allowing an assignation to *Skolithos* ichnofacies. This study reveals energy to be a major controlling factor determining ichnofacies attributes and distribution in ancient deep seaways. Within these seaways, highly energetic conditions typical of shallower settings are present in deeper environments (i.e., slope), contributing to ichnodiversity impoverishment in ichnofacies.

## Introduction

Oceanic gateways play a key role in controlling global ocean circulation and climate systems<sup>1</sup>. Ancient seaways are unique environments in which a complex interplay of processes may take place (i.e., oceanic-, tidal-, bottom-, turbiditic- and wind-currents)<sup>2,3</sup>. The constricted morphology of the seaway usually funnels and amplifies the currents that shape the seafloor (i.e., tidal currents)<sup>4</sup>. Previous sedimentological studies of ancient seaways have been largely focussed on shallow counterparts (generally between 100–150 m water depth)<sup>4-6</sup>. Few examples of published evidence on deep ancient seaways (> 150 m) and associated deposits can be found. However, oceanographic studies have shown that deep seaways are different from shallow ones, with bottom-currents sometimes playing a dominant role<sup>7-9</sup>. The Rifian Corridor is one of those few examples (Fig. 1)<sup>2,3,10,11</sup>.

During the Late Miocene, the Atlantic Ocean and the Mediterranean Sea were connected by a complex network of marine gateways through south Iberia and north Africa –the Betic and Rifian corridors, respectively<sup>12,13</sup>. The Rifian Corridor was a main deep seaway of this network (ref, Fig. 1). This gateway progressively closed (<6.9 Ma) due to tectonically induced uplift, leading to the onset of the Mediterranean Salinity Crisis in the Late Miocene<sup>13,14</sup>. During the Late Tortonian the seaway evolved into a narrow, deep corridor hosting a complex interplay of processes<sup>2,3</sup>.

Ichnological analysis comprises a wide range of tools (i.e., ichnofabric approach, ichnofacies model) that prove very useful in sedimentary basin research<sup>15</sup>. The ichnofacies model is of special interest for detailed palaeoenvironmental reconstructions and for recognizing, differentiating and interpreting sedimentary environments<sup>16-19</sup>. Recent steps in ichnological research have established means of recognising and characterising contouritic processes, revealing the importance of ichnology as a proxy for discerning between contourites, turbidites, hemipelagites and pelagites<sup>20-24</sup>, but not without scepticism<sup>25</sup>. At any rate, the relationship between deep-sea settings and trace fossils is very complex and depends highly upon the palaeoenvironmental factors that affect trace makers<sup>26</sup>.

Trace fossil research on seaway/strait environments mainly refers to shallow marine settings as brackish ecosystems (i.e., estuarine complexes, resulting in the so-called “brackish-water model”<sup>27,28</sup>), beach–shoreface complexes with evidence of tidal processes<sup>29</sup>, or compound dune fields<sup>30</sup>. Still, detailed trace fossil analysis of ancient deep seaways has never been carried out. The aim of this research is to conduct a detailed ichnological analysis of selected outcrops of the Rifian Corridor, as a unique opportunity to assess trace fossil variations to interpret an ancient deep-water seaway where shallow marine processes (i.e., tidal variations), pelagic/hemipelagic settling, turbiditic supplies and contouritic flows closely (less than 20 km) interact<sup>2,3</sup>. We evaluate the importance of palaeoenvironmental factors such as nutrients, oxygenation, and flow velocity in a setting dominated by bottom currents, and their incidence on the trace maker community. The utility of the ichnofacies model is underlined in the framework of improving high-resolution palaeoenvironmental reconstructions in different depositional environments of ancient deep gateways.

### **Trace fossil assemblages at the Rifian Corridor**

In both contouritic and turbiditic deposits, ichnodiversity is low, whereas trace fossil abundance is high in the former and moderate in the latter. In general, shallow marine deposits from the southern Rifian Corridor feature an abundant and moderately diverse trace fossil assemblage. Within the selected outcrops, the clear ichnological variability can be attributed to the different facies.

The Sidi Harazem turbiditic ichnoassemblage consists of 5 ichnogenera – *Ophiomorpha* (*O. rudis*), *Planolites*, *Spirophyton*, *Thalassinoides*, and *Zoophycos* (Fig. 3 E-H)– and the thick sandstone beds are more bioturbated than the marly ones. *Ophiomorpha* is the most abundant ichnogenus and appears in the thick turbiditic sandstone beds; *Thalassinoides* are common, *Planolites* rare, and *Zoophycos* and *Spirophyton* are occasionally found. The trace fossil assemblage of marly pelagic and hemipelagic deposits from the Sidi Harazem consists of abundant undifferentiated structures and scarce *Planolites*-like and *Thalassinoides*-like traces.

The sandy contourites in Kirmta and Sidi Chahed comprise a highly abundant and scarcely diverse trace fossil assemblage (4 ichnogenera), dominated by *Macaronichnus* and *Scolicia*, frequent *Planolites*, and common *Thalassinoides* (Fig. 2). Trace fossils were predominantly found in the planar stratified and cross-bedded sandstones. Turbidites show an absence of discrete trace fossils.

The Ain Kansera section is characterised by a shallow marine ichnoassemblage with high ichnodiversity and an abundance of vertical structures, including 9 ichnogenera localized in the sandstone beds: *Conichnus*, *Diplocraterion*, *Macaronichnus*, *Ophiomorpha*, *Parahaentzschelinia*, *Planolites*, *Scolicia*, *Skolithos*, and *Thalassinoides* (Fig. 3 A-D). The sandstone beds with swaley cross-stratification show a change in the trace fossil assemblage towards the top of the outcrop. The lower sandstone beds present dominant *Conichnus* and *Macaronichnus*, common *Parahaentzschelinia* and *Thalassinoides*, and rare *Diplocraterion*, *Planolites*, and *Scolicia*. The upper sandstone beds register the disappearance of *Conichnus* and *Parahaentzschelinia*, while *Ophiomorpha* and *Skolithos* become dominant.

### **Ichnofacies characterisation**

The trace-fossil assemblage of Sidi Harazem is typified by *Ophiomorpha* and *Thalassinoides*. *Ophiomorpha* is generally but not exclusively characteristic of high-energy environments (i.e., shoreface) in well-sorted, shifting sandy substrates, constituting a common element of the *Skolithos* and *Cruziana* ichnofacies<sup>17,18</sup>. However, the appearance of *Ophiomorpha* in deep-sea environments is also registered, and usually explained as an effect of casual transport of the trace makers by currents from shallow marine environments into the deep-sea<sup>32,33</sup>. Uchman<sup>34</sup> proposed the *Ophiomorpha* ichnosubfacies within the *Nereites* ichnofacies for the record of ichnoassemblages dominated by *Ophiomorpha rudis* registered in thick sandstone beds related with channels and proximal lobes in turbiditic systems<sup>35</sup>. Accordingly, the Sidi Harazem trace fossil assemblage could be associated with *Ophiomorpha* ichnosubfacies. Ichnosubfacies/ichnofacies assignation is tentative due to the absence of other components of this ichnosubfacies (e.g., *Scolicia*, *Nereites*, graphoglyptids); this uncertainty is tied to outcrop limitations, e.g. the low exposure of turbiditic soles and difficulties in observing discrete trace fossils in the non-compact hemipelagic and pelagic deposits.

The trace fossil assemblages of Kirmta and Sidi Chahed feature high abundance and low ichnodiversity, being dominated by *Macaronichnus* and *Scolicia*. *Macaronichnus* is usually interpreted as a shallow marine (up to foreshore) trace fossil<sup>36</sup> that occasionally appears in deeper environments<sup>37,38</sup> and is commonly associated with the *Skolithos* ichnofacies<sup>17,18,19,39</sup>. *Scolicia* presents a wide environmental range, but is a typical element of the shelfal *Cruziana* ichnofacies<sup>39</sup>. The proximal expression of the *Cruziana* ichnofacies is defined as a transition between the distal expression of the *Skolithos* ichnofacies and the archetypal *Cruziana* ichnofacies, dominated by deposit-feeding structures having numerable dwellings and suspension feeding forms<sup>40</sup>. The low ichnodiversity observed within the contourite facies from Kirmta and Sidi Chahed outcrops, together with the ubiquity of the dominant trace fossils, hamper a conclusive ichnofacies assignation. Still, though *Macaronichnus* is typical of the *Skolithos* ichnofacies, it may punctually appear in proximal *Cruziana* ichnofacies<sup>40</sup>. Considering the dominance of horizontal traces produced by deposit and detritus feeders over dwellings and suspension feeding structures, contourite ichnoassemblages at the Rifian Corridor, registered at Kirmta and Sidi Chahed outcrops, can therefore be tentatively assigned to an impoverished proximal *Cruziana* ichnofacies<sup>18</sup>.

The trace-fossil assemblage of Ain Kansera is characterised by moderate ichnodiversity with a dominance of vertical (*Skolithos* and *Ophiomorpha*), cylindrical or conic-shaped (*Conichnus*) dwelling burrows of suspension feeders and passive predators. Horizontal traces produced by mobile fauna are scarce, mainly associated with *Macaronichnus* trace makers. According to these ichnological features, shallow marine facies at the Rifian Corridor –represented by Ain Kansera sediments– can be clearly assigned to the *Skolithos* ichnofacies, with predominant burrow systems having vertical, cylindrical, or U-shaped components of suspension feeders and passive predators, and a scarcity of horizontal traces<sup>17,18,19,39,41</sup>.

### **Ichnofacies in seaways: hydrodynamic energy and the incidence of bottom currents in the Rifian Corridor**

Over the past years, detailed ichnological research has revealed the major incidence of particular environmental factors (e.g., organic-matter content, oxygenation, and sedimentation rate) on ichnological attributes from deep-sea environments, including ichnofacies characterisation and distribution<sup>26</sup>. The deep sea is a complex environment where several depositional processes co-exist, including pelagic/hemipelagic settling, bottom currents and gravity flows<sup>9</sup>. Trace fossil analysis has proven useful for discerning and characterising such sedimentary environments and associated deposits<sup>21</sup>. Hydrodynamic conditions are a very significant limiting factor for trace makers, inducing variations in distribution and behaviour, hence in the preservation of trace fossils<sup>19,29,42,43</sup>. Typically, ichnoassemblages related to high energy conditions are characterised by vertical dwelling structures of infaunal suspension feeders and/or passive predators, forming low-diversity suites; ichnoassemblages related to low energy conditions are dominated by horizontal traces of deposit and detritus feeders, as well as higher diversity<sup>19</sup>. Ichnofacies identification is mainly based on the recognition of key features that connect biological structures with physical parameters (i.e., environmental conditions)<sup>17,18,19</sup>. Accordingly, ichnofacies reflect specific combinations of organisms' responses to a wide range of environmental conditions.

In the case of seaways, prevailing hydrodynamic conditions are a main environmental factor, along with controlling depositional processes and sedimentation regimes<sup>6</sup>. Even though the number of trace fossil studies is considerably lower than in other clastic shallow or deep marine environments, ichnological analysis has proven to be useful to characterise waves, tides or storms in shallow seaways<sup>29</sup>, overlooking deep seaways and their implications. Deep seaways with narrow palaeogeographical configuration, as is the case of the Rifian Corridor<sup>10</sup>, would promote higher energetic conditions than those typical of deep-sea environments. In the study area, clearly distinct sedimentary environments –in terms of hydrodynamic conditions, bathymetry, rate of sedimentation, etc.– are closely spaced<sup>2</sup>, passing from shallow marine to turbiditic slope systems in less than 20 km (Fig. 4). Such variations in palaeoenvironmental conditions are supported by ichnofacies characterisation and distribution.

Turbidite deposits from Sidi Harazem, emplaced on the slope of the Rifian Corridor, are typified by vertical trace fossils, mainly by the record of *Ophiomorpha rudis*. These ichnological attributes are similar to

those associated with particular sub-environments (e.g., channels and proximal turbiditic lobes) of the turbiditic systems conforming the *Ophiomorpha rudis* ichnosubfacies inside the *Nereites* ichnofacies<sup>35</sup>.

Sandy contourite 2D- and 3D-dune facies (upper slope environment) (Fig. 4) from Sidi Chahed and Kirmta are related to high-energy deep-water environments. However, they are dominated by horizontal trace fossils (*Macaronichnus* and *Scolicia*) produced by mobile deposit- and detritus-feeders, discarding a direct assignation to the *Skolithos* ichnofacies. In this case, palaeoenvironmental conditions other than hydrodynamic energy must be considered to explain the dominance of horizontal forms and the absence of vertical biogenic structures. The record of densely *Macaronichnus* ichnoassemblages in these contourite sediments was recently linked to high nutrient supply provided by ancient bottom currents<sup>38,44</sup>. This agrees with the record of *Scolicia*: its abundance and size usually increase in conjunction with greater amounts and nutritious values of benthic food<sup>20,45</sup>. Thus, the strong palaeo-MOW bottom currents that dominated the slope may have created well-oxygenated and nutrient-rich benthic environments, favouring colonisation by trace makers that could exploit such accumulations of organic matter inside the sediment. *Macaronichnus* and *Scolicia* producers could develop an opportunistic behaviour, determining a rapid and complete bioturbation, avoiding colonisation by other trace makers – including suspension feeders– and an ichnodiverse trace fossil assemblage. These ichnological features resemble *Cruziana* ichnofacies attributes. Notwithstanding, the high ichnodiversity so common in *Cruziana* ichnofacies is absent here. The great abundance and low ichnodiversity observed for the contourite facies appears to indicate the absence of an archetypical *Cruziana* ichnofacies, but the development of a proximal *Cruziana* ichnofacies. Bottom currents and their associated deposits (i.e., contourites) have been previously linked to both *Cruziana* and *Zoophycos* ichnofacies in Cyprus Miocene carbonate contourite deposits<sup>22,23</sup>, meaning that contourite deposits are not exclusively related to a single ichnofacies. The replacement from *Zoophycos* to *Cruziana* ichnofacies was interpreted to be mainly controlled by sea level dynamics<sup>23</sup>.

The shallow marine facies from Ain Kansera (shoreface environment) are dominated by vertical, cylindrical, or U-shaped dwelling burrows (*Conichnus*, *Ophiomorpha* and *Skolithos*) of suspension feeders (Fig. 4). These attributes are usually related to high energetic conditions developed in shallow marine environments conforming the *Skolithos* ichnofacies<sup>18</sup>.

In short, at the Rifian Corridor, ichnofacies distributions from proximal to distal settings are controlled by bottom currents (palaeo-MOW), with hydrodynamic conditions being the major palaeoenvironmental limiting factor. Especially interesting is the development of proximal *Cruziana* ichnofacies in deeper settings from the slope environments; bottom currents generated high energetic conditions similar to those of shallow/proximal areas.

## Conclusions

During the Late Miocene, the Rifian Corridor (Morocco) connected the Atlantic Ocean and the Mediterranean Sea. The particular palaeogeographical configuration led this ancient deep seaway to be

affected by variable palaeoceanographic processes and associated deposits (e.g., shallow marine sandstones, channelized sandstone contourite facies, and turbidites intercalated between deep-sea hemipelagites), inducing different ichnological features in terms of ichnofacies composition and distribution. Turbidite deposits are typified by vertical trace fossils (i.e., *Ophiomorpha*), with assignment to the *Ophiomorpha rudis* ichnosubfacies. Contourite deposits record ichnological assemblages dominated by *Scolicia* and *Macaronichnus*, with a plausible assignment to an impoverished proximal *Cruziana* ichnofacies. Shallow marine environments are dominated by vertical trace fossils (e.g., *Conichnus*, *Ophiomorpha* and *Skolithos*) conforming *Skolithos* ichnofacies. Ichnofacies distribution in the studied ancient seaways is mainly controlled by the prevailing hydrodynamic regimes, but further ichnological analysis is needed to determine the incidence of other palaeoenvironmental factors.

## Methods

### *Geological setting*

The Rifian Corridor (Morocco) connected the Atlantic Ocean and the Mediterranean Sea during the Late Miocene (Fig. 1). The outcrops studied herein are located on the northern flank of the Saiss Basin in the South Rifian Corridor, west of Taza-sill<sup>10</sup> (Fig. 1). This basin comprises middle to upper Miocene foreland deposits<sup>31</sup> and records a unique contourite channel system related to the palaeo-Mediterranean Outflow Water (Palaeo-MOW<sup>2</sup>), which resulted from net evaporation in the Mediterranean leading to dense water formation. Regional tectonic activity favoured the development of turbiditic and gravity flows, inducing a complex deep system in which variable sedimentary processes interacted<sup>2</sup>.

Four outcrops (Fig. 1) from the Saiss Basin were selected for study: i) Sidi Harazem (34°01'52.67"N, 4°52'47.69"W), ii) Kirmta (34°10'15.07"N, 5°14'21.43"W) iii) Sidi Chahed (34°05'58.07"N, 5°18'15.12"W), and iv) Ain Kansera (34°07'34.06"N, 4°51'20.04"W):

The Sidi Harazem outcrop consists mainly of upper Tortonian (between 7.80 and 7.51 Ma) sandstone and marlstone intercalations<sup>10</sup>. The sandstone beds, up to 4 m thick, are commonly structureless, normally graded, and composed of poorly to moderately sorted, medium to coarse sands. Locally, channel-like features are observed. The deposits have been associated to a basinal turbidite system with benthic foraminiferal assemblages indicating water depths of 250–400 m<sup>10</sup>.

The Sidi Chahed sections, previously studied by Capella *et al.*<sup>10</sup> and de Weger *et al.*<sup>2</sup>, and the Kirmta outcrop, previously studied by de Weger *et al.*<sup>2</sup>, consist of three main channelized upper Tortonian (7.8 – 7.51 Ma) sandstone units encased in blue marls. Both outcrops contain different orders of unidirectional traction structures, ranging from ripples to m-scale 3D-dunes. Interbedded slump deposits have been identified within the main sandstone bodies, while turbidites have been recognized between the main sandstone bodies that are encased by marlstones<sup>2</sup>. Both outcrops were deposited within a palaeodepth range from the upper slope to the outer shelf (150–400 m water depth)<sup>2,10</sup>.

The Ain Kansera outcrop consists of upper Tortonian (between 7.51 and 7.31 Ma) sandstone and marlstone intercalations<sup>10</sup>. Sandstone bed thicknesses range from 1 to 10 m, the beds containing medium to coarse and very coarse sands. They consist of a compositional mix of siliciclastic and bioclastic sand, and regularly contain hummocky and swaley cross-stratification. Benthic foraminiferal assemblages and the presence of hummocky cross-stratification indicate an inner shelf environment (water depths of 50–100 m)<sup>10</sup>. Toward the top, the thick sandstone intervals probably represent a shallower (15–50 m water depth) wave-dominated infralittoral setting.

### *Methodology*

Trace fossil specimens from the aforementioned sections were studied first at the outcrop and then in laboratory. Outcrop analysis focus on macroscopic morphological burrow features (i.e., orientation, shape, length / diameter, cross-cutting relationships, and taphonomy). Moreover, abundance and facies relationship were study in detail. Collected specimens were examined in the laboratory, with special attention to ichnotaxonomical features. The images of some photographed specimens (outcrop and laboratory) were treated with image software<sup>46</sup>. Collected samples are housed in the Department of Stratigraphy and Palaeontology, University of Granada.

## **Declarations**

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### **Data availability**

All data analysed in this study are summarised in this published article. The original datasets are not publicly available due to size restrictions, but are available from the corresponding author upon request.

### **Author contributions**

O.M-S and F.J.R-T. designed the study and performed ichnological analysis and palaeoenvironmental interpretations. W. de W. conducted sedimentary analysis. Finally, all authors discussed the results and contributed to the final version of the manuscript.

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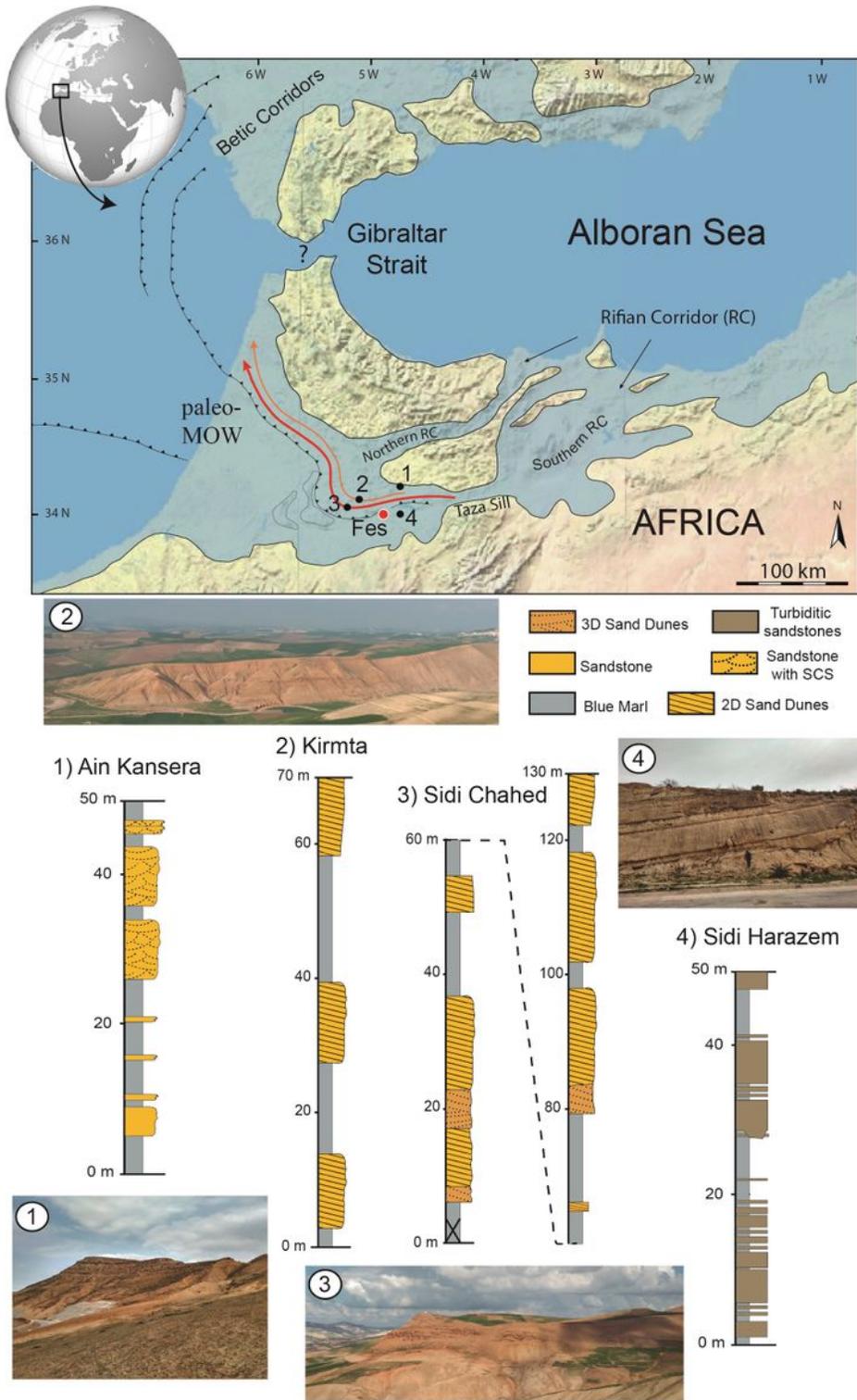
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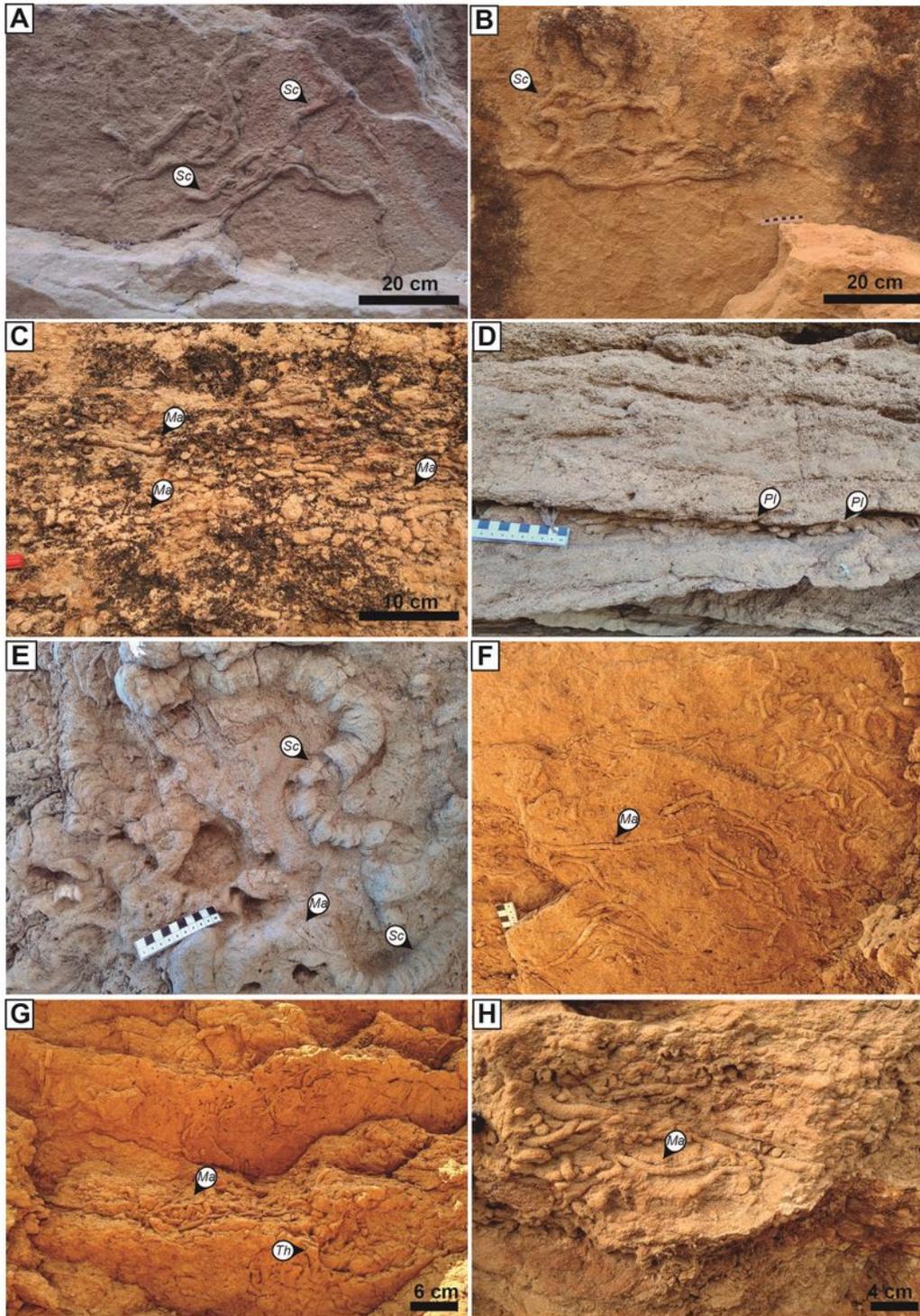
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## Figures



**Figure 1**

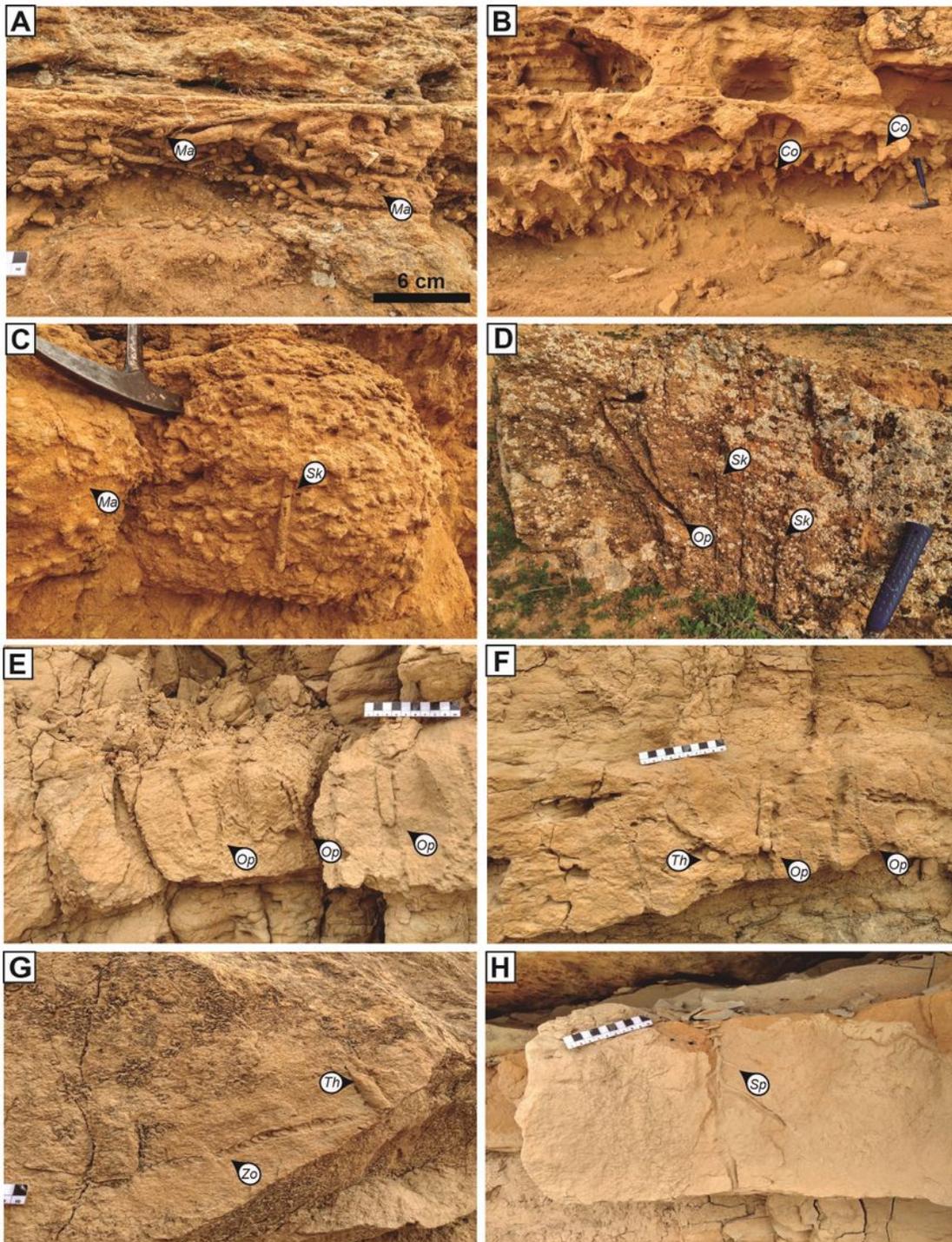
Palaeogeographic reconstruction of the late Miocene western Mediterranean with the location of the studied outcrops; red (lower) and orange (upper) arrows show palaeo-Mediterranean Outflow Water (palaeo-MOW) branches (modified from de Weger et al.2). Below, schematic sedimentary logs of the studied outcrops.



**Figure 2**

Trace fossil specimens from the sandy contourite deposits at Sidi Chahed (A-D) and Kirmta (E-H) outcrops. A-B) Scolicia specimens in the sole of sandy clastic contouritic beds of Sidi Chahed; C) Close-up view of Macaronichnus at Sidi Chahed; D) Planolites inside the interbedding of the foresets at Sidi Chahed. E) Scolicia and some Macaronichnus at Kirmta; F-G) Macaronichnus isp. and some

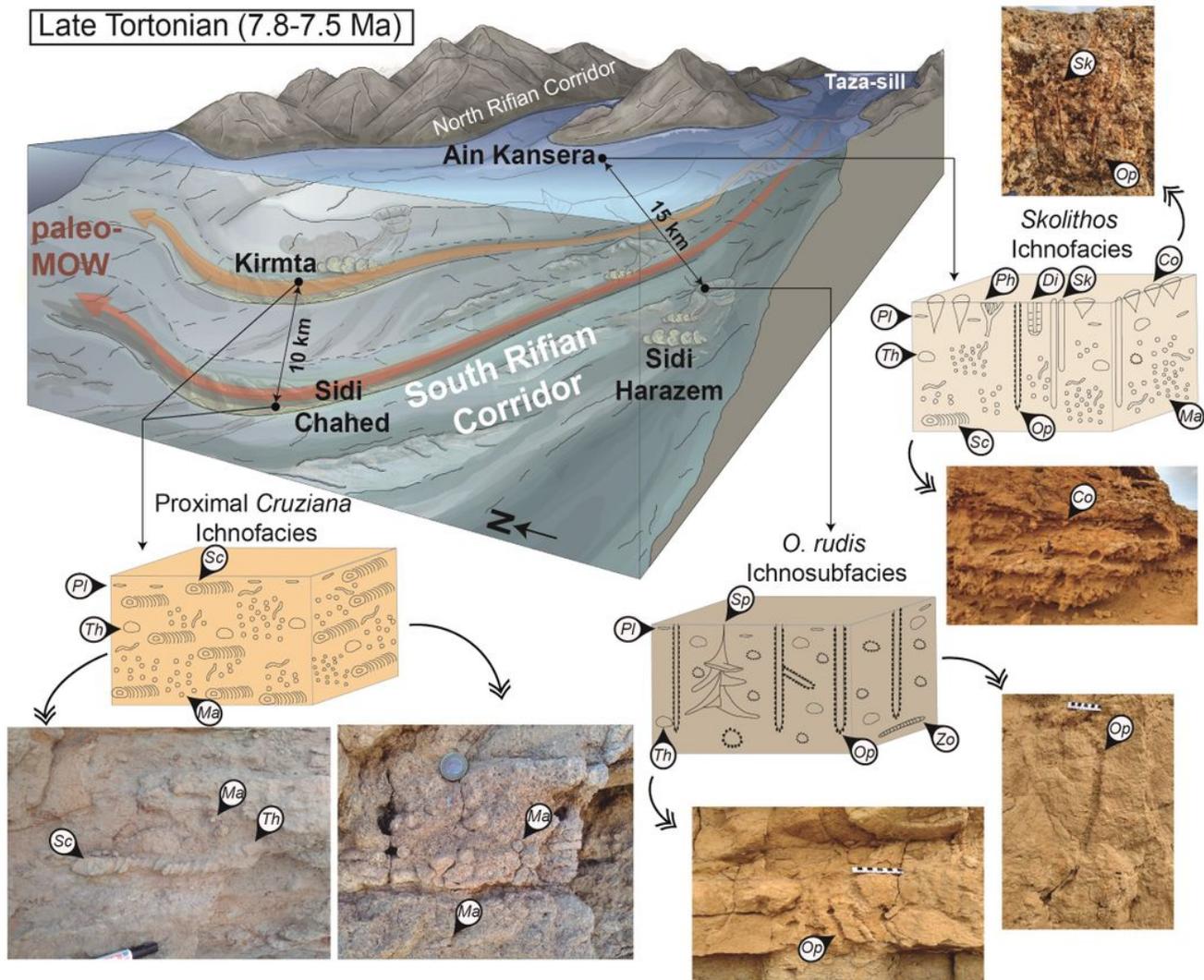
Thalassinoides in the sole of sandy clastic contouritic beds at Kirmta; H) Close-up view of Macaronichnus at Kirmta. Macaronichnus (Ma), Planolites (Pl), Scolicia (Sc), and Thalassinoides (Th).



**Figure 3**

Trace fossil specimens from shallow marine deposits at Ain Kansera (A-D) and turbiditic deposits at Sidi Harazem (E-H). A) Close-up view of Macaronichnus at Ain Kansera; B) Densely Conichnus assemblage at Ain Kansera; C) Macaronichnus specimens cross-cut by a Skolithos at Ain Kansera; D) Skolithos and

Ophiomorpha at Ain Kansera; E-F) Ophiomorpha (*O. rudis*) at Sidi Harazem; G) Zoophycos cross-cut by a Thalassinoides at Sidi Harazem; H) Close-up view of Spyrophyton at Sidi Harazem. Conichnus (Co), Macaronichnus (Ma), Ophiomorpha (Op), Skolithos (Sk), Spyrophyton (Sp), Thalassinoides (Th), and Zoophycos (Zo).



**Figure 4**

Palaeogeographic model of the late Miocene Rifian Corridor (Morocco) with ichnofacies distribution (lower red and upper orange branches indicate palaeo-MOW location; modified from de Weger et al.2). Conichnus (Co), Diplocraterion (Di), Macaronichnus (Ma), Ophiomorpha (Op), Parahaentzschelinia (Ph), Planolites (Pl), Scolicia (Sc), Skolithos (Sk), Spyrophyton (Sp), Thalassinoides (Th), and Zoophycos (Zo).