Abstract

Carbonate drifts have so far not been as intensely investigated as their siliciclastic equivalents, especially from an ichnological perspective. The aim of this work is therefore to provide an overview of the different bioturbation styles in carbonate drifts for ichnologists and sedimentologists working in such deposits. Different types of carbonate drifts from the Maldives were studied to address this objective. The cores recovered during IODP Expedition 359 were examined to provide the sedimentological and ichnological data for a detailed analysis of the ichnology of carbonate drifts. The ichnological characteristics of the Maldives drifts are compared to other carbonate drifts in order to discuss similarities and differences and thus provide an overview of the general characteristics of carbonate drift ichnology. These drifts are located in the Santaren Channel which lines Great Bahama Bank, along the Marion Plateau in Australia, in the Limassol and Larnaca basins in Cyprus, and in the Danish Basin in Denmark. The common characteristics of bioturbation in carbonate drifts are (1) the complete bioturbation of the sediment with bioturbation indexes between 4 and 6, (2) the occurrence of distinctive trace fossils limited to facies contacts or condensed intervals, (3) a typical ichnoassemblage consisting of *Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, and *Palaeophycus,* (4) the contiguous occurrence of ichnogenera from different tiers, with only *Zoophycos* and *Chondrites* as deep tiers, (5) distinct infills of the traces including particulate organic-matter, pyrite, silica, and celestine. In addition, the main ichnofacies of carbonate drifts is the *Zoophycos* ichnofacies. Ichnofabrics grade from coarse-grained and completely bioturbated to ichnofabrics with present to rare trace fossils and preserved sedimentary structures. The type and intensity of the bioturbation is controlled by the amount of organic matter and the oxygenation at the seafloor that is determined by the action of bottom currents and the sea-level fluctuations affecting the carbonate factory in carbonate platforms bordering the basins where the carbonate drifts form. The study of the bioturbation in core and outcrop provides paleoenvironmental information about carbonate-drift deposits that complement the classical sedimentological data.

Keywords: Ichnofacies, Ichnofabrics, Bioturbation, Contourites, Periplatform carbonates

1. INTRODUCTION

Drifts are important sedimentary environments because they record paleoclimatological and paleoceanographical information at a higher resolution than does pelagic background sedimentation (Rebesco, 2005; Rebesco *et al*., 2014). Carbonate drifts have up to now not been as broadly investigated as their siliciclastic equivalents (Stow *et al*., 2002; Viana and Rebesco, 2007; Rebesco and Camerlenghi, 2008; Rebesco *et al*., 2014). Several studies, however, document their importance in the development of tropical carbonate platform edifices (Mullins at al., 1980; Anselmetti *et al*., 2000; Isern *et al*., 2004; Betzler *et al*., 2009, 2013, 2014; Eberli *et al*., 2010; Lüdmann *et al*., 2012, 2013; Mulder *et al*., this volume; Paulat *et al*., this volume). Studies on the ichnology of siliciclastic drifts have demonstrated that such deposits are characterized by a high degree of bioturbation (Stow *et al*., 1998, 2002; Wetzel *et al*., 2008; Rebesco *et al*., 2014; Rodríguez-Tovar and Hernández-Molina, 2018). The study of the bioturbation in drifts may be of interest to paleoenvironmental, paleoceanographical, and paleoclimatological interpretation of the drift deposits as well as for their characterization as hydrocarbon reservoirs (Rodríguez-Tovar and Hernández-Molina, 2018).

Understanding of bioturbation in carbonate drifts is very limited and is mostly focused on the problems of such deposits in relative to their siliciclastic counterparts, especially in terms of masking of the primary structures by diagenesis (Kahler and Stow, 1998; Hüneke and Stow, 2008). The aim of this work is therefore to provide an overview of the different bioturbation styles in carbonate drifts and to stablish a background for ichnologists and sedimentologists working in such deposits.

For addressing these objectives, different types of carbonate drifts from the Maldives were studied, as the Maldives can be considered as a type locality for carbonate drifts (Lüdmann *et al*., 2013, 2018). There, in the deep-water realm of the Inner Sea giant elongated drift bodies have formed since the Miocene. They exhibit geometries and seismic characteristics comparable to their siliciclastic counterparts, including mounded shapes and associated moats (Lüdmann *et al*., 2013). Cores from these carbonate drifts were recovered during the cruise M74/4 NEOMA (Betzler *et al*., 2013) and during the International Ocean Discovery Program (IODP) Expedition 359 (Betzler *et al*., 2016, 2017, 2018). These cores provide sedimentological and ichnological data for a detailed analysis of the ichnology of carbonate drifts. The ichnological characteristics of the Maldives drifts are compared with other carbonate drifts from the Santaren Channel lining Great Bahama Bank, the Marion Plateau in eastern Australia, the Limassol and Larnaca basins in Cyprus, and the Danish Basin in Denmark (Fig. 1A) to assess similarities and differences and thus provide an overview of general characteristics of carbonate drift ichnology. We present a compilation of different bioturbation styles in carbonate drifts and provide the base for further detailed studies on their paleoenvironmental conditions.

2. GEOLOGICAL SETTING

The Maldives archipelago in the central equatorial Indian Ocean is a 3-km-thick isolated tropical-carbonate edifice located southwest of India (Fig. 1B; Aubert and Droxler, 1992; Purdy and Bertram, 1993). The carbonates formed on an early Paleogene (60–50 Ma) faulted volcanic basement (Duncan and Hargraves, 1990). Carbonate drifts in the Maldives archipelago have been developed since ~ 13 Ma (Betzler *et al*., 2009, 2016, 2018; Lüdmann *et al*., 2013) and are arranged in 10 depositional sequences (ds1-ds10) defined by their respective lower boundaries DS1-DS10 (Lüdmann *et al*., 2013; Betzler *et al*., 2016, 2017, 2018). In the Maldives, there are three main types of carbonate drifts according to their geometries, internal structure, and composition including mounded drifts (Fig. 2B) and delta drifts (Fig. 2C) close to the drowned platforms, as well as sheeted drifts and dunes in the Inner Sea and channels among atolls (Betzler *et al*., 2018, Fig. 2C). Delta drift deposits comprise ds1 to ds4 in the proximal areas of the Inner Sea (Fig. 2C). These drift bodies deposited at the exit of passages through the drowned parts of the platform, while remaining banks and atolls continued to grow (Betzler *et al*., 2009, 2013; Lüdmann *et al*., 2013). Lobes were fed by easterly currents and reworked by a current system flowing obliquely or normally to this main stream and the sediment accumulated by this current system progressively filled the Inner Sea from west to east (Lüdmann *et al*., 2013). In the distal areas of the Inner Sea and in the proximal areas from ds3 to ds10, sheeted drifts and submarine dunes occur (Betzler *et al*., 2013; Lüdmann *et al*., 2013). Starting with seismic sequence ds6, at the end of the Messinian, the opening of a southern gateway introduced northward flow of bottom currents into the Inner Sea, resulting in the deposition of giant elongated drifts attached to the eastern flank of the basin, filling it from east to west (Lüdmann *et al*., 2013). Detached drifts form at the downcurrent flanks of the atolls (Betzler *et al*., 2009, 2013), and the currents controlling the drift deposition in the Maldives prevail during the Quaternary (Betzler *et al*., 2013; Reolid *et al*., 2017; Bunzel *et al*., 2017). The water depth at what the drifts were deposited changed through time from ~50 m at the time of the delta drift deposition (Reolid *et al*., this volume) to ~500 m in present day (Betzler *et al*., 2017).

The Bahamas archipelago is a carbonate province consisting of several isolated platforms situated on the southern end of the eastern continental margin of the United States. In the Santaren Channel, at a water depth of ~600-700 m and ~30 km from the western platform edge of the Great Bahama Bank, there is a continuous drift sequence of Neogene to present-day in age that interfingers with prograding carbonate-bank deposits of the Bahamas (Eberli *et al.*, 1997; Kroon *et al.*, 2000; Anselmetti *et al.*, 2000; Bergman *et al.*, 2010; Paulat *et al.*, this volume).

The Marion Platform in northeastern Australia was a large carbonate edifice that drowned during the Middle-Late Miocene (John and Mutti, 2005; Eberli *et al.*, 2010). A system of carbonate drifts has since then dominated the sedimentation on the Marion Plateau (John and Mutti, 2005; Eberli *et al.*, 2010). These drift deposits are Late Miocene to present-day in age and were deposited at water depths of more than 200 m (Eberli *et al.*, 2010).

In the area of Cyprus, deep-sea sediments started to deposit over the Cretaceous oceanic crust between the Maastrichtian and early Miocene, first as turbidites and later on as slow pelagic deposition (Stow *et al.*, 2002; Hüneke and Stow, 2008). During the latest Eocene to early Miocene the deposition was affected by the influence of bottom currents (Kahler and Stow, 1998). The water depth at the time of the drift deposition was in the range of 2000-3000 m (Stow *et al.*, 2002).

The Maastrichtian chalk in Denmark spreads over a large extension of Denmark and the North and Baltic sea. It is of pelagic origin and was permanently affected by the action of bottom currents that resulted in mounded drifts, a sediment wave complex, and an elongate moat-drift system (Anderskouv *et al.*, 2007; Surlyk and Lykke-Andersen, 2007; Damholt and Surlyk, 2004). The water depth of the sea was of several hundred meters with up to 800 m in the deepest areas of the Danish Basin, well below the photic zone (Lauridsen *et al.*, 2011).

3. MATERIALS AND METHODS

During the IODP Expedition 359 Sites U1466, U1467, U1468, and U1471 were cored in the Inner Sea to recover a sedimentary sequence encompassing a carbonate drift succession (Miocene to Pleistocene). Core retrieval, handling and all on board measurements including downhole logging and core to seismic correlation are described in detail in Betzler *et al*. (2017). The characterization of the different slope, drift, and basinal facies as well as the first approach to the bioturbation at the study sites relies on preliminary on-board visual core descriptions and later detailed analysis of high-resolution photographs obtained by the Section Half Imaging Logger (SHIL), which captures continuous high-resolution images (Betzler *et al*., 2017). These data were backed up with the petrographic analysis of circa 200 thin-sections to identify microfacies and components. The nomenclature for the facies and microfacies of carbonate rocks follows Dunham (1962) and Embry and Klovan (1974). The age assignments of the succession rely on calcareous nannoplankton and planktonic foraminifer events (Betzler *et al*., 2016, 2017). The natural gamma radiation from downhole logs (HSGR) and core measurements (NGR) was used to characterize the organic-matter content of the sediment according to Betzler *et al*. (2016) and Reolid and Betzler (2018). The piston core NEOMA 1143 was retrieved during RV Meteor cruise M74/4 and has a length of 12.95 m (Betzler *et al*., 2013). It was divided into two halves, photographed, and studied for sedimentology and ichnology.

The ichnological study of the carbonate drifts of the Maldives was backed up with the data of carbonate drifts from Bahamas, the Marion Plateau, Cyprus, and the Danish Basin (Fig. 1A). In Bahamas, at ODP Site 1006A (20º23.989'N, 79º27.541'W), the studied interval is Miocene to Pliocene in age and comprised cores 37X to 75X, 330.6 to 698.1 mbsf. The studied drift intervals from the Marion Plateau at ODP Sites 1192A (20º34.306'S, 152º24.257'E) and 1195B (20º24.283'S, 152º40.243'E) span from cores 5H to 15H (29.5 to 125.5 mbsf) and cores 5H to 13H (36.9 to 122.4 mbsf) respectively. These drifts are Late Miocene to Pliocene in age. The drift deposits of Cyprus were studied at the Miocene Lymbia (34º59.5'N, 33º28.7'E) and Petra Tou (34º39.7'N, 32º39.1'E) sections. A nice example of the Maastrichtian chalk deposits in the Danish Basin crops out in Stevns Klint (55º18'N, 12º26.8'E).

The systematic ichnological analysis was conducted on digitally-enhanced (light, contrast, and color) high-resolution images of core section halves (Reolid and Betzler, 2018). The analysis was continuous, section-by-section, for the IODP and ODP sites and spotted in the field locations of Cyprus (Lymbia and Petra Tou sections) and Denmark (Stevns Klint section). Unfortunately, for old ODP expeditions there are no high-resolution photographs available in the data repository, and the ichnological analysis relies on onboard low-resolution core-photographs, close-ups, and core-descriptions by the onboard sedimentologists. The spotted field-observations in Cyprus and Denmark were implemented through the available literature on these drifts. The quantification of the bioturbation intensity follows the method of Taylor and Goldring (1993). Identification of the main ichnotaxa, measurement of the burrow sizes, of the tiering, and cross-cutting relationships were also recorded where possible, but unfortunately, they are not statistically representative. The ichnofabrics were defined according to the bioturbation index, the ichnoassemblage, and the sediment type (Reolid and Betzler, 2018).

4. RESULTS

4.1 Maldives carbonate drifts

The texture, composition, and ichnology of the drift successions at Sites U1466, U1467, U1468, and U1471 change from proximal to distal settings, and from the northern to the southern part of the Kardiva Channel (Fig. 1B). A summary of the main drift types and their bioturbation can be found in Table 1. At Site U1466 and U1468 there are deposits associated with a delta drift complex that progrades towards the E, i.e. the Inner Sea (ds1 to ds3, Fig. 2; Lüdmann *et al.*, 2018). Site U1467 records a succession of sheeted drifts and submarine dunes (ds4 to ds10, Fig. 2). Site U1471 in the southern branch of the Kardiva Channel has deposits associated to the delta drift and the overlying sheeted drifts. Core NEOMA 1143 retrieved sediment from a mounded drift (Fig. 2C).

The drift deposits of the Maldives overlie the slope and basinal sediments of a partially drowned Miocene Carbonate platform. The slope to basinal deposits of this platform consist of bioclastic packstone to wackestone with benthic and planktonic foraminifera. The youngest slope sediments are intensely bioturbated with indices of 4 to 5 (Fig. 3). Scarce individual burrows of *Thalassinoides* can be identified out of the mottled background (Reolid and Betzler, 2018). At Site U1466, the change from the slope to the drift deposits coincides with an abrupt increase of the degree of bioturbation whereas it is more gradual at Site U1468, i.e. in a more distal slope position (Fig. 3).

4.1.1 IODP Site U1466

In the northern branch of the Kardiva Channel, at Site U1466 the delta drift facies consists of fine-grained packstone to wackestone, locally grainstone, with abundant bioclasts and minor benthic and planktonic foraminifera. From DS1 up to 200 mbsf the sediment of the delta drift is completely bioturbated without individual burrows or a mottling texture (Fig. 3A). From 200 to 160 mbsf there is a partially lithified packstone where bioturbation may be expressed as small lithified-nodules floating in the sediment (Fig. 4B). Towards the top of the delta drift succession large benthic foraminifera including *Lepidocyclina*, *Miogypsina*, *Operculina*, and *Nummulites*, together with equinoid remains may be present. In this interval, bioturbation cannot be determined because of the coarse grain size of the deposits. In the overlying sheeted drift and sand dunes there are some changes in color and texture that may be interpreted as a bioturbation (Fig. 4). The bioturbation degree is 5 to 6 and the only traces are likely *Thalassinoides* and are represented by a bioclastic grainstone with a packstone infill. From 75 mbsf to the sea floor there are local changes in the sediment packing that may be interpreted as biodeformational features.

4.1.2 IODP Site U1468

Basinwards, at Site U1468, the delta drift sediments consist of packstone and wackestone that gradually change upwards into grainstone to rudstone (Fig. 2). Components are abundant silt sized bioclasts in the lower part and a mixture of large benthic foraminifera and bioclasts towards the top (Fig. 4). From the base of the drift up to 400 mbsf the sediment is intensely bioturbated (BI=5-6) with scarcely identifiable burrows of *Thalassinoides* and *Palaeophycus* (Fig. 3 and 4A,). Above, the bioturbation is so intense that no individual burrows or mottling texture are observed. This part of the succession contains scattered chert nodules with rounded to elongated morphologies that could be related to large trace fossils such as *Thalassinoides* (Fig. 5A). From 300 to 225 mbsf there is a partially lithified wackestone where bioturbation may be present, represented by small lithified nodules floating in the sediment (Fig. 4B). Chertified burrows may also occur (Fig. 5A). Between 200 mbsf and 160 mbsf there is a cryptic mottling texture, and from 160 to 90 mbsf there is an alternation of packstone and grainstone with abundant large benthic foraminifera where rarely poorly-preserved traces can be observed (Fig. 4C, F). These traces may correspond to *Thalassinoides* and usually contain abundant organic matter in their infills (Fig. 5B). This interval is partly mottled. From 90 to 50 mbsf the grain size is coarse and no bioturbation can be determined.

Overlying the delta drift deposits, the sheeted drift at Site U1468 consists of unlithified to partially lithified planktonic foraminifera-rich packstone to grainstone completely homogenized by the bioturbation (BI=6; Fig. 4D). Components include mix shallow-water and pelagic bioclasts including *Halimeda*, echinoids, iron stained intraclasts, otoliths, and pteropods (Fig. 4G).

4.1.3 IODP Site U1471

In the southern part of the Kardiva Channel, at Site U1471, the deposits of the delta drift are fine-grained planktonic foraminifera-rich packstone alternating with coarse-grained bioclastic-rich grainstone. Benthic foraminifera and equinoid remains are common. Large benthic foraminifera are locally abundant, especially between 890 and 880 mbsf. Packstone intervals are darker in color, and their thickness ranges between 2 and 35 cm. These intervals have higher organic content and exhibit wavy and/or finely laminated layering (Fig. 6A). The bioturbation is intense with indexes around 4-5 in the packstone and 6 in the grainstone intervals (Fig. 6A). The ichnoassemblage varies upcore starting with *Thalassinoides*, *Planolites*, *Phycosiphon*, *Zoophycos*, *Chondrites* and minor *Palaeophycus*, with some interval especially rich in *Phycosiphon*. At 830 mbsf, *Palaeophycus* starts to be more significant, and *Zoophycos*, *Phycosiphon* and *Chondrites* become accessories.

The grainstone layers are lighter in color and are completely homogenized by the intense bioturbation. Just locally some large *Thalassinoides* can be identified with a packstone infill. The contacts between the packstone and the grainstone may be sharp, gradual, and eventually bioturbated, with trace fossils commonly infilled by the coarser material (Fig. 6A). From 805 mbsf up to approximately 615 mbsf the facies consists of an alternation of wackestone and packstone. The ichnoassemblage is similar to that of the directly underlying interval but the bioturbation degree is progressively higher upcore (Fig. 6B). In the wackestone intervals it is possible to identify individual traces in contrast with the completely bioturbated packstone intervals. In the transition interval from delta to sheeted drift, from 700 to 615 mbsf, the bioturbation of the sediment is pervasive and just some *Zoophycos* and minor *Palaeophycus* can be identified out of the mottled background (Fig. 6B). In some intervals, discrete burrows present infills rich in organic matter (Fig. 5C). From 615 mbsf to the top of the hole, the sheeted drift facies is mostly a packstone with intercalations of wackestone, both completely homogenized by the bioturbation (Fig. 6C). *Thalassinoides* may be locally identified out of the background bioturbation and may present celestine infill (Fig. 5D). The uppermost unlithified sediment commonly displays mottled texture (Fig. 6D).

4.1.4 IODP Site U1467

At Site U1467 the sheeted drift sediment is a wackestone to packstone with abundant planktonic foraminifera, silt-sized bioclasts, common benthic foraminifers (locally some *Amphistegina*), and few to present echinoid spines and particulate organic matter (Fig. 2). Bioturbation is intense from the base of the hole up to 500 mbsf with common to abundant *Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, and *Palaeophycus* (Fig. 7A). In this part of the succession, there is an alternation of light and dark sediments. Darker intervals range in thickness from 1 to 30 cm and represent up to a 30% of the cores. The sediment composition is similar in both intervals with more bioclasts in the light ones (Fig. 7E) and more organic matter in the dark intervals (Fig. 7F). The NGR values are higher in the dark intervals but the bioturbation degree and assemblage are almost identical in the light and dark intervals (Fig. 2). From 540 to 370 mbsf the contrasts in color are progressively fading. The degree of lithification of the sediment decreases upcore from lithified to partially lithified (Betzler *et al*., 2017). The bioturbation is intense and consists of the same ichnoassemblage as in the underlying interval with *Zoophycos* being locally dominant (Fig. 7B). In parts, the bioturbation is so intense that it is not possible to identify individual burrows, locally even the mottling disappears and the sediment is completely homogenized. From 370 to 200 mbsf burrows are progressively less significant and biodeformational structures dominate. *Thalassinoides*, *Chondrites*, *Planolites*, and *Zoophycos* are just locally identifiable in the darker intervals (Fig. 7C). From 200 mbsf to the sea floor, the bioturbation degree is intense and sediments are mottled or even completely homogenized, and trace fossils represented by *Thalassinoides* occur in some scattered dark sediment intervals (Fig. 7D). The sediment in the uppermost part of the hole consists of planktonic foraminifera rich wackestone with some fish debris and scattered large benthos such as brachiopods and cold-water corals (Fig. 7G).

4.1.5 Core NEOMA 1143

The sediment of the mounded detached drift east of Goidhoo Atoll (Fig. 1B) is mainly a periplatform ooze with planktonic foraminifera, pteropods, otoliths, mollusk remains, benthic foraminifera, sponge spicules, echinoid debris, and rare solitary corals (Betzler *et al*., 2013). The succession is arranged in alternating light and dark colored greenish to olive gray intervals. The bioturbation is intense and mostly consists of biodeformational structures. Just locally individual trace fossils of *Thalassinoides* and *?Planolites* may be identified out of the mottled background (Fig. 8).

4.2 Other carbonate drifts

4.2.1 Bahamas

The drift sediment consists of fine-grained wackestone to packstone, locally mudstone, with abundant planktonic foraminifera, benthic foraminifera, bioclasts, peloids, echinoid debris, and fish remains. There are 110- to 300-cm-thick intervals of alternating darker and lighter sediment with fish debris better preserved in the dark intervals (Eberli *et al.*, 1997). Firmgrounds are locally present and may be bioturbated (Fig. 9A). Bioturbation is pervasive throughout the drift facies homogenizing completely the sediment (Fig. 9B and C). Just in some intervals, and at the position of the firmgrounds, the bioturbation degree is lower and allows identification of distinctive burrows out of the mottled background including *Thalassinoides*, *Chondrites*, and *Planolites*. Larger burrows are up to 1-2 cm in diameter. Grains inside the burrows may be pyritized, especially the planktonic foraminifera (Fig. 9C).

4.2.2 Marion Plateau

The recovered drift facies consists of planktonic foraminifera-rich wackestone to mudstone at the bottom of the drift deposits that change into packstone and grainstone at the top. The sediment is completely homogenized by the bioturbation and no sedimentary structures are preserved. The homogenization is especially intense in the coarser grainstone intervals. In the wackestone and packstone there are alternations of lighter and darker intervals, in response to variations of the clay content that locally allow the recognition of individual trace fossils out of the mottled background. The burrows may be stained black from finely disseminated pyrite and/or particulate organic matter (Fig. 9D). There are firmgrounds where the trace fossils present distinct sediment infill (Fig. 9E). Among the identifiable trace fossils there are *Thalassinoides*, *Zoophycos* (Fig. 9F), and rarely *Scolicia* and *Chondrites*.

4.2.3 Cyprus

Stow *et al*. (2002) described part of the late Oligocene early Miocene Lefkara Formation in Cyprus as a type example of a carbonate contourite deposit. The calcilutite/calcisiltite to marly calcilutite of the Lymbia and Petra Tou sections are well bedded with up to 30-cm thick beds that can be massive, finely-parallel laminated, or with lenticular bedding (Hüneke and Stow, 2008). The sediment consists of fine-grained planktonic-foraminifera wackestone to packstone with rare equinoid fragments and fish remains. The facies is locally mudstone, which is interpreted to reflect minor current winnowing (Stow *et al*., 2002). The sediment is completely bioturbated except for intervals with a fine parallel lamination. Individual traces are medium to poorly preserved. Where visible, the main ichnoassemblage consists of *Thalassinoides*, *Chondrites*, *Planolites*, and *Zoophycos* with *Ophiomorpha* and *?Helminthoides* also present (Hüneke and Stow, 2008; Rodríguez-Tovar and Hernández-Molina, 2018). The diagenesis of the carbonates may have obscured the recognition of the facies and trace fossils (Hüneke and Stow, 2008).

4.2.4 Denmark

The drift deposits consist of fine-grained chalk made out of the debris of coccolithophorid algae as well as planktonic foraminifera, calcispheres and skeletal remains of minute suspension-feeding invertebrates (Surlyk and Lykke-Andersen, 2007). The facies displays a cyclicity consisting of decimeter-thick bioturbated beds alternating with slightly thinner non-bioturbated, mainly laminated beds (Damholt and Surlyk, 2004). The bioturbated beds contain diverse trace fossils including common *Zoophycos*, *Chondrites*, *Planolites*, *Thalassinoides* and *Phycosiphon*. *Asterosoma* may be present but its identification is equivocal. *Thalassinoides* may be locally abundant and preserved in chert concretions (Anderskouv *et al*., 2007). The laminated beds lack syndepositional bioturbation and only contain scattered well-preserved deep-tier *Zoophycos* and locally also thin *Chondrites* penetrating downwards from the overlying bioturbated units (Damholt and Surlyk, 2004).

5. DISCUSSION

5.1 Main ichnological features in carbonate drifts

A list of the main ichnological features in carbonate drifts is presented in Table 2. The first feature that all carbonate drifts do have in common is the intense and pervasive bioturbation. This is also a diagnostic element of siliciclastic and mixed carbonate-siliciclastic drifts (Stow, 2002; Stow and Faugères, 2008; Rebesco *et al*., 2014; Alonso *et al*., 2016; Dorador and Rodríguez-Tovar, 2016). The intense bioturbation ranges from mottling that destroys pre-existing sedimentary structures to complete homogenization of the sediment (Pemberton *et al*., 2008). The intensity of a bioturbation is a criterion that allows the differentiation of carbonate drift deposits from other periplatform deposits (Fig. 3). The intensity of bioturbation of carbonate drifts is apparently dependent of the sediment grain size. Coarse-grained sediment, grainstone and rudstone, displays a bioturbation degree slightly higher than intervals of silt-sized wackestone and mudstone (Figs. 4 and 6). But in any case, the bioturbation degree in the fine-grained facies is also high. Similar intensity of bioturbation in fine-grained drifts is also reported from chalk deposits of the Danish drifts (Anderskouv *et al.*, 2007; Rasmussen and Surlyk, 2012).

Not only the intense bioturbation, but also the homogeneity of some facies, with respect to the mineralogy and grain composition, results in little to no sediment-color contrast between the burrow infill and the background sediment (Knaust *et al.*, 2012). This additionally hinders the recognition of individual trace fossils in carbonate drifts, and the contrast may even be obscured by diagenesis (Hüneke and Stow, 2008).

Two general types of bioturbation can be distinguished in carbonate drifts: (1) Trace fossils with sharp outlines and characteristic recurrent geometries that allow their classification in terms of ichnotaxonomy, and (2) biodeformational structures with more diffuse outlines and non-recurrent geometry. The occurrence of discrete trace fossils is mostly restricted to some horizons, such as the transitions between lighter and darker colored intervals (Fig. 7) or at firmgrounds (Fig. 9).

When the bioturbation degree and the sediment allow for it, the identifiable ichnoassemblage is common for the different carbonate drifts discussed herein. The carbonate drift ichnoassemblage is dominated by *Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, and *Palaeophycus*. *Taenidium* and *Nereites* may be also present according to the reports of ODP legs 166 and 194, but its recognition in cores and core photographs is not univocal (Eberli *et al*., 1997; Isern *et al*., 2004). Ichnogenera from different tiers typically occur together (Fig. 7). In the Maastrichtian chalk of Denmark, the occurrence of deep tiers in the assemblage is used for the differentiation of the ichnofabrics (Lauridsen *et al*., 2011), but this is not always possible in the other study cases.

Among the described cases the more common infills consist of particulate organic matter and chert. Locally pyrite is present. The chert is probably the result of the dissolution of the biogenic silica of different organisms including radiolarians, diatoms, and sponge spicules (Maliva and Siever, 1989; Fabricius, 2007). Celestine is locally common in the Maldives drifts and it is interpreted as the result of remobilization of fluids saturated in $SrSO_4$ during the transformation of Sr-bearing aragonite of some bioclasts into calcite (Hanor, 2004; Betzler *et al*., 2017).

5.2 Ichnofacies and Ichnofabrics

The concept of ichnofacies refers to the ichnological content of the rock resulting of the activity of organisms under certain conditions of energy, nutrients, oxygenation, or sedimentation rates (MacEarchern *et al*., 2007). According to the trace assemblage reported from the different carbonate drifts (*Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, *Palaeophycus*, and minor *Taenidium* and *Nereites)*, *Cruziana* and *Zoophycos* ichnofacies (Seilacher, 1967) are the dominant ichnofacies in such deposits. The *Cruziana* ichnofacies is characterized by a high diversity of trace fossils mostly a combination of deposit feeding and permanent dwelling including an assemblage as diverse as *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Phoebichnus*, *Phycoides*, *Planolites*, *Rosselia*, *Rhyzocoralium*, *Siphonichnus*, *Taenidium*, *Teichichnus*, *Thalassinoides*, and *Zoophycos* (Benton and Harper, 1997; Gilbert and Martinel, 1998; MacEachern *et al*., 2007). Grazing structures as *Helminthopsis* or *Phycosiphon* are common and passive carnivore structures as *Palaeophycus* may be present (MacEachern *et al*., 2007). In shallow environments with *Cruziana* ichnofacies *Arenicolites* and *Ophiomorpha* are common (MacEachern *et al*., 2007). In contrast, the *Zoophycos* ichnofacies are dominated by feeding structures of shallow and deep tiers including *Zoophycos*, *Helminthopsis*, *Phycosiphon*, *Planolites*, *Nereites*, and minor *Chondrites*, *Scolicia*, *Thalassinoides*, and *Spyrophyton* (MacEachern *et al*., 2007).

Cruziana ichnofacies is typical of shallow environments from tidal flats to the open offshore (Benton and Harper, 1997; MacEachern *et al*., 2007; Gerard and Bromley, 2008). The *Zoophycos* ichnofacies is related to slope to basinal deposits, the basinward equivalent of the *Cruziana* ichnofacies (Ekdale, 1988; Goldring, 1993; MacEachern *et al*., 2007). The trace-fossil assemblages documented in carbonate drifts are a mixture of *Cruziana* and *Zoophycos* ichnofacies, but according to the dominant paleobathymetry of such deposits the *Zoophycos* ichnofacies is more representative of carbonate drifts. However, the main ecological factors, such as organic-matter input, sedimentation rate, grain size, and oxygenation vary significantly in the deep sea, especially when bottom currents are involved, and therefore such ichnofacies cannot be univocally linked to a specific water depth (Wetzel, 1983; Ekdale, 1988; Goldring, 1993; MacEachern, 2007; Uchman and Wetzel, 2011).

As a complementary study to the ichnofacies analysis, ichnofabric analysis was applied to the studied carbonate drifts. The ichnofabrics are those aspects of the texture and internal structure of the rock resulting from all phases of bioturbation (Ekdale and Bromley, 1983), comprising the primary sedimentary conditions and the later sediment reworking during one or more phases of bioturbation (Taylor and Goldring, 1993; Taylor *et al*., 2003; Gerard and Bromley, 2008; Buatois and Mángano, 2011; Ekdale *et al.*, 2012; Reolid and Betzler, 2018). From the ichnofabric perspective, there are three main types of ichnofabrics (IF) in carbonate drifts, including (1) completely-homogenized coarse-grained deposits, (2) intensely bioturbated fine-grained deposits; and (3) those with present to absent bioturbation and preserved sedimentary structures (Fig. 10).

The first type (IF1 in Table 1) includes a range of facies from coarse-grained packstone, grainstone and rudstone (Fig. 10). The bioturbation degree according to the scale of Droser and Bottjer (1986) and Hansen and MacEachern (2007) is 6 and the occurrence of discrete trace fossils is extremely rare. Discrete trace fossils are almost exclusively from the ichnogenus *Thalassinoides* and may present particulate organic matter in their infills (Fig. 5). These ichnofabrics are exclusive to the topsets of the delta drift in the Maldives.

The second type (IF2 in Table 1) of ichnofabrics includes facies ranging from mudstone to packstone and bioturbation degrees between 4 and 6 (Fig. 10). Ichnofabrics of packstone intervals usually present a completely-homogenized to mottled background (IF2A, bioturbation index of 6). Trace fossils are hardly identifiable and usually are *Thalassinoides*- or *Planolites*-like. Fine-grained ichnofabrics, including mudstone, wackestone, and minor packstone, display a well-developed mottled background, mainly consisting on biodeformational structures overprinted by scarce trace fossils (IF2B, bioturbation indexes of 4 to 5). The main ichnogenera are *Zoophycos, Thalassinoides*, *Planolites*, and *Chondrites*. *Phycosiphon* and *Palaeophycus* may be present and *Taenidium* and *Nereites* are rare. The ichnofabrics do not show any clear cross-cutting relationship, and just the presence or absence of *Zoophycos* and *Chondrites* may indicate differences in the tiering. The ichnofabrics may accordingly be differentiated into shallow and deep according to the occurrence of these two ichnogenera. These ichnofabrics (IF2B) commonly intercalate with intervals completely homogenized with no or rare individual burrows (IF2A). This ichnofabric association is similar to that reported from hemipelagites (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012). In the case of the very-fine grained materials of Denmark the ichnofabrics show the same alternation of heavily bioturbated sediment with poorly preserved trace fossils (Ichnofabric A of Lauridsen *et al*., 2011) and ichnofabrics with preserved trace fossils out of the intensely bioturbated background (Ichnofabrics C of Lauridsen *et al*., 2011). A similar bimodal distribution of completely homogenized ichnofabrics with ichnofabrics with discrete burrows is also characteristic of siliciclastic and mixed carbonate/siliciclastic drifts (Dorador and Rodríguez-Tovar, 2016).

The last type of ichnofabrics (IF3 in Table 1) which can be identified in carbonate drifts corresponds to the thinly laminated intervals at the bottom of the delta drift deposits at Site U1471 in the Maldives (Fig. 6), at the Lymbia section in Cyprus (Stow *et al*., 2002), and in the Danish drifts (Damholt and Surlyk, 2004). The ichnofabric consists of fine-grained packstone with high bioturbation degree (4-6) alternating with intervals with low bioturbation index and preserved primary sedimentary structures, index from 1 to 3 (Fig. 10). The trace fossils of this ichnofabric are *Thalassinoides* and *Planolites*. The preservation of the primary structures in the carbonate drifts is rare because of the intense bioturbation. This is in a certain contrast to some siliciclastic drifts, where sedimentary structures as the reported parallel fine-lamination and lenticular bedding are common (Stow and Faugères, 2008; Wetzel *et al*., 2008).

5.3 Paleoenvironmental interpretation

The diagnostic features of the bioturbation in carbonate drifts, the ichnofacies, and the ichnofabrics are the result of a range of factors affecting the depositional environment. The two main factors affecting these deposits are the availability of organic matter and the oxygenation, both closely depending on the bottom current regime.

5.3.1 Ichnological content and oxygenation of carbonate drifts

According to Taylor *et al*. (2003) "highly bioturbated sediment can represent no other than a well oxygenated sea floor". The occurrence of pervasive bioturbation in carbonate drifts is therefore interpreted as the result of good sea-floor oxygenation. The high degree of bioturbation in drift deposits is likely related to the input of oxygen in the environment by bottom currents (Wetzel *et al*., 2008; Rebesco *et al*., 2014) which transport well-oxygenated cold-water masses (Salon *et al*., 2008; Zenk, 2008). In contrast, drifts deposited under the influence of oxygen-poor waters, as those of polar margins are not or rarely bioturbated (Ekdale, 1988; Gilbert *et al*., 1998; Lucchi *et al*., 2002; Lucchi and Rebesco, 2007). In summary, most environments where oxygen is not a limiting factor display moderate to high diversity of trace fossils (Ekdale, 1988), and such is the case of carbonate drifts.

5.3.2 Bioturbation and organic matter content

In environments where the oxygen is not a limiting factor, the organic-matter content may exert a control on the intensity and type of bioturbation (Wetzel and Uchman, 1998; Taylor *et al*., 2003). In the examples discussed herein there are alternations of light and dark colored intervals (Eberli *et al*., 1997; Isern *et al*., 2004; Betzler *et al*., 2017), some of them exclusively controlled by the amount of organic matter in the sediment (Betzler *et al*., 2016, 2017). In the case of the

Maldives, the organic-richer dark intervals usually display high values of gamma radiation (Fig. 2) and are characterized by a relatively lower degree of bioturbation with identifiable individual traces. *Zoophycos* is typical of the dark intervals and is considered as an indicator of organic matter deposition (Dorador *et al*., 2016). *Chondrites*, also significant in these intervals, is an indicator of poor oxygenation below the sediment/water interface in the Danish drifts where they occur with small sizes (Rasmussen and Surlyk, 2012). However, as *Chondrites* always occur in intensely bioturbated sediment, it is more likely to indicate enrichment in organic matter than oxygen depletion (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012). In most of the cases, the ichnofabrics with lower bioturbation indices and deeper tiers are typically result of high organic matter content (Savrda and Bottjer, 1986, 1989).

5.3.3 Drift sedimentation and the ichnological content

The presence in the study cases of completely homogenized or mottled intervals rather than discrete burrows might be explained by lowered rates of sediment accumulation intercalated into the drift successions. Low sedimentation-rates allow bioturbation to keep pace with deposition destroying primary sedimentary structures and individual burrows (Stow and Faugères, 2008). The lithology also exerts a certain control on the type of bioturbation as sediment texture, grain size, and sorting determine the accumulation and preservation of organic matter in the sediment, and thus the ichnoassemblage and bioturbation index (Reolid and Betzler, 2018). In the Maldives drifts there is a primary lithological control on the ichnofabrics where coarser grained sediments have intensely bioturbated ichnofabrics with rare *Thalassinoides*-like burrows (IF1, Figs. 4, 5B, and 10), in contrast with the relatively more diverse ichnoassemblage documented in finer sediments (IF2B, Figs. 7 and 10). A better development of the bioturbation in fine-grained deposits seems to be a common characteristic of drift deposits independently of the composition, i.e. siliciclastic, volcanoclastic, or carbonate (Rebesco *et al*., 2014; Rodríguez-Tovar and Hernández-Molina, 2018).

The consistency of sea-floor sediment also exerts a control on the bioturbation (Ekdale, 1988; Taylor *et al*., 2003). The alternation of intervals with medium- to well-preserved traces with others completely bioturbated with rare well-preserved trace-fossils at IODP Site U1471 in the Maldives or in the carbonate drifts in Cyprus are interpreted as changes in substrate consistency associated with sedimentation breaks during drift formation (Rodríguez-Tovar and Hernández-Molina, 2018). The preservation of the trace fossils which is generally poor indicates that the surfaces of most of these carbonate drifts were soup- to softgrounds. Locally firmgrounds with well-defined traces may occur which related to omission surfaces created by enhanced currents (Eberli *et al*., 1997; Isern *et al*., 2004; Rodríguez-Tovar and Hernández-Molina, 2018; Reolid *et al*., in this volume). Such omission surfaces are a distinctive feature of drift deposits elsewhere (Hüneke and Stow, 2008; Rodríguez-Tovar and Hernández-Molina, 2018). Rodríguez-Tovar and Hernández-Molina (2018) defined 6 different associations from facies with preserved primary structures (Types A-B) to completely mottled facies with softground facies (Types D-E). Firmgrounds with trace fossils with different infill than that of the surrounding sediment are the Type F for Rodríguez-Tovar and Hernández-Molina (2018). Type B according to these authors is characterized by the presence of traction sedimentary structures partly destroyed by bioturbation, and it is typical of thin beds of calcareous sandy contourites. In the Maldives there is an equivalent to this association in the laminated intervals at the base of the delta drift at Site U1471 (Fig. 6A). Primary traction sedimentary structures represent unfavorable conditions for the bioturbating organisms, in contrast with the later improvement in conditions that allows the sediment bioturbation (Fig. 6A; Rodríguez-Tovar and Hernández-Molina, 2018). Primary traction structures are also documented in the carbonate drifts of Denmark and Cyprus (Damholt and Surlyk, 2004, Hüneke and Stow, 2008). In general terms, the style of bioturbation and the type of substrate place carbonate drifts within the association types D to E of Rodríguez-Tovar and Hernández-Molina (2018). It is proposed that carbonate drifts have an additional Type G to represent the facies completely homogenized by the bioturbation with rare soupground traces or mottling that occurs at the base of the drift succession in the Maldives (Fig. 4A).

5.3.4 Carbonate drifts and pelagites

The best preservation of trace fossils documented in carbonate drifts occur in the lower part of Site U1467 in the Maldives (Fig. 7A) and in the Maastrichtian chalk of Denmark (Rasmussen and Surlyk, 2012). The location of Site U1467 in the center of the Maldives Inner Sea was probably less affected by bottom currents at the time of the deposition of the delta drift in contrast with the proximal Sites U1466 and U1468. Accordingly, the style of bioturbation of the lower sequences at this site is more similar to a pelagite or hemipelagite than to drift deposits *sensu stricto*. Pelagites are sediment deposited by pelagic settling and consist of fine-grained sediments (Rebesco *et al*., 2014). In carbonates settings they are dominated by planktonic foraminifera, pteropods, and nannofossils (Flügel, 2004). The deep-sea sediment is commonly soft or soupy and usually well oxygenated. Accordingly, the bioturbation in such deposits consists of a mixture of discrete trace fossils mostly of the *Zoophycos*/*Cruziana* ichnofacies and biodeformational structures in the background (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012). This kind of preservation of the bioturbation in a drift may indicate that the sedimentation is mainly dominated by pelagic settling and that currents are a secondary factor.

5.3.5 The role of sea-level and bottom currents on the ichnological content

The recognition of the bioturbation is favored by the cyclic alternation of darker and lighter intervals as is the case at Site U1467 (Fig. 7). Such alternations may be related to changes in the intensity of the currents. Lower-energy currents allow the settling of organic matter (Fig. 7F) while higher-energy currents promote the winnowing of the organic matter and the reworking and breakage of the bioclasts (Fig. 7E). The local occurrence of parallel fine-lamination and lenticular bedding in carbonate drifts is in line with the action of temporary accelerated currents (Stow *et al*., 2002; Stow and Faugères, 2008; Wetzel *et al*., 2008). In shallow environments such as in the delta drifts of the Maldives not only the current exerts a control on the bioturbation. Changes in the base level by sea-level fluctuations or enhanced in-situ carbonate production determine the type and intensity of the bioturbation (Fig. 4C and 5B; Reolid *et al*., this volume). In the case of the carbonate drifts of the Santaren Channel and the Marion Plateau the changes in color are related to the amount of clay in the sediment, that is determined by the energy of the currents as is the case with the organic matter in the Maldives (Eberli *et al*., 1997; Kroon *et al*., 2000; Isern *et al*., 2004; John and Mutti, 2005). Similar cyclic alternation of darker and lighter colored sediment in the detached carbonate drifts of the Maldives in core NEOMA 1143 was linked to sea-level fluctuations in the Milankovitch band that control the carbonate export from the shallow water carbonate factory (Fig. 9; Betzler *et al*., 2013). Thus, the changes in the sediment composition and the concomitant changes in the style of bioturbation are the result of the interplay of sea-level fluctuations that control the productivity in the shallower areas and the nature of the carbonate input and bottom currents that control the water oxygenation and the redistribution of the sediment.

6. CONCLUSIONS

This study of cores from carbonate drifts of the Maldives and other onshore and offshore current-controlled carbonate drifts allows for the recognition of some common bioturbation characteristics in carbonate drifts.

1. In general, the carbonate drift sediment is completely bioturbated with bioturbation indexes between 4 and 6, rarely bioturbation indexes are 1 in intervals related to enhanced bottom currents. The intensity of the bioturbation, the nature of the sediment, and the lack of contrast of carbonate grains hinders the characterization of the bioturbation.
2. The recognition of individual trace fossils against the mottled background is mostly limited to facies contacts or condensed intervals. The typical carbonate drift ichnoassemblage consists of *Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*,

Chondrites, *Phycosiphon*, and *Palaeophycus*; *Taenidium* and *Nereites* may be also present.

3. The recognition of a clear tiering is difficult in carbonate drifts. Ichnogenera from different tiers typically occur together. Locally *Zoophycos* and *Chondrites* may stand as deep tiers.
4. The trace fossils may contain distinct infills including particulate organic-matter, pyrite, silica, and celestine.
5. The main ichnofacies of carbonate drifts are the *Zoophycos* ichnofacies.
6. There are three main types of ichnofabrics in carbonate drifts: 1) Coarse-grained and completely bioturbated sediment typical of delta drifts; 2) intensely bioturbated fine-grained deposits that may or may not present discrete trace fossils out of the mottled background; and 3) sediment with present to absent trace fossils and preserved sedimentary structures.

The type and intensity of the bioturbation is controlled by the amount of organic matter and the oxygenation at the seafloor. Changes in the type and intensity of the bioturbation can be used by researchers to characterize the action of bottom currents and the sea-level fluctuations affecting the carbonate factory.

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REFERENCES

Alonso, B., Ercilla, G., Casas, D., Stow, D.A.V., Rodríguez-Tovar, F.J., Dorador, J. and **Hernández-Molina, F.J.** (2016) Contourite vs gravity-flow deposits of the Faro Drift (Gulf of Cadiz) during the Pleistocene: sedimentological and mineralogical approaches. *Mar. Geol.* **377**, 77-94.

Anselmetti, F.S., Eberli, G.F. and **Ding, Z.D.** (2000) From the Great Bahama Bank into the Straits of Florida: A margin architecture controlled by sea-level fluctuations and ocean currents. *Geol. Soc. Am. Bull.*, **112**, 829-844.

Anderskouv, K., Damholt, T. and **Surlyk, F.** (2007) Late Maastrichtian chalk mounds, Stevns Klint, Denmark - Combined physical and biogenic structures. *Sed. Geol.*, **200**, 57-72.

Aubert, O. and **Droxler, A.W.** (1992) General Cenozoic evolution of the Maldives carbonate system (equatorial Indian Ocean). *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **16**, 113-136.

Benton, M. and **Harper, D.A.T.** (1997) Basic Paleontology. *Geol. Magazine*, **135**, 819-842.

Bergman, K.L., Westphal, H., Janson, X., Poiriez, A. and **Eberli, G.P.** (2010) Controlling parameters on facies geometries of the Bahamas: an isolated carbonate platform environment. In: Carbonate Depositional Systems: Assessing Dimensions and Controlling Parameters (Eds H. Westphal, B. Riegl and G.P. Eberli), pp. 5–80.

Betzler, C., Hübscher, C., Lindhorst, S., Reijmer, J.J.G., Römer, M., Droxler, A., Fürstenau, J. and **Lüdmann, T.** (2009) Monsoon-Induced Partial Carbonate Platform Drowning (Maldives, Indian Ocean). *Geology*, **37**, 867-870.

Betzler, C., Lüdmann, T., Hübscher, C. and **Fürstenau, J.** (2013) Current and Sea-Level Signals in Periplatform Ooze (Neogene, Maldives, Indian Ocean). *Sed. Geol.*, **290**, 126-137.

Betzler, C., Lindhorst, S., Eberli, G.P., Lüdmann, T., Möbius, J., Ludwig, J., Schütter, I., Wunsch, M., Reijmer, J.J.G. and **Hübscher, C.** (2014) Periplatform drift: the combined result of contour current and off-bank transport along carbonate platforms. *Geology*, **42**, 871-874.

Betzler, C., Eberli, G.P., Kroon, D., Wright, J.D., Swart, P.K., Nath, B.N., Alvarez-Zarkikian, C.A., Alonso-Garcia, M., Bialik, O.M., Blatter, C.L., Guo, J.A., Haffen, S., Horozal, S., Inoue, M., Jovane, L., Lanci, L., Laya, J.C., Mee, A.L., Lüdmann, T., Nakakuni, M., Niino, K., Petruny, L.M., Pratiwi, S.D., Reijmer, J.J.G., Reolid, J., Slagle, A.L., Sloss, C.R., Su, X., Yao, Z. and **Young, J.R.** (2016) The Abrupt Onset of the Modern South Asian Monsoon Winds. *Scientific Reports*, **6,** 29838.

Betzler, C., Eberli, G.P., Alvarez Zarikian, C.A. and **the Expedition 359 Scientists** (2017) Maldives Monsoon and Sea Level. Proceedings of the International Ocean Discovery Program, 359: College Station, TX (International Ocean Discovery Program). http://dx.doi.org/10.14379/iodp.proc.359.2017.

Betzler, C., Eberli, G.P., Lüdmann, T., Reolid, J., Kroon, D., Reijmer, J.J.G., Swart, P.K., Wright, J.D., Young, J.R., Alvarez-Zarikian, C.A., Alonso-García, M., Bialik, O.M., Blättler, C.L., Guo, J.A., Haffen, S., Horozal, S., Inoue, M., Jovane, L., Lanci, L., Laya, J.C., Mee, A.L.H., Nakakuni, M., Nath, B.N., Niino, K., Petruny, L.M., Pratiwi, S.D., Slagle, A.L., Sloss, C.R., Su, X. and **Yao, Z.** (2018) Refinement of Miocene sea level and monsoon events from the sedimentary archive of the Maldives (Indian Ocean). Progress in Earth and Planetary Science 5. DOI 10.1186/s40645-018-0165-x.

Buatois, L.A. and **Mángano, M.G**. (2011) Ichnology: Organism-Substrate Interactions in Space and Time. *Cambridge University Press, Cambridge*, 358 pp.

Bunzel, D., Schmiedl, G., Lindhorst, S., Mackensen, A., Reolid, J., Romahn, S., Betzler, C. (2017) A multi-proxi analysis of Late Quaternary ocean and climate variability for the Maldives, Inner Sea. *Clim. Past*, **13**, 1791-1813.

Damholt, T. and **Surlyk, F.** (2004) Laminated-bioturbated cycles in Maastrichtian chalk of the North Sea: oxygenation fluctuations within the Milankovitch frequency band. *Sedimentology*, **51**, 1323-1342.

Dorador, J. and **Rodríguez-Tovar, F.J.** (2016) Stratigraphic variation in ichnofabrics at the “Shackleton Site” (IODP Site U1385) on the Iberian Margin: Paleoenvironmental implications. *Mar. Geol.*, **377**, 118-126.

Dorador, J., Wetzel, A. and **Rodríguez-Tovar, F.J.** (2016) Zoophycos in deep-sea sediments indicates high and seasonal primary productivity: Ichnology as a proxy in palaeoceanography during glacial–interglacial variations. *Terra Nova*, **28**, 323-328.

Droser, M.L. and **Bottjer, D.J.** (1986) A semiquantitative field classification of ichnofabric. *J. of Sed. Petrol.*, **56**, 558-559.

Duncan, R.A. and **Hargraves, R.B.** (1990) ^{40}Ar/^{39}Ar geochronology of basement rocks from the Mascarene Plateau, the Chagos Bank, and the Maldives Ridge. In:*, Sci. Results* (Eds R.A. Duncan, J. Backman, and L.C. Peterson*), Proceedings of the Ocean Drilling Program*, **115**, 43-51.

Dunham, R.J. (1962) Classification of carbonate rocks according to depositional texture. In: *Classification of Carbonate Rocks* (Ed W.E. Ham), *AAPG Memoir*, **1**, 108-121.

Eberli, G.P., Swart, P.K., McNeill, D.F., Kenter, J.A.M., Anselmetti, F.S., Melim, L.A. and **Ginsburg, R.N.** (1997) A Synopsis of the Bahama Drilling Project: Results from two Deep

Core Borings drilled on the Great Bahama Bank. In: Proc. Ocean Drill. Program (Eds G.P. Eberli, P.K. Swart, M. Malone, *et al.*), *Init. Rep.*, **166**, 23-41.

Eberli, G.P., Anselmetti, F.S., Isern, A.R. and **Delius, H.** (2010) Timing of changes in sea-level and currents along the Miocene platforms of the Marion Plateau, Australia. In: *Cenozoic Carbonate Systems of Australasia* (Eds W.A. Morgan, A.D. George, P.M. Harris, J.A. Kupecz and J.E: Sarg J.E.), *SEPM Spec. Publ.*, **95**, 219-242.

Ekdale, A.A. (1988) Pitfalls of Paleobathimetric Interpretations Based On Trace Fossil Assemblages. *Palaios*, **3**, 464-472.

Ekdale, A.A. and Bromley, R.G. (1983) Trace fossils and ichnofabric in the Kjølby Gaard Marl, uppermost Cretaceous, Denmark. *Bull. geol. Soc. Denmark*, **31**, 107-119.

Ekdale, A.A., Bromley, R. and **Knaust, D.** (2012) The ichnofabric concept. In: *Trace Fossils as Indicators of Sedimentary Environments* (Eds D. Knaust and R.G. Bromley), *Dev. Sedimentol.*, **64**, 139-155.

Embry, A.F. and **Klovan, J.E.** (1972) Absolute water depth limits of late Devonian ecological zones. *Geologische Rundschau*, **61**, 672-686.

Fabricius, I. L. (2007). Chalk: composition, diagenesis and physical properties. *Bull. Geol. Soc. Denmark*, 55, 97-128.

Flügel, E. (2004) Microfacies of carbonate rocks: analysis, interpretation and application. *Springer, New York*, 976 pp.

Gerard, J. and **Bromley, R.** (2008) Ichnofabrics in Clastic Sediments: Application to Sedimentological Core Studied (Ed J. Gerard), *Madrid*, 100 pp.

Gilbert, J.M. and Martinel, J. (1998) The ichnofacies model, 30 years later. Revista Española de Paleontología, **13**, 167-174.

Gilbert, I.M., Pudsey, C.J. and **Murray, J.** (1998) A sediment record of cyclic bottom-current variability from the northwest Weddell Sea. *Sed. Geol.*, **115**, 185-214.

Goldring, R. (1993) Ichnofacies and Facies Interpretation. *Palaios*, **8**, 403-405.

Hanor, J.S. (2004) A model for the origin of large carbonate- and evaporite-hosted celestine ($SrSO_4$) deposits. *J. Sed. Res.*, **74**, 168-175.

Hansen, C.D. and **MacEachern, J.A.** (2007) Application of the asymmetric delta model to along-strike facies variations in a mixed wave- and river-influenced delta lobe, Upper Cretaceous Basal Belly River Formation, central Alberta. In: *Applied Ichnology* (Eds J.A. MacEachern, K.L. Bann and S.G. Pemberton), *SEPM Short Course Notes*, **52**, 256-272.

Huneke, N.V. and **Stow, D.A.V.** (2008) Identification of ancient contourites: problems and palaeoceanographic significance. In: *Contourites* (Eds M. Rebesco and A. Camerlenghi), *Dev. Sedimentol.*, **60**, 323-344.

Isern, A., Anselmetti, F.S. and **Blum, P.** (2004) A Neogene carbonate platform, slope and shelf edifice shaped by sea level and ocean currents, Marion Plateau (Northeast Australia). In: *Seismic imaging of carbonate reservoirs and systems* (Eds G.P. Eberli, J.L. Masaferro and J.F. Sarg), *AAPG Mem.*, **81**, 291-307.

John, C.M. and **Mutti, M.** (2005) The response of heterozoan carbonate systems to Paleoceanographic, climatic and eustatic changes: a perspective from slope sediments of the Marion Plateau (ODP Leg 194). *J. Sed. Res.*, **75**, 51-65.

Kahler, G. and **Stow, D.A.V.** (1998) Turbidites and contourites of the Paleogene Lefkara Formation, southern Cyprus. *Sed. Geol.,* **115**, 215-231.

Knaust, D. (2012) Methodology and techniques. In: *Trace Fossils as Indicators of Sedimentary Environments* (Eds D. Knaust and R.G. Bromley), *Dev. Sedimentol.*, **64**, 245-271.

Kroon, D., Willians, T., Pirmez, C., Spezzaferri, S., Sato, T. and **Wright, J.D.** (2000) Coupled early Pliocene-middle Miocene bio-cyclostratigraphy of site 1006 reveals orbitally induced cyclicity patterns of Great Bahama Bank carbonate production. In: *Sci. Results* (Eds P.K. Swart, G.P. Eberli, M.J. Malone and J.F. Sarg), *Proc. ODP*, **166**. 155-165.

Lauridsen, B.W., Surlyk, F. and **Bromley, R.G.** (2011) Trace fossils of a cyclic chalk-marl succession; the upper Maastrichtian Rørdal Member, Denmark. *Cretaceous Res.*, **32**, 194-202.

Lucchi, R.G. and **Rebesco, M.** (2007) Glacial contourites on the Antarctic Peninsula margin: insight for palaeoenvironmental and palaeoclimatic conditions. In: *Economic and Palaeoceanographic Significance of Contourite Deposits* (Eds A.R. Viana and M. Rebesco), *Geol. Soc. London Special Publ.*, **276**, 111-127.

Lucchi, R.G., Rebesco, M., Camerlenghi, A., Busetti, M., Tomadin, L., Villa, G., Persico, D, Morigi, C., Bonci, M.C. and **Giorgetti, G.** (2002). Mid-late Pleistocene glacimarine sedimentary processes of a high-latitude, deep-sea sediment drift (Antarctic Peninsula Pacific margin). *Mar. Geol.*, **189**, 343-370.

Lüdmann, T., Wiggershaus, S., Betzler, C. and **Hübscher, C.** (2012) Southwest Mallorca Island: a cool-water carbonate margin dominated by drift deposition associated with giant mass wasting. *Mar. Geol.*, **307-310**, 73-87.

Lüdmann, T., Kalvelage, C., Betzler, C., Fürstenau, J. and **Hübscher, C.** (2013) The Maldives, a Giant Isolated Carbonate Platform Dominated by Bottom Currents. *Mar. Petrol. Geol.*, **43**, 326-340.

Lüdmann, T., Betzler, C., Eberli, G.P., Reolid, J., Reijmer, J.J.G., Sloss, C.R., Bialik, O.M., Alvarez-Zarkikian, C.A., Alonso-Garcia, M., Blatter, C.L., Guo, J.A., Haffen, S., Horozal, S., Inoue, M., Jovane, L., Kroon, D., Lanci, L., Laya, J.C., Mee, A.L., Nakakuni, M., Nath, B.N., Niino, K., Petruny, L.M., Pratiwi, S.D., Slagle, A.L., Su, X., Swart, P.K., Wright, J.D., Yao, Z. and **Young, J.R.** (2018) Carbonate delta drifts: a new drift type. *Mar. Geol.*, **401**, 98-111.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L. and **Dafoe, L.T.** (2007) Use of trace fossils in genetic stratigraphy. In: *Trace Fossils. Concepts, Problems, Prospects* (Ed. W. Miller.), Elsevier, *Amsterdam*, pp. 105-128.

Maliva, R.G. and **Siever, R.** (1989) Nodular chert formation in carbonate rocks. *J. of Geol.*, **97**, 421-433.

Mulder, T., Ducassou, E., Hanquiez, V., Principaud, M., Fauquembergue, K., Tournadour, E., Chabaud, L., Reijmer, J.J.G., Recouvreur, A., Gillet, H., Borgomano, J. and **Schmitt, A.** (submitted) Contour current imprints and contourite drifts in the Bahamian Archipelago.

Mullins, H.T., Neumann, A.C., Wilber, R.J., Hine, A.C. and **Chinburg, A.J.** (1980) Carbonate sediment drifts in northern Straits of Florida. *Bull. Am. Assoc. Pet. Geol.*, **64**, 1701-1717.

Paulat, M., Lüdmann, T., Betzler, C. and **Eberli, G.P**. (submitted) Neogene paleoceanographical changes recorded in a carbonatic contourite drift (Santaren Channel, Bahamas).

Pemberton, S.G., MacEachern, J.A., Gingras, M.K. and **Saunders, T.D.A.** (2008) Biogenic chaos: Cryptobioturbation and the work of sedimentologically friendly organisms. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **270**, 273-279.

Purdy, E.G. and **Bertram, G.T.** (1993) Carbonate Concepts from the Maldives, Indian Ocean. *AAPG Studies in Geology*, **34**, 56 pp.

Rasmussen, S.L. and **Surlyk, F.** (2012) Facies and ichnology of an Upper Cretaceous chalk contourite drift complex, eastern Denmark, and the validity of contourite facies models. *J. Geol. Soc. Lond.*, **169**, 435-447.

Rebesco, M. (2005) Contourites. In: Encycopedia of Geology 4 (Eds. R.C. Selly, L.R.M. Cocks, L.R. Plimer), Elsevier, *Oxford*, pp. 513-527.

Rebesco, M., Camerlenghi, A. (Eds.), 2008. Contourites. *Dev.Sedimentol.*, **60**, 663 pp.

Rebesco, M., Hernández-Molina, F.J., Van Rooij, D. and **Wåhlin, A.** (2014) Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Mar. Geol.*, **352**, 111-154.

Reolid, J. and **Betzler, C.** (2018) Ichnofabrics logs for the characterization of the organic content in carbonates. *Mar. Petrol. Geol*., **95**, 246-254.

Reolid, J., Reolid, M., Betzler, C., Lindhorst, S., Wiesner, M. G. and **Lahajnar, N.** (2017) Upper Pleistocene cold-water corals from the Inner Sea of the Maldives: taphonomy and environment, *Facies*, **63**, 1-20.

Reolid, J., Betzler, C., Lüdmann, T. and **Bohlen, M.** (submitted) Sedimentology of carbonate delta drifts.

Rodríguez-Tovar, F.J. and **Hernández-Molina, F.J.** (2018) Ichnological analysis of contourites: Past, present and future. *Earth-Sci. Rev.*, **182**, 28-41.

Salon, S., Crise, A. and **Van Loon, A.J.** (2008) Dynamics of the bottom boundary layer. In: *Contourites* (Eds M. Rebesco and A. Camerlenghi), *Dev. Sedimentol.*, **60**, 83-97.

Savrda, C.E. and **Bottjer, D.J.** (1986) Trace fossil model for reconstruction of palaeooxygenation in bottom-waters. *Geology*, **14**, 3-6.

Savrda, C.E. and **Bottjer, D.J.** (1989) Anatomy and implications of bioturbated beds in 'black shale' sequences: examples from the Jurassic Posidonienschiefer (southern Germany). *Palaios*, **4**, 330-342.

Seilacher, A. (1967) Bathymetry of trace fossils. *Mar. Geol.*, **5**, 413-428.

Stow, D.A.V. and **Faugères, J. C.** (2008) Contourite facies and the facies model, In: *Contourites* (Eds M. Rebesco and A. Camerlenghi), *Dev. Sedimentol.*, **60**, 223-256.

Stow, D.A.V., Faugères, J.-C., Viana, A.R. and **Gonthier, E.** (1998) Fossil contourites: a critical review. *Sediment. Geol.*, **115**, 3-31.

Stow, D.A.V., Kahler, G. and **Reeder, M.** (2002). Fossil contourites: type example from an Oligocene palaeoslope system, Cyprus. In: *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics* (Eds D.A.V. Stow, C.J. Pudsey, J.A. Howe, J.C. Faugères and A.R. Viana), *Geol. Soc. London Memoirs*, **22**, 443-455.

Surlyk, F. and **Lykke-Andersen, H.** (2007) Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. *Sedimentology*, **54**, 405-422.

Taylor, A.M. and **Goldring, R.** (1993) Description and analysis of bioturbation and ichnofabric. *J. Geol. Soc.*, **150**, 141-148.

Taylor, A.M., Goldring, R. and **Gowland, S**. (2003) Analysis and application of ichnofabrics. *Earth-Sci. Rev.*, **60**, 227-259.

Uchman, A. and **Wetzel, A.** (2011) Deep-sea ichnology: the relationships between depositional environment and endobenthic organisms. In: *Deep-Sea Sediments* (Eds H. Hüneke and T. Mulder). *Dev. Sedimentol.*, **63**, 517-556.

Viana, A.R. and **Rebesco, M.** (2007) Economic and palaeoceanographic significance of contourite deposits. *Geol. Soc., London, Special Publication*, **276**, 350 pp.

Wetzel, A. (1983) Biogenic sedimentary structures in a modern upwelling region: NW African continental margin. In: *Coastal Upwelling and Its Sediment Record* (Eds J. Thiede and E. Suess), *Part B: Sedimentary Records of Ancient Coastal Upwelling. Plenum, New York*, 123-144.

Wetzel, A. and **Uchman, A.** (2012) Hemipelagic and pelagic basin plains. In: *Trace Fossils as Indicators of Sedimentary Environments* (Eds D. Knaust and R.G. Bromley), *Dev. Sedimentol.*, **64**, 673-701.

Wetzel, A., Werner, F. and **Stow, D.A.V.** (2008) Bioturbation and biogenic sedimentary structures in contourites. In: *Contourites* (Eds M. Rebesco and A. Camerlenghi), *Dev. Sedimentol.*, **60**, 183-202.

Zenk, W. (2008) Abyssal and contour currents. In: *Contourites* (Eds M. Rebesco and A. Camerlenghi), *Dev. Sedimentol.*, **60**, 35-57.

FIGURES

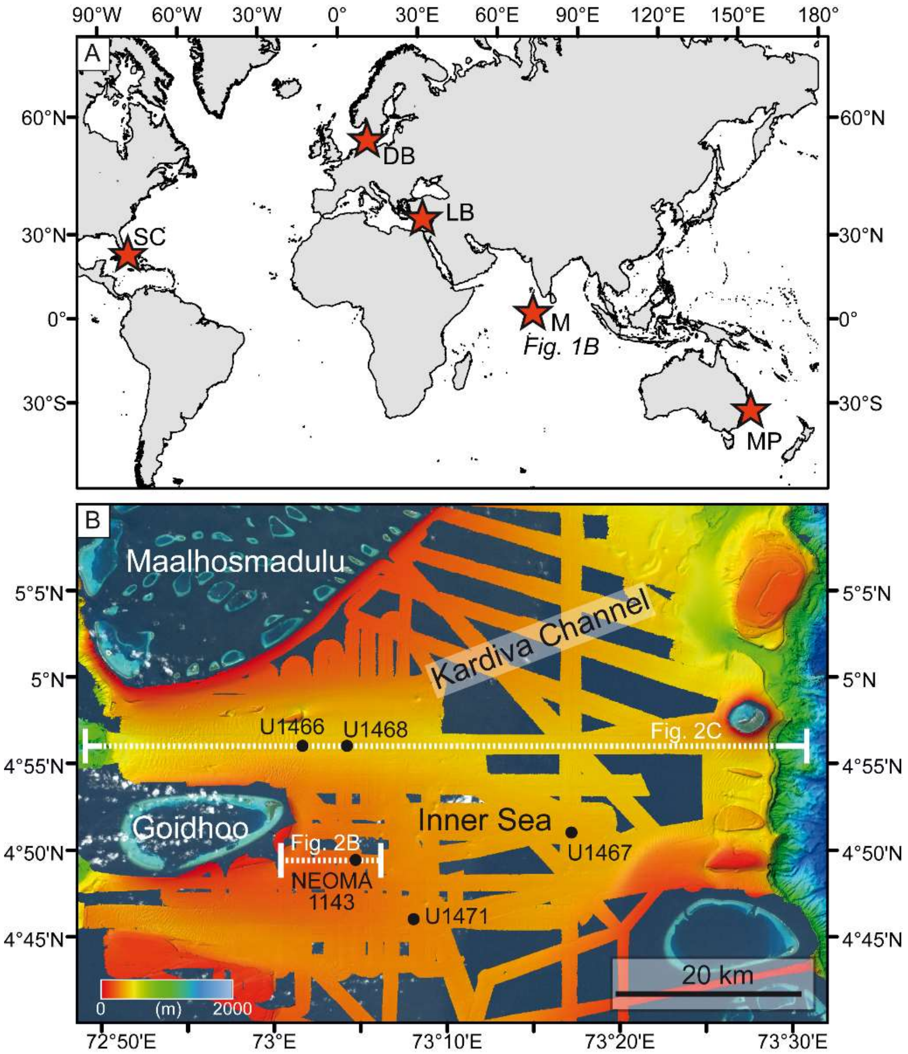

Figure 1: A Location of the carbonate drifts studied in this work. From left to right: the drifts at Santaren Channel (SC) lining Great Bahama Bank, the drifts of the Danish basin (DB) in Denmark, the drifts of the Limassol and Larnaca Basins (LB) in Cyprus, the drifts of the Inner Sea of the Maldives (M), and those of the Marion Plateau (MP) in Australia. **B** Close up of the study area of the Maldives with the location of the study sites and seismic lines in Figure 2.

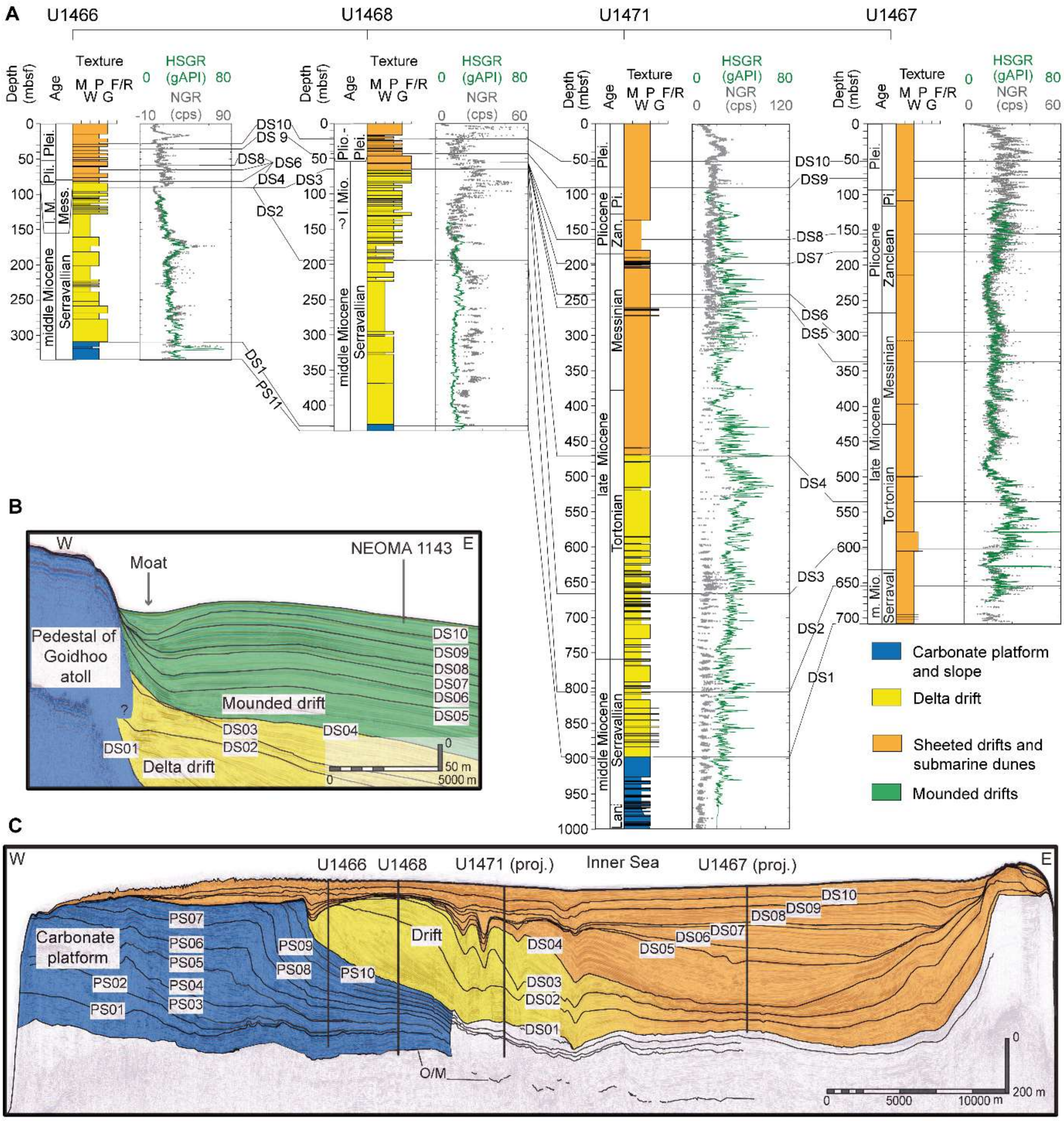

Figure 2: **A** Lithological columns of the IODP sites cored in the drift deposits of the Maldives (modified after Betzler *et al*., 2018). Each profile includes depth (mbsf), age, sediment texture, and natural gamma radiation from downhole logs (HSGR) and core measurements (NGR). The sequence boundaries of the platform (PS) and drift sequences (DS) are marked by horizontal lines. For definition of these boundaries see Betzler *et al*. (2017). **B** Seismic line P54 (location in Fig. 1) showing the position of NEOMA core 1143 in a mounded drift (modified after Betzler *et al*., 2013). **C** Seismic line P65 (Location in Fig. 1) showing the positions of the studied IODP Sites drilled in delta and sheeted drift deposits (modified after Betzler *et al*., 2018).

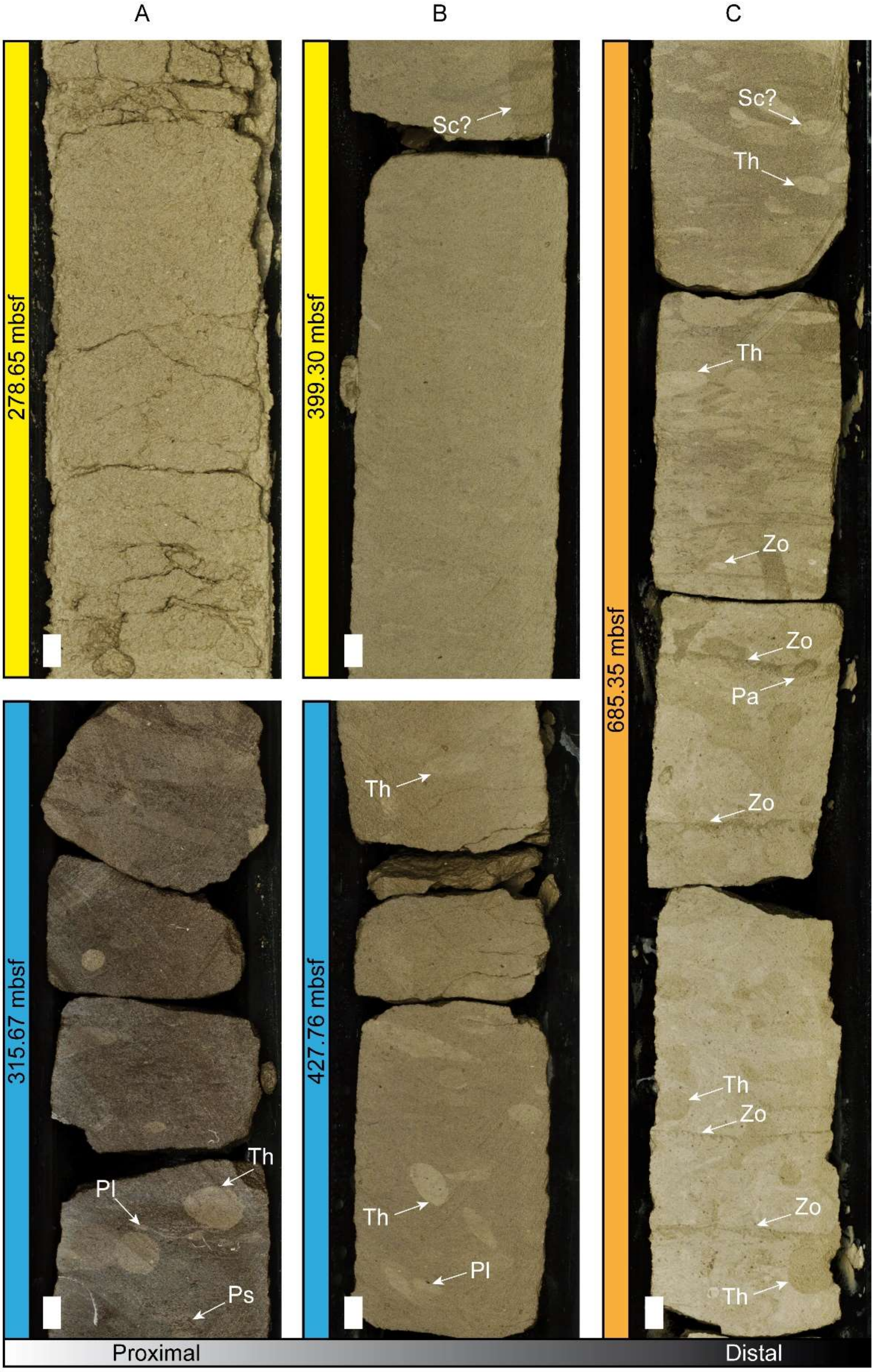

Figure 3: Core photographs of the facies and bioturbation changes of the bottom part of the delta drift (yellow) of the Maldives from the proximal Site U1466 (**A**) to U1468 (**B**), and the

sheeted drifts (orange) at the distal Site U1467 (**C**). Figures 3A and 3B also display the directly underlying slope sediments (blue) to evidence the increase in the bioturbation degree from the slope to the drift deposits. The main ichnotaxa are *Phycosiphon* (Ps), *Palaeophycus* (Pa), *Planolites* (Pl), *Thalassinoides* (Th), *Scolicia* (Sc), and *Zoophycos* (Zo). Scale bar =1 cm.

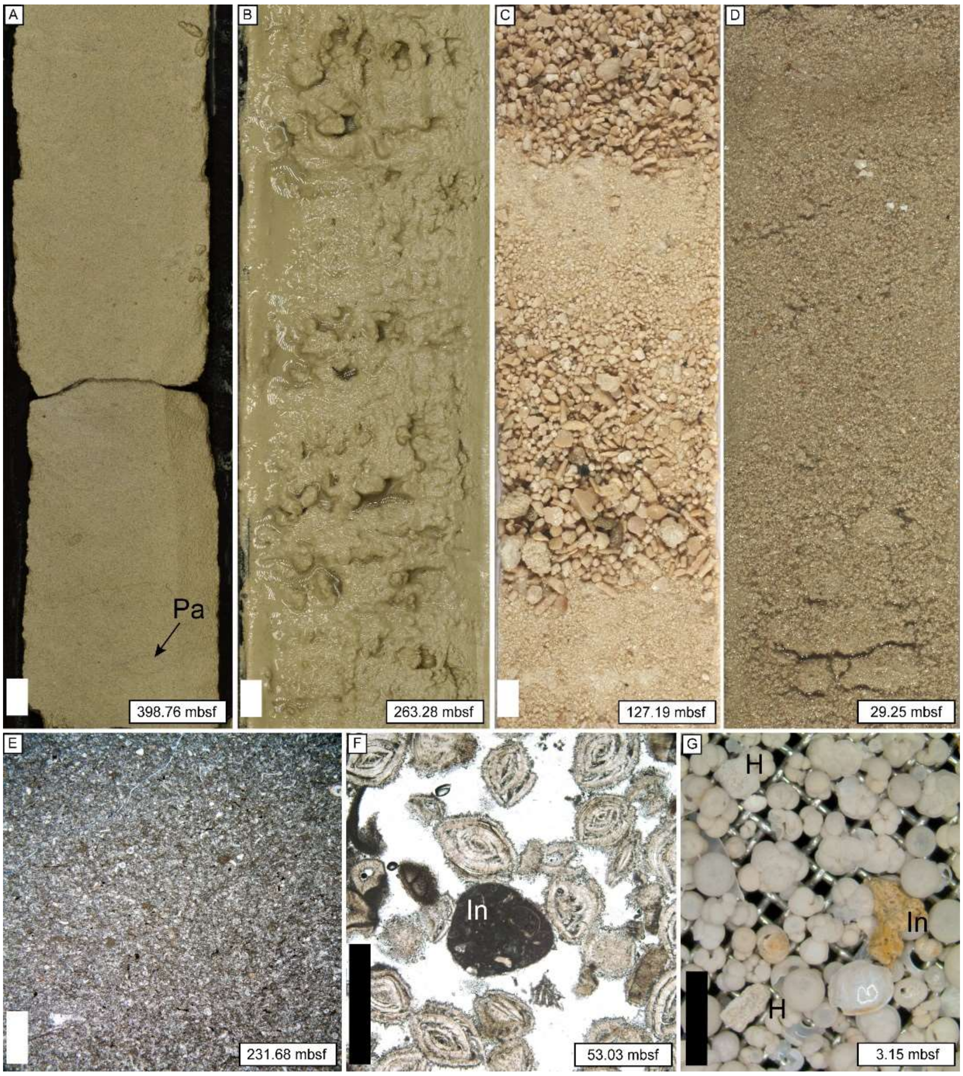

Figure 4: Facies of the delta and sheeted drift at the proximal IODP sites (U1466 and U1468) of the Maldives modified after Lüdmann *et al*. (2018) (scale bar for core photographs=1 cm, scale bar for photomicrographs=1 mm). **A** Core photograph of a fine-grained bioclastic packstone at Site U1468. **B** Core photograph of an unlithified wackestone with intraclasts at Site U1468. **C** Core photograph of a large benthic foraminifera-rich rudstone to grainstone with a fining upward grain size trend at Site U1468. Echinoid spines, large benthic foraminifera and intraclasts are common. **D** Core photograph of a partially lithified packstone to grainstone at Site U1468. The better lithifies areas probably correspond to *Thalassinoides* burrows. **E** Photomicrograph of the fine-grained packstone at Site U1466. **F** Photomicrograph of the rudstone to grainstone facies at U1468 with abundant *Amphistegina* and intraclasts (In). **G**

Photomicrograph of a grainstone to packstone at Site U1468 with abundant planktonic foraminifera and *Halimeda* plates (H) and intraclasts.

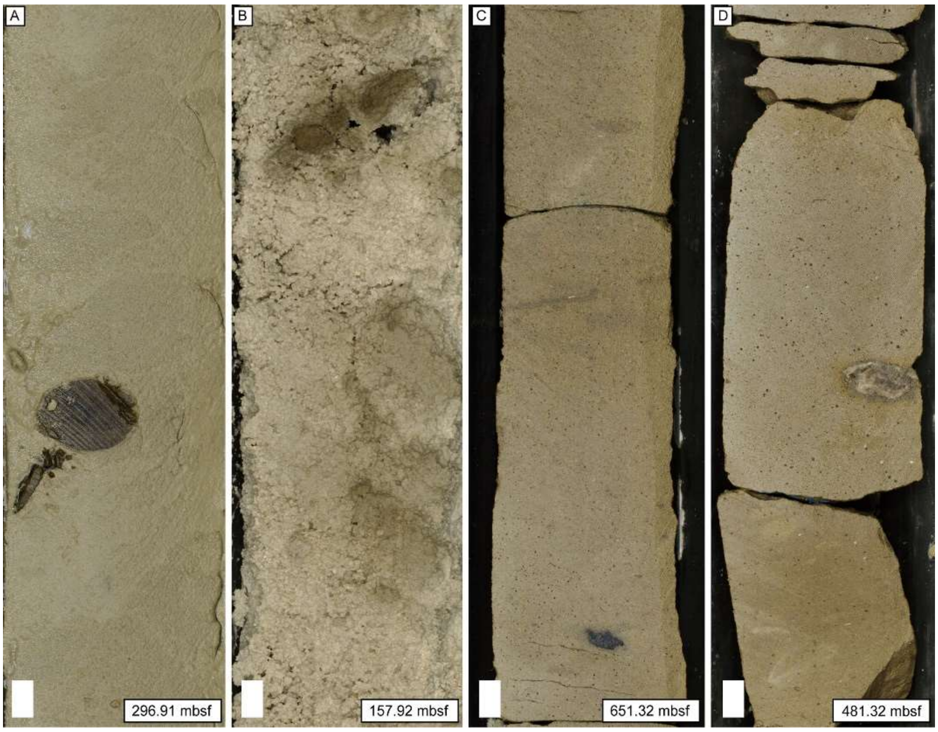

Figure 5: Distinct infills in traces from the carbonate drifts of the Maldives (scale bar=1 cm). **A** *Thalassinoides* preserved in chert at Site U1468. **B-C** *?Thalassinoides* burrows enriched in particulate organic matter at Site U1468 (B) and U1471 (C). **D** *Thalassinoides* preserved in celestine at Site U1471.

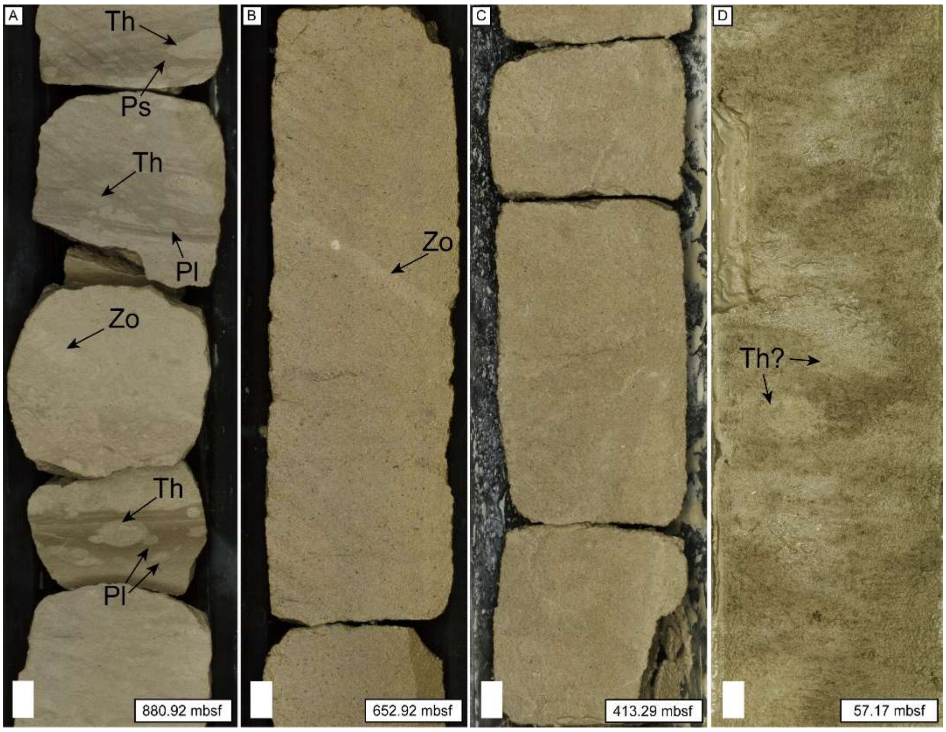

Figure 6: Facies and bioturbation of the drift deposits at Site U1471 of the Maldives (scale bar=1 cm). **A** Core photograph of alternating intensely bioturbated grainstone/packstone intervals with finely laminated packstone intervals. Trace fossils in the laminated intervals are infilled by the overlying grainstone. **B** Core photograph of an almost completely homogenized packstone with rare discrete trace fossils. **C** Core photograph of bioturbated packstone without discrete trace fossils. **D** Core photograph of a mottled packstone. *Phycosiphon* (Ps), *Planolites* (Pl), *Thalassinoides* (Th), and *Zoophycos* (Zo).

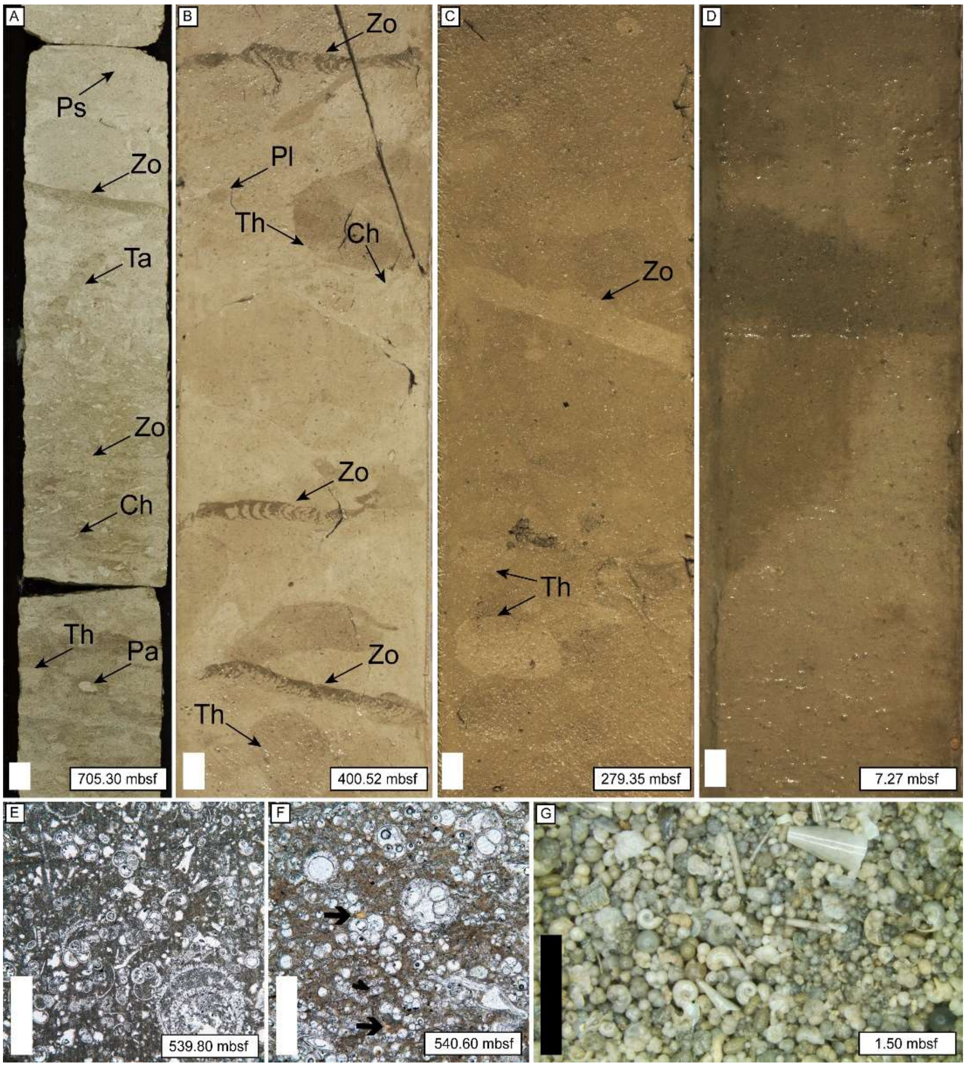

Figure 7: Facies and bioturbation of the sheeted drift deposits at Site U1467 in the Maldives (scale bar for core photographs=1 cm, scale bar for photomicrographs=1 mm, black bar=1 cm). **A** Core photograph of a dark- and a light-colored interval of fine-grained wackestone with abundant discrete trace fossils. **B** Core photograph of fine-grained wackestone with abundant *Zoophycos* out of the heavily bioturbated background. **C** Core photograph intensely bioturbated wackestone with diffuse trace fossils out of the mottled background. **D** Core photograph of an unlithified wackestone with large trace fossils (*Thalassinoides*?). **E** Photomicrograph of a light interval of a fine-grained wackestone. Note the extensive fragmentation of the planktonic foraminifera. **F** Photomicrograph of a dark interval of the fine-grained wackestone with preserved organic matter and fish debris (black arrow). **G** Photomicrograph of a grainstone from the uppermost part of the drift with abundant pelagic fauna including planktonic

foraminifera and pteropods. The main ichnotaxa are *Chondrites* (Ch), *Palaeophycus* (Pa), *Phycosiphon* (Ps), *Planolites* (Pl), *Taenidium* (Ta), *Thalassinoides* (Th), and *Zoophycos* (Zo).

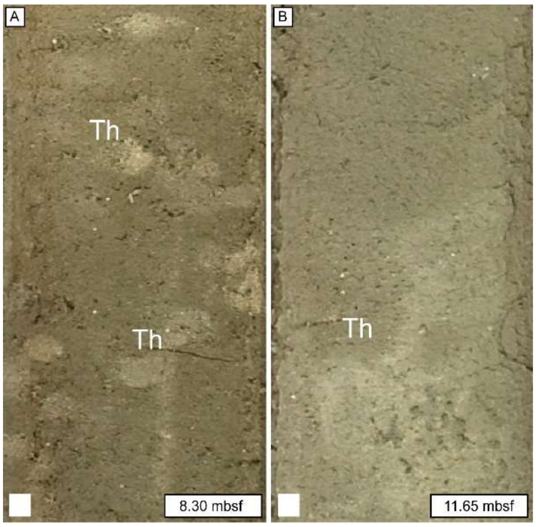

Figure 8: Facies and bioturbation of the detached drift recovered by core NEOMA 1143 in the Maldives (scale bar=1 cm). **A** Fine-grained ooze with some large bioclast and traces of Thalassinoides out of the mottled background. **B** Contact between light (aragonite-rich) and dark (aragonite-poor) sediment. The traces of *Thalassinoides* in the light interval are infilled by the overlying dark material.

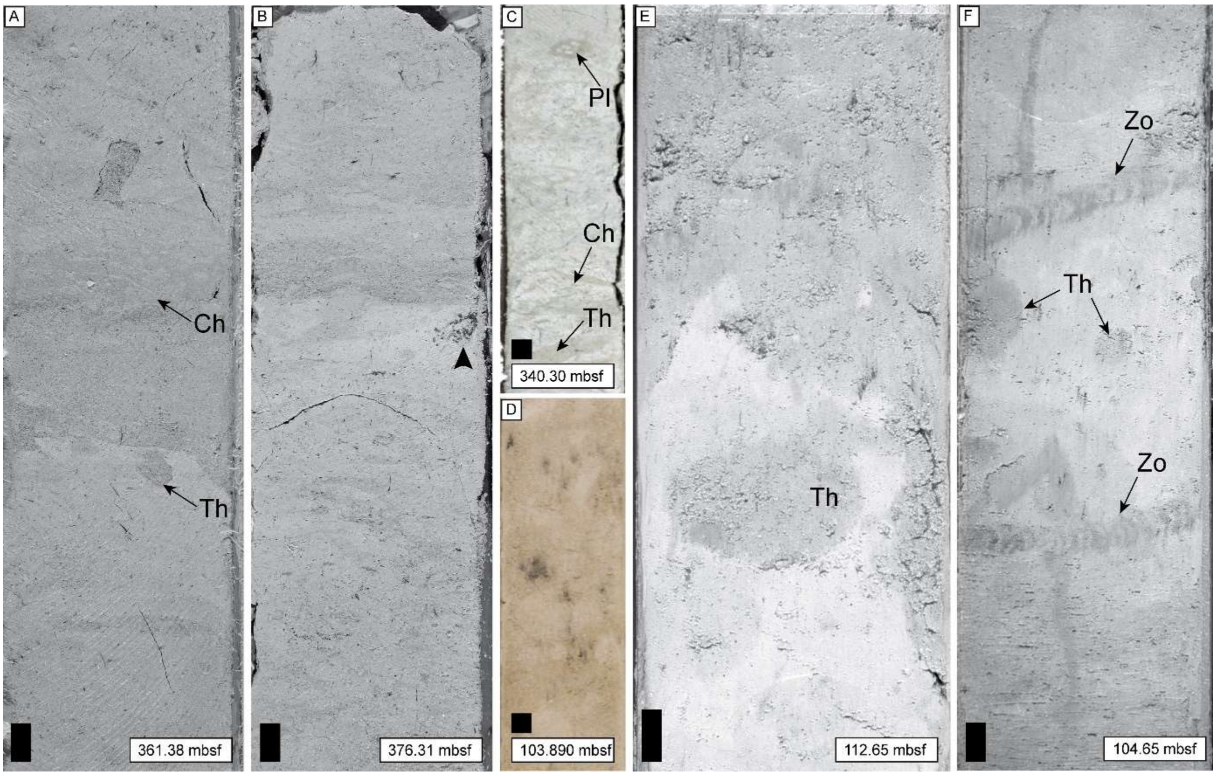

Figure 9: Representative facies and bioturbation of drift from Bahamas and Australia (scale bar=1 cm). **A-B** Core photograph of a firmground at Site 1006A in the Santaren drift of Bahamas. The firmground was burrowed and the overlying sediment is mostly bioturbated by *Chondrites* (A). The black arrow-head indicates trace fossils preserved in pyrite (B). **C** Core photograph of heavily bioturbated wackestone/packstone with diverse trace fossils at Site 1006 in Bahamas. **D** Core photograph of a mottled wackestone at Site 1195B in Australia with accumulation of particulate organic matter in trace fossils (Thalassinoides?). **E** Core photograph of a firmground at Site 1192A. **F** Core photograph of a bioturbated wackestone with discrete trace fossils out of the mottled background. *Chondrites* (Ch), *Planolites* (Pl), *Thalassinoides* (Th), and *Zoophycos* (Zo).

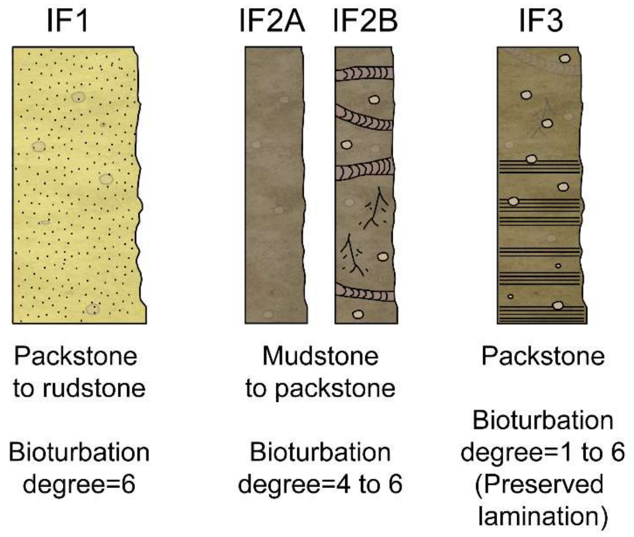

Figure 10: Schematic model of the main ichnofabrics observed in carbonate drifts. Bioturbation index according to Droser and Bottjer (1986). The different trace fossils illustrate the occurrence of distinctive bioturbation out of the mottled background.

956 **Table 1.** Summary of main types of carbonate drifts and their ichnological and sedimentological
957 features (facies, bioturbation index, main ichnogenera, and ichnofabrics).
958

Drift type	**Sediment texture**	**Bioturbation index (BI)**	**Main ichnogenera**	**Ichnofabrics (IF)**
Delta drift.	Fine-grained packstone to coarse-grained grainstone to rudstone.	5-6 Locally 1-3 in laminated intervals.	*Thalassinoides*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, and *Palaeophycus* in fine-grained facies. *Thalassinoides* in coarse-grained facies.	**IF1** Coarse-grained sediment is completely bioturbated (BI=6) rarely with *Thalassinoides* traces. **IF2** Alternation of ichnofabrics 2A and 2B **IF2A** Fine-grained material completely bioturbated (BI=6) with local *Thalassinoides*- and *Planolites*-like traces. **IF2B** Fine-grained sediment intensely bioturbated (BI=4-5)

				with diverse trace fossils. **IF3** Fine-grained sediment with low bioturbation (BI=1-3) and preserved primary sedimentary structures.
Sheeted drift.	Fine-grained wackestone to packstone.	4-6.	*Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, and *Palaeophycus*. *Taenidium* and *Nereites* may be also present. *Ophiomorpha* and *?Helminthoides* may be present in drifts reworking calciturbidites.	**IF2** Alternation of ichnofabrics 2A and 2B **IF2A** Fine-grained material completely bioturbated (BI=6) with local *Thalassinoides*- and *Planolites*-like traces. **IF2B** Fine-grained sediment intensely bioturbated (BI=4-5) with diverse trace fossils.
Mounded drift.	Chalk-ooze. Fine-grained	4-6	*Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*,	**IF2** Alternation of ichnofabrics 2A and 2B

	wackestone to packstone.	Locally 2-3 in laminated intervals.	*Chondrites*, *Phycosiphon*, and *Palaeophycus*. *Asterosoma* may be present.	**IF2A** Fine-grained material completely bioturbated (BI=6) with local *Thalassinoides*- and *Planolites*-like traces. **IF2B** Fine-grained sediment intensely bioturbated (BI=4-5) with diverse trace fossils. **IF3** Fine-grained sediment with low bioturbation (BI=2-3) and preserved primary sedimentary structures.

Table 2. List of the main ichnological features in carbonate

1. Completely bioturbated sediment with bioturbation indexes between 4 and 6.
2. Distinctive trace fossils against the mottled background are limited to facies contacts or condensed intervals. The intense bioturbation, lack of contrast of the carbonate sediment, and diagenesis difficult the identification of trace fossils.
3. The typical ichnoassemblage consists of *Thalassinoides*, *Scolicia*, *Planolites*, *Zoophycos*, *Chondrites*, *Phycosiphon*, and *Palaeophycus*. *Taenidium* and *Nereites* may be also present.
4. Ichnogenera from different tiers typically occur together, only *Zoophycos* and *Chondrites* may locally stand as deep tiers.
5. Trace fossils may present distinct infills including particulate organic-matter, pyrite, silica, and celestine.
6. *Cruziana* and *Zoophycos* are the main ichnofacies.
7. The ichnofabrics grade from coarse-grained and completely bioturbated to ichnofabrics with present to absent trace fossils and preserved sedimentary structures.