Research Paper

Ichnological evidence for bottom water oxygenation during organic rich layer deposition in the westernmost Mediterranean over the Last Glacial Cycle

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ABSTRACT

Organic rich layers (ORLs), deposited in the westernmost Mediterranean over the Last Glacial Cycle, have been studied integrating sedimentological and ichnological information from sediment records recovered at Ocean Drilling Program Leg 161 Sites 976 and 977. The conducted study has served to redefine the ORLs initially differentiated in sediment records from Sites 977 and 976, with seven new ORLs recognized, as well as extensions and subtraction of some parts in the ORLs previously defined. In addition, three different ORL types are distinguished according to sedimentological and ichnological features. Type 1 with intermediate thickness is highly bioturbated, mainly consisting of abundant Scolicia and Planolites, frequent Chondrites, and possible Thalassinoides in the base, which are interpreted as supporting dysoxic conditions during deposition. Type 2, corresponding to thicker intervals, shows alternance of highly to moderately bioturbated parts, revealing variable oxygen conditions—from moderate to extreme dysoxic or even suboxic. Type 3 consists of short, laminated intervals characterized by the absence of bioturbation, indicating anoxic or suboxic conditions and determining unfavourable macro benthic habitat. The amended ORLs show a correlation between the Sea Surface Temperatures and established climatic events over the Last Glacial Cycle in the Western Mediterranean.

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1. Introduction

The present study is centred on the cyclic deposition of organic carbon rich sediments from the Alboran Sea Basin over the Last Glacial Cycle. We have analysed two sediment records at the East and at the West of Alboran Sea Basin (Fig. 1), which come from two drilling sites from the Leg 161 of the Ocean Drilling Program (ODP).

These organic-rich sediments deposited in the Western Mediterranean are normally called organic-rich layers (ORLs) differentiating them from the Eastern Mediterranean “Sapropels”. The studied time interval the Mediterranean spans since the beginning of the penultimate interglacial and Marine Isotope Stage 5, ~130 ka, until the end of the Würm Glaciation over the northern hemisphere, ~11 ka (e.g., Dansgaard et al., 1993). Despite ORLs being layers enriched in Total Organic Carbon (TOC) and cyclically deposited like the sapropels, they are not equivalent layers, probably entailing a more complex set of conditions behind their deposition. ORLs are not always synchronic with sapropels and do not seem to follow the insolation maxima as sapropels do (von Grafenstein et al., 1999; Cacho et al., 2002; Rogerson et al., 2008; Rohling et al., 2015). Whereas sapropels have been extensively studied (among many others, Kidd et al., 1978; Sigl et al., 1978; Rohling and Hilgen, 1991; Rohling, 1994; Cramp and O’Sullivan, 1999; Rohling et al., 2015; Grimm et al., 2015; Grant et al., 2016; Wu et al., 2018), ORLs from the Western Mediterranean are largely unexplored, with the exception of the most recent one, the ORL1 (Bárccena et al., 2001; Cacho et al., 2002; Rogerson et al., 2008; Rodrigo-Gámiz et al., 2011; Jiménez-Espejo et al., 2015; Martínez-Ruiz et al., 2015; Pérez-Arnismo et al., 2020). However, ORLs also represent important organic carbon accumulations and record the response of the Mediterranean to palaeoceanographic and climate variability.

In general, most organic matter (OM) in the marine environment is mineralized either from primary productivity or from continental input before its burial; but when production exceeds degradation part of it is preserved in the sediment (e.g., Middelburg et al., 1999; Berner, 2003).
The dominant factor in OM preservation has been intensively debated for decades (e.g., Calvert, 1987; Pedersen and Calvert, 1990; Hedges and Keil, 1995; Hedges et al., 1997; Moodley et al., 2005; Arndt et al., 2013; LaRowe et al., 2020) particularly in view of the high variability observed over space and time in the deep ocean (Canfield, 1994; Berner, 2003; Blair and Aller, 2012; Arndt et al., 2013). For instance, past oceans have had generalized O2 depleted zones in which considerable amounts of OM accumulated and were preserved in the geological records (Jenkyns, 2010). Yet in modern oceans, the presence of large oxygen-depleted areas is limited to a very few places —e.g., the isolated basins of the Black Sea or the Baltic Sea—or the oxygen minimum zones derived from biological productivity that appear in some upwelling continental margins like Namibia or Peru. The amount of OM preserved depends on an interlaced combination of factors, such as the quantity of OM reaching the bottom due to productivity (Emeis et al., 2000), and the velocity of degradation, in turn, related to oxygenation and burial velocity, hence sedimentation rate. Other factors that can affect the degradation of OM include composition, electron acceptor availability, benthic microbial community, physical properties, and macrobenthic activity (e.g., LaRowe et al., 2020). Because the relative importance of these factors varies over time and space, OM rich intervals in the geological record could point to very diverse signatures (e.g., Aller, 1982; Middelburg, 1989, 2018; Mollenhauer et al., 2007; Zonneveld et al., 2010; Arndt et al., 2013; LaRowe et al., 2020). TOC values in the Western Mediterranean can reach values of 2.27%, as registered in the Balear Basin, or 2% in the Alboran Sea Basin, or even values over 6% in the Ionian Sea (Murat, 1999). During ODP Leg 16, the Shipboard scientific party established a limit of 0.8% TOC to define ORLs, contrasting with the values of 2% used during leg 160 of the ODP in the Eastern Mediterranean to define sapropels (Kidd et al., 1978; Murat, 1999; Emeis et al., 2000). Background TOC values found in the Western Mediterranean are also higher than those of the Eastern Basin.

In the Eastern Mediterranean Sea, the simultaneous occurrence of high productivity along with low oxygenation in the bottom waters is held to be the main factor behind sapropel deposition (e.g., Rohling et al., 2015). In the Western Mediterranean, previous work has evidenced that the main factors controlling ORL deposition are productivity and bottom water oxygenation, based on foraminifera, biomarker, and geochemical analysis (Casford et al., 2003; Meyers and Arnaboldi, 2005; Pérez-Asensio et al., 2020, among others). Debate persists about which causes are predominant, or if all events could have the same set of conditions (Rohling et al., 2015). Recent studies in the Western Mediterranean propose that productivity alone cannot produce the low oxygen conditions necessary for ORL deposition, for which reason decreasing deep-water ventilation would also be required (Rogerson et al., 2008; Rodrigo-Gámiz et al., 2011; Pérez-Asensio et al., 2020). The sedimentation rate also influences TOC content and its dilution in the sediment (e.g., Tyson, 2001); however, the fact that it remains high in the Alboran Sea Basin in the studied time would mean it is not a main controlling factor for ORL deposition in this setting.

The deep-water stagnation that leads to ORL deposition has been proposed to be produced by a combination of low aspiration over the Gibraltar Strait (Rogerson et al., 2008; Rohling et al., 2015; Pérez-Asensio et al., 2020) and a decrease in the rate of deep-water sinking over the Gulf of Lion related to buoyancy changes (Millot, 1999; Cacho et al., 2002; Frigola et al., 2008; Rogerson et al., 2008; Pérez-Asensio et al., 2020). Changes in the precipitation-evaporation balance can moreover induce salinization of the superficial waters during certain periods —not necessarily the colder periods— inducing buoyancy variations that could enhance deepwater sinking during warmer phases (Cisneros et al., 2019). Variations in deep-water ventilation are also related to climatic swifts over the northern hemisphere, for example, the ones resulting in Dansgaard-Oeschger and Heinrich events (Sierro et al., 2005; Frigola et al., 2008; Rohling et al., 2015). Despite a reported decrease in ventilation during Heinrich events due to the freshening and decreased density of superficial waters (Sierro et al., 2005; Frigola et al., 2008; Rohling et al., 2015), which may precondition posterior low oxygenation events, its effect alone would hardly suffice to promote ORL deposition. ORL1 does not show a clear correlation with these events (Rogerson et al., 2008). Variations in the Levantine Intermediate Water have also been invoked to explain the absence of influence of Heinrich events in the ORLs, due to compensation of its possible effects (Rogerson et al., 2008). Still, further investigation is required for reconstructing the palaeoceanographic conditions leading to ORL deposition elsewhere than the ORL1 (14.5–8.5 ka), which has been more profusely studied (Pérez-Folgado et al., 2004; Rogerson et al., 2008; Bazzicalupo et al.,

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Fig. 1. Location of the ODP Sites used for the study (Sites 977 and 976). The blue arrow shows the main circulation pattern of the Western Mediterranean Deep Water towards the Gibraltar Strait (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
2. Regional setting

Over the decades, diverse studies explored ventilation and circulation in the Mediterranean using models, direct observations or proxies (e.g., Wüst, 1961; Millot, 1999; Pinardi and Masetti, 2000; Millot and Taupier-Letage, 2005; Sierro et al., 2005; Frigola et al., 2008; Rogerson et al., 2008; Naranjo et al., 2012; Pinardi et al., 2015; Bazzicalupo et al., 2018; Perez-Arenillas et al., 2020). The insights they provide for paleocirculation reconstructions have changed over time, from the early stationary models to current models based on dynamic changes and sub-basin switching circulation patterns. The general and simplified oceanographic setting of the water masses in the Mediterranean includes three masses that extend over the Eastern and Western Mediterranean, in turn, are divided into multiple sub-basins. Mediterranean circulation shows an anti-estuarine pattern (Millot, 1999; Millot and Taupier-Letage, 2005) with a less saline water mass —the Atlantic Water (AW)— entering through the Gibraltar Strait and circulating superficially, dominated by winds towards the Eastern Mediterranean. Then, when it reaches the eastern part of the Mediterranean, due to excessive evaporation in the Levantine Basin, it gains salinity and density; in conjunction with northern dry winds, it suffers cyclonic sinking, thereby generating the Levantine Intermediate Water (LIW) (Bethoux and Gentili, 1999; Millot and Taupier-Letage, 2005; Pinardi et al., 2015). The LIW circulates towards the west at middle depths and finally leaves the Mediterranean over the Gibraltar Strait, contributing to Atlantic circulation (Baringer and Price, 1999; Jimenez-Espejo et al., 2015; Naranjo et al., 2015). Two other water masses, the Western and Eastern Mediterranean Deep Water (WMDW and EMDW) flow in the deep parts of the two basins, resulting from the seasonal sinking of LIW and surface waters in the northern parts of the two sub-basins owing to open sea convention and cascading that is favoured by cold winds coming from the continent during winters (e.g., Medoc Group et al., 1970; Millot, 1999; Millot and Taupier-Letage, 2005; Schroeder et al., 2008, 2012; Durrieu de Madron et al., 2013; Naranjo et al., 2015; Somot et al., 2018; Cisneros et al., 2019). The WMDW, the water mass located at the bottom of the Western Mediterranean, is formed in the Gulf of Lions in winter by the above process of cyclonic sinking (e.g., Rhein, 1995) and is also important for Mediterranean outflow, mixing with the LIW and directly contributing by means of Bernoulli Aspiration (Rogerson et al., 2008; Millot, 2014).

The Alboran Sea Basin (Fig. 1), the westernmost Mediterranean Basin, is of particular interest for palaeoenvironmental reconstructions for two reasons: 1) its high sedimentation rates allow for exceptional high-resolution studies of past oceanic conditions (e.g., Cacho et al., 2000, 2006; Martrat et al., 2007; Rodrigo-Gámiz et al., 2011, 2014; Martínez-Ruiz et al., 2015), and 2) its location between the Atlantic and the Mediterranean climate regimes, being influenced by both, and hence a key region for reconstructing the Atlantic influx and the Mediterranean Outflow as well as the Mediterranean water masses dynamics (e.g., Heburn and La Violette, 1990; Naranjo et al., 2015). The entry of AW through the Gibraltar Strait affects productivity in the Alboran Sea Basin, as the anticyclonic gyres and Atlantic Jet cause upwelling in the northern parts of the Basin (Saran, 2000). The Mediterranean water coming out from the Gibraltar Strait —the Mediterranean Outflow Water— influences the Atlantic overturning circulation, AMOC (Hernández-Molina et al., 2014; Bahri et al., 2015; Jiménez-Espejo et al., 2015). The Alboran Sea also receives the influence of water masses coming from the eastern basins, the LIW, and the WMDW.

The study sites are found at depths of 1984 and 1108 mbsl, under the influence of the WMDW (Bethoux et al., 1999). The varying conditions influencing deep water sinking in the northern sector of the basin may have influenced ORL deposition in this setting. Decreasing WMDW formation could have promoted dysoxic bottom waters over time, given that the dissolved oxygen in the Western Mediterranean Deep Water has been correlated (among other factors) to the deepwater removal influenced by climatic shifts (e.g., Rogerson et al., 2008; Mavropoulou et al., 2020).

The records studied entail an initial identification of ORLs and sediment characteristics established during ODP Leg 161. Afterwards, for many years, diverse work focused on the foraminiferal record and environmental and palaeoclimatological reconstructions have been published (e.g., Martrat et al., 2004, 2014; Pérez-Folgado et al., 2004; Combourieu Nebout et al., 2009). Notwithstanding, most of these studies focus on the Holocene and the most recent ORL. Research into the older ORLs is nearly absent and stands as a challenge for better understanding the origin of these organic-rich layers.

3. Materials and methods

The studied sediment record corresponds to the Sites 977 and 976 from Leg 161 of the ODP, and its general sedimentology and characteristics were described during the ODP cruise (i.e., Shipboard Scientific Party, 1996a), and subsequent analyses strove to identify and define ORLs present in the record (Shipboard Scientific Party, 1996a, b; Murat, 1999). Both Sites are in the Alboran Sea Basin (Fig. 1): Site 977 deeper, at 1984 m, at the east of the Alboran Ridge; and Site 976 lies at 1108 m depth in the western Alboran Sea Basin. The sediments of the selected time interval (Last Glacial Cycle) correspond to open marine hemipelagic facies (Fig. 2) consisting of nannofossil-rich silty clay with an average clay content of 81% in Site 977 (Shipboard Scientific Party, 1996a) along with nannofossil rich clay, calcareous silty clay, and clay having 30–50% of carbonate content at Site 976 (Shipboard Scientific Party, 1996b).

The age models for these records were obtained from Martrat et al. (2004, 2014), and linear interpolation was used to correlate our depth data with age.

Ichnological analysis of the selected record was based on core images obtained from the ODP database. At Site 976, images were gathered from four available holes, drilled next to each other, so as to arrive at a more precise ichnological characterization (Fig. 2). Here, ichnological analysis entailed the application of high-resolution digital image treatment using Photoshop™ Software (Magwood and Ekdale, 1994;
4. Results

4.1. Greyscale analysis in Site 977

The grey value plot presents a pattern of clear variations that correlate well with the interval and the internal variation of the previously defined ORLs (Fig. 3). Yet it also shows variations not directly correlated with the ORLs identified on ODP Leg 161 (Shipboard Scientific Party, 1996a, b). Overall, the ORLs have a characteristic decrease in grey values (contrast of 20 to 30 points with respect to the surrounding sediment), especially L4, L5, L7, and L8. Internal variability is observed in L2 and L3, however, as well as in L1, which presents an extended range of variability, having a peak beyond the range of the layer as defined in the Initial Report.

During ODP Leg 161, at least 40 ORLs were described in the first 417 m of the holes drilled in the basin. At Site 977, eight of them are located in the upper 26 m corresponding to the Last Glacial Cycle. The obtained greyscale values improve the original ORL differentiation. Original ORLs (L1 to L8) were therefore characterized in greater detail, and new ORL intervals could be identified.

In view of the ORLs initially defined, the newly conducted analysis on ORL L1 reveals a grey value increase that extends further than the original interval (Shipboard Scientific Party, 1996a, b). The ORLs L4, L5, L7 and L8 (L6 is not visible) present a clear peak in grey value that is well-correlated with the darker laminated or bioturbated layers observed in the core images, supporting the original characterization (presented in Fig. 3).

In sum, the more recently conducted research allows for a tentative definition of new ORL intervals not considered in the original proposal based on fluctuations in greyscale values.

Accordingly, a total of seven new ORL intervals are defined here (a to g, blue colour bands, in Figs. 3), and previous ORLs, originally defined during ODP campaign, intervals have been modified, through extensions or subtractions (green and red colour bands, respectively, in Fig. 3). Moreover, ORLs L2 and L3 should be reconsidered, by the subtraction of some parts, as a possible succession of different events. The new colour bands are differentiated by contrast in the greyscale (reported contrast of between 12 and 24). The TOC values measured during the ODP campaign in the new layers go from 0.4% to 0.8%, below the established limit, but these data should be taken with caution and are of low resolution. The thickness of the new layers goes from 10 cm for layer a to 40 cm for layer g, for instance, the largest one observed.

4.2. Trace fossil assemblage

Trace fossil assemblages from the studied records at Sites 977 and 976 present a low-to-moderate diversity, consisting of Chondrites, Planolites, Thalassinoides, Scolicia and less frequent Zoophycos (Casanova-Arenillas et al., 2021) (Table 1). Concerning the ORLs intervals, Chondrites, Planolites, and Scolicia are the most abundant ichnotaxa.

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Fig. 2. General lithological logs of the studied holes from Sites 977 and 976 with the position of the ORLs (L1 to L8 in Site 977 and A1 to A6 in Site 976) and the corresponding TOC values (Shipboard Scientific Party, 1996a, b). In site 977 only one hole was drilled, the 977A. 4 holes that were drilled in Site 976 according to the depths reported previously in ODP studies and published Tovar and Dorador, 2014, 2015). This method increases the visibility of biogenic structures, providing for particularly successful results with modern sediment cores, where the visibility of the traces due to low lithification is very limited.

The main ORLs for ichnological analysis were distinguished according to the depths reported previously in ODP studies and published in the ODP Leg 161 Initial Reports (Shipboard Scientific Party, 1996a, b), being based on TOC values, magnetic susceptibility and colour.

A greyscale analysis was performed in view of average vertical grey values using ImageJ® software (e.g., Schindelin et al., 2012). The average grey value for the pixels in the horizontal lines of the images is obtained, after which a plot is made to represent the vertical grey value variation. Greyscale analysis has proven useful to visualize colour changes throughout sediment cores, and in particular, changes in reflectance. By identifying “darkness” and thus possible ORL intervals, these greyscale plots can mark the location of OM enriched intervals in the sediments. Several thin horizons along the cores were excluded from this study, since changes in grey values detected were at times due to artefacts such as variations in the position of the camera, or cracks and surface imperfections produced during the treatment of the core sections. The greyscale analysis was conducted only at Site 977. The available images from Site 976 were of comparatively poor quality—sediment colour is much more homogeneous than in Site 977, the only visible colour variations being a consequence of the incidence of light when photographed. Thus, the greyscale data served for a detailed analysis of the ORLs originally defined by the Shipboard Scientific Party, as well as for the addition of new ones.
4.3. Ichnological features in the organic-rich layers

The ichnological analysis of the ORLs reveals significant variability mostly related to the presence/absence of traces, degree of bioturbation, ichniodiversity, and distribution.

4.3.1. Bioturbation in the originally defined ORLs from Site 977

The eight ORLs (L1 to L8) identified in Site 977 during ODP Leg 161 (Shipboard Scientific Party, 1996a, b) range from highly bioturbated to non-bioturbated and laminated sediments (Fig. 4; Table 2).

ORL L1 (~9 ka – 14 ka) is about 30 cm thick, presenting a mottled background with locally identifiable discrete traces. The bottom of ORL L1 presents abundant bioturbation, in particular Planolites, Scolica and Thalassinoides, and potential Chondrites. The size of the traces decreases upward. ORL L2 (~32 ka – 39 ka) corresponds to a thicker interval of 220 cm. A mottled background is locally observed. The trace fossil assemblage consists of Chondrites, Planolites, Scolica and Thalassinoides at the base. The abundance and size of biogenic structures are lower than in ORL L1, but also show a variable record throughout both ORLs, in association with colour variation in the sediment. ORL L3 (~46 ka – 62 ka) is similar in thickness to ORL L2, around 310 cm, and shares the assemblage of Chondrites, Planolites, Scolica and Thalassinoides at its base, but is less bioturbated. Like ORL L2, it shows variations in the trace fossil assemblage and the sediment colour through the ORL. In turn, ORL L4 (~85.5 ka – 86.3 ka) is a thin layer, 30 cm, characterized by clear horizontal lamination and colour banding, and a generalized absence of bioturbation. Only occasionally in the lighter parts, small and sparse Chondrites can be tentatively identified. ORL L5 (~91 ka – 93 ka) is 20 cm-thick, being very similar to ORL L4. ORL L6 (~105.8 – 110 ka) is between two core sections and its characteristics are not at all clear in the available images. ORL L7 (~125.5 ka – 126.6 ka) is 25 cm-thick and resembles ORLs L5 and L4, except that at the top of this layer, a massive and sandy interval appears in which discrete traces attributable to Planolites of less than 1 cm can be observed. ORL L8 (~127.6 ka – 129.3 ka) is a bioturbated layer, 40 cm-thick, very similar to ORL L1. The trace fossil assemblage consists of Chondrites, Planolites, and Scolica with an upward increase in the trace size and bioturbation percentage.

4.3.2. Bioturbation in the ORLs from Site 976

The six ORLs (A1 to A6) from records at Site 976 differentiated during ODP Leg 161 (Shipboard Scientific Party, 1996a, b) are characterized by the presence of bioturbation and the absence of lamination (Fig. 5; Table 3). The ORLs from Site 976 present an incomplete chronostratigraphy and cannot be directly correlated in age or appearance with the ones from Site 977. Still, detailed characterization is interesting to discern lateral variations within the Basin and during ORL deposition.

ORL A1 has a similar appearance in the four drilled holes (Figs. 2 and 5), corresponding to a 90 cm bioturbated section and showing a mottled background. The trace fossil assemblage comprises Chondrites, Planolites, Thalassinoides, and Scolica, the last especially abundant in the lower part. A decrease in the degree of bioturbation, abundance and size of trace fossils is observed upward. ORL A2 presents features similar to those of ORL A1, with Chondrites, Planolites and Thalassinoides, and Scolica in the lower part. A reduction in size and abundance of the discrete traces is observed upward. Locally, a weak banding could be differentiated in the middle part, associated with the darker sediments. ORL A3 appears as a long, 320 cm, not always well-preserved layer. Bioturbation is moderate, with local increases in abundance in the middle and upper parts. Some darker intervals lack trace fossils, but banding/lamination is likewise absent. The trace fossil assemblage mainly comprises Chondrites, Planolites and Thalassinoides, with occasional Scolica. Tentatively, some structures could be assigned to Zoophycos. ORL A4 refers to a 150–170 cm thick section with low and sparsely distributed bioturbation, though higher abundance is noted upward. The trace fossil assemblage consists of Chondrites, Planolites and Thalassinoides, with Scolica mainly in the upper part. Tentatively, like in ORL A3, some structure(s) could be assigned to Zoophycos. ORL A5 is a thin, 2 to 10 cm thick, bioturbated layer with Chondrites and Planolites, and probably Scolica. Locally, weak banding is envisaged. +ORL+ A6 +, about 60–70 cm thick, is moderately bioturbated, with an assemblage of Chondrites, Planolites, Scolica and Thalassinoides.

4.4. Ichnological and sedimentological features: Types of ORLs

Ichnological (ichnotaxonomy, distribution, size, and abundance of the traces) and sedimentological features —including the thickness of the ORL intervals and grey values in the studied records— allowed us to characterize different ORL types beyond the ones originally described at Sites 976 and 977 (Shipboard Scientific Party, 1996a, 1996b). Differentiation was more feasible for Site 977, as the images and data were more detailed, whereas for Site 976 merely general discernment was attempted. Only the originally described ORLs from ODP are included in this analysis to detail palaeoenvironmental interpretations previously proposed. The differentiated types are as follows (Fig. 6):

Type 1: Characterized by a thickness ranging from 30 to 40 cm in Site 977 and up to 120 cm in 976. Bioturbation is generalized, with the presence of a mottled background, and with trace fossils registered throughout the entire ORL, but showing differences from bottom to top. At the base, burrows are abundant and range from 5 cm to a few millimetres. The size and abundance gradually decrease upward. Trace fossil assemblage consists of abundant Scolica and Planolites, frequent Chondrites, and possible Thalassinoides in the base. ORL L1 and ORL L8 of
Site 977 (Table 2), and ORLs A1, A2 and A6 from Site 976 (Table 3) are assigned to this type.

Type 2: Characterized by thick intervals, up to 310 cm, and cyclic changes in colour and bioturbation features, as well as a clear greyscale internal fluctuation. In Site 977, they correspond to the ORLs L2 and L3 (Table 2), and in Site 976, they could be assigned to the ORLs A3 and A4 (Table 3). Given their thickness and features, an evident differentiation from other parts of the cores, not associated with ORLs, is unclear. Even though a transition from non-ORL bioturbated sediment with big traces to an ORL having unbioturbated or low-bioturbated sediments is recognized. Type 2 also includes heavily to moderately bioturbated intervals.

Type 3: It is characterized by well-developed laminations and absence of bioturbation, as well as an evident peak in the inverted greyscale, and magnetic susceptibility reduction, determining a good differentiation from the surrounding sediments. This type is assigned to ORLs L4, L5 and L7 of Site 977, corresponding to intervals about 20 to 30 cm thick, registered from the end of the penultimate glacial maximum to present (Table 2). It cannot be discarded that ORL L6 could also correspond to type 3, but the location between two coring sections makes a conclusive assignation difficult. At Site 976, these laminated ORLs are not present (Table 3).

5. Discussion

During ODP Leg 161, other than the classical definition of ORLs based on TOC values (Murat, 1999), the shipboard party relied on further characteristics, e.g., colour and magnetic susceptibility. In the Alboran Sea Basin, significantly higher sedimentation rates than in the eastern basins led to dilution and lower TOC content in ORLs and higher background values. Thus, the ORL definition was based on a 0.8% minimum TOC together with colour contrast and magnetic susceptibility (Murat, 1999). In addition to this, as mentioned, the greyscale was used to extend information based on the observed ichnological features, even though not all the original ORLs present a clear differentiation when the core surface is observed.

5.1. Ichnological features in the ORLs and environmental implications: The role of anoxia

In general, the ichnological information has proven to be a very useful proxy for the characterization of past anoxic events as the Faranoí Event (upper Hauterivian; Rodríguez-Tovar and Uchman, 2017), the Bonarelli Event (Cenomanian-Turonian boundary; Uchman et al., 2008, 2013a, 2013b; Rodríguez-Tovar et al., 2009, 2020b; Rodríguez-Tovar and Uchman, 2011; Monaco et al., 2012, 2016) and the Toarcian Oceanic Anoxic Event (Early Toarcian; i.e., Rodríguez-Tovar and Uchman, 2010; Reolid et al., 2014; Míguez-Salas et al., 2017, 2018; Rodríguez-Tovar et al., 2017, 2019b). For further information, see the recent review on the Toarcian Oceanic Anoxic Event revealing the variable oxygenation and the absence of global and generalized anoxia (Rodríguez-Tovar, 2021).

The ichnological characteristics of more recent sediments such as the ORLs have been poorly studied, however. Scarce and undetailed references to bioturbation were originally included in ORLs descriptions in the ODP Leg 161 Initial Reports (Shipboard Scientific Party, 1996b), and just recently more detailed ichnological analyses were undertaken (Pérez-Asensio et al., 2020).

The occurrence of ORLs involves complex processes that may depend on such factors as primary productivity, anoxic conditions, and sedimentation rate, which play a variable role according to different authors (Müller and Suess, 1979; Pedersen and Calvert, 1990; Kuyers et al., 2002; Rohling et al., 2015). Again, not only the increase in the OM flux is determinant for the formation of these layers; in fact, oxygen restriction without enhanced productivity might not result in ORLs deposition (Rogerson et al., 2008).

According to the obtained data, some of the ORLs registered during the Last Glacial Cycle in the Alboran Sea Basin at Sites 977 and 966 support dysoxic (2.0–0.2 ml/l O₂) to suboxic (0.2–0.0 ml/l O₂) and anoxic conditions (0.0 ml/l O₂), following values from Tyson and
tervals presenting low or absent bioturbation. This suggests variable variations in colour, TOC, and trace fossil assemblage are observed, with environmental conditions during ORL deposition. In Type 2 ORL, dance and size of biogenic structures reveal the deterioration of palae (corresponding to non-ORLs) with TOC values below 0.8% are observed, and the local presence of lamination.

During deposition of the Type 1 ORL, generalized dysoxic conditions are found, and oxygen levels are maintained above the oxygen threshold. The ichnological assemblage associated with such conditions features a well-developed trace maker community. Upward, decreases in both abundance and size of biogenic structures reveal the deterioration of palaeo-environmental conditions during ORL deposition. In Type 2 ORL, variations in colour, TOC, and trace fossil assemblage are observed, with lighter sediment presenting moderately abundant traces and darker intervals presenting low or absent bioturbation. This suggests variable oxygen conditions during the ORL deposition, from moderately to extremely dysoxic (Fig. 7C).

Type 3 ORL corresponds to laminated and non-bioturbated short intervals, indicating an inhabitable macrobenthic environment. The absence of a macrobenthic trace maker community supports suboxic or anoxic conditions (Fig. 7D).

According to the above, even though ORLs have been commonly related with periods of deep-water stagnation and oxygen depletion (e.g., Rogerson et al., 2008; Rohling et al., 2015; Pérez-ASENSIO et al., 2020), and largely associated with laminated, non-bioturbated, or only scarcely bioturbated sediments, our results are indicative of significant variability in palaeo-environmental conditions. All the originally proposed ORLs at Site 976 and most of those at Site 977—corresponding to ORLs types 1 and 2—are bioturbated, including both discrete traces and bioturbated sediment. This fact supports the absence of generalized anoxic conditions during some of the ORL intervals in the Alboran Sea Basin, but rather oxygenated conditions favouring the development of a macrobenthic trace maker community and, in turn, bioturbation. Only ORLs assigned to Type 3, showing lamination and absence/scarcity of bioturbation, could be indicative of such anoxic conditions.

5.2. ORL position, fact or artefact?

Traditionally ORLs are defined by increased TOC values with respect to surrounding sediments. Nonetheless, post-depositional modifications can lead to a drop in TOC percentages—the presence of “ghost” layers only detectable by geochemical data, as observed in other basins (Jung et al., 1997; Larrañaga et al., 2006; Löwemark et al., 2006). Thus, colour and ichnological information evidencing variations in oxygen conditions even when TOC enrichment has been lost could be used to recognize ORL intervals irrespective of TOC values. Based on this possibility, we tentatively propose the existence of new intervals, including some that could have TOC contents below the 0.8% TOC threshold.

In Fig. 8 these new intervals are presented, including some images that serve to visualize variations in the core surface. The intervals are thin and tend to correlate with the fluctuations observed in the [Ca\(^{2+}\)] plot and the Sea Surface Temperature (SST) (Fig. 8). Such good correlation evidences that colour variations respond to climate changes taking place in the Northern Hemisphere and over the Alboran Sea.

As mentioned before, in addition to the new ORL intervals proposed, some of the original ORLs have been modified by extensions or subtractions of certain parts. One clear example is ORL1, profusely studied, with a well-known position and age. According to the grey-scale analysis, its position relative to the ODP initial reports must be modified, by extension in the lower part, suggesting that this layer is probably thicker than originally indicated. This proposal is concordant with the age obtained in studies of the ORL1 in other records in the Mediterranean Sea (Cacho et al., 2002; Rogerson et al., 2008; Rodrigo-Gámez et al., 2011; Martínez-Ruiz et al., 2015). Furthermore, the extension is in consonance with proposed ages of ORL L1 in the Alboran Sea (Jiménez-ESPEJO et al., 2015; Pérez-ASENSIO et al., 2020), since when converting the depth data to age using the Martrat et al. (2004) age model, the ORL L1 extends from 14 ka to 8 ka. The opposite occurs with ORLs L2 and L3, where colour changes might evidence an overestimation of the thickness of ORL L2 and L3 originally considered.

According to the above, the originally proposed ORL position, number, thickness and age in the Alboran Sea Basin could be different in some cases. Variations in the colour and ichnological features within thicker ORLs could, moreover, be indicative of changes in palaeo-environmental conditions during the ORLs deposition, revealing interruptions during ORL deposition or the existence of multiple shorter ORL events that were combined in the original description.

5.3. Palaeoenvironmental and palaeoceanographic implications

It must be stressed that ORLs cannot be correlated with the eastern sapropels (Rohling et al., 2015): a major difference, apart from lower carbon content, resides in chronology, since ORLs were not always deposited during the same time intervals. As stated by Rogerson et al. and Pearson (1991), as indicated by variability in the ichnological features and the local presence of lamination.

In oxic conditions with a steady flux of benthic food, light sediments (corresponding to non-ORLs) with TOC values below 0.8% are observed, and a well-developed trace maker community determines a variable number of discrete traces imposed upon a mottled background (Fig. 7A). The ichnological assemblage associated with such conditions features the presence of more or less abundant Thalassinoides and Planolites, with punctual Scolicia and Zoophyces. Oxygen levels are maintained above the dysoxic threshold with certain fluctuations, which produced the variations evident in the trace fossil assemblage and abundance.

During deposition of the Type 1 ORL, generalized dysoxic conditions with abundant benthic food gave rise to discrete traces, and a mottled background, in combination with darkly coloured sediments and high TOC values of 0.8 to 1.2% (Fig. 7B). Dysoxic conditions impeded a well-developed trace maker community. Upward, decreases in both abundance and size of biogenic structures reveal the deterioration of palaeo-environmental conditions during ORL deposition. In Type 2 ORL, variations in colour, TOC, and trace fossil assemblage are observed, with lighter sediment presenting moderately abundant traces and darker intervals presenting low or absent bioturbation. This suggests variable oxygen conditions during the ORL deposition, from moderately to extremely dysoxic (Fig. 7C).

Type 3 ORL corresponds to laminated and non-bioturbated short
(2008), ORLs do not occur during pluvial maxima every time; and the origin cannot, therefore, be directly related to the irruption of freshwater. In the Eastern Mediterranean sapropel origin is described as a result of an increase in precipitation and subsequent freshening of the surface layer that produces buoyancy increase and deep-water stagnation, in combination with productivity blooms produced by the nutrients reaching the sea within the rivers (Rohling et al., 2015). It is possible, however, that the irruption of freshwater from continental ice not coincident with pluvial maximum, especially from the Alps, could induce the buoyancy increase decoupled from pluvial maxima during deglaciation events (Rogerson et al., 2008).

Recent works, focused on the same ODP Sites from the Alboran Sea Basin, demonstrate that there is a correlation between the ichnological features variations and palaeoceanographic conditions, especially in terms of changes in ventilation and benthic food availability (Casanova-Arenillas et al., 2021). Thus, the integration of ichnological information with other sedimentological characteristc is one key for understanding the palaeoenvironment associated with the different types of ORLs over the Last Glacial Cycle. The occurrence of the ORLs—whether previously defined or tentatively proposed here—is coherent with restricted ventilation during some of the warming periods over the last interglacial, and at least partial oxygenation occurring between these depositional events (Fig. 8). The significance of these restriction events in combination with factors including the LIW characteristics could have led to the differences among the different ORLs, or even stand as the main cause behind these differences, as LIW composition can affect the sinking and composition of the WMDW (Incarbona and Sprovieri, 2020).

Notably, during Heinrich events, low saline water coming from the polar iceberg melting entered through the Gibraltar Strait, impacting circulation in the Mediterranean (Cacho et al., 2002; Sierra et al., 2005), notwithstanding, it did not produce substantial deep-water restriction (Sierra et al., 2005), which is coherent with the apparent absence of any relation between the Heinrich events and either the greyscale of the bioturbational features in the studied record. Over the Last Glacial Cycle, intense variation in atmospheric conditions resulted in rapid changes in climate conditions over the Western Mediterranean (Martrat et al., 2004; Bizzalupuro et al., 2018), hence in the atmosphere/ocean dynamics, affecting deep-water masses and their ventilation (Cacho et al., 2002). In particular, the last glacial maximum is associated with cold and arid conditions (Lionello, 2012) that affected oceanographic conditions driving ORL formation. Still, the correlation of ORLs with climatic events is not fully understood. Comparison of the three differentiated types of ORLs at Site 977 with the SST record (Martrat et al., 2004) in conjunction with the use of calcium ion concentration data ([Ca$^{2+}$]) for better visualization of the stadial/interstadial variation in the northern hemisphere (Rasmussen et al., 2014), and the magnetic susceptibility and TOC contents (Shipboard Scientific Party, 1996b), would evidence diverse environmental conditions for these ORL types (Fig. 8). Meanwhile, [Ca$^{2+}$] in the ice cores is an excellent proxy for stadial in the northern hemisphere, as it records the dust concentration, which is indicative of changes in regional and hemispheric circulation (Fischer et al., 2007, Rasmussen et al., 2014).

Table 2

<table>
<thead>
<tr>
<th>ORL</th>
<th>Type</th>
<th>Sedimentary features</th>
<th>Ichnological features</th>
<th>grey values</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>977</td>
<td>1.1</td>
<td>Type 1</td>
<td>30 to 40 cm sections with no sedimentary structures</td>
<td>Abundant Scolicia and presence of Planolites, Chondrites and Thalassinoides at the base of the layer. The size and abundance of the traces decrease from bottom to top of the section</td>
<td>105-95</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>Type 2</td>
<td>220 cm section with high cyclical variability in colour</td>
<td>Highly bioturbated in the base with Thalassinoides, Planolites and Chondrites. A gradual decrease in size and abundance of the discrete traces</td>
<td>113-88</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>Type 2</td>
<td>310 cm section with cyclical variability in colour and sedimentological features. Higher values in greyscale towards the top of the section</td>
<td>Bioturbated in the base with Chondrites, Thalassinoides and Scolicia</td>
<td>123-87</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>Type 3</td>
<td>30 cm short section with lamination and two greyscale levels, higher values in the top middle section</td>
<td>Low bioturbated to no-bioturbated, with only Chondrites as a possible discrete trace. Abrupt decrease of bioturbation at the beginning of the ORL</td>
<td>119-106</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>Type 3</td>
<td>20 cm short section with lamination. Abrupt changes in the greyscale values alternating between darker and lighter sediments</td>
<td>Low to no-bioturbated, with only Chondrites as possible discrete trace</td>
<td>115-110</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>Type 3*</td>
<td>Not studied in detail due to core limitations</td>
<td>From the base to the sand intrusion, no to low bioturbation with only Chondrites as a possible trace. The top of the layer presents a dark coloured interval with abundant Planolites</td>
<td>116-92*</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>Type 3</td>
<td>40 cm laminated section, with alternating changes in greyscale value. The top presents a sand intrusion followed by non-laminated sediment</td>
<td></td>
<td>90-72</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>Type 1</td>
<td>40 cm section with no lamination. Greyscale variations with two intervals, with lighter sediment in the base</td>
<td>Abundant Scolicia, presence of Planolites and Chondrites. Abundance and size of the Scolicia higher in the top of the layer, making the colour of the sediment lighter</td>
<td>103-86</td>
</tr>
</tbody>
</table>
allowing for a diverse trace maker community. At the end of the Last Glacial Period, enhanced primary productivity has been linked to Atlantic inflow in the Alboran Basin because of the wind and jet induced upwellings (Ausín et al., 2015a, 2015b) during the end terminations and Younger Dryas; a similar context could be envisaged for the TII.

Type 2, including thicker ORL intervals with internal cyclic changes in bioturbation and colour than when plotted with SST and \([\text{Ca}^{2+}]\), shows a correlation with the D-O interstadial-stadial cycles. Assuming a direct correlation between the climate changes in the Mediterranean and the deep-sea bottom conditions (e.g., Martrat et al., 2004; Frigola et al., 2008), these cyclic variations suggest oxygenation changes throughout the entire Alboran Basin during the period of deposition of these thicker layers.

Type 3 ORL correlates with warm periods, except for ORL L4, which is associated with a cold phase. Type 3 is interpreted to be related to suboxic/anoxic conditions based on the absence of bioturbation and a well-developed lamination. When considering climate conditions, the relation to warming phases is recognized but points to highly variable correlation; at different phases of a warm interstadial, at the beginning and the end of the warming phase, and at the peak of the interstadial
Interestingly, some of the Type 3 ORL ages coincide with the low $\delta^{18}O$ values in Soreq cave speleothems (Bar-Matthews et al., 2000) from the Eastern Mediterranean related to sapropel formation: ORL L4 (~85.5–86.3 ka) could match low $\delta^{18}O$ (~85–79 ka) related to S3 formation (83 ka; Rossignol-Strick and Paterne, 1999), while ORL L7 (~125.5–126.6 ka) fits with the low $\delta^{18}O$ (~124–119 ka) related to S5 formation (124.2 ± 2 ka; Rossignol-Strick and Paterne, 1999). Even though we cannot assign a type to ORL L6, due to visibility issues, it is dated at ~105.8–110 ka, and could coincide with the $\delta^{18}O$ (~108–100 ka) related to S4 (103.3 ± 3.4 ka, Rossignol-Strick and Paterne, 1999). This means that not all the ORLs are decoupled from the sapropel events in the East, and that the conditions producing sapropels likewise bear an impact on ORL formation at certain points of the geological record, and interestingly this coincidence is with the best defined, bioturbation lacking, suboxic/anoxic ORLs from the Alboran Sea Basin.

Considering the subtractions and additions of the Original ORLs (Fig. 8) and the new, tentatively defined ORLs (a, b, d, e, f, g in Fig. 8), a clear coincidence can be seen in many cases with the climatic variations of the northern hemisphere. The fact that some of them appear in the middle of warm periods or during warming phases agrees with the theoretical model of deep-water renewal being controlled by winter’s cold north winds, and to the entry of freshwater from continental ice

### Table 3

<table>
<thead>
<tr>
<th>ORL</th>
<th>Type</th>
<th>Sedimentary features</th>
<th>Ichnological features</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>976</td>
<td></td>
<td></td>
<td>Highly bioturbated with Chondrites, Planolites and Thalassinoides. Scolicia is abundant in the base and probably present in the middle part of the interval. Burrow sizes increase from the bottom to the middle (30 cm) and then decrease to the top</td>
<td>1.13, 0.8, 0.95, 0.93</td>
</tr>
<tr>
<td>A1</td>
<td>Type 1</td>
<td>100 cm layer without identifiable sedimentary structures</td>
<td>Presence of Scolicia in the base. Chondrites, Planolites and Thalassinoides can be identified in the rest of the interval. The abundance and size of the burrows increase from the bottom to the top of the layer (especially seen in hole C), with a decrease from the middle part (60 cm) in hole D</td>
<td>1.09, 1.1, 0.97, 0.75, 0.560</td>
</tr>
<tr>
<td>A2</td>
<td>Type 1</td>
<td>110 to 50 cm layer without identifiable sedimentary</td>
<td>Presence of Chondrites, Planolites and Thalassinoides in the bottom, middle and top of the section. Zoophycos appears at the top of the layer. The size and abundance of the burrows are low, increasing in the middle (190–210 cm) and top of the ORL section</td>
<td>0.97, 1.08, 0.75, 0.560</td>
</tr>
<tr>
<td>A3</td>
<td>Type 2</td>
<td>A long section of up to 320 cm. Variation in grey value with several colour cycles</td>
<td>Possible presence of Scolicia in the middle and top of the layer. Zoophycos in the top</td>
<td>0.82, 1.1, 0.97, 0.92, 1.01</td>
</tr>
<tr>
<td>A4</td>
<td>Type 2</td>
<td>Length up to 170 cm in section without identifiable</td>
<td></td>
<td>1.19, 1.42, 1.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sedimentary structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>–</td>
<td>Short 10–5 cm layer with no structures</td>
<td>Highly bioturbated with Chondrites and Planolites</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>Type 1</td>
<td>50–60 cm long with greyscale variations from dark to lighter sediment</td>
<td>Chondrites, Planolites and Thalassinoides. Scolicia over the beginning of the layer. The trace size and abundance decrease from the bottom to the top of the layer</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6.** Examples of differentiated ORL types with description and schematization.

**Fig. 7.** Top: Schematization of the oxic regimes and tiering according to Tyson and Pearson (1991). Bottom: Scenarios for oxygen conditions according to the ORL types proposed (see text for explanation).
Fig. 8. Correlation between the greyscale and colour values, TOC, magnetic susceptibility, and sea surface temperature (SST) for Site 977. The position of the ORLs is indicated, with differentiation between the original proposal from the initial reports (grey), the added parts (green) and the removed parts (red), and the new defined ORLs (a to g; blue). MIS: Marine Isotope Stage. The 6 Heinrich Events are indicated in the left part of the figure. In addition, 4 details of the core surface of both new defined ORLs and changes in the previously defined ORLs are added indicated with the letters A, B, C and D. [Ca$^{2+}$] here is a proxy for stadial in the northern hemisphere, as it records the dust concentration over Greenland, indicative of changes in regional and hemispheric circulation changes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
6. Conclusions

A detailed sedimentological and ichnological analysis of the ORLs deposited over the Last Glacial Cycle in the Alboran Sea Basin and recorded at ODP Sites 977 and 976, reveals the presence of different types of ORLs, and supports variable environmental conditions over this time interval resulting in ORL deposition. Three ORL types (1, 2 and 3) are recognized according to variable palaeoenvironmental parameters, and main variations in oxygen conditions. Type 1, with an intermediate thickness (30 to 40 cm), corresponds to high to moderate bioturbated intervals. The trace fossil assemblage consists of abundant Scolicia and Planolites, frequent Chondrites, and possible Thalassinoïdes in the base, supporting dysoxic conditions during deposition, which prevented a well-developed trace maker community. Type 2 corresponds to thicker intervals (up to 310 cm), showing an alternate of highly to moderately bioturbated intervals, revealing variable oxygen conditions from moderate to extremely dysoxic or even suboxic ones. Type 3 consists of thin (20 to 30 cm), laminated intervals characterized by an absence of bioturbation, indicating anoxic or suboxic conditions and determining an unfavourable macrobenthic habitat.

Ichnological and colour analyses made it possible to refine the original ORL characterization, by adding new ones, or extending or subtracting parts of the initially described ORLs. Seven new intervals have been tentatively added (a, b, c, d, e, f, g) to the originally proposed ORLs at Site 977. The amended ORLs show a correlation with the Sea Surface Temperatures and the recognized climatic events over the Last Glacial Cycle in the Alboran Sea Basin.

The conducted integrative research improves the original definition of the ORLs based exclusively on colour contrast, magnetic susceptibility, and TOC, thus providing new insights to advance our understanding of ORL deposition in the Western Mediterranean.

Data availability

The available data for greyscale can be accessed in the supplementary material as “GreyScale 977”.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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