Marine Geology 437 (2021) 106502

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Contourite and mixed turbidite-contourite systems in the Mozambique Channel (SW Indian Ocean): Link between geometry, sediment characteristics and modelled bottom currents

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ARTICLE INFO

Editor: Michele Rebesco

Keywords:
Bottom current
Contour current
Oceanic circulation
Deep-water environment
Sediment drift
Contourite depositional system

ABSTRACT

Oceanic currents can profoundly reshape the seafloor and even modify the characteristics of turbidite systems. Multiple erosional and depositional features directly formed by bottom currents (i.e. contourites), as well as by the interaction between bottom currents and turbidity currents or turbidite systems (i.e. mixed turbidite-contourite systems) have been identified in the Mozambique Channel (SW Indian Ocean) in multibeam bathymetry, seismic reflection data, sub-bottom profiler images and sediment cores. In this study, we characterise the morphology, stacking pattern and sedimentary characteristics of these sedimentary systems, and analysed the properties of bottom currents at these systems using a hydrodynamic numerical model. Modelled bottom currents are the highest at abraded surfaces and moats, but they also display a relatively high variability, suggesting that the observed erosion is not the result of a constant or persistent current but rather of episodes of intense circulation. Modelled bottom currents at contourite terraces are not significantly different from currents at related plastered drifts, where accumulation is enhanced. The formation of contourite terraces can thus not solely be explained by the mean oceanic circulation and eddies, implying that other processes such as internal waves may play a relevant role in their formation. Three different types of mixed turbidite-contourite systems were observed: one characterised by asymmetric channel-levee systems formed by the synchronous interaction of bottom currents and turbidity currents, one characterised by a phased interaction that resulted in the erosion of the channel flanks by bottom currents, and another one in which both synchronous and phased interaction played a relevant role in the evolution of the system. Finally, we propose a simplified classification of contourites that can be applied to any contourite system worldwide, and that comprises erosional and depositional features, including muddy and sandy contourite deposits.

1. Introduction

Ocean circulation can affect sedimentation from shallow waters to the deep sea and form contourite depositional systems (Rebesco et al., 2014). These systems are composed of both depositional (i.e. contourite drifts) and erosional features (e.g. abraded surfaces, moats, channels and furrows) formed by currents flowing near the seafloor (i.e. bottom currents; Hernández-Molina et al., 2008a, 2008b; Rebesco et al., 2014). The first observations of deposits generated by the thermohaline circulation in the deep sea were published in the 1960s (Heezen and Hollister, 1964;

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https://doi.org/10.1016/j.margeo.2021.106502
Received 29 January 2021; Received in revised form 22 April 2021; Accepted 30 April 2021
Available online 6 May 2021

Hollister, 1967). After these pioneering studies, numerous contourites have been identified in different types of environments and at all water depths, also in lakes, and their formation has been related to all types of bottom currents, including balanced flows (e.g. currents related to the mean oceanic circulation, eddies, Ekman transport) and unbalanced flows (e.g. internal tides, internal solitary waves, near-inertial flows) and is not only restricted to the thermohaline circulation (Rebesco et al., 2014 and references therein).

Understanding the characteristics of contourites and the processes that control their formation and evolution is important for multiple research topics: (i) paleoceanographic and paleoclimatic reconstructions (Knutz, 2008; McCave, 2008); (ii) submarine geohazards (Miramontes et al., 2018); (iii) continental-scale submarine geomorphology (Mosher et al., 2017); (iv) turbidite-contourite interaction (Miramontes et al., 2019a, 2020a; Fonnesu et al., 2020; Fuhrmann et al., 2020); (v) microplastic accumulation (Kane et al., 2020); and (vi) development of particular ecosystems such as cold-water corals (Hebbeln et al., 2016). Despite the broad interest in current-related sedimentation, sometimes the identification of contourites remains challenging, especially at small scale from the analysis of sediment cores and outcrops (Stow and Smillie, 2020). Moreover, little is still known about the physical processes that control the formation of contourites. Bottom currents are commonly considered to be "persistent" because their effect can be observed in the sedimentary record at large scale over thousands to millions of years (Stow et al., 2002; Rebesco, 2005, 2014). Although *in situ* measurements and modelling studies of bottom currents in the deep-sea remain scarce (Hunter et al., 2007; de Lavergne et al., 2016), increasing number of studies suggest that bottom currents at the origin of contourites present strong temporal variability (e.g. Thran et al., 2018; Miramontes et al., 2019b; de Weger et al., 2020).

The main criteria used for the identification of contourites are commonly based on the geometry and internal architecture of the deposits using multibeam bathymetry and seismic data (Faugères et al., 1999; Rebesco et al., 2014). Recent studies also suggest that turbidites, contourites and hemipelagites can be differentiated using principal component analysis of grain size and geochemical composition, together with sedimentary macrofacies, microfacies and ichnofacies analyses (de Castro et al., 2021a, 2021b). Moreover, it has been shown that contourite drifts, identified from their large-scale geometry, can contain other types of deposits at bed scale such as hemipelagites and turbidites (de Castro et al., 2021b). It is therefore recommended to analyse the deposits at different scales, from small-scale sedimentary characteristics (e.g. lamination, bioturbation), to medium-scale sediment body geometry and the large-scale oceanographic and tectonic setting (Stow and Smillie, 2020). Most of the studies and classifications of contourites focus on large muddy contourite drifts in siliciclastic systems (Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2002; Hernández-Molina et al., 2008a), which are commonly characterised by the bigradational contourite facies model (Gonthier et al., 1984; Stow et al., 2002). However, contourites are very diverse, and include for instance, carbonate contourites (Eberli and Betzler, 2019) and sandy contourites (Brackenridge et al., 2018). The main classification of contourites commonly used at present was proposed by Faugères et al. (1999), Rebesco and Stow (2001) and Rebesco (2005). It focuses on the sedimentary deposits and on the context in which they are formed, and it is based on the geometry and internal architecture of deposits imaged with seismic data. The classification is complex, and it is often difficult to clearly identify different types of contourite drifts. Moreover, it is not evident whether different drift types are associated with different processes. For instance, many contourite drifts (elongated separated mounded drifts, confined drifts, infill drifts and patch drifts) are associated with a moat, and all have similar morphologies. Furthermore, this classification system is focused on muddy contourite drifts and makes no direct reference to sandy contourites (Hernández-Molina et al., 2008a; Rebesco et al., 2014 and references therein).

This study has two main aims: 1) The first aim is to provide a new comprehensive classification of contourites that will help the identification of contourite depositional systems in the sedimentary record, and that is based on an update, integration and simplification of previous classifications (Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2002; Hernández-Molina et al., 2008a; García et al., 2009), using as examples sedimentary features from the Mozambique Channel. 2) The second aim is to establish a better link between the different types of contourites and the oceanographic processes that form them, by analysing the characteristics of bottom currents from a numerical model at the different zones affected by bottom currents in the Mozambique Channel. We chose this study area because of its abundance and diversity of current-related sedimentary features, and because the physical oceanography of this area is relatively well known and information of bottom currents from a numerical model is available (Fierens et al., 2019; Miramontes et al., 2019a; Thiéblemont et al., 2019).

2. Regional setting

2.1. Geological setting

The Mozambique Channel is an elongated, north-south oriented basin, located on the East African margin (Southwest Indian Ocean) between Mozambique and Madagascar. The Mozambique Basin is considered its southward extension (Fig. 1). Maximum water depths range between 2700 m in the narrowest part of the channel in the north, and 5000 m in the southern part of the Mozambique Basin (Fig. 1).

The Mozambique Channel formed during the breakup of Gondwana from the Early-Middle Jurassic times until the Early Cretaceous period (Mahanjane, 2014; Thompson et al., 2019; Li et al., 2021). This geodynamic evolution created a marginal fracture ridge (Davie Ridge in the NE part of the channel), large igneous provinces of oceanic origin (the Mozambique Ridge and the Madagascar Ridge with a N-S orientation in the southern part of the basin), a continental basement high (the Beira High in the central-western part of the channel), and in the centre of the basin volcanic seamounts and islands (Eparses Islands), some of which are capped by carbonate platforms (Fig. 1). Isolated carbonate platforms started to form during Oligocene-Miocene times (Courgeon et al., 2016; Leroux et al., 2020), and evolved in close relationship with tectonic movements and renewed volcanic activity (Courgeon et al., 2017; Deville et al., 2018). The Eparses Islands still host modern carbonate platforms (Jorry et al., 2016), but several other carbonate platforms atop volcanic edifices drowned during Late Miocene to Early Pliocene times (Courgeon et al., 2016).

Sedimentation in the Mozambique Channel and Basin is bounded in the north and west by the African continent and the Mozambique Ridge, and in the east by Madagascar and the Davie Ridge (Castelino et al., 2017; Fig. 1). The Zambezi and Limpopo Rivers are the main rivers delivering sediment to the margin and the deep oceanic regions (Walford et al., 2005). However, sediment is also supplied from the western side of Madagascar, for instance by the Mangoky and the Tsiribihina Rivers (Fierens et al., 2019). The submarine channels related to the Zambezi and Mangoky/Tsiribihina River systems join in the Mozambique Channel at ~22.5°S and feed a single turbidite system, named the Zambezi turbidite system, which started to develop at the beginning of the Oligocene (Droz and Mougenot, 1987; Fierens et al., 2019). The Zambezi turbidite system comprises a large lobe system in the south distal Mozambique Basin, mainly developed before 350 kyr, and a ponded semi-confined fan spread out in the north-western area between the Mozambican slope and the Eparses Islands formed during late Quaternary (Fig. 1; Fierens et al., 2019, 2020). At present, the Zambezi River does not supply sediment directly to the turbidite system and the sediment is mainly dispersed northwards by longshore currents (Schulz et al., 2011). Other smaller turbidite systems, that also deliver sediment to the basin, are related to submarine canyons located in the southern and northern Mozambican slope (Fig. 1; Thiéblemont et al., 2019). Carbonate sediment is also exported to the deep seafloor in the

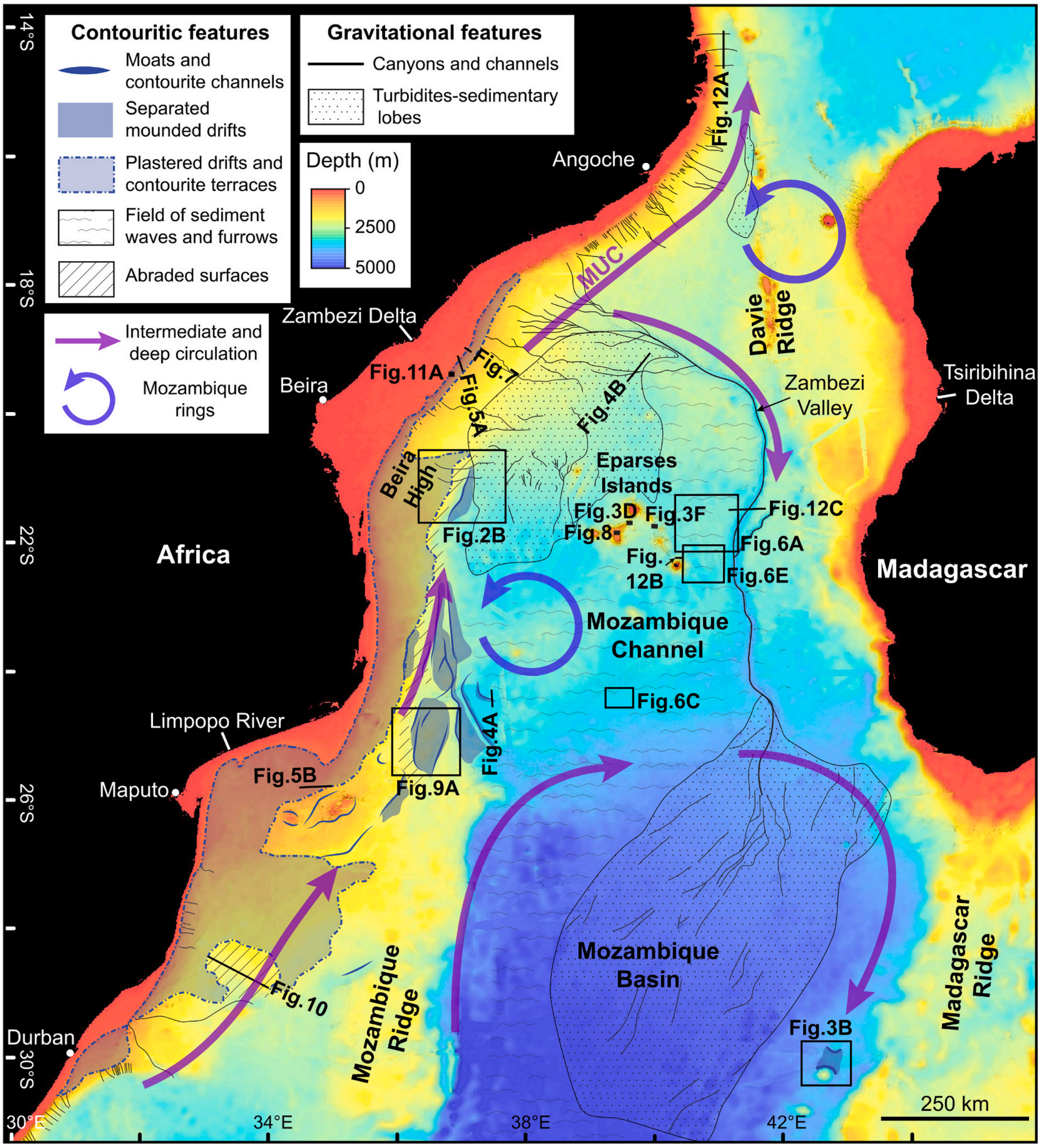

Fig. 1. Bathymetric map of the Mozambique Channel showing the main contouritic and gravitational sedimentary features (based on Thiéblemont et al., 2019; and Fierens et al., 2019). The large purple and blue arrows indicate the general oceanic currents in the area. MUC: Mozambique Undercurrent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basin from several isolated platforms and atolls in the form of fine-grained aragonite and calciturbiditic sands (Counts et al., 2018, 2019; Jorry et al., 2020).

2.2. Oceanographic setting

Surface and intermediate currents are part of the greater Agulhas Current system and enter the Mozambique Channel from the north (Lutjeharms, 2006). These currents mainly flow southwards as large anticyclonic eddies with diameters of ≥300 km that can affect the entire water column and reach the seafloor (de Ruijter et al., 2002; Halo et al., 2014). Intermediate (Antarctic Intermediate Water, AAIW) and deep-water masses (North Atlantic Deep Water, NADW, and Antarctic Bottom Water, AABW) enter the Mozambique Channel from the south and flow northwards along the eastern African margin as the Mozambique Undercurrent (MUC) (Fig. 1; Ullgren et al., 2012). AAIW and the upper part of the NADW continue to flow northwards along the northern Mozambican margin, but the lower part of the NADW and the AABW are constrained by the northward shallowing bathymetry, especially below 2500 m water depth, and flow back southwards along the western margin of Madagascar (Fig. 1; Ullgren et al., 2012; Miramontes et al., 2019a). This intense circulation controls sedimentation and seafloor geomorphology in the Mozambique Channel at all depths, from the shelf (Flemming and Kudrass, 2018) and top of seamounts (Miramontes et al., 2019c), to the deep part of the basin (Kolla et al., 1980; Breitzke et al., 2017; Fierens et al., 2019; Miramontes et al., 2019a; Thiéblemont et al., 2019).

3. Materials and methods

The multibeam bathymetry used in this study was acquired during the oceanographic cruises of the PAMELA project (Bourillet et al., 2013): PTOLEMEE (2014, R/V L'Atalante; Jorry, 2014), PAMELA-MOZ01 (2014, R/V L'Atalante; Olu, 2014), PAMELA-MOZ02 (2014, R/V L'Atalante; Robin and Droz, 2014), PAMELA-MOZ03 (2016, R/V Pourquoi pas?; Moulin and Aslanian, 2016), PAMELA-MOZ04 (2015, R/V Pourquoi pas?, Jouet and Deville, 2015) and PAMELA-MOZ05 (2016, R/V Pourquoi pas?; Moulin and Evain, 2016). The regional bathymetric map was generated using a compilation of the GEBCO bathymetry (GEBCO_08, version 2010-09-27, http://www.gebco.net), with a 30 arc-second resolution, and the multibeam bathymetry of the PAMELA cruises, with a 100-m horizontal resolution. Local maps were generated for this study to illustrate in detail different sedimentary features using multibeam bathymetry acquired during the PAMELA cruises with increased resolution that ranges from 3 m in the upper Mozambican slope, 5 m atop seamounts, and 30–40 m in the deep part of the Mozambique Channel and Mozambique Basin.

The seismic dataset used to image the internal sedimentary architecture is exclusively composed of 2D profiles and includes different types of data:

- Regional multiclient 2D multi-channel seismic reflection profiles acquired by the companies WesternGeco in 2013–2014 and CGG in 2013–2014.
- 72-channel high-resolution (HR) mini GI-gun seismic reflection profiles (central frequency 125–150 Hz) acquired during the PTOLEMEE and PAMELA-MOZ04 cruises.
- 24-channel fast high-resolution (SR) mini GI-gun seismic reflection profiles (central frequency 50–60 Hz) acquired during the PTOLEMEE, PAMELA-MOZ02 and PAMELA-MOZ04 cruises.
- Sub-bottom profiler (SDS) data (1800–5300 Hz) acquired during the PAMELA-MOZ03 and PAMELA-MOZ04 cruises.

The estimations of sediment thickness and height provided in this study based on seismic profiles were calculated considering a constant velocity of 1500 m s^{-1}, as an approximation to the observed average acoustic velocity (1512 m s^{-1}) measured at IODP site U1476A (Hall et al., 2017).

Three Calypso piston cores from the Mozambican margin are used in this study for visual description and grain-size analyses. Cores MOZ4-CS17 (32.46 m long) and MOZ4-CSF19 (9.24 m long) were collected during the PAMELA-MOZ04 cruise, and core MOZ3-CS07 (11.67 m long) was collected during the PAMELA-MOZ03 cruise. Grain-size measurements were performed on samples from cores MOZ4-CS17 and MOZ4-CSF19 at 10-cm intervals using a Malvern Mastersizer 3000 laser diffraction particle size analyser at Ifremer laboratories. We also use in the present study an image of the seafloor obtained at the approximate location of core MOZ4-CSF19 with the deep-towed SCAMPI camera system during the PAMELA-MOZ04 survey.

Modelled bottom currents were obtained using the Regional Ocean Modelling System (ROMS, CROCO version: https://www.croco-ocean.org/) at a regional scale with a resolution of 1/36° (~2.6 km). Since the first Rossby radius of deformation is around 40–100 km in the Mozambique Channel (Halo et al., 2014), this simulation resolves the mesoscale processes. In this study, we used mean and maximum bottom currents (calculated from 22 years of simulation, 1993–2014) previously published by Miramontes et al. (2019a), and we also calculated modelled mean bottom Eddy Kinetic Energy (EKE). EKE was calculated as $\frac{1}{2}\left(u'^{2}+v'^{2}\right)$, where $u' = u - \overline{u}$ and $v' = v - \overline{v}$. $\overline{u}$ and $\overline{v}$ are the temporal mean of the velocity over the whole period of time, and thus EKE provides information about the variability of bottom currents (Cossa et al., 2016). Metrics of bottom currents at the sites of contourite depositional systems and turbidite-contourite systems were obtained in the software ArcGIS using the Zonal Statistics tool. The extension and location of the different features within the sedimentary systems were obtained from Thiéblemont et al. (2019), Fierens et al. (2019) and the present study. The horizonal resolution of the model (~ 2.6 km) permits to resolve bottom currents in the main large-scale contourite features that commonly extend over 10s and 100s of km (Table 1). The moats mapped by Thiéblemont et al. (2019) have widths that mainly range between 3 and 15 km and are often over 100 km long (Fig. 1). They are therefore comparable with model results. Other smaller scale contourite features that are shown in this study are below the resolution of the model or outside the boundaries of the model. Therefore, modelled bottom currents could not be analysed in these areas.

The identification of contourites in the present study is mainly based on the morphology and internal architecture of the sedimentary features observed using seismic and bathymetric data, following the concepts proposed by Faugères et al. (1999), Faugères and Stow (2008), Nielsen et al. (2008) and Rebesco et al. (2014). The term "contourite drift" is used to refer to the sediment accumulations formed by bottom currents, as recommended by Rebesco et al. (2014). Contourite drifts often have an elongated mounded shape parallel to the slope and can be associated with concave incisions (moats or contourite channels). Some contourite drifts (i.e. detached drifts) develop obliquely or perpendicularly to the main slope trend and are often related to large topographic changes in the margin. Bottom currents can also induce widespread erosion characterised by truncations, and these erosional surfaces are classified as abraded surfaces (Rebesco et al., 2014).

4. Results

Contourites could be identified throughout the entire Mozambique Channel, from the upper slope and top of seamounts, to the deep part of the basin, based on discoveries from previous studies (Breitzke et al., 2017; Wiles et al., 2017; Babonneau et al., 2018; Fierens et al., 2019;

Table 1
Summary of the water depth and size of the different contouritic and mixed turbiditic-contouritic features observed in the Mozambique Channel, and average modelled bottom-current metrics and standard deviation at these zones.

	Separated mounded drifts	Detached mounded drifts	Plastered drifts	Sediment waves	Contourite terraces	Moats	Abraded surfaces	Zambezi Valley	Mixed system north
Water depth (km)	1.6–4	–	0.3–2	2.4–5.2	0.15–2.8	0.6–4	1.8–2.8	2.4–4.2	2–2.7
Across-slope extent (km)	1–65	28–100	5–120	–	5–110	0.25–15	25–30 (North) and 115 (South)	At least 900 (upper limit not known)	No data
Alongslope extent (km)	1–180	25–400	40–1500	–	80–1500	2–160	570 (North) and 100 (South)	Valley up to 50 and thalweg up to 10	5–8
Average mean speed (cm s^{-1})	8.4 ± 2.4	–	8.4 ± 2.4	8.2 ± 2.3	8.0 ± 3.3	9.2 ± 3.2	10.0 ± 3.3	8.8 ± 2.7	5.6 ± 2.2
Average maximum speed (cm s^{-1})	30.3 ± 8.4	–	37.2 ± 9.2	30.5 ± 8.0	35.2 ± 12.4	39.1 ± 14.1	41.1 ± 7.8	33.8 ± 8.1	23.3 ± 8.2
Average mean EKE (cm^2 s^{-2})	30.2 ± 16.0	–	43.4 ± 23.6	28.9 ± 14.6	38.4 ± 26.1	43.9 ± 33.1	49.0 ± 21.3	32.5 ± 17.0	20.4 ± 14.1

No information about water depth and bottom currents is provided for detached mounded drifts because these deposits are relict. The across-slope and alongslope extent of sediment waves is not indicated because the orientation, crest length and wave length of these bedforms are very variable (see details in the text). EKE: Eddy kinetic energy.

Miramontes et al., 2019a,2019c,2020b; Ponte et al., 2019; Thiéblemont et al., 2019, 2020) and also on new discoveries from this study. Contourites seem to be more widely developed in the western part of the basin (along the Mozambican margin) than in the eastern part (along the margin of Madagascar; Fig. 1). Turbidity currents are also an important source of sediment in these areas. Many of the turbidite systems in the Mozambique Channel present characteristics that evidence that they have been affected by bottom currents, and are thus classified as mixed turbidite-contourite systems. The characteristics of both pure contourite depositional systems and mixed turbidite-contourite systems of the Mozambique Channel are detailed in the following sections.

4.1. Contourite depositional systems

Contourite depositional systems are composed of zones dominated by sediment deposition (contourite drifts) and zones dominated by erosion (erosional features). The different contouritic features formed by deposition, winnowing and erosion that have been identified in the Mozambique Channel are described here separately.

4.1.1. Depositional features – muddy contourite drifts

4.1.1.1. Separated mounded drifts. Separated mounded drifts are contourite deposits often related to steep slopes and that are parallel to the main trend of the slope. They are always associated with an incision (contourite channel or moat), where non-deposition or erosion dominates. Separated mounded drifts are characterised by a mounded shape with internal reflections dipping towards the moat (Rebesco et al., 2014).

Separated mounded drifts have mainly been identified in the deep part of the basin at water depths ranging from 1600 to 4000 m (Table 1): i) at the foot of the continental slope (Fig. 2A), and ii) at the foot of seamounts related to the Madagascar Ridge (Fig. 3A and B) and related to the Eparses Islands (Fig. 3C–F).

The separated mounded drift located at the foot of the Mozambican slope has a mounded shape with a crest that transitions basinward towards deeper and flatter seafloor. The width of the separated mounded drift, considered from the basinward limit of the moat to the inflection point of the slope between the drift crest and the flat basin floor, is about 10 km (Fig. 2A). Wiles et al. (2017) estimated the width of this contourite drift to be about 30 km, but probably extended the location of the drift further basinwards and did not limit it to the inflection point. At its initiation stage, this contourite drift was flatter. With time, the drift crest became more prominent and migrated in upslope direction (Fig. 2A). The separated mounded drift is characterised by relatively low amplitudes compared to the adjacent moat and other deposits in the basin (Fig. 2A).

The separated mounded drifts related to the seamounts near the Madagascar Ridge have held a stable position geographically, with no apparent migration (Fig. 3A). The contourite drift has a relatively constant thickness that thins towards the moat, with no prominent drift crest (Fig. 3A). The deposit extends over 65 km between the seamount and the foot of slope of the Madagascar Ridge. It is covered by large-scale sediment waves with irregular shapes and orientations, with wavelengths up to 3 km and heights up to 40 m. Some of these bedforms are subcircular in plan view while others are longitudinal and mainly parallel to the moat (Fig. 3B).

Multiple seamounts with a wide variety of sizes are found between the Southern Eparses Islands (Bassas da India and Europa; Fig. 1). Separated mounded drifts of relatively small scale (1–2 km wide) are located at the foot of these volcanic edifices. The contourite drifts that are confined between two bathymetric highs and bounded by two moats, have a mounded shape with a crest in the centre and internal reflections dipping towards both moats (Fig. 3C and D). The width of the separated mounded drift shown in Fig. 3C and D ranges between 1 and 2 km, and its thickness reaches about 100 m. The separated mounded drift that is related to a single volcanic edifice (Fig. 3E and F) also has a pronounced mounded shape with a crest that is about 2 km wide and elevated 50 m above the bottom of the moat and 75 m above the surrounding basin floor.

4.1.1.2. Detached mounded drifts. In contrast to separated mounded drifts, detached mounded drifts are not completely parallel to the main slope trend and they can result from a change in the morphology of the margin (Rebesco et al., 2014).

Two very large detached mounded drifts formed during Late Cretaceous-Early Miocene in the Mozambique Channel (Fig. 4; Ponte et al., 2019; Thiéblemont et al., 2020). These contourite drifts have a southern part that is parallel to the main local slope and a northern part that detaches and develops perpendicular to the Mozambican continental slope (see Thiéblemont et al., 2020 for more details). The detached mounded drift located in the SW part of the Mozambique Channel (Limpopo drift in Thiéblemont et al., 2020) has a width of about 28 km and a height (from the top of the drift crest to the coeval basin floor) of about 525 m (Fig. 4A). The detached mounded drift located in the northern part of the Mozambique Channel (Zambezi drift in Thiéblemont et al., 2020) is much larger with a width of about 100 km and a height of about 1050 m (Fig. 4B). Both drifts have an asymmetric mounded shape with seismic reflections that are condensed and even truncated on one flank, and thicker deposits on the other flank. The drifts migrate in the direction of the flank with enhanced sedimentation, northwards in the Limpopo drift and southwestwards in the Zambezi drift (Fig. 4). The SW flank of the Zambezi drift contains sediment waves that migrate upslope (Fig. 4B).

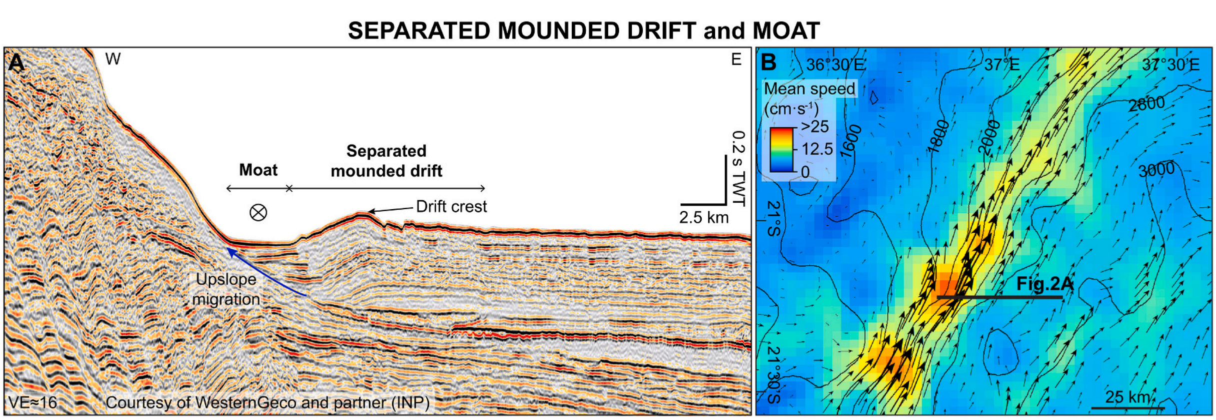

Fig. 2. (A) Multi-channel seismic reflection profile showing a separated mounded drift and a moat (courtesy of WesternGeco and partner (INP); modified from Thiéblemont et al., 2019). (B) Mean modelled bottom-current velocity at the foot of the Mozambican slope (modified from Thiéblemont et al., 2019).

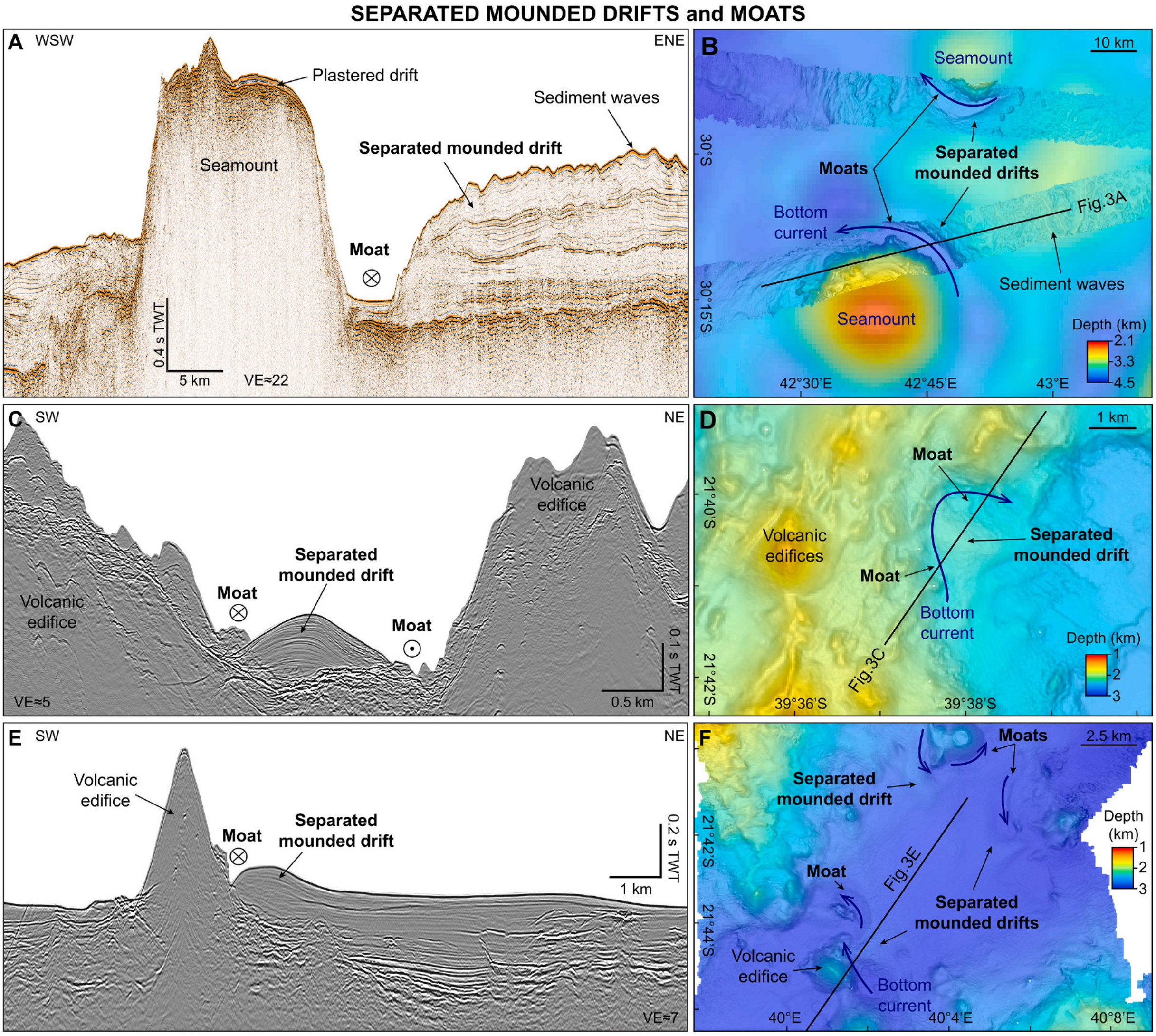

Fig. 3. (A) MOZ02-SR-21b multi-channel seismic reflection profile and (B) multibeam bathymetry showing separated mounded drifts and moats at two seamounts near the Madagascar Ridge (modified from Miramontes et al., 2019a). (C) PTO-HR-30 and (E) MOZ04-SR-192c multi-channel seismic reflection profiles showing small separated mounded drifts and moats associated with volcanic edifices at the foot of carbonate platforms and seamounts. (D) and (F) show the location of (C) and (E) in multibeam bathymetry. See Fig. 1 for location.

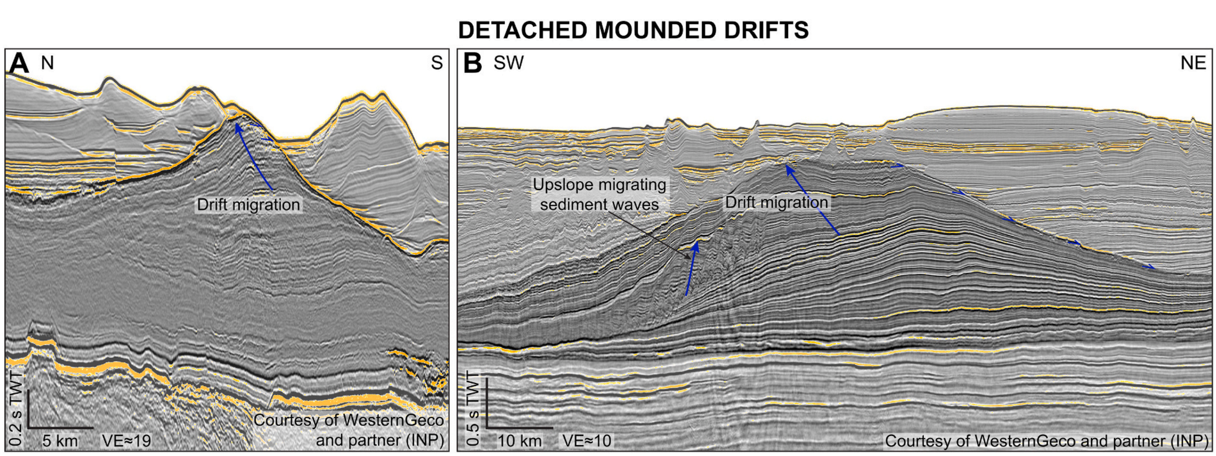

Fig. 4. Multi-channel seismic reflection profiles, courtesy of WesternGeco and partner (INP), showing ancient detached drifts of Late Cretaceous-Middle Miocene age (modified from Thiéblemont et al., 2020): (A) Limpopo drift and (B) Zambezi drift. See Fig. 1 for location.

4.1.1.3. Plastered drifts. Plastered drifts are contourite drifts commonly located on slopes and characterised by a convex morphology, typically with a gentle slope gradient in their upslope and a steeper slope gradient downslope (Fig. 5). The upslope parts of plastered drifts, often characterised by a gentler slope, are classified as contourite terraces (see next subsection) and contain coarser sediment than the remainder of the plastered drift (Fig. 5A). Groups of plastered drifts and contourite terraces characterise most of the present-day continental slope of the Mozambican margin, especially of the southern and central parts, at water depths ranging between 150 and 2000 m (Fig. 1; Table 1; Thiéblemont et al., 2019). The plastered drift located in the upper slope, offshore of the Zambezi Delta, is associated with a contourite terrace with a slope gradient below 2°. Maximum slope gradients up to 6° are found below the zone of maximum thickness of the plastered drift (Fig. 5A). The plastered drift located offshore the Limpopo River (Fig. 5B) is associated with a particularly flat contourite terrace with slope gradients below 0.5°, and an increase in slope gradient in the downslope part of the plastered drift reaching 2°. The downslope part of the plastered drift was affected by slope instability and contains head-wall scars and mass transport deposits. A small separated mounded drift developed at a head wall scar (Fig. 5B). Small plastered drifts can be also observed on the top of seamounts (Fig. 3A).

4.1.1.4. Sediment waves. The seafloor in the central and southern parts of the Mozambique Channel and the Mozambique Basin is characterised by the presence of numerous sediment waves at 2400–5200 m water depth (Fig. 1; Table 1; Breitzke et al., 2017; Fierens et al., 2019). The size and orientation of the sediment waves observed in the Mozambique

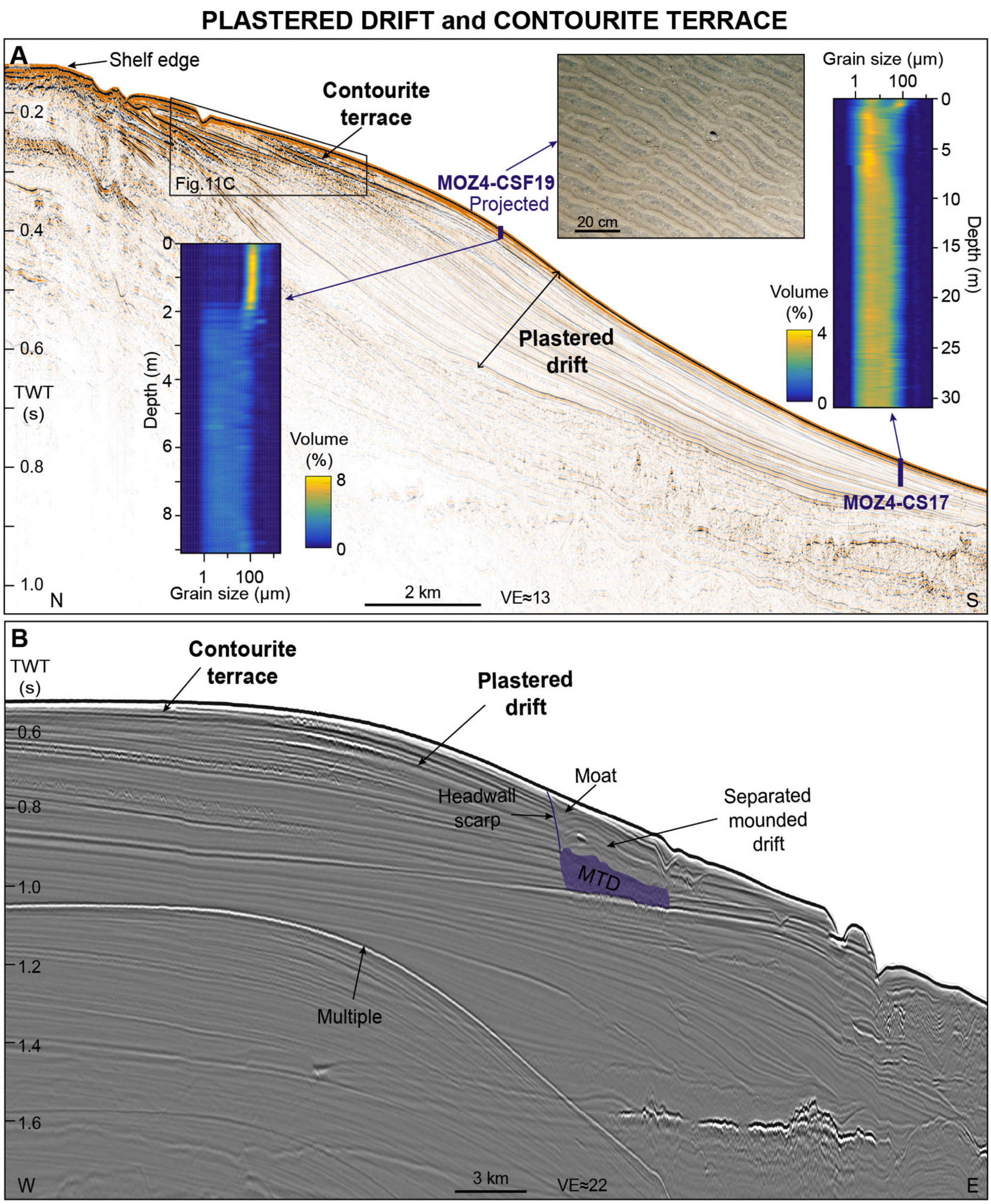

Fig. 5. Examples of plastered drifts and contourite terraces. (A) MOZ04-HR-108 multi-channel seismic profile of the upper slope off the Zambezi Delta. Grain-size distribution of sediment cores MOZ4-CSF19 and MOZ4-CS17 collected in the lower part of the contourite terrace and in the lower part of the plastered drift show that the terrace is composed of coarser sediment than the plastered drift. An image of the seafloor obtained near the location of core MOZ4-CSF19 shows the presence of ripples. (B) MOZ02-SR-03b multi-channel seismic profile of the upper slope off the Limpopo River. MTD: Mass Transport Deposit. See Fig. 1 for location.

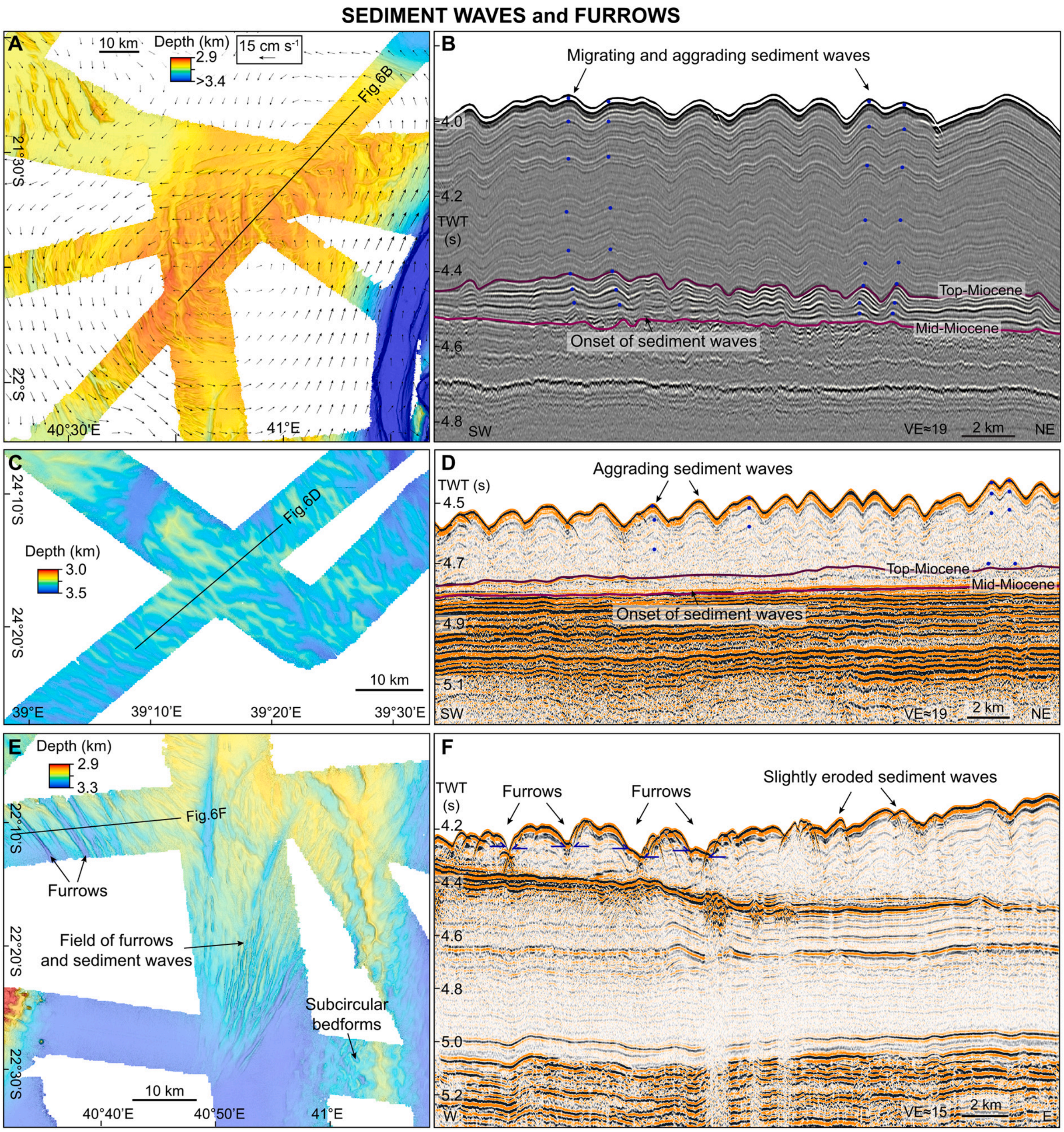

Fig. 6. Sediment waves located in the deep part of the basin. (A, C, E) Multibeam bathymetry showing sediment waves and furrows in three different zones of the Mozambique Channel, including modelled mean bottom-current velocity in (A). (B) MOZ04-SR-224b, (D) PTO-SR-001 and (F) PTO-SR-015 multi-channel seismic reflection profiles showing sediment waves and furrows. The blue dots in (B) and (D) indicate the position of the crests to highlight their migration and aggradation, and the age of the purple horizons is based on the stratigraphy of Ponte et al. (2019). The blue arrows in (F) show the erosional truncations at the furrows. See Fig. 1 for location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Channel are highly variable, and sediment waves with different orientations are often superimposed (Fig. 6A). Sediment waves located in the Mozambique Channel between the Eparses Islands and the Zambezi Valley commonly have wavelengths ranging from 0.8 to 3.5 km and heights ranging from 15 to 75 m. Some sediment waves have a NNW-SSE orientation, while others are oriented parallel to the bathymetric contours, forming a subcircular pattern around a bathymetric high (Fig. 6A). Sediment waves started to form after Mid-Miocene, according to the stratigraphy proposed by Ponte et al. (2019) (Fig. 6B and D). The oldest sediment waves are characterised by high amplitude continuous reflections, and some of the crests migrate towards the SW and others towards the NE (Fig. 6B). In contrast, after the end of Miocene, sediment waves show low amplitude continuous reflections and are mainly aggradational (Fig. 6B). The location of the sediment waves has remained relatively constant over time (Fig. 6B).

The sediment waves observed south of the Eparses Islands present similar dimensions, with wavelengths ranging from 1.3 to 2 km and heights ranging from 30 to 55 m (Fig. 6C and D). The crests of these sediment waves have a NW-SE orientation and present common bifurcations (Fig. 6C). These sediment waves are slightly asymmetrical. Most of them have a steeper NE side, but others are steeper in their SW side. The sediment waves are characterised by low amplitude continuous reflections in the younger part and low amplitude discontinuous seismic reflections in the older part, and do not show a clear migration of the crests (Fig. 6D).

In some areas, such as east of the Europa Islands, sediment waves seem to be affected by erosion and are found in zones where furrows are also present. In this area, subcircular bedforms are also common (Fig. 6E).

4.1.2. Features formed by winnowing and reworking – sandy contourites

4.1.2.1. Contourite terraces and dunes. Contourite terraces are relatively flat surfaces (slope gradient up to 2°) that generally form the upslope part of plastered drifts (Fig. 5) and are found along the Mozambican slope at water depths of 150–2800 m (Table 1). They are often considered mixed depositional-erosional contourite features, where both sedimentation and erosion occur (Thiéblemont et al., 2019). Sediment accumulation in contourite terraces is commonly lower compared with the centre of the plastered drift, and truncations and erosional surfaces are often present on contourite terraces (Figs. 5 and 7). These terraces are usually dominated by sandy sediments while plastered drifts are commonly dominated by muddy sediments (Fig. 5A). The contourite terrace located in the upper slope of the Mozambican margin offshore the Zambezi Delta is mainly composed of siliciclastic sand and presents abundant ripples at the present-day seafloor (Fig. 5A; de Castro et al., 2021b). The contourite terrace is partly covered by sand dunes with crests that show two main orientations oblique to the slope: a main *E*-W orientation and a superimposed secondary N-S orientation (Fig. 7; Miramontes et al., 2020b). The dunes have wavelengths of 20–150 m and heights of 0.15–1.50 m, their size decreases upslope and the main dunes with an E-W orientation migrate obliquely upslope, according to the orientation and asymmetry of the dunes (Fig. 7; Miramontes et al., 2020b).

4.1.2.2. Sandbanks and dunes. The tops of seamounts in the Mozambique Channel are often devoid of sediment, and bedrock outcrops directly onto the seafloor. However, sediment can be accumulated in relatively sheltered areas on the top of seamounts, especially in local depressions that are partly protected from the intense oceanic circulation (Fig. 8). These sediment accumulations are isolated and have a lenticular shape thinning towards the borders of the deposit (Fig. 8C). They are often covered by dunes whose crests are oriented almost perpendicularly to both the main axis of the deposit and to the primary slope trend (Fig. 8A). These deposits are composed of calciclastic sand of pelagic origin and reworked from drowned carbonate platforms, and are classified as sandbanks (Miramontes et al., 2019c).

4.1.2.3. Sandy condensation layers. Sandy condensation layers are sediment deposits mainly composed of fine to medium pelagic bioclastic sand with a very high content of foraminifera (Fig. 9). In the Mozambique Channel such deposits could be observed atop a bathymetric high located on the lower slope north of the Mozambique Ridge that corresponds to a separated mounded drift that is at present inactive, as revealed by the abundant erosional truncations (Fig. 9; Babonneau et al., 2018; Thiéblemont et al., 2019). This sandy condensation layer has a thickness of over 10 m, exceeding the penetration of the sediment core MOZ3-CS07 and of the sub-bottom profiler (Fig. 9; Babonneau et al., 2018). The whole core is composed of bioclastic sand with 80% of particles bigger than 100 μm and with a carbonate content measured between 60 and 70%. The deposit is located on the western flank of the inactive separated mounded drift and presents a wedge shape thinning upslope. Other sandy condensation layers were also recognised along the flanks of the Zambezi Valley with a thickness of 0.8–1.75 m (Fig. 1; Miramontes et al., 2019a).

4.1.3. Erosional features

Erosional features in contourite depositional systems can have variable spatial extents, ranging from localized channels, moats and furrows, to broad erosional or abraded surfaces that can extend over

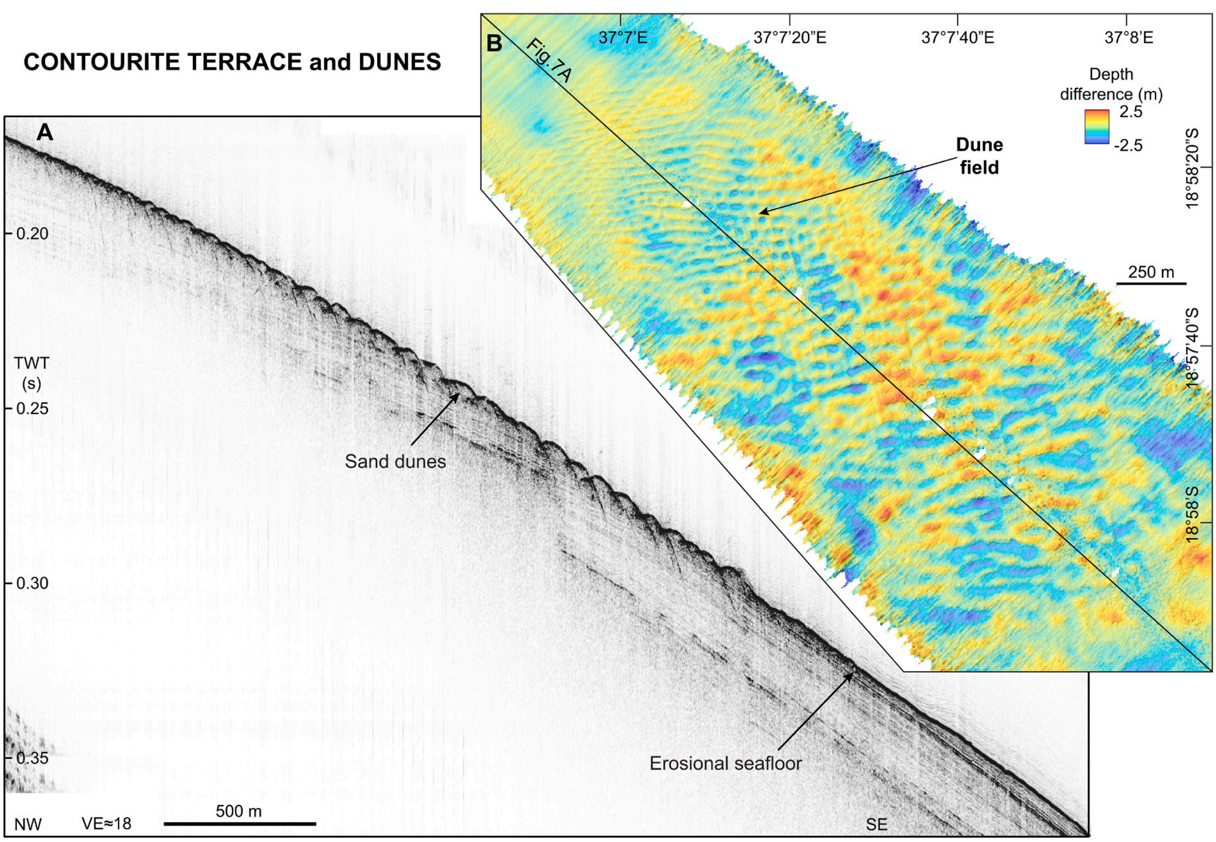

Fig. 7. Dune field located on the upper slope off the Zambezi Delta. (A) MOZ04-SDS-102a sub-bottom profiler image (modified from Miramontes et al., 2020b). (B) Differential bathymetry relative to the mean bathymetric surface of the dune field (modified from Miramontes et al., 2020b). See Fig. 1 for location.

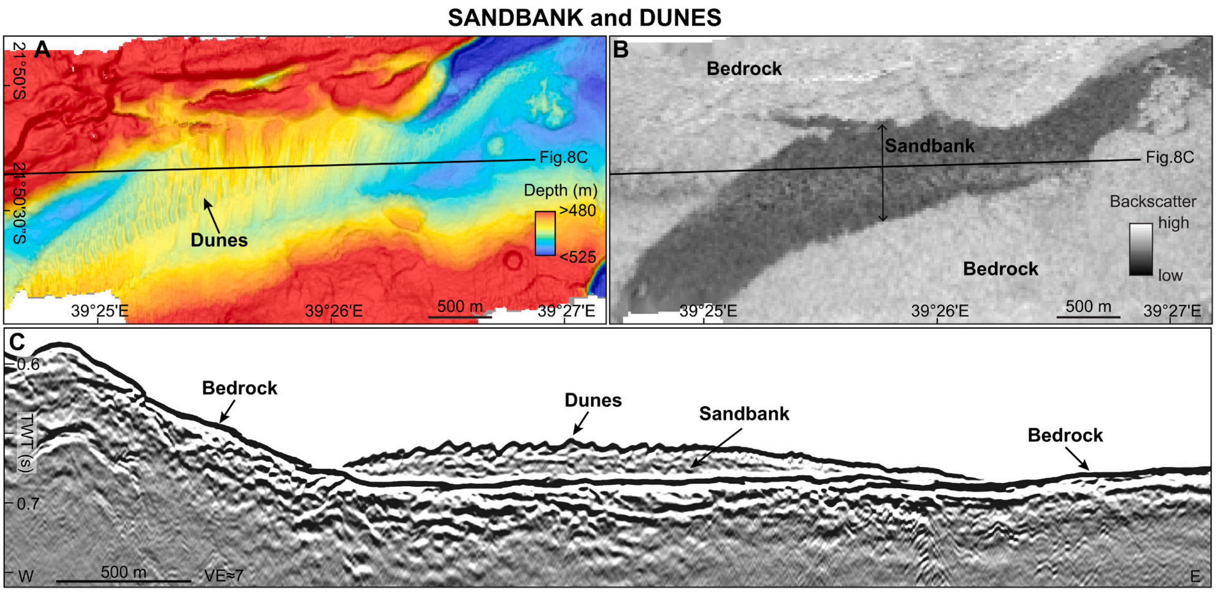

Fig. 8. (A) Multibeam bathymetry, (B) backscatter and (C) PTO-HR-039 multi-channel seismic reflection profile of a sandbank covered by sand dunes located on the top of the Jaguar Bank (modified from Miramontes et al., 2019c). See Fig. 1 for location.

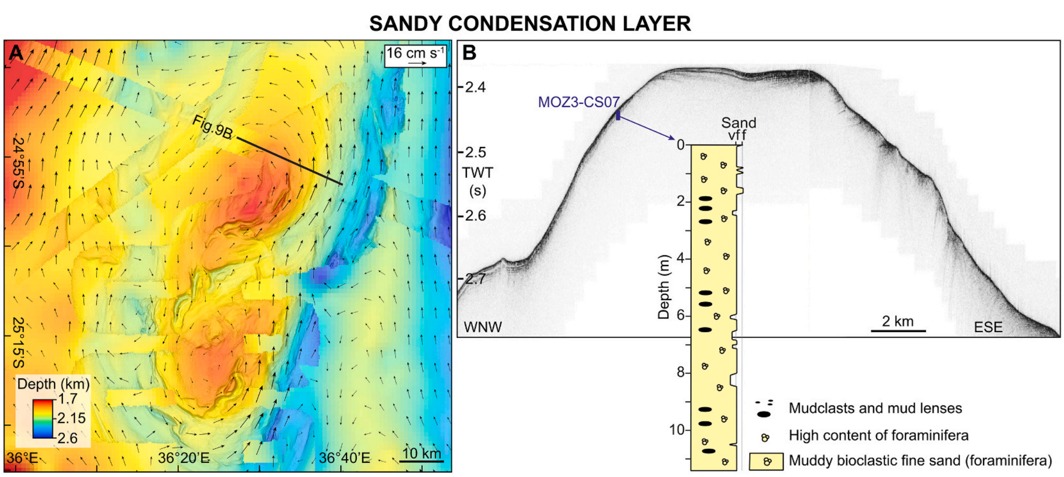

Fig. 9. (A) Multibeam bathymetry and modelled mean bottom currents of a topographic high eroded and incised by bottom currents. See Fig. 1 for location. (B) MOZ03-SDS-0038 sub-bottom profiler image of the topographic high and sedimentary log of sediment core MOZ03-CS07 collected on a sandy condensation layer that covers its western flank.

hundreds of square kilometres. The different types of erosional features formed by bottom currents and observed in the Mozambique Channel are described below.

4.1.3.1. Moats. Separated mounded drifts in the Mozambique Channel are always associated with moats. Moats are incisions dominated by erosion and non-deposition found between the contourite drift and the topographic obstacle that guides the current (Hernández-Molina et al., 2008a). In the Mozambique Channel and Basin, moats have been found at water depths ranging between 600 and 4000 m (Table 1). The moat located at the foot of the slope of the Mozambican margin is very flat and characterised by high amplitude subsurface reflections (Fig. 2A). The moat migrated upslope and became wider over time. At the present-day seafloor, it is at its bottom ~3 km wide and of ~90 m high, measured from the bottom of the moat to the top of the contourite drift crest (Fig. 2A).

Moats related to seamounts and volcanic edifices are slightly different from those located on the continental slope; they do not migrate, and their position remains stable in time (Fig. 3). Moats related to the seamounts near the Madagascar Ridge are narrower and deeper towards the east (upstream of the bottom current) than towards the west (downstream of the bottom current) (Fig. 3B). The eastern part of the southernmost moat has a width of 3–4 km and a depth of ~500 m with a very flat floor. Sedimentation rate in this moat has been low since the onset of its formation, with a maximum accumulation in the moat of about 90 m (Fig. 3A). The detailed size and geometry of this moat downstream of the contour current (westward) cannot be clearly depicted due to the limited coverage of the multibeam bathymetry, but it is clearly shallower and wider, and it transitions into a sedimentary deposit characterised by the presence of longitudinal bedforms to the west of the seamount (Fig. 3A and B). The northern moat starts to form on the southeastern part of the seamount, with a width at the bottom of ~700 m and a height of ~260 m, becoming wider (~6 km) and shallower (~200 m) towards the west (Fig. 3B). The flanks of the moats adjacent to the contourite drift contain elongated bedforms that are parallel to the slope (Fig. 3A and B).

The moats related to volcanic edifices near the Eparses Islands are relatively small, with widths (measured at the bottom of the moat) that typically oscillate between 250 and 500 m and heights (measured from the bottom of the moat to the top of the drift crest) of 25–85 m (Fig. 3C–F). These moats are devoid of sediments according to multi-channel high-resolution seismic data (Fig. 3C and E). The internal reflections of the contourite drift downlap on the moat (Fig. 3C and E).

4.1.3.2. Abraded surfaces. Abraded surfaces are zones where strong bottom currents significantly eroded the seafloor, resulting in widespread erosional truncations in seismic reflection profiles (Fig. 10). Two main abraded surfaces have been found along the Mozambican margin, one located west of the Mozambique Ridge (Figs. 1 and 10) and the second one in the lower continental slope in the zone between offshore the Limpopo River and the Zambezi Delta (Fig. 1; Thiéblemont et al., 2019).

4.1.3.3. Channels. A very rectilinear channel parallel to slope contours has been observed on the contourite terrace located on the upper Mozambican slope (155–170 m water depth) offshore of the Zambezi Delta (Figs. 1 and 11). The channel extends at least along 60 km and has a steeper upslope flank and a gentler downslope flank. It is 134–580 m wide and 2–13 m deep. In contrast to moats, the channel is purely erosive, with erosional truncations on both channel flanks and without significant sediment deposition inside the channel (Fig. 11C; Miramontes et al., 2020b).

4.1.3.4. Furrows. Furrows are found in the basin floor of the Mozambique Channel within the large area covered by sediment waves, especially between the Eparses Islands (Europa) and the Zambezi Valley (Fig. 1). The furrows observed east of Europa Island are 600–1500 m wide and 60–90 m deep (Fig. 6E and F), but in other areas of the Mozambique Channel furrows can be up to 3000 m wide and 100 m deep (Breitzke et al., 2017). Some of the furrows have a V-shape, while others have a relatively flat bottom and U-shape. Erosional truncations are observed on seismic profiles at the flanks of the furrows (Fig. 6F).

4.2. *Mixed turbidite-contourite systems*

Siliciclastic and carbonate turbidite systems in the Mozambique Channel have particular characteristics suggesting that they have been affected by the action of bottom currents. A series of parallel submarine channels located in the northernmost part of the Mozambique margin with an *E*-W orientation have a clear asymmetric morphology at 2000–2700 m water depth (Figs. 1 and 12A; Table 1). They are ~5–8 km wide with incisions ~150–300 m deep (Fig. 12A; Table 1). All the channels migrate southwards and have a better-developed northern levee with a gentler flank than the southern levee. The channel thalweg is deeper in the southern part and is characterised by a scour at the foot of the southern flank (Fig. 12A).

The channel-levee system located north of the Europa Island (part of the Eparses Islands) is associated with the carbonate platform of this island (Figs. 1 and 12B; Counts et al., 2018). The system is asymmetric and the channel migrates westwards. The outer part of the eastern levee extends over 10 km, while the outer part of the western levee is only about 3 km wide. The maximum thickness of the channel-levee system is ~260 m (Fig. 12B). Other bottom-current related sedimentary features can be observed in the vicinity of this mixed system. A separated mounded drift and a moat associated with volcanic edifices are located west of the channel-levee system. The eastern levee is eroded in its outer part that corresponds to the beginning of a field of furrows (Fig. 12B).

The Zambezi Valley is the main conduit for sediment transport of the Zambezi turbidite system and is also considered to be a mixed turbidite-contourite system (Fig. 1; Fierens et al., 2019; Miramontes et al., 2019a). It has a particular morphology consisting of a large V-shaped valley, that contains a U-shaped thalweg. The valley is up to ~50 km wide and ~700 m deep (incision depth) and the thalweg is up to ~10 km wide and almost 300 m deep (Fig. 12C; Table 1; Fierens et al., 2019). The valley flanks are eroded, especially the eastern flank, and levees are absent along the main valley axis. The western flank of the V-shaped valley is in part covered by sediment waves that are also found throughout the basin floor (Figs. 1 and 12C).

4.3. *Modelled bottom currents*

Erosional features such as moats and abraded surfaces show the most energetic bottom currents, with average mean speeds of 9 and 10 cm s^{-1}, and average maximum speeds of 39 and 41 cm s^{-1}. The average mean EKE in these areas is 44 and 49 $cm^2 s^{-2}$, respectively (Fig. 13; Table 1). Bottom currents are slightly weaker in zones with contourite drifts. Similar average mean speeds of 8.2–8.4 cm s^{-1} are found for separated mounded drifts, plastered drifts and sediment waves. Average maximum speeds and average mean EKE are higher in areas where plastered drifts are found (37 cm s^{-1} and 43 $cm^2 s^{-2}$) than in separated mounded drifts and sediment waves (30 cm s^{-1} and 29–30 $cm^2 s^{-2}$). Modelled bottom currents in contourite terraces generally range in between the values of main erosional features (i.e. abraded surfaces, moats) and of the main depositional features (i.e. separated mounded drifts, sediment waves), with an average mean speed of 8 cm s^{-1}, an average maximum speed of 35 cm s^{-1} and an average mean EKE of 38 $cm^2 s^{-2}$. Bottom currents along the Zambezi Valley show, on average, values slightly higher than the adjacent field of sediment waves, with an average mean speed of 8.8 cm s^{-1}, an average maximum speed of 34 cm s^{-1} and an average mean EKE of 32 $cm^2 s^{-2}$. In contrast, bottom currents at the mixed turbidite-contourite of the northern Mozambican margin are weak, with an average mean speed of 5.6 cm s^{-1}, an average maximum speed of 23 cm s^{-1} and an average mean EKE of 20 $cm^2 s^{-2}$ (Fig. 13; Table 1).

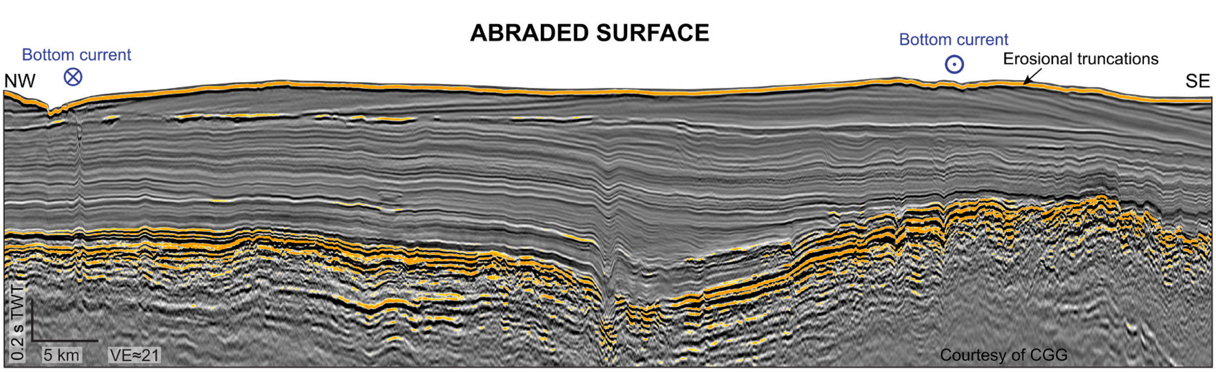

Fig. 10. Multi-channel seismic reflection profile, courtesy of CGG Multiclient and New Ventures, showing an abraded surface located at the foot of the slope of the southern Mozambican margin (modified from Thiéblemont et al., 2019). The direction of bottom currents is based on model results. See Fig. 1 for location.

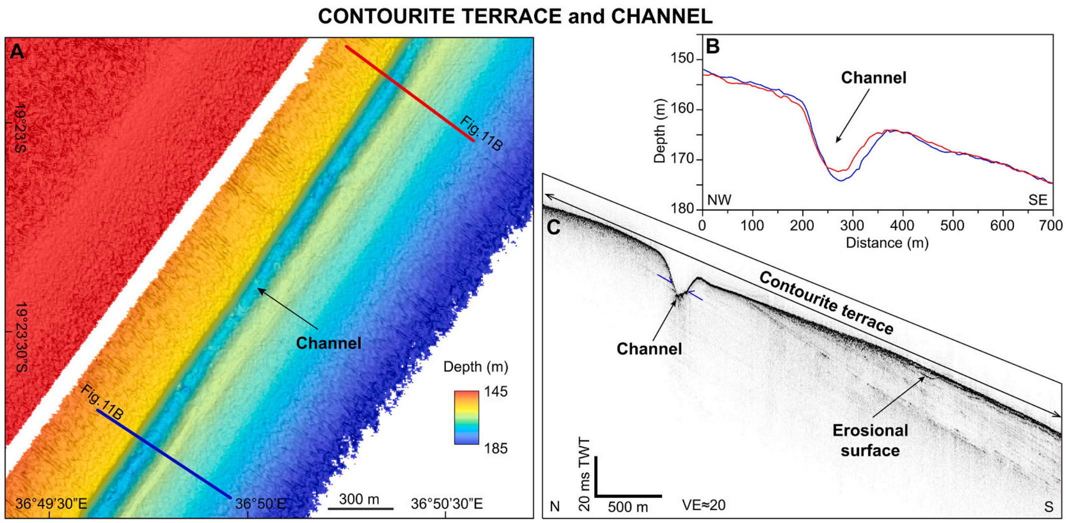

Fig. 11. (A) Multibeam bathymetry, (B) topographic profiles and (C) MOZ04-SDS-108b sub-bottom profiler image showing a channel located in the contourite terrace of the upper slope off the Zambezi Delta (modified from Miramontes et al., 2020b). See Fig. 1 for location of (A) and Fig. 5 for (C).

5. Discussion

5.1. Oceanographic processes related to contourite formation

Modelled bottom currents show in general a good agreement with the observed sedimentary features, with the strongest bottom currents in the zones of erosion and weaker currents in the zone of sediment accumulation (Fig. 13; Table 1). Especially clear is the link between the elongated abraded surface located at the foot of the Mozambican slope and a strong bottom current related to the Mozambique Undercurrent (Figs. 13 and 14; Miramontes et al., 2019a; Thiéblemont et al., 2019). Abraded surfaces correspond to the most energetic modelled bottom currents in the study area (Fig. 13; Table 1). However, there are some differences in bottom currents over the elongated abraded surface located in the central part of the Mozambican slope (between offshore the Limpopo River and the Zambezi Delta) and over the abraded surface located west of the Mozambique Ridge (Figs. 1 and 13). While bottom currents over the elongated abraded surface can reach mean speeds up to 23 cm s^{-1} and show a clear northward flow along the slope, current speed is lower over the southern abraded surface up to 14 cm s^{-1} (Fig. 13A). The direction of the bottom currents in this southern area is variable (Fig. 10). Its orientation on the western part is mainly northward, whereas in the eastern part it is southward due to the interaction of the north-flowing current with the seafloor topography (Fig. 10). Bottom currents in the southern abraded surface show a high variability, with mean speeds mainly oscillating between 6 and 10 cm s^{-1}, while maximum speeds mainly range between 34 and 50 cm s^{-1} (Fig. 13). This suggests that the observed erosion is not the result of a continuous relatively strong bottom current but rather of repeated events of high intensity.

Mean and maximum modelled bottom-current speeds in moats are on average higher than in the related separated mounded drifts (Fig. 13). This spatial difference in bottom-current magnitude is clear at the foot of the Mozambican slope. Here, intense bottom currents are located on the slope and on the moat, while weak bottom currents are located on the separated mounded drift (Fig. 2B). This type of bottom-current distribution and the associated sedimentary deposits are similar, for instance, to that observed in the systems of the NW Mediterranean Sea (Miramontes et al., 2019b) and the Greater Antilles (Tucholke and Ewing, 1974). The average speeds calculated in this study for separated mounded drifts may however be overestimated compared to the current velocities that originally formed the contourite drift, because some of the contourite drifts classified by Thiéblemont et al. (2019) as separated mounded drifts (based on low resolution seismic reflection profiles) seem to be relict deposits that have been partly eroded and reworked by bottom currents (Fig. 9; Babonneau et al., 2018). The sedimentary deposit classified as a separated mounded drift by Thiéblemont et al. (2019), is strongly eroded and characterised by the presence of erosional truncations and channels around the structure, especially on its eastern part (Fig. 9). Modelled bottom currents are stronger in the eastern part and flow around the topographic high in agreement with the geological observations (Fig. 9A).

According to the modelling results in the Mozambique Channel, the intensity of bottom currents in contourite terraces and plastered drifts is on average similar, but bottom currents show a large variability even within a single contourite terrace (Fig. 13). The weakest bottom currents are modelled in the shallowest contourite terrace offshore the Limpopo River, mainly because this area is an embayment protected from the southward flowing surface current, where an anticyclonic eddy often forms (Fig. 13; Cossa et al., 2016). This could explain the higher sediment accumulation and the less evidence of erosion on this terrace compared to the contourite terrace offshore of the Zambezi Delta (Fig. 5). In the NW Mediterranean Sea and the northern Argentinean continental slope, modelled bottom currents at contourite terraces are stronger than at the adjacent plastered drifts, but often only the internal part of the terrace located landwards shows intense bottom currents (Miramontes et al., 2019b; Wilckens et al., 2021). Balanced flows can thus not completely explain the formation of contourite terraces. It has been suggested that contourite terraces may be generated by internal waves that may form at the interface between water masses (Hernández-Molina et al., 2016; Thiéblemont et al., 2019). Internal waves can probably favour erosion and the formation of secondary features such as channels, dunes and erosional surfaces, especially in upper continental slopes, where pycnoclines with higher density gradients are present (Reeder et al., 2011; Ma et al., 2016). These features are observed on the contourite terrace of the upper slope offshore the Zambezi Delta (Figs. 7, 11 and 14; Miramontes et al., 2020b). It has not been clearly demonstrated, however, whether internal waves are responsible for the generation of contourite terraces in their entirety.

The large field of sediment waves that covers the central and southern parts of the Mozambique Channel was suggested to be related to the passage of eddies (Fig. 14; Breitzke et al., 2017). On average, modelled bottom currents are relatively slow in the zone of sediment waves, with values similar to those in separated mounded drifts (Fig. 13; Table 1). However, the southern part of the field shows more intense bottom currents that can reach mean speeds up to 22 cm s^{-1}, maximum

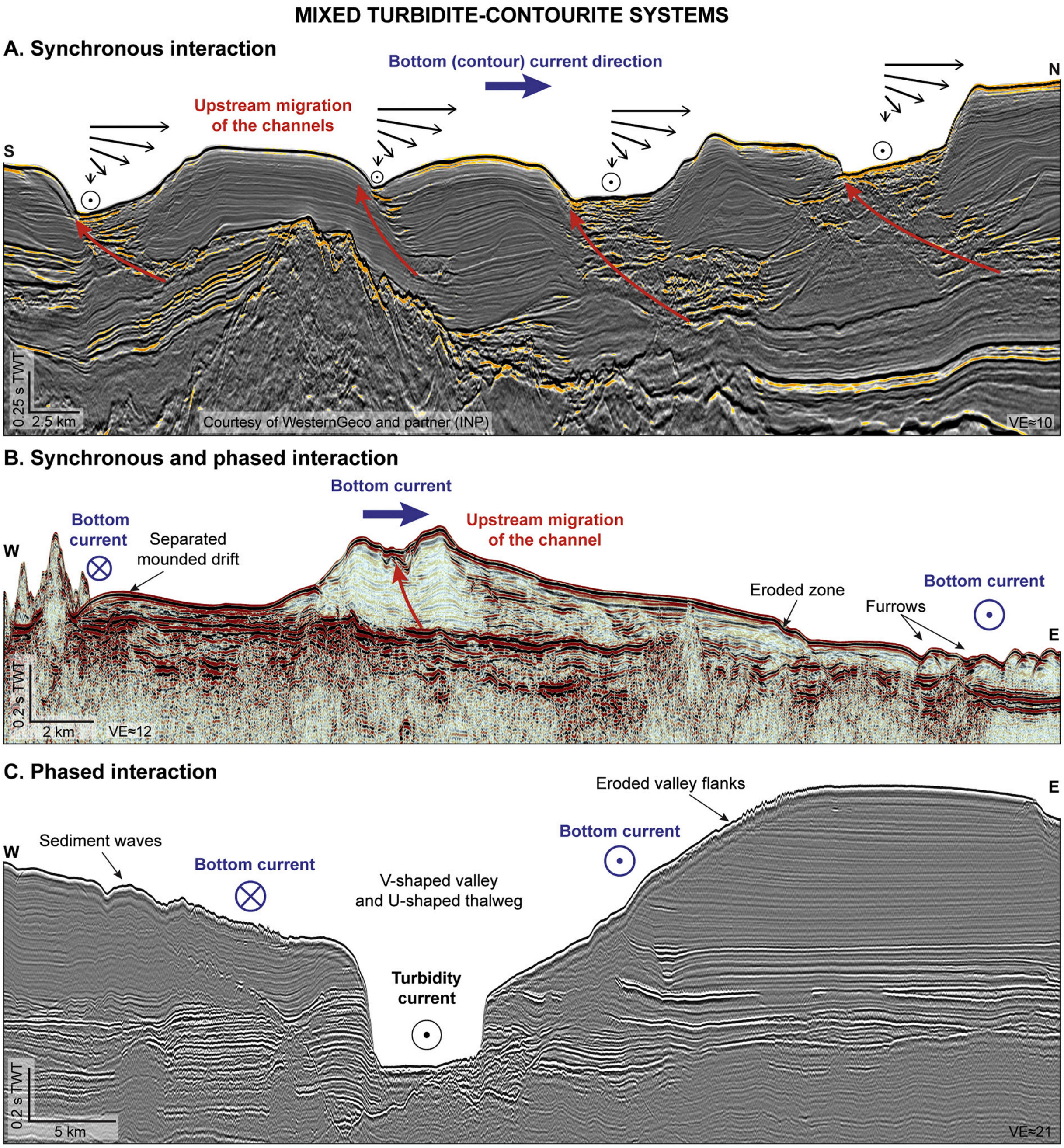

Fig. 12. Examples of mixed turbidite-contourite systems. (A) Multi-channel seismic reflection profile, courtesy of WesternGeco and partner (INP), of asymmetric channel-levee systems that migrate upstream of the bottom currents, formed by the synchronous interaction of bottom currents and turbidity currents. (B) PTO-SR-015 multi-channel seismic reflection profile of a carbonate channel-levee system related to Europa Island (modified from Counts et al., 2018). (C) PTO-SR-785 multi-channel seismic reflection profile of the Zambezi Valley, characterised by V-shaped flanks that are eroded and reshaped by bottom currents (modified from Miramontes et al., 2019a). See Fig. 1 for location.

speeds up to 70 cm s^{-1} and mean EKE up to 130 cm^2 s^{-2} (Fig. 13). This zone corresponds to the area where more erosional surfaces and channels are associated with the sediment waves (Breitzke et al., 2017). The complex morphology and often irregular orientation of these sediment waves (Fig. 6; Breitzke et al., 2017; Fierens et al., 2019) suggest that they may be related to processes that can have variable directions such as eddies. However, the location, size and morphology of many of these bedforms are relatively constant over time (Fig. 6B and D), and many of these bedforms are oriented parallel to the mean modelled bottom currents (Fig. 6A). Kolla et al. (1980) suggested that downstream migrating sediment waves observed in the southern part of the Mozambique Basin were formed by internal waves propagating at a benthic thermocline cap and that other processes may generate the aggrading bedforms found in the northern part of the Mozambique Basin and in the Mozambique Channel. A similar mechanism was also proposed for the formation of abyssal sediment waves in the central part of the Argentine Basin (Flood, 1988). It is likely that all the mentioned processes are present in the basin floor, and each plays an important role in the formation of bedforms, contributing to the observed diversity in size, orientation and internal structure.

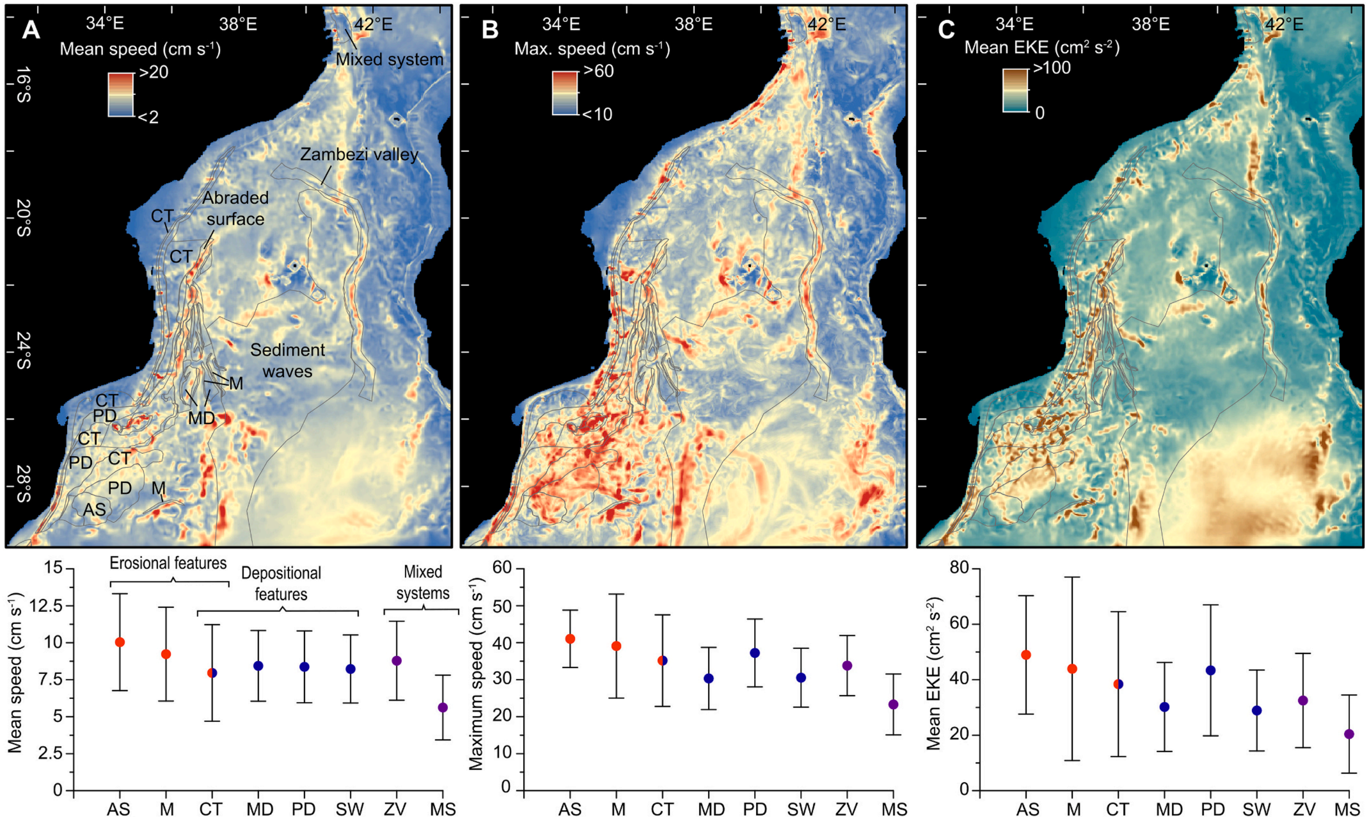

Fig. 13. Maps showing the mean modelled speed of bottom currents modified from Miramontes et al. (2019a) (A), maximum modelled speed modified from Miramontes et al. (2019a) (B) and mean eddy kinetic energy, EKE, (C), together with the location of the different parts of the analysed sedimentary systems and the graphs showing the average mean speed (A), average maximum speed (B) and average mean eddy kinetic energy (C) and standard deviation at these locations. AS: abraded surface, M: moat, CT: contourite terrace, MD: separated mounded drift, PD: plastered drift, SW: sediment waves, ZV: Zambezi Valley, MS: mixed system in northern Mozambique.

5.2. Factors controlling the development of mixed turbidite-contourite systems

The transfer of sediment from the continent to the deep sea through turbidity currents has conventionally been considered a downslope gravity-driven process, which could not be strongly affected by oceanic circulation. This was suggested to be related to the high energy of turbidity currents compared to ocean currents, and to the confinement of turbidity currents inside submarine canyons and channels (Mulder et al., 2008). However, several studies show that bottom currents can strongly affect the geometry and sedimentary characteristics of turbidite systems, forming mixed turbidite-contourite systems (e.g. Mulder et al., 2008; Fonnesu et al., 2020; Fuhrmann et al., 2020; Miramontes et al., 2020a). These mixed systems can result from different types of interactions between oceanic currents and turbidity currents (Mulder et al., 2008; Fonnesu et al., 2020):

a) Passive interaction occurs when contouritic and turbiditic processes and their related deposits coexist in the same continental margin, but different processes control their formation independently, resulting in two different and separate depositional systems. We can observe this type of interaction in the western part of the Mozambique Channel. Along the continental slope and at the foot of the slope, a contourite depositional system is present and consists of a series of contourite terraces and plastered drifts, an abraded surface and a separated mounded drift with a moat. This contourite system is crossed in some areas by submarine channels that deliver sediment to the intermediate basin dominated by turbidites located between the slope and the Eparses Islands (Fig. 1; Fierens et al., 2019, 2020). Although both systems co-exist in the same area, they do not interact, i.e. gravity-driven processes do not affect the evolution of the contourite system and bottom currents do not affect the evolution of the turbidite system.

b) Phased interaction: This type of mixed systems is formed when bottom currents and turbidity currents occur at the same place but at different times. An example of phased interaction in the Mozambique Channel is the Zambezi Valley (Fig. 12C), and partly in the Europa carbonate mixed system (Fig. 12B). Although the main channel-levee system from Europa was probably not formed under the phased interaction of bottom currents and turbidity currents, the outer part of the eastern levee was eroded by bottom currents after its deposition, evidencing a partial phased interaction (Fig. 12B). The Zambezi Valley has a V-shaped morphology with proportions much larger than most of the well-known submarine canyons and channel systems, especially at distances further than 400 km from the shelf (Fierens et al., 2019). The flanks of the V-shaped valley are eroded (Fig. 12C), in some parts covered by contouritic sand (Miramontes et al., 2019a) and have no levees (Fierens et al., 2019). This particular shape is probably related to the intense bottom currents flowing along the channel flanks, which have a modelled average mean speed of 8.8 cm s^{-1} and an average maximum speed of 34 cm s^{-1} (Fig. 13; Table 1; Miramontes et al., 2019a). Turbidity currents probably only affect the U-shaped thalweg and do not overspill the oversized V-shaped valley (Fig. 12C; Fierens et al., 2019). In this kind of phased, mixed turbidite-contourite systems, bottom currents reshaped part of the submarine valley originally formed by turbidity currents. This process may generate a positive feedback because the more bottom currents erode and enlarge the valley walls, the stronger the acceleration of bottom currents along the valley will be.

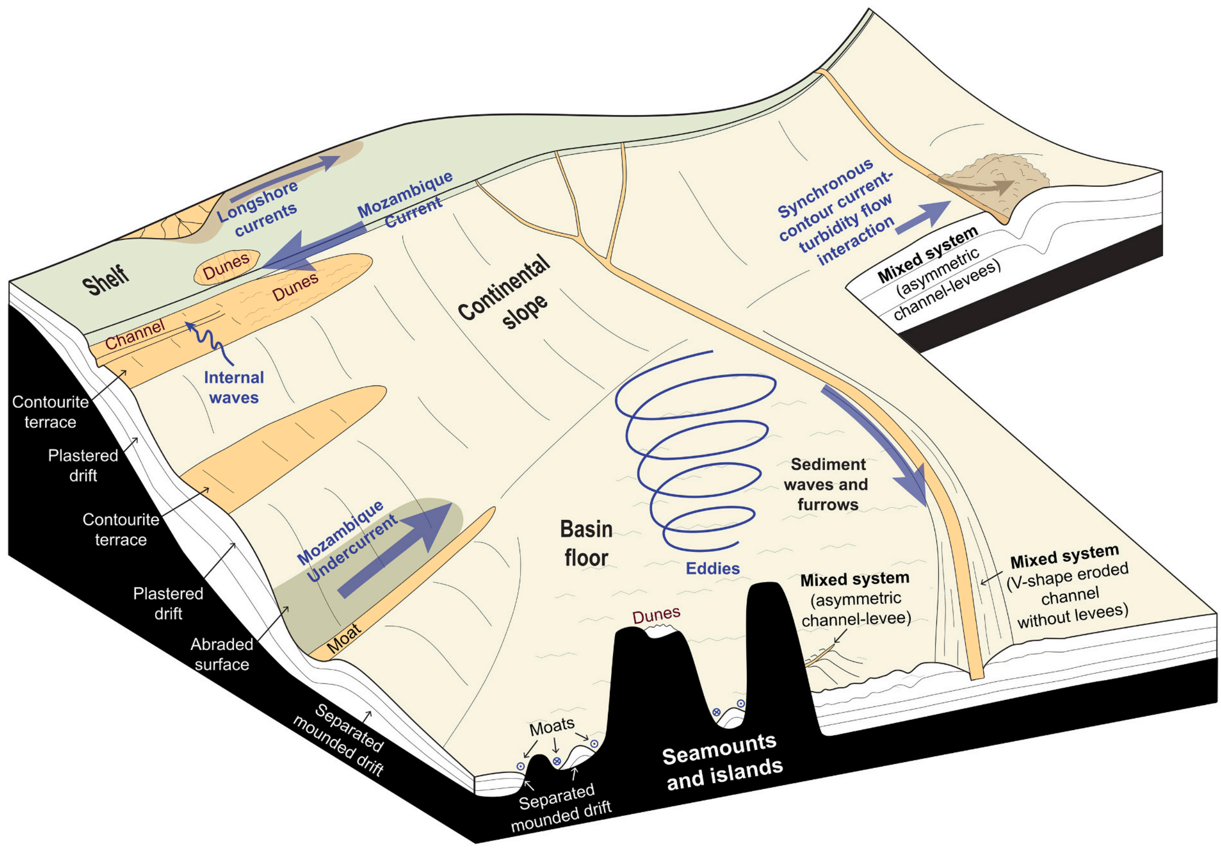

Fig. 14. 3D sketch summarising the main pure contouritic features and mixed turbiditic-contouritic features observed in the Mozambique Channel.

c) Synchronous interaction: When bottom currents and turbidity currents occur simultaneously, they can interact and generate combined flows, which will result in a particular geometry (i.e. asymmetric channel-levee systems; Miramontes et al., 2020a). This type of mixed turbidite-contourite system can be observed in the northern Mozambican lower slope (Figs. 12A and 14). These systems are very similar to systems observed further north along the Mozambican margin in the Rovuma basin (Fonnesu et al., 2020; Fuhrmann et al., 2020). Modelled bottom currents at these asymmetric channel-levee systems are relatively low, with an average mean speed of 5.6 cm s^{-1}, but they reach on average a maximum speed of 23 cm s^{-1} (Fig. 13; Table 1). These values are similar to those measured near the seafloor in the lower slope of the Rovuma basin, where asymmetric-levee systems were also observed (Fuhrmann et al., 2020). According to flume experiments performed by Miramontes et al. (2020a), bottom currents flowing alongslope with a speed equivalent to 10% of the maximum speed of the turbidity current can significantly modify the flow properties and induce the formation of an asymmetric channel levee system. Therefore, the modelled bottom currents would be able to modify turbidity currents with speeds of 50–200 cm s^{-1}, which are values typically observed in marine systems (Khripounoff et al., 2012; Azpiroz-Zabala et al., 2017). Bottom currents do not only profoundly affect the transfer of sediment and related particles (e.g. organic carbon and microplastics) in zones of very intense circulation, but this effect may be important in most of the basins even in zones of weak and moderate currents. It is thus necessary to consider the interaction between alongslope and downslope processes in order to better interpret paleoreconstructions based on the sedimentary record, to estimate carbon sequestration in deep-sea sediments, to assess the impact of microplastic in deep-water environments and to predict the presence, extent and quality of hydrocarbon reservoirs.

5.3. Classification of contourites

In this study, we propose a classification of contourite depositional systems that includes muddy and sandy contourites, as well as erosional features related to bottom currents (Fig. 15). The classification of muddy contourites is based on previous classifications by Faugères et al. (1999), Rebesco and Stow (2001) and Rebesco (2005), and the modifications proposed in this study are explained in this section. The proposed classification of erosional features is mainly based on the classifications by Hernández-Molina et al. (2008a) and García et al. (2009) with slight modifications. The proposed classification is supported by examples from the Mozambique Channel, but it could also be applied universally to any other contourite depositional system.

The term "contourite" refers to sediments deposited or substantially reworked by the action of bottom currents (Stow et al., 2002; Rebesco, 2005). It therefore includes all the components of a contourite depositional systems, both depositional and erosional features (Fig. 15). We consider three main groups of contouritic features: 1) dominated by deposition resulting in the formation of contourite drifts; 2) dominated by sediment winnowing and reworking forming sandy contourite deposits; 3) dominated by sediment erosion and non-deposition that induce the formation of incisions and erosional surfaces (Fig. 15). Within each of these groups, we can also distinguish between large-scale and small-scale features. Contourites can form large deposits at scales of several tens or hundreds of kilometres in length (such as the large detached mounded drifts observed in the Mozambique Channel; Fig. 4), or only at metre to centimetre-scale in the case of dunes (Figs. 7 and 8) and ripples (Fig. 5A). These small-scale features can be superimposed upon large-scale contouritic features, and they are thus included separately in the classification (Fig. 15).

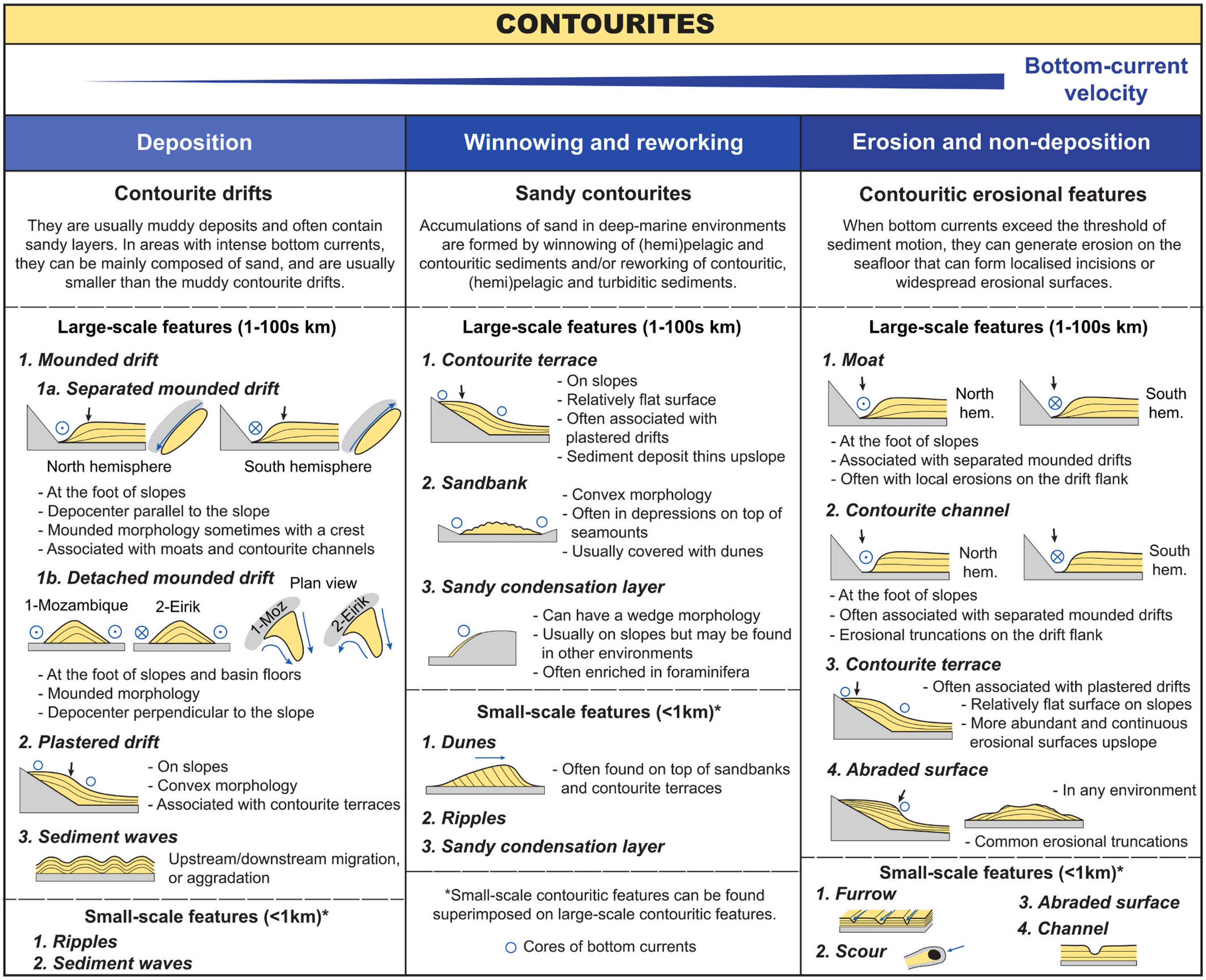

Fig. 15. Classification of contourites based on their general geometry and internal architecture, and the related bottom-current intensity.

5.3.1. *Contourites dominated by deposition*

Contourite drifts are mainly found in zones with weak bottom currents and are mainly composed of mud. However, muddy contourites can also contain sandy layers that are formed during periods of intensified bottom currents and that often show a bigradational sequence (Gonthier et al., 1984; de Castro et al., 2021b). Large-scale contourite drifts are classified as mounded drifts, plastered drifts and sediment waves. Mounded drifts can be subdivided in separated mounded drifts and detached mounded drifts (Fig. 15).

Separated mounded drifts are elongated deposits parallel to the slope that are separated from the slope by an incision, either a moat or a contourite channel (Figs. 2 and 3). They can either have a well-developed crest adjacent to the moat (Figs. 2A and 3E) or have a relatively constant thickness that only significantly decreases in the vicinity of the moat (Fig. 3A). Separated mounded drifts often present an upslope migration (Fig. 2A), but they only aggrade when they are related to very steep slopes such as seamounts (Fig. 3A, C and E). When separated mounded drifts are located in a small confined depression, two moats may form bounding the separated mounded drift on both sides (Fig. 3C). This type of drift was previously classified as a confined drift (Rebesco and Stow, 2001). But we suggest that, since the morphology and generation mechanism is identical to separated mounded drifts, it is not necessary to use a new term solely to state that the separated mounded drift is located in a confined basin and is associated with two moats.

Detached mounded drifts are formed when bottom currents flowing alongslope detach from the main slope and generate a deposit in the middle of two parallel- or opposite-flowing bottom currents. The detached mounded drift has an orientation perpendicular or oblique to the main slope and is often located in zones where the slope forms an edge (Hernández-Molina et al., 2008b; Mulder et al., 2019; Thiéblemont et al., 2020). In cross-section, detached mounded drifts show a mounded shape that is not directly related to a moat or a slope (Fig. 15). They can be asymmetric with both a flank with lower accumulation and sometimes with erosional truncations, and a flank with more sediment accumulation. Detached mounded drifts typically migrate in the direction of the flank with higher accumulation (Fig. 4). In the examples shown in the Mozambique Channel, bottom currents are interpreted to have flown parallel along both sides of the detached mounded drift (Fig. 15; Thiéblemont et al., 2020). In other zones, such as in the Eirik drift, bottom currents flow along the drift and thus flow in opposite directions on each side of the deposit (Fig. 15; McCave and Tucholke, 1986; Hunter et al., 2007).

Plastered drifts are a type of contourite drift that have a convex morphology and are typically formed on slopes (Figs. 5 and 15). The upper part of the plastered drift has a gentle slope that forms a contourite terrace. The thickness of plastered drifts is maximal in the centre of the deposit and the deposit thins upslope (towards the contourite terrace) and downslope (Fig. 5). The main difference between a separated mounded drift and a plastered drift is that plastered drifts are not associated with moats or contourite channels, but with relatively flat surfaces (i.e. contourite terraces).

Sediment waves are large bedforms with wavelengths ranging from several hundreds of meters to several kilometres and can cover vast zones of the basin floor (Figs. 1 and 5). In previous classifications, sediment waves were considered to be part of sheeted drifts that are often found on abyssal plains (Hernández-Molina et al., 2008b; Rebesco et al., 2014). However, sheeted drifts are very difficult to identify based on their geometry as they only become slightly thinner towards the edges (Rebesco et al., 2014), and are thus not easily differentiated from other deep-water deposits such as hemipelagites and turbidites. The identification of sediment wave fields is more evident and they are therefore included in the classification here proposed, instead of sheeted drifts (Fig. 15).

All of the above-mentioned major contourite drifts can contain superimposed minor depositional features, such as ripples and sediment waves. A clear example of this is the sediment wave field that developed on the gentle flank of the detached mounded drift in the northern Mozambique Channel (Fig. 4B).

5.3.2. Contourites dominated by winnowing and reworking

Sandy contourites are contourite deposits formed in relatively high-energy environments, where bottom currents remove fine-grained sediments and favour the concentration of sand (sediment winnowing). Strong currents can also rework sediments, transporting sediments and forming accumulations of sand. These sandy deposits may be isolated, for instance, on the tops of seamounts, forming lenticular deposits here named sandbanks (Figs. 8 and 15). Sandy contourites can also form contourite terraces, which are zones characterised by a gentle slope, associated with plastered drifts and commonly found on continental slopes (Figs. 5 and 15). In areas with limited detrital sediment supply, bottom currents can winnow fine-grained pelagic sediments creating accumulations enriched in foraminifera that are here classified as sandy condensation layers (Fig. 9B). These deposits can be clearly identified from sediment cores and sometimes show a wedge shape in sub-bottom profiles (Babonneau et al., 2018; Miramontes et al., 2019a). Sandy condensation layers can be widespread in an area, forming a major depositional feature of several meters of thickness (Fig. 9B), or they may be more localized forming thinner and smaller deposits that could be considered small-scale features (Fig. 15). Contourite terraces and sandbanks can often also be covered by small-scale features such as dunes and ripples (Figs. 5, 7, 8 and 15).

5.3.3. Contourites dominated by sediment erosion and non-deposition

Erosional features are formed in areas of high energy, where bottom currents are strong enough to erode the slope or inhibit sediment deposition. Two of the major erosional features are moats and contourite channels, which are commonly associated with separated mounded drifts (Figs. 2 and 3). The difference between a moat and a contourite channel is that contourite channels are more erosive and generate truncations in the adjacent separated mounded drift (Fig. 15; Hernández-Molina et al., 2008a; and references therein). Bottom currents can erode large areas of the seafloor, forming abraded surfaces (Fig. 10). Erosional surfaces are often present in contourite terraces that are associated with plastered drifts (Figs. 5 and 11C). However, erosion rarely occurs along the entire contourite terrace, and is often restricted to specific areas, especially in the uppermost limit of the terrace (Figs. 5A and 11C). Other small-scale erosional features can be formed on top of other large-scale contourite features, such as furrows, scours, abraded surfaces or channels (Fig. 15). For instance, a channel is located on the top of the contourite terrace offshore the Zambezi Delta (Figs. 5A and 11). In contrast to the classification of Hernández-Molina et al. (2008a), we do not include marginal valleys (also referred as scours or troughs) separately because of their similarities to moats and contourite channels. The term "marginal valley" was often used to classify incisions related to ridges and isolated obstacles such as seamounts, diapirs or mud volcanoes. The terms "moats" and "contourite channels" were more often used for incisions on continental slopes (Hernández-Molina et al., 2008a; García et al., 2009). However, we suggest that this environmental difference does not justify a different classification and we thus recommend only the classification of incisions either as moats or contourite channels.

This new classification is based primarily on the morphology of the contourites and it helps identify the sedimentary deposits formed by the action of bottom currents. This is very important to perform qualitative palaeoclimatic and palaeoceanographic reconstructions based on the sedimentary record (Knutz, 2008). It is however still difficult to quantitatively reconstruct past oceanographic conditions based on the morphology and architecture of the sediment bodies or on the sediment characteristics, although important progress has been done with the calibration of the sortable silt approach in some areas (McCave et al., 2017). Advances in physical oceanography and process sedimentology are still necessary to be able to link the different types of contourites and their sedimentary characteristics to specific oceanographic processes and bottom-current intensities.

6. Conclusions

A large part of the seafloor of the Mozambique Channel and the Mozambique Basin has been affected by bottom currents, forming contourite depositional systems and mixed turbidite-contourite systems. Most of the Mozambican continental slope is dominated by a series of contourite terraces and plastered drifts. Contourite terraces are relatively flat surfaces that correspond to the upper part of plastered drifts. They often consist of sand and can contain superimposed sand dunes, erosional surfaces and channels. Plastered drifts, on the other hand, have a convex-up shape and are mainly composed of mud. Modelled bottom currents in contourite terraces and plastered drifts are similar, suggesting that the formation of contourite terraces may not be solely related to the mean oceanic circulation. However, differences in the sedimentary architecture among contourite terraces may be related to the interaction of currents with the margin topography and the formation of eddies. Bottom currents are weaker on the contourite terrace offshore of the Limpopo River compared to the terrace offshore the Zambezi River, resulting in a higher sediment accumulation and less evidence of erosion. At the Mozambique margin, the lower slope and the foot of the slope are characterised by abraded surfaces and moats where modelled bottom currents are intense. Separated mounded drifts form in the zone adjacent to moats where bottom currents are weaker. The central and southern parts of the basin floor are covered by large sediment waves and furrows of different sizes and orientations that are often superimposed on each other. The diversity of characteristics of sediment waves suggests that they may have originated through different oceanographic processes including bottom currents related to the mean oceanic circulation, eddies and internal waves.

Bottom currents also affected turbidite systems in the Mozambique Channel, resulting in the formation of three types of mixed turbidite-contourite systems. The synchronous interaction of alongslope bottom currents and turbidity currents in the lower slope of the northern Mozambican margin and of the Europa Island generated asymmetric channel-levee systems that migrate upstream of the contour current. Bottom currents also eroded the levees of the Europa-Island system after its deposition, and thus also resulted from a phased interaction between bottom currents and turbidity currents. In contrast, the Zambezi Valley is solely the result of a phased interaction. The submarine valley, originally formed by turbidity currents, has been eroded by bottom currents flowing along the valley flanks, which has formed the particular V-shape morphology of the Zambezi Valley.

The large diversity of contourite features observed in the

Mozambique Channel has allowed us to propose a new classification of contourites that includes muddy and sandy contourites, as well as erosional features. This classification is not specific to the SW Indian Ocean, and it can therefore be applied to other systems. In conclusion, our results provide new examples of the characteristics of contourite depositional systems and mixed turbidite-contourite systems, as well as of the link between contouritic features and modelled bottom currents, that can help identify and interpret current-related features in other settings and thus help improve palaeoreconstructions and the prediction of sedimentary facies.

Data availability

The numerical data collected during the oceanographic cruises of the PAMELA project (doi:10.18142/236) are stored at SISMER (http://en.data.ifremer.fr/SISMER). Sediment cores collected offshore Mozambique are curated at IFREMER core repository in Plouzané (France). Core data related to this article can be requested at:

Core MOZ3-CS07: IGSN BFBGX-127435 (http://igsn.org/BFBGX-127435); core MOZ4-CS17: IGSN BFBGX-85865 (http://igsn.org/BFBGX-85865), core MOZ4-CS19: IGSN BFBGX-128004 (http://igsn.org/BFBGX-128004). The access to these data is however restricted and has to be accepted by the partners of the PAMELA project. The industrial seismic data are licensed multiclient data. Access to this dataset has to be directly negotiated with the seismic contractors. The model simulations were performed using the HPC resources of IDRIS under the allocation 2018-A0040107630. Numerical model outputs are available on the IDRIS THREDDS Data Server, https://vesg.ipsl.upmc.fr/thredds/catalog/idris_work/ryff001/catalog.html.

Declaration of Competing Interest

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

Acknowledgements

We thank the captains, crews and onboard scientific teams of the PTOLEMEE, PAMELA-MOZ01 and PAMELA-MOZ02 surveys onboard the R/V L'Atalante, as well as the PAMELA-MOZ03, PAMELA-MOZ04 and PAMELA-MOZ05 surveys onboard the R/V Pourquoi pas? The oceanographic surveys of the PAMELA project and the fellowship of Ruth Fierens were co-funded by TOTAL and IFREMER as part of the PAMELA project. The PAMELA (Passive Margin Exploration Laboratories) project is a scientific project led by IFREMER and TOTAL in collaboration with Université de Bretagne Occidentale, Université Rennes 1, Université Pierre and Marie Curie, CNRS and IFPEN. The authors sincerely thank TOTAL S.E., WesternGeco and CGG for permission to use the seismic datasets in this study. The research of A. Thiéblemont was funded by TOTAL as part of the Frontier Exploration research program. We are grateful to the guest editor U. Nicholson and to the two anonymous reviewers for their valuable suggestions that greatly improved the manuscript.

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