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MERCURY INTRUSION POROSIMETRY TO EVALUATE THE INCIDENCE OF BIOTURBATION ON POROSITY OF CONTOURITES

FRANCISCO J. RODRÍGUEZ-TOVAR[1,*], OLMO MIGUEZ-SALAS[1] & JAVIER DORADOR[2]

[1]Departamento de Estratigrafía y Paleontología, Universidad de Granada, 18002 Granada, Spain.
E-mails: fjrtovar@ugr.es; olmoms@ugr.es
[2]Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK. E-mail: Javier.Dorador@rhul.ac.uk
*Corresponding Author.

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*Abstract***.** The effect of bioturbation on rocks' flow-media properties (e.g., porosity and permeability) and its impact on reservoir quality has been previously documented. However, the occurrence of ichnological features and their impact on rock properties in contourite deposits, a facies of economic interest, is poorly known. The study evaluates the effects of bioturbation on different types of contourite facies, particularly dominantly calcareous contourites and sandy clastic contourites, using mercury intrusion porosimetry. Porosity (total, intraparticle and interparticle) is characterized in selected samples, comparing the host rock with the infills of the trace fossils; *Macaronichnus*, *Parahaentzschelinia* and *Scolicia* from El Adergha and Kirmta sections in Morocco, and *Chondrites*, *Planolites* and *Thalassinoides* from Petra Tou Romiou, Agios Konstantinos, and Kalavassos outcrops in Cyprus. The obtained data reveal variance between porosities according to different types of contourite facies and trace fossils. Total porosity shows similar values for the host sediment in clastic and calcarenitic contourites, but interparticle porosity is nearly absent in calcarenitic contourites, where intraparticle porosity is almost exclusive. This is owing to the abundance of foraminifera chambers that increase intraparticle primary porosity. Regarding the ichnotaxa, higher total porosity values were obtained from the infilling material of *Parahaentzschelinia*, *Scolicia* and *Macaronichnus*, which could be related with the redistribution of grains by trace makers during feeding activity. Considering the impact of bioturbation on reservoir quality, there are significant differences between clastic and calcareous contourites. In the clastic contourites, bioturbation increases in the total porosity, particularly interparticle porosity, suggesting a positive impact for the reservoir properties of the studied units. However, in calcarenitic and muddy chalk contouritic facies, bioturbation has a minor effect on porosity and no predictable influence on the flow-media characteristics.

Introduction

Over the last 20 years, the modification of rock´s petrophysical properties – e.g., porosity and permeability – by bioturbation, and its impact on reservoir quality have been explored (Gingras et al. 2004a, 2012; Pemberton & Gingras 2015; see recent review in Liu et al. 2019). Bioturbation potentially alters the fabric and texture of a sedimentary rock, including primary sedimentary structures (i.e., lamination), redistribution of grains, and, at a minor scale, compaction. It also prompts certain geochemical changes owing to the incorporation of organic matter, organism activity, feeding behavior, etc., determining significant changes of the primary sedimentary matrix (Gingras et al. 2012; Pemberton & Gingras 2015; Liu et al. 2019). Bioturbation was

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initially considered to be a reducing factor for porosity and permeability, but several studies have shown that substantial enhancement is also produced (Over 1990; Gingras et al. 2004b, 2012; Pemberton & Gingras 2015). Pemberton and Gingras (2005) classified flow media based on the sedimentological, ichnological, diagenetic, and stratigraphical context, recognizing several interrelated scenarios. In the wake of their paper, some studies have explored a variety of depositional environments, sedimentary rocks, and ichnotaxa, evaluating the influence of bioturbation on the distribution of porosity and permeability, and the implications for reservoir exploitation (i.e., Gordon et al. 2010; Knaust 2013, 2017; La Croix et al. 2013, 2017; Eltom et al. 2019; Liu et al. 2019; Knaust et al. 2020).

Contourites, as sediments deposited or substantially reworked by the persistent action of bottom currents (Rebesco et al. 2014), may play an important two-fold role in petroleum systems (Viana & Rebesco 2007; Viana et al. 2007; Viana 2008; Rebesco et al. 2014; Shanmugam 2017). At the regional/global scale, changes in the seafloor topography induced by bottom currents can alter sediment accumulation and create sub-basins conforming sediment traps or serving as gateways for sediment transfer (Rebesco et al. 2014). Coarse-grained contourites can form hydrocarbon reservoirs, whereas fine-grained contourites might represent seals and/or source rocks. Overall, comparatively little information exists on the incidence of ichnological features on rock properties in contourite deposits, a facies of economic interest. The limited data pertaining to the influence of bioturbation in modifying porosity and permeability in contourites can be traced to the lack of detailed ichnological analyses conducted on contourites. From the earliest reports of contourites, ichnological data has played an important role, being even considered as a diagnostic feature of contourite facies (see Rebesco et al. 2014). However, detailed ichnological analyses have been scarce until the last years, revealing the importance of ichnology as a proxy for characterization and interpretation of contourites and the differentiation respect to other deep-sea deposits as turbidites and hemipelagites/pelagites (e.g., Wetzel et al. 2008; Rodríguez-Tovar & Hernández-Molina 2018; Dorador et al. 2019, 2021; Miguez-Salas & Rodríguez-Tovar 2019a,b, 2020; Rodríguez-Tovar et al. 2019a, b; de Castro et al. 2020a, b; Hüneke et al. 2020; Miguez-Salas et al. 2020).

On this context, the number of ichnological studies involving outcrop contourite deposits has increased significantly, particularly in the case of clastic and calcareous contourites, from muddy to silty/sandy grain size (see Miguez-Salas & Rodríguez-Tovar 2020). The new ichnological information available supports studies about bioturbation and reservoir properties in contourite deposits. The aim of the present research is to apply, for the first time, the mercury intrusion porosimetry technique to evaluate the effects of bioturbation on different types of contourite facies. Particularly, sandy clastic and calcareous contourites from the Late Miocene Rifian Corridor of Morocco (Capella et al. 2017) and the Eocene-Early Miocene of Cyprus (Stow et al. 2002), respectively.

Material and methods

Studied samples

The studied samples were selected after detailed outcrop and laboratory observations of the contouritic facies from Morocco and Cyprus (Fig. 1). Selection was based on the lithology (type of contourite) and the ichnological features present — i.e. ichnotaxa, abundance of bioturbation, and burrow infill characteristics (passive *versus* active) of the trace fossils (Miguez-Salas & Rodríguez-Tovar 2019b, 2020).

Clastic contourites (El Adergha and Kirmta sections, Morocco). Clastic contourites samples were collected from El Adergha and Kirmta sections, outcroping in the Saiss Basin (Rifian Corridor; Morocco) (Fig. 1). Both outcrops record contouritic sandstones from the Late Tortonian (Capella et al. 2017). The El Adergha outcrop consists of two main sandstone units (Fig. 1); the lower unit presents 4-5 m of sandy to silty heterolithic planar bedding facies with ripple lamination, whereas the upper sandstone is up to 20 m thick and contains cross-stratified bedsets that are part of westward migrated 2D dunes. The Late Tortonian Kirmta section consists of three sand units encased by blue marls. The sand units are over 500 m wide, up to 10 m thick, and display concave-up channel geometries. The channels show minor erosional incision and are filled by a 2D unidirectional dunes; foresets are difficult to recognize due to inten-

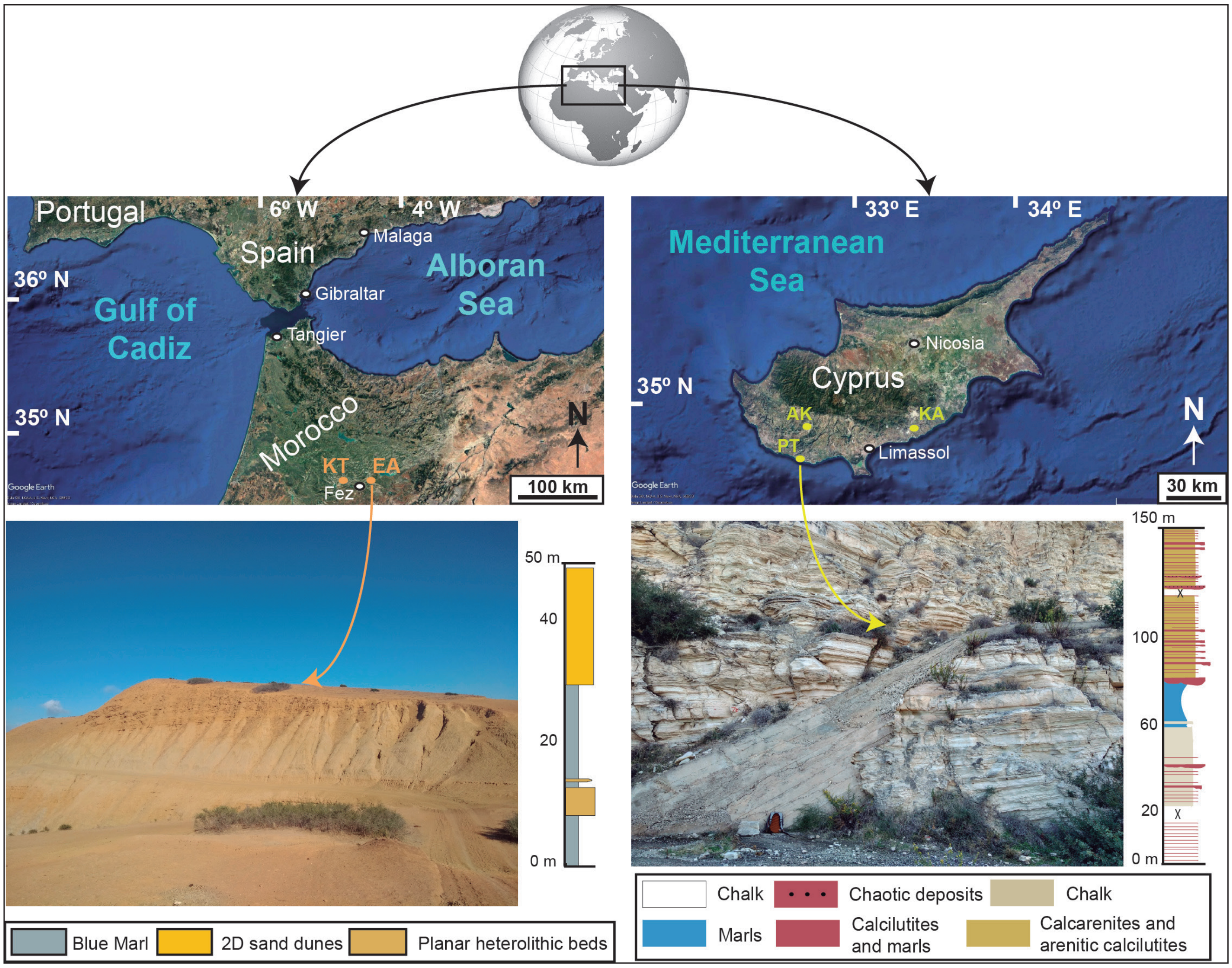

Fig. 1 - Location of studied sections in Morocco: El Adergha (EA) and Kirmta (KT); and Cyprus: Petra Tou Romiou (PT), Kalavassos (KA) and Agios Konstantinos (AK); with outcrop views of El Adergha and Petra Tou Romiou.

se bioturbation. Bed thicknesses are of dm-scale, with a maximum thickness of 80 cm. Selected samples in El Adergha and Kirmta sections containing *Macaronichnus*, *Parahaentzschelinia* and *Scolicia* (Miguez-Salas & Rodríguez-Tovar 2020; Figs. 2A-C, 3).

Calcarenitic contourites (Petra Tou Romiou and Agios Konstantinos sections) and muddy chalk contouites (Kalavassos section) (Cyprus). Calcarenitic and muddy chalk contourites were collected in Cyprus; calcarenitic contourites in Petra Tou Romiou and Agios Konstantinos sections and muddy chalk contourites in Kalavassos section (Fig. 1). Eocene-Middle Miocene deep-water deposits in Cyprus mainly correspond to the Lefkara and Pakhna formations (Edwards et al. 2010). The Lefkara Formation mainly consists of pelagic or hemipelagic chalky sediment accumulation, with a significant influence of bottom currents and punctual distal turbiditic episodes (Miguez-Salas & Rodríguez-Tovar 2019a, b; Hüneke et al. 2020). The Pakhna Formation, deposited during the Early to Late Miocene, presents calcilutitic and calcarenitic bioclastic contourites of different thicknesses (Hüneke et al. 2020). The Petra Tou Romiou outcrop is a 150-m thick carbonate-dominated succession that records the middle-upper Lefkara Formation and the Pakhna Formation (Fig. 1; Hüneke et al. 2020). Selected samples from the Petra Tou Romiou outcrop belong to facies F3a, thin calcarenite beds with gradational boundaries and globigerinid wackestone–packstone microfacies, from Hüneke et al. (2020), interpreted as bioclastic sandy bottom-current deposits (reworking of pelagic sediments), and include *Thalassinoides* (Miguez-Salas & Ro-

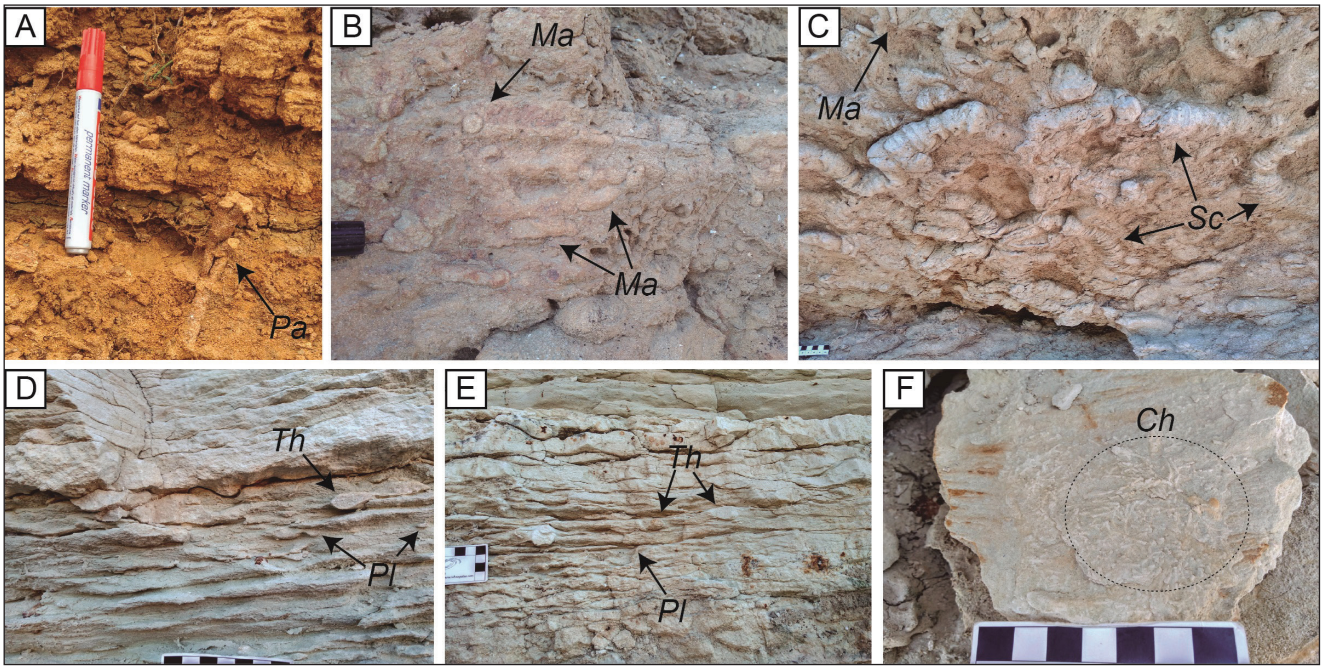

Fig. 2 - Outcrop views of selected ichnotaxa in the studied sections. A) *Parahaentzschelinia* (*Pa*) from the El Adergha section. B) *Macaronichnus* (*Ma*) from the El Adergha section. C) *Macaronichnus* (*Ma*) and *Scolicia* (*Sc*) from the Kirmta section. D, E) *Planolites* (*Pl*) and *Thalassinoides* (*Th*) from the Petra Tou Romiou section. F) *Chondrites* (*Ch*) from the Kalavassos section.

dríguez-Tovar 2019a, b; Figs. 2D-E, 3). The Agios Konstantinos section shows a well-developed succession of the Pakhna Formation, around 150 m thick, with contourite, reworked turbidite and turbidite facies. Selected samples also correspond to F3a from Hüneke et al. (2020), but contain *Planolites* (Fig. 3). The Kalavassos section shows part of the Lefkara Formation with chalky calcilutites (Stow et al. 2002). Selected samples correspond to facies F2a from Hüneke et al. (2020), consisting of pelagic carbonate mud/calcareous muddy contourites (reworking of pelagic sediments), and display *Chondrites* and *Thalassinoides* (Figs. 2F, 3).

Mercury intrusion porosimetry

Mercury intrusion porosimetry is used to evaluate open porosity (interconnected pores) and pore-size distribution in the range from 0.003 to 350 µm (see Molina et al. 2011; Coletti et al. 2016, for a review). Since mercury is a nonwetting liquid, penetration into pores must be forced by external pressure, the required pressure being inversely proportional to the size of the pores. Mercury fills larger pores first, and as pressure increases, smaller ones. Pressure intrusion data are provided by the porosimeter, which determines volume and size distributions according to the Washburn equation (Pirard et al. 2002). Mercury intrusion porosimetry analysis allows for evaluating both the porosity between the individual particles (interparticle porosity) and the porosity within the particles (intraparticle porosity). According to the user guide (operating manual) of the mercury porosimetry analyzer (*Quantachrome® Instruments*):

$$\text{Interparticle porosity (\%)} = 100\ V_v/V_b$$

$$\text{Intraparticle porosity (\%)} = 100\ V_t\text{-}V_v/V_b$$

where V_b is the bulk volume of the sample, V_v is the volume of mercury intruded up to the Interparticle Filling Limit and V_t is the total volume of mercury intruded up to the maximum pressure.

According to Coletti et al. (2016), two main limitations are associated with mercury intrusion porosimetry: a) the assumption that pores are perfectly cylindrical in shape, and that mercury moves from larger pores to smaller ones, discarding the opposite cases; thus mercury enters voids at a pressure determined only by the size of the entry points, and not the true size of the pore itself (Giesche 2006); and b) at high intrusion pressures (exceeding 414 MPa), the pore structure may be damaged, determining an artificial increase in the small pore fraction.

ICHNOTAXA	DESCRIPTION - INTERPRETATION	REFERENCES
Chondrites 	Oval or circular spots (1-3 mm-wide burrow diameters), occasional branches, with common white infillings. *Chondrites* is recorded in a wide stratigraphic and marine facies range. Interpreted as a fodinichnion, or produced by chemosymbiotic organisms. Related to low-oxygen-tolerant organisms showing an opportunistic behaviour, commonly associated with organic-rich deposits.	Osgood, 1970; Bromley and Ekdale, 1984; Vossler and Pemberton, 1988; Seilacher, 1990; Fu, 1991; Miguez-Salas and Rodríguez-Tovar, 2019a; Baucon et al., 2020
Macaronichnus 	Straight to slightly sinuous cylindrical burrows, actively filled by slightly light-coloured sand respect to a darker surrounding mantle. Specimens with diameter of 3-6 mm, without branching are assigned to *Macaronichnus* isp., those with diameters of 7-15 mm showing, locally, regularly spaced lobes flanked on both sides in the mantle, and occasional true branching are assigned to *Macaronichnus segregatis degiberti*. *Macaronichnus* is associated with deposit-feeder opheliid polychaetes, typically in sand-rich shallow-marine (up to foreshore) high-energy settings, being regular constituents of the *Skolithos* ichnofacies; less commonly, also occur in deeper environments.	Clifton and Thompson, 1978; Seike, 2007; Pemberton et al., 2012; Rodríguez-Tovar and Aguirre, 2014; Miguez-Salas et al., 2020; Miguez-Salas and Rodríguez-Tovar, 2020
Parahaentzschelinia 	Numerous irregular sand-filled tubes, with smooth walls, radiating vertically or slightly obliquely upward to the sediment surface from one master shaft. Tube diameters from 3 to 15 mm, the master shaft (10-20 mm). The penetration depth is up to 90 mm. *Parahaentzschelinia* is usually related with a combination of behaviours, primarily related to feeding. Typical of shallow marine environments, associated with the *Skolithos* ichnofacies. Deep-marine are related with the *Ophiomorpha rudis* ichnosubfacies within the *Nereites* ichnofacies.	Knaust, 2017; Reynolds and McIlroy, 2017; Luo et al., 2020; Miguez-Salas and Rodríguez-Tovar, 2020
Planolites 	Unlined, not branched, straight to tortuous, smooth to striated burrows with structureless fill lithologically different from the host sediment. In *Planolites* the contrasting burrow fill was processed by the tracemaker which can include a wide range of organisms. Ubiquitous trace fossil in marine and non-marine settings, being a common element of shallow-tier ichnofabrics.	Pemberton et al., 1992; Keighley and Pickerill, 1995; Rodríguez-Tovar and Uchman, 2004, 2017; Rodríguez-Tovar et al., 2009; Knaust, 2017; Miguez-Salas and Rodríguez-Tovar, 2019b
Scolicia 	Sinuous structures fluctuating from slightly sinuous to winding and meandering forms. The two parallel sediment stings are difficult to observe. The backfilling patterns are better observed on hyporelief specimens. Burrows present an oval/semi-circular shape with diameters from 1 to 5 cm. Produced by the deposit-feeding activity of irregular echinoids. *Scolicia* ichnogenus is typical of deep-marine *Nereites* ichnofacies and the shelf expression of the *Cruziana* ichnofacies.	MacEachern et al., 2012; Belaústegui et al., 2017; Miguez-Salas and Rodríguez-Tovar, 2020
Thalassinoides 	Unlined cylindrical or subcylindrical horizontal forms, with diameters of 2 to 7 cm, filled with calcarenitic sediments. Burrow margins are predominantly smooth. Commonly interpreted as produced by decapod crustacean shallow to mid-tier deposit feeders, yet suspension feeding strategies have also been proposed. Facies-crossing form, occurring in a great variety of marine environments, but typical of shallow-marine oxygenated deposits, as component of the *Cruziana* ichnofacies, in soft but cohesive sediments.	Kern and Warme, 1974; Ekdale et al., 1984; Frey et al., 1984; Bromley, 1996; Monaco et al., 2007; Rodríguez-Tovar et al., 2008, 2017; Wetzel, 2008; Miguez-Salas et al., 2017; Miguez-Salas and Rodríguez-Tovar, 2019a

Fig. 3 - Main ichnological features of the studied ichnotaxa.

For the mercury intrusion porosimetry analysis a PoreMaster 60 GT (Quantachrome Instruments) mercury porosimeter was used, and a surface tension and contact angle of mercury of 480 mN m-1 and 130°, respectively, were chosen. The pore diameter interval ranged from 0.002 to 200 µm, which corresponds to the highest (410 MPa) and lowest (1 kPa) head pressures. Samples of approximately 2 cm^3 were freshly cut and oven-dried for 24 h at 40-50 °C before being analysed. The samples were analysed after determination of the saturated hydraulic conductivity and the soil water retention curve tests.

Results

To evaluate how bioturbation influences porosity distributions in the studied contourite facies, the mercury intrusion porosimetry analyses were conducted on both the trace fossil infill and on the host rock (Table 1; Fig. 4).

In the clastic contourite facies from El Adergha and Kirmta sections, total porosity in the host rock varies from 11.2% to 14.4%, respectively; in both cases intraparticle porosity is higher that interparticle porosity (respectively 6.6% vs 4.6%, and 9.2% vs 5.2%) (Table 1; Fig. 4). At the El Adergha

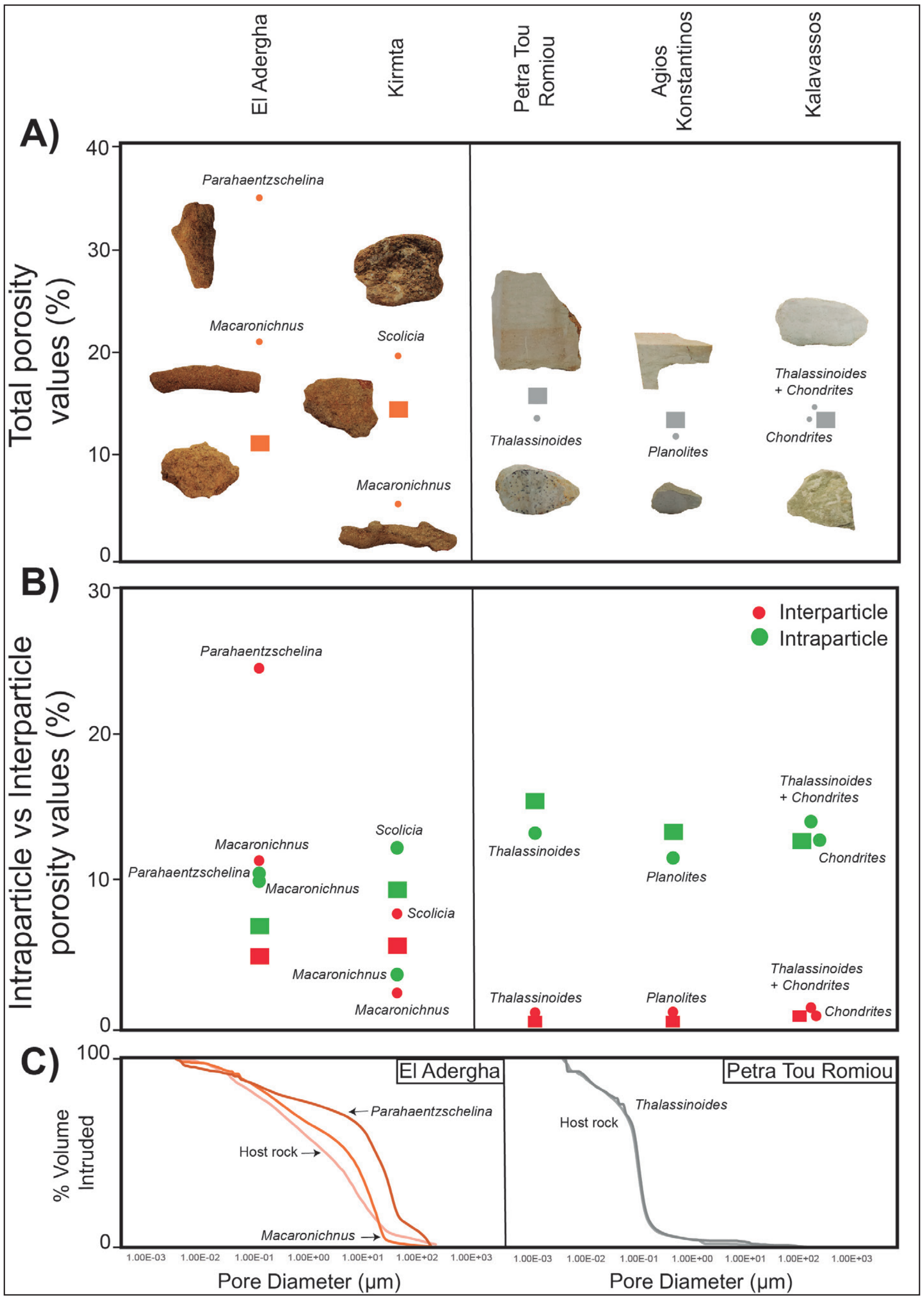

Fig. 4 - A-B) Distribution of porosity [total (A), interparticle and intraparticle (B)] from the host rock (squares) and the infilling material of ichnotaxa (circles) of the selected samples (see photographs) from the studied clastic (El Adergha and Kirmta; Morocco), calcarenitic (Petra Tou Romiou and Agios Konstantinos; Cyprus) and muddy chalk (Kalavassos; Cyprus) sections. C) Mercury porosimetry intrusion curves (host rock and infilling material of ichnotaxa) from selected El Adergha (*Macaronichnus* and *Parahaentzschelinia*) and Petra Tou Romiou (*Thalassinoides*) sections, showing pore diameter values.

section, total porosity in the infilling material of trace fossils varies from 20.9% in *Macaronichnus* to 34.7% in *Parahaentzschelinia*, in both cases interparticle porosity being higher than intraparticle porosity (11.2% vs 9.8% for *Macaronichnus* and 24.4% vs 10.3% for *Parahaentzschelinia*) (Table 1; Fig. 4). At the Kirmta section, total porosity in the infilling material of trace fossils varies from 5.4% in *Macaronichnus* to 19.6% in *Scolicia*, intraparticle porosity being higher than interparticle porosity in both cases, but especially in *Scolicia* (3.3% vs 2.0% for *Macaronichnus* and 12.1% vs 7.5% in *Scolicia*) (Table 1; Fig. 4).

Of special relevance in the calcarenitic (Petra Tou Romiou and Agios Konstantinos outcrops) and muddy chalk (Kalavassos section) contourite facies from Cyprus is the similarity between porosity values irrespective of the section, type of porosity, type of contourite and trace fossils involved (Table 1; Fig. 4). Moreover, in no case was intraparticle porosity similar to the total porosity —interparticle porosity was very low (< 1). Therefore, the total porosity of host rock shows similar values of 15.6% and 13.5% in calcarenitic facies from Petra Tou and Agios Konstantinos sections, respectively. Likewise, similar values were obtained for intraparticle porosity (15.3% vs 13.2%), and interparticle porosity (0.3% in both cases) of the host rock (Table 1; Fig. 4). In terms of ichnotaxa, similar total porosity va-

	Morocco (Miocene Sandstone)						Cyprus (Carbonate Drift Eocene-Miocene)					
Section	**El Adergha**			**Kirmta**			**Petra Tou Romiou**		**Agios Konstantinos**		**Kalavassos**	
	Host rock	*Ma*	*Pa*	Host rock	*Sc*	*Ma*	Host rock	*Th*	Host rock	*Pl*	*Th+Ch*	Host rock+*Ch*
Intruded volume (interparticle) (cc)	0.0335	0.0828	0.1497	0.0346	0.0464	0.0135	0.0023	0.0026	0.0019	0.0029	0.0024	0.0054
Intruded volume (intraparticle) (cc)	0.0488	0.0724	0.0631	0.0605	0.0746	0.0219	0.1054	0.0673	0.0854	0.0673	0.0712	0.0748
Total intrude volume (cc)	0.0822	0.1552	0.2127	0.0951	0.121	0.0354	0.1076	0.0699	0.0874	0.0702	0.0735	0.0802
Total interparticle porosity (%)	4.56	11.17	24.44	5.25	7.51	2.04	0.33	0.51	0.30	0.49	0.46	0.90
Total intraparticle porosity (%)	6.65	9.76	10.30	9.19	12.07	3.32	15.32	13.07	13.16	11.37	13.87	12.60
He density (g/cc)	2.65	2.68	2.68	2.67	2.66	2.68	2.67	2.68	2.67	2.67	2.69	2.68
Theoretical porosity (%)	11.21	20.94	34.74	14.43	19.59	5.34	15.66	13.59	13.46	11.84	14.32	13.50
Total porosity (%)	**11.21**	**20.94**	**34.74**	**14.43**	**19.58**	**5.36**	**15.65**	**13.58**	**13.45**	**11.85**	**14.34**	**13.50**

Tab. 1 - Porosity information (total, interparticle and intraparticle) from the host rock and the infilling material of ichnotaxa of the selected samples from the studied sections in Morocco (El Adergha and Kirmta) and Cyprus (Petra Tou Romiou, Kalavassos and Agios Konstantinos). Note: cc = cubic centimetres; He = Helium; *Ch* = *Chondrites*; *Ma* = *Macaronichnus*; *Pa* = *Parahaentzschelinia*; *Pl* = *Planolites*; *Sc* = *Scolicia*, *Th* = *Thalassinoides*.

lues were obtained for passively filled *Thalassinoides* (13.6%), actively filled *Planolites* (11.8%), *Thalassinoides* and *Chondrites* (14.3%) and *Chondrites* (13.5%) samples, and values are also similar for intraparticle and interparticle porosity (Table 1; Fig. 4).

Discussion

The obtained data evidence variability between the type of contourite facies, trace fossils and porosity values, revealing a complex relationship, with three cases clearly differentiated: Case A) similar total porosity in the host rock and in the trace fossil infill, with high intraparticle porosity and very low interparticle porosity; Case B) different total porosity in the host rock and in the trace fossil infill, with higher intraparticle than interparticle porosity, and Case C) lower total porosity in the host rock than in the trace fossil infill, with lower intraparticle than interparticle porosity (see detailed explanation below, Fig. 5).

Type of contourites and porosity

Analysis of data from clastic (El Adergha and Kirmta sections), calcarenitic (Petra Tou Romiou and Agios Konstantinos outcrops) and muddy chalk (Kalavassos section) contourite facies comes to show similarities, but also significant differences, probably associated with the primary sedimentary matrix and secondary processes.

Total porosity of the host sediment gives similar values in clastic and calcarenitic contourites. They range from 11.2% for clastic contourite facies from El Adergha, to 15.6% for calcarenitic facies at Petra Tou Romiou outcrop (see Fig. 4). However, a significant difference is observed with respect to the inter/intraparticle porosity. Interparticle porosity is relatively high in clastic contourites (6.6% in El Adergha and 9.2% in Kirmta), whereas it is almost absent in calcarenitic contourites (0.3% in Petra Tou Romiou and Agios Konstantinos), where intraparticle porosity is nearly exclusive (15.3% in Petra Tou Romiou and 13.2% in Agios Konstantinos).

The similar total porosity obtained for the different contourite facies regardless of the grain size (sand to mud) may be related to the applied methodology. As indicated above, the mercury intrusion porosimetry technique used allows one to evaluate open porosity (interconnected pores) and pore-size distribution in the wide range from 0.003 to 350 μm. This means it can measure even very small pores, as those from calcarenitic and muddy chalk contourites (see differences in pore diameter values between the selected El Adergha and Petra Tou Romiou sections; Fig. 4C). If these pores are abundant, the technique provides a high general porosity value similar to the one that would be registered if analysing samples with a lower number of larger intraclast spaces (e.g., clastic contourites composed by larger clasts).

In turn, the difference between inter/intraparticle porosity can be explained by microfacies composition and diagenetical processes. Microfacies of calcarenitic contourites from Petra Tou Romiou (facies F3a) in revealed them to typically be globigerinid wackestone-packstones, with abundant disperse or locally clustered foraminifera (Hüneke et al. 2020). Similarly, muddy contourites (facies F2a in Hüneke et al. 2020) are characterized by the almost exclusive presence of planktic foraminifers (superfamily Globigerinacea) with well-preserved

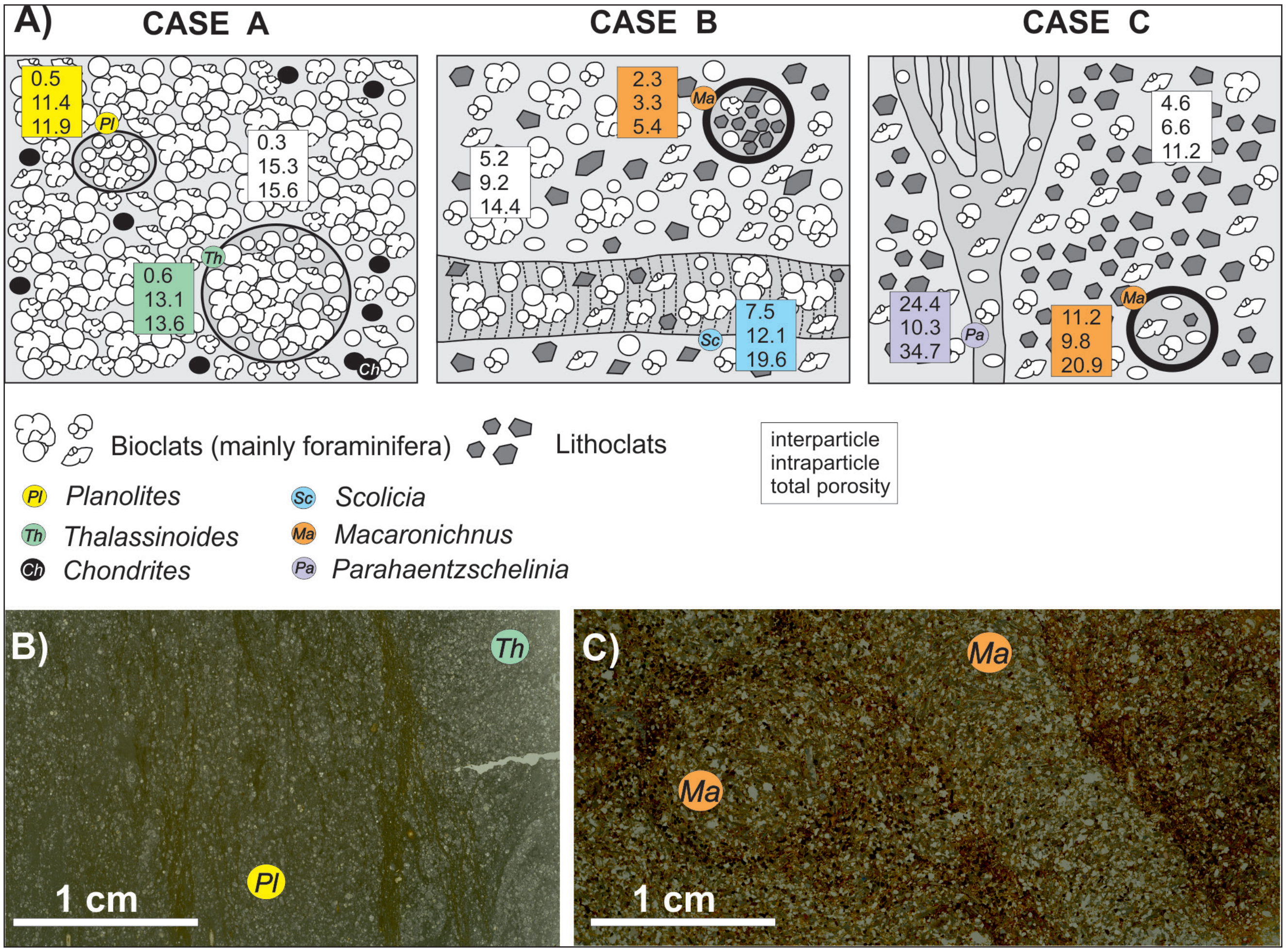

Fig. 5 - A) Sketch showing the different cases according to the relationship in the studied samples between the values in porosity in the host rock and in the infilling material of ichnotaxa. CASE A) Similar total porosity in the host rock and in the infilling material of *Planolites* and *Thalassinoides*, with high intraparticle porosity and very low interparticle porosity (Petra Tou Romiou section, Cyprus). CASE B) Different total porosity in the host rock and in the infilling material of *Macaronichnus* (lower) and *Scolicia* (higher), with higher intraparticle than interparticle porosity (Kirmta section, Morocco). CASE C) Lower total porosity in the host rock than in the infilling material of *Macaronichnus* and *Parahaentzschelinia*, with lower intraparticle than interparticle porosity in *Parahaentzschelinia*, and higher intraparticle than interparticle porosity in *Macaronichnus* (El Adergha section, Morocco). B-C) Microfacies of calcarenitic contourites from Petra Tou Romiou (B) and clastic contourites from Kirmta (C) sections, illustrating CASE A) and CASE B), respectively.

spherical tests. Thus, abundant foraminifera increase intraparticle primary porosity due to the numerous empty chambers.

Trace fossils and porosity

The analytical results point to different sorts of relationship between trace fossil infilling material and porosity. Bioturbation was initially considered to be a reducing factor for porosity and permeability, since burrowers reduce sorting and can favor sediment homogeneization, but several studies have shown that substantial enhancement is also produced, favouring fluid flow (Over 1990; Gingras et al. 2004b, 2012; Pemberton & Gingras 2005; Gordon et al. 2010). As indicated by Knaust (2012), small-scale heterogeneities, combined with sedimentary, ichnological, diagenetic and structural features, generally influence reservoir quality (Knaust et al. 2020). Diffuse bioturbate texture, as a bioturbated mottled background, and discrete burrows, can be considered of a major impact on the rock matrix, control distribution of porosity for oil accumulation. Architectural elements and characteristics of burrows such as density, tiering, size, orientation, architecture, lining and fill have a variable impact on rock properties and reservoir quality (Pemberton & Gingras 2005; Tonkin et al. 2010; Knaust 2013, 2017). Some of these features are associated to the behavior of the trace maker.

According to the above, to evaluate the relationship between bioturbation and porosity in the case study, ichnological features must be considered together with the interpretation of registered ichnotaxa, such as *Chondrites*, *Macaronichnus*, *Parahaentzschelinia*, *Planolites*, *Scolicia*, and *Thalassinoides* (Fig. 3). The highest total porosity values were found for *Parahaentzschelinia* (34.7%) and *Scolicia* (19.6%); they are variable in *Macaronichnus* (20.9% and 5.4%), and values are similar in *Thalassinoides*, *Planolites* and *Chondrites* (13.6%, 11.8%, and 13.5%, respectively).

Most of the involved trace fossils are associated with feeding activities, mainly by deposit feeders, showing active infill (fill emplaced into the burrow by the burrower; Bromley 1990, 1996; Buatois & Mángano 2011), as is the case of *Macaronichnus*, *Planolites*, and *Scolicia*. In other cases, as in *Thalassinoides*, usually interpreted as passive massive infill from an overlying layer, typically coarser-grained, is introduced gravitationally into the burrow (Bromley 1990, 1996; Buatois & Mángano 2011).

Parahaentzschelinia can exhibit a combination of behaviors, primarily related to feeding, produced by the activity of a tellinid bivalve, either in a sub-surface position or, most commonly, on surface detritus (Knaust 2017); and secondly as equilibrium adjustments (Luo et al. 2020). According to Knaust (2017) this trace shows either a passive or active infill.

Scolicia entails an active meniscate fill, forming a characteristic structure, commonly packed as backfill meniscate, resulting from mechanic manipulation (Bromley 1990, 1996; Buatois & Mángano 2011). The irregular echinoids excavate sediment in the front, which is transported to the back part and packed with mucus in a meniscus structure (de Gibert & Goldring 2008). Whether as active massive fill or as active meniscate fill, the loosened grains ahead are transported backwards via digestion or mechanical transport. Thus, during burrowing, the sediment is redeposited behind as the organism moves forward (Bromley 1990, 1996; Buatois & Mángano 2011). This activity determines an important redistribution of grains that significantly affects the primary porosity of the rock. *Macaronichnus* shows an active massive fill, structureless, typically contrasting with the host sediment, resulting from ingestion and excretion (Bromley 1990, 1996; Buatois & Mángano 2011). The producer, a selective deposit-feeding polychaete, feeds on epigranular biofilms and organic detritus in sand (Nara & Seike 2019 and references therein). *Macaronichnus segregatis* is widely interpreted as a pascichnial trace produced by a polychaete that selectively ingests light-material. The burrow is characterized by the presence of a mineralogical segregation within the tube, showing a core made up of low density material, light-colored felsic sand grains, surrounded by a rim of high density, dark colored mafic sand grains (Rodríguez-Tovar & Aguirre 2014; Nara & Seike 2019 and references therein). Particularly, Nara and Seike (2019) propose an exploratory behavior (sequorichnia) for *Macaronichnus segregatis degiberti* Rodríguez-Tovar & Aguirre, 2014. *Chondrites* is related with diverse producers, behaviors (regarded as feeding, chemisymbiotic or farming trace), and types of fill (actively backfilled or passively filled burrow) (Baucon et al. 2020 for a recent review). *Planolites* is characterized by a homogeneous active massive fill (Bromley 1990, 1996; Buatois & Mángano 2011). *Thalassinoides* is related with domichnia/fodichnia behavior, showing a passive infill.

Accordingly, the higher total porosity values registered in *Parahaentzschelinia*, *Scolicia* and *Macaronichnus* could be linked to the redistribution of grains by trace makers during feeding activity. In the particular case of *Macaronichnus*, commonly associated with reservoir exploitation (e.g., Gingras et al. 2002; Pemberton & Gingras 2005; Gordon et al. 2010; see Dorador et al. 2021 for a recent review), with lower porosity values, this may be attributed to the type of *Macaronichnus* studied —*Macaronichnus segregatis* or *Macaronichnus segregatis degiberti*— showing different behavior and thus a variable infilling process. However, we cannot totally discard that this difference has to do, at least in part, with the variable location of the porosity analysis in the *Macaronichnus* burrows, involving the infilling material and/or the halo (Dorador et al. 2021).

Similar porosity values in actively (*Chondrites* and *Planolites*) and passively (*Thalassinoides*) infilled burrows, in the calcarenitic (Petra Tou Romiou and Agios Konstantinos outcrops) and muddy chalk (Kalavassos section) contourite facies, can be explained by: a) a continuous deposition of similar facies, or b) a diagenetic overprint. In the first case, sediments above the sampled calcarenitic and muddy chalk contourite facies are similar in composition, determining that the infilled sediment (corresponding to the host rock or coming from above) in both active or passive traces has a composition similar to that of the host rock, hence similar porosity values. In the second case, we cannot discard that a diagenetic overprint homogenizes the total porosity values from different traces registered in the same facies; intensive diagenetic pressure dissolution obscuring most of the primary traction structures has been recently documented (Hüneke et al. 2020).

Type of contourites, ichnological features and porosity impact

Integration of the obtained data considering type of contourite, trace fossil and porosity values, enabled us to assess the role of bioturbation in porosity variations and therefore its impact on reservoir quality. In the studied cases, two different groups can be discerned (Fig. 5):

In calcarenitic and muddy chalk facies, the burrow infill of the trace fossils (*Thalassinoides*, *Planolites* and *Chondrites*) shows porosity values similar to those of the host rock, regardless of passive or active infill (Case A in Fig. 5A, 5B). In this case, bioturbation has a minor effect on porosity, due to continuous conditions in sedimentation or diagenetic overprint (see above) determining a neutral impact for reservoir exploitation.

In clastic contourites, all the trace fossils (*Parahaentzschelinia*, *Scolicia*, *Macaronichnus*), enhance the porosity of the matrix, especially *Parahaentzschelinia*. At the Kirmta section, bioturbation determines an increase in both intraparticle and interparticle porosity in the case of *Scolicia*, and a decrease in the case of *Macaronichnus*, most notably in the intraparticle porosity (Case B in Fig. 5A, 5C). Thus, in general for the studied clastic contourites, bioturbation determines the increase in total porosity, particularly the interparticle porosity, and has a positive impact on reservoir exploitation. At El Adergha section, bioturbation (*Parahaentzschelinia* and *Macaronichnus*) determines an increase in total porosity with respect to the host rock, mainly affecting interparticle porosity (Case C in Fig. 5A). Knaust (2017) indicates for *Parahaentzschelinia* that the incorporation of various amounts of mud into the burrows may have a slightly negative impact on reservoir quality. In the case study, the positive impact is noteworthy and most likely related to the minor incorporation of mud into the burrows, and the increase in porosity between radiating tubes.

Conclusions

Porosity analysis using mercury intrusion porosimetry reveals a variable incidence of bioturbation on contourite deposits, depending on the type of contourite facies and the ichnotaxa involved. We analyzed selected samples of dominant-calcareous contourites from the Eocene-Early Miocene of Cyprus with *Chondrites*, *Planolites* and *Thalassinoides*, and sandy clastic contourites from the Late Miocene Rifian Corridor of Morocco with *Macaronichnus*, *Parahaentzschelinia* and *Scolicia*, comparing the host rock with the infilling material. Total porosity shows similar values for the host sediment in clastic and calcarenitic contourites. However, significant differences in interparticle/intraparticle porosity are registered — interparticle porosity is almost absent in calcarenitic contourites, where intraparticle porosity is dominant, mainly related to the microfacies composition and the abundance of foraminifera chambers. Higher total porosity values were obtained for the infilling material of *Parahaentzschelinia*, *Scolicia* and *Macaronichnus*, possibly related to the trace maker behavior and redistribution of grains during feeding activity. The role of bioturbation in rock porosity modification of the studied contourites and its impact on reservoir quality would be variable. For clastic contourites, bioturbation determines an increase in total porosity, especially in interparticle porosity, meaning a positive impact for reservoir exploitation; yet in calcarenitic and muddy chalk facies, bioturbation has a minor effect on porosity and therefore a neutral impact on reservoir exploitation.

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