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ORIGINAL RESEARCH PAPER

Response of Cenozoic turbidite system to tectonic activity and sea-level change off the Zambezi Delta

Jude A. Castelino[1] · Christian Reichert[2] · Wilfried Jokat[1]

Abstract Submarine fans and turbidite systems are important and sensitive features located offshore from river deltas that archive tectonic events, regional climate, sea level variations and erosional process. Very little is known about the sedimentary structure of the 1800 km long and 400 km wide Mozambique Fan, which is fed by the Zambezi and spreads out into the Mozambique Channel. New multichannel seismic profiles in the Mozambique Basin reveal multiple feeder systems of the upper fan that have been active concurrently or consecutively since Late Cretaceous. We identify two buried, ancient turbidite systems off Mozambique in addition to the previously known Zambezi-Channel system and another hypothesized active system. The oldest part of the upper fan, located north of the present-day mouth of the Zambezi, was active from Late Cretaceous to Eocene times. Regional uplift caused an increased sediment flux that continued until Eocene times, allowing the fan to migrate southwards under the influence of bottom currents. Following the mid-Oligocene marine regression, the Beira High Channel-levee complex fed the Mozambique Fan from the southwest until Miocene times, reworking sediments from the shelf and continental slope into the distal abyssal fan. Since the Miocene, sediments have bypassed the shelf and upper fan region through the Zambezi Valley system directly into the Zambezi Channel. The morphology of the turbidite system off Mozambique is strongly linked to onshore tectonic events and the variations in sea level and sediment flux.

Keywords Mozambique Fan · Turbidite systems · Late Cretaceous bottom current · Beira High Channel-levee system · African Uplift · Zambezi River

Introduction

River-fed turbidite systems (e.g., Amazon, Mississippi, Bengal, Indus, Congo, etc.) build fans, channels and channel related features that can extend for over 1000 km and are more than 100 km wide (Mutti and Normark 1991; Weimer and Link 1991). They not only host major oil plays offshore but are also excellent archives to study past climate variations. It is well established that turbidite systems and submarine fans are the results of a complex interplay between numerous environmental parameters, amongst which tectonics, sea-level and sediment supply dominate (Stow et al. 1985). In general, this interplay can be interpreted from geophysical and sedimentological datasets, where these are available, allowing fans to be ultimately linked to a handful of controlling parameters. The formation and growth of the largest submarine fan, the Bengal Fan, trace their origin to the Himalayan orogeny and the monsoon climate that controls sediment supply in the Indian subcontinent (Curray et al. 2003; France-Lanord et al. 2015; Krishna et al. 2016). The morphology and growth of the Amazon Fan, in contrast, are linked to the intensification of weathering and erosion of the Andes during their Late Miocene uplift at a time of rapid sea level variations during glacial and interglacial cycles (Figueiredo et al. 2009; Flood et al. 1991; Gorini et al. 2014; Milliman et al. 1975).

✉ Jude A. Castelino
Jude.Castelino@awi.de

1 Alfred Wegener Institute, Hemholtz Centre for Polar und Marine Research (AWI), Am Alten Hafen 26, 27568 Bremerhaven, Germany

2 Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hanover, Germany

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In contrast, most recent studies of the Mozambique fan off SE Africa have been driven by the needs of the hydrocarbon industry in the wake of significant gas discoveries (INP 2014). In spite of its globally significant volume (Table 1), the relationships between the history and development of the Mozambique Fan (Fig. 1) and its African source regions therefore remain sparsely studied. In particular, the fan offers the possibility to understand the contentious Cenozoic uplift history of southern Africa (Brown et al. 2014; Daszinnies et al. 2009; Emmel et al. 2011; Partridge and Maud 1987; Roberts and White 2010). The aim of this study is to fill this gap in knowledge via analysis of the fan's internal seismic stratigraphy in a new network of multi-channel seismic reflection (MCS) data, tied to stratigraphic information available from hydrocarbon industry studies in the Zambezi Delta Depression (ZDD) (Fig. 1) (Coffin 1992; De Buyl and Flores 1986; Mahanjane et al. 2014; Nairn et al. 1991; Salazar et al. 2013; Salman and Abdula 1995).

Geological setting and previous work

The Mozambique Fan occupies the Mozambique Channel, a north–south trending ocean basin that formed during Gondwana breakup in Jurassic and early Cretaceous times. The Mozambican margin bounds the upper fan deposits to the north and west, and the Madagascar margin and Davie Ridge bound them to the east, in an almost triangular basin and that opens southwards into the Southwest Indian Ocean (Fig. 1). The Zambezi River is one of the primary sources for sediment supply to the upper fan with as much as 60 Mio tonnes being drained annually into the basin (Kolla et al. 1980b; Van der Lubbe et al. 2014; Walford et al. 2005). The thickest (up to 12 km) sedimentary sequence is located in the ZDD, with thicknesses of 6–8 km in other parts of the Central Mozambique Basin (Castelino et al.

2015; Mahanjane 2012; Salazar et al. 2013; Salman and Abdula 1995).

The sediment discharge history of the Zambezi River is characterized by considerable variability since the Mesozoic (Castelino et al. 2015; Walford et al. 2005). Those authors correlated surges in sediment accumulation during Late Cretaceous (75–65 Ma), Oligocene (34–24 Ma) and Late Miocene- Pleistocene (5–1.8 Ma) times to episodes of epeirogenic uplift onshore (Partridge and Maud 1987) and increases in catchment area (Walford et al. 2005). Prior to the late Miocene-Pleistocene, the parts of the present-day Zambezi catchment area currently upstream of the Victoria Falls (Fig. 2), delivered sediment to the Limpopo further south (Goudie 2005). Apatite fission track analyses in northern Namibia show accelerated cooling periods during the Cretaceous, at ~70 Ma and 110–90 Ma, that postdate the rifting related to the opening of the Atlantic ocean (Brown et al. 2014; Wildman et al. 2016). These cooling periods have been interpreted in terms of rock uplift, and the subsequent denudation of the uplifted surface has been estimated to between 4.5 km along the Namibian margin to 1 km inland (Brown et al. 2014; Gallagher and Brown 1999; Tinker et al. 2008). The effect of this denudation is observed in sedimentary basins along the southwest Atlantic margin where a peak sediment influx is recorded at between 80 and 70 Ma (Dingle and Hendey 1984; Rouby et al. 2009). Similarly, in the Malawi Basin in Northern Mozambique, apatite fission track analysis is interpreted in terms of enhanced denudation around ~75 Ma (Daszinnies et al. 2009). An increase in sediment input in the Mozambique Basin can therefore be linked to what was apparently a widespread phase of Late Cretaceous uplift in southern Africa and resulted in fan development off the Zambezi during Late Cretaceous-Eocene times (Castelino et al. 2015; Walford et al. 2005). Using shallow geophysical and coring-based data, several studies (Droz and Mougenot 1987; Kolla et al. 1980b) describe how the present Mozambique

Table 1 Dimensions of some well-studied modern-day fans (source: Curray et al. 2003) and the dimensions of Mozambique Fan (1) (Kolla et al. 1980b) (2) (Castelino et al. 2016; this study)

Fan	Length (km)	Width (km)	Area×10³ (sq.km)	Max Thickness (m)	Water depth apex (m)	Water depth distal (m)
Bengal and Nicobar	3800	2000	?	16,500	1400	5500
Indus	1500	<960	1100	>9000	1500	4600
Mozambique	1800 (1)	400 (1)	<720 (1)	8000 (2)	1600 (2)	5000 (2)
Amazon	>700	250–700	330	4200	1500	4800
Mississippi	540	570	>300	4000	1200	3300
Monterey	400	250	75	2000	1280	4570
Astoria	>250	130	32	2200	1140	2840
La Jolla	40	50	1.2	1600	550	1100

Fan morphology is built of sediments supplied via second-order turbidite systems that begin as a series of valleys on the East African and Madagascan shelves (e.g., the Zambezi, Serpa-Pinto, Limpopo-Save, Labathie and Tsirihibina valleys; Fig. 1). They divide the eastward flowing Zambezi turbidite system originating on the Mozambican shelf into three parts, namely, (1) the slope-incising network of canyons referred to as the Zambezi Canyon that precedes (2) the Zambezi Valley, which erodes shallow strata on the continental rise and meanders south at 41°E before (3) giving way further downstream to a stable, almost N-S oriented feature termed the Zambezi Channel. The Zambezi Channel at the present day displays features typical of a channel-levee system with thick sediment deposits on either side of the channel but appears to be inactive and infilled with chaotic or sheeted sediment deposits. Prior to the Zambezi deposits, the sediment deposits of the Serpa-Pinto Valley oriented in a north–south direction along the Davie Ridge dominated the Upper Fan from Oligocene to Miocene (Droz and Mougenot 1987). Piston core data from the Mozambique Fan indicate a terrigenous origin of the Quaternary sediments, for the most part delivered presumably via the Zambezi Channel (Kolla et al. 1980a, b). Droz and Mougenot (1987) suggested early on that the upper reaches of sediment dispersal pathways over the shelf are relatively unstable, but their work was restricted because of poor quality and insufficient seismic data. Studies on sediment cores show a strong variability of sediment dispersal to the north along the shallow margin in the Holocene times linked to the flooding of the shelf after Last Glacial Maximum (LGM) (Beiersdorf et al. 1980; Schulz et al. 2011; Van der Lubbe et al. 2014).

Oceanographic setting

At the present day, a complex oceanographic setting controls the deposition of the fan sediments. The Mozambique Current (MCE), a branch of the North East Madagascar Current (NEMC), is the most prominent water mass transport in the channel contributing to a net southward flow of 15 Sv. (Fig. 2). Large anti-cyclonic eddies, which reach as deep as the base of the Mozambique Channel, dominate the southward propagation of the current through the Mozambique Channel, and feed into the Agulhas Current further south around 30°S (Ridderinkhof and De Ruijter 2003; Schouten et al. 2003). Along the southern East African Margin a weak northward flowing Mozambique undercurrent, at 1500–2500 m water depth, carries 5 Sv of intermediate and deep water masses originating from the Atlantic ocean (Antarctic Intermediate Water-AAIW and North Atlantic Deep Water-NADW) (de Ruijter 2002; Wiles et al. 2014).

Data and methods

We use nine interpreted multi-channel seismic (MCS) profiles totalling 2200 km in length recorded with a G-gun cluster (volume: 42.6–67.2 L at 145 bar) and 3000 m streamer (240 channels, 12.5 m hydrophone spacing). These data were acquired in 2007 as part of the MoBaMaSis project (Castelino et al. 2015; Reichert 2007) and were subsequently processed using standard procedures for frequency filtering with 10–60 Hz bandpass filter, multiple suppression and post-stack F-K migration (Fig. 3). Shipborne swath bathymetry acquired during the expedition and a subsequent expedition (Jokat 2014), in addition to a global bathymetric grid (GEBCO) are examined to study the morphology of the ancient and modern turbidite systems at different times since Late Cretaceous. Lithostratigraphic information was incorporated from previous studies (Castelino et al. 2015; De Buyl and Flores 1986; Droz and Mougenot 1987) having been compiled from the nearby offshore wells Zambezi-1 and Zambezi-3 (Fig. 3) and other onshore wells. The attendant seismic stratigraphy is described by Castelino et al. (2015), and consists of six units labelled MBSU 1–6 that correspond to packages of Jurassic, Lower Cretaceous, Upper Cretaceous, Paleogene, Miocene and Quaternary sediments respectively used as background information for this study (Table 2).

Results-Morphology of the ancient turbidite systems-

The part of the Upper Mozambique fan originating from the Zambezi comprises of at least three prominent pathways or turbidite systems that were successively active for tens of millions years since Late Cretaceous according to the seismic stratigraphy. (1) The oldest of these systems is located close to the continental shelf to the north of the present-day mouth of the Zambezi and was active in the Late Cretaceous until at least Eocene. We refer to its deposits as the Zambezi Fan (Figs. 4, 5, 6). It overlies the continuous Top Lower Cretaceous Unconformity. The evolution of the fan can be interpreted in profiles BGR07-201, BGR07-202 and BGR07-203 (Figs. 4, 5, 6). Close to the shelf edge, several valleys or channels are interpreted from their fills and slope-apron deposits (Fig. 4, BGR07-203). The dispersal of sediments via basin floor fan (BFF) is interpretable in BGR07-202 (Fig. 5), in the form of a number of lenticular convex-upward sediment wedges (4–6 s TWT). In line BGR07-201, several of these wedges are located in the deeper channel where they are juxtaposed with mass wasting deposits originating on the continental rise (Fig. 6, 5–5.5 s TWT). The maximum sediment thickness at the peak of the fan exceeds 1 km in all profiles where
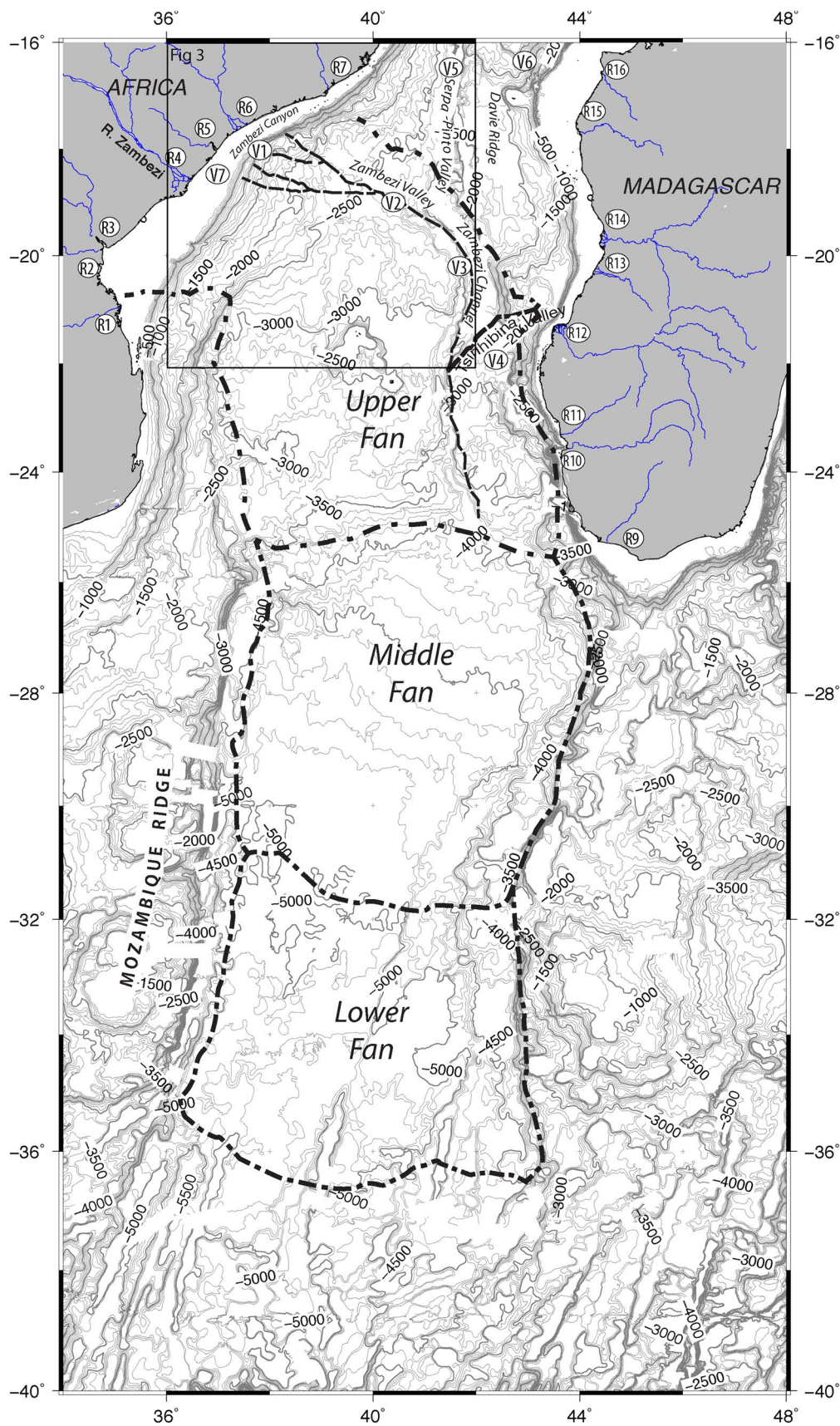
◀**Fig. 1** GEBCO Bathymetric map of Mozambique Basin showing the extent (*dot-dash* line) and different parts of the Mozambique Fan (identified by Kolla et al. (1980a, b). The depressions of the Tsiribihina, Serpa-Pinto and Zambezi Valleys that feed the Upper Mozambique Fan can be observed in the bathymetry. The Zambezi Channel (*dashed line*) with a broad meander disperses into the Middle Fan. Abbr: R1 = R. Save; R2 = R. Buzi R3 = R. Pungwe R4 = R. Zambezi R5 = R. dos Bons Sinais, R6 = R. Licungo R7 = R. Ligonha R8 = R. Menarandra R9 = R. Onilahy 10 = R. Fiherenana R11 = R. Mangoky R12 = R. Morondava R13 = R. Tsiribihina R14 = R. Manambaho R15 = R. Maningoza R16 = R. Mahavavy sud; V1 = Zambezi Canyons; V2 Zambezi Valley; V3 = Zambezi Channel; V4 = Tsiribihina Valley; V5 = Serpa-Pinto Valley; V6 = Labathie Valley; V7 = Chinde-Zambezi Canyon

they intersect. The thickest parts of the younger sediment wedges are located progressively further south, revealing that the depocentre migrated southwards. While the northern fan lobe grows slowly during this period, the southern fan lobe aggrades and migrates southwards making an almost triangular shape (Fig. 6; SP 1400–2200).

After Oligocene times, the sediment delivery system switched to the south over Sofala Zambesia Bank (SZB), incising several valleys and channels in the process (Figs. 7, 8). The Sofala Zambezia bank represents the present-day shelf that has prograded and aggraded since Miocene times (Fig. 3). Further down-slope, this system forms a large channel-levee complex on the submarine terrace over Beira High. We term this feature the Beira High Channel-levee Complex (Figs. 7, 8). The Beira-High Channel-levee complex structure is observed in profiles BGR07-206 and BGR07-208 (Figs. 7, 8; 3–5 s TWT). Both profiles show two distinct depositional patterns that stack up to 2 s TWT in thickness and up to 80 km wide. The lower deposits (Phase 1) are composed of several channels and smaller submarine fan lobes overlying canyons that were incised during the mid-Oligocene marine regression. In the upper unit (Phase 2), a single deep incising valley with high levee deposits is observed. Simultaneously prograding-aggrading clinoforms at the shelf with turbidity deposits onlap the
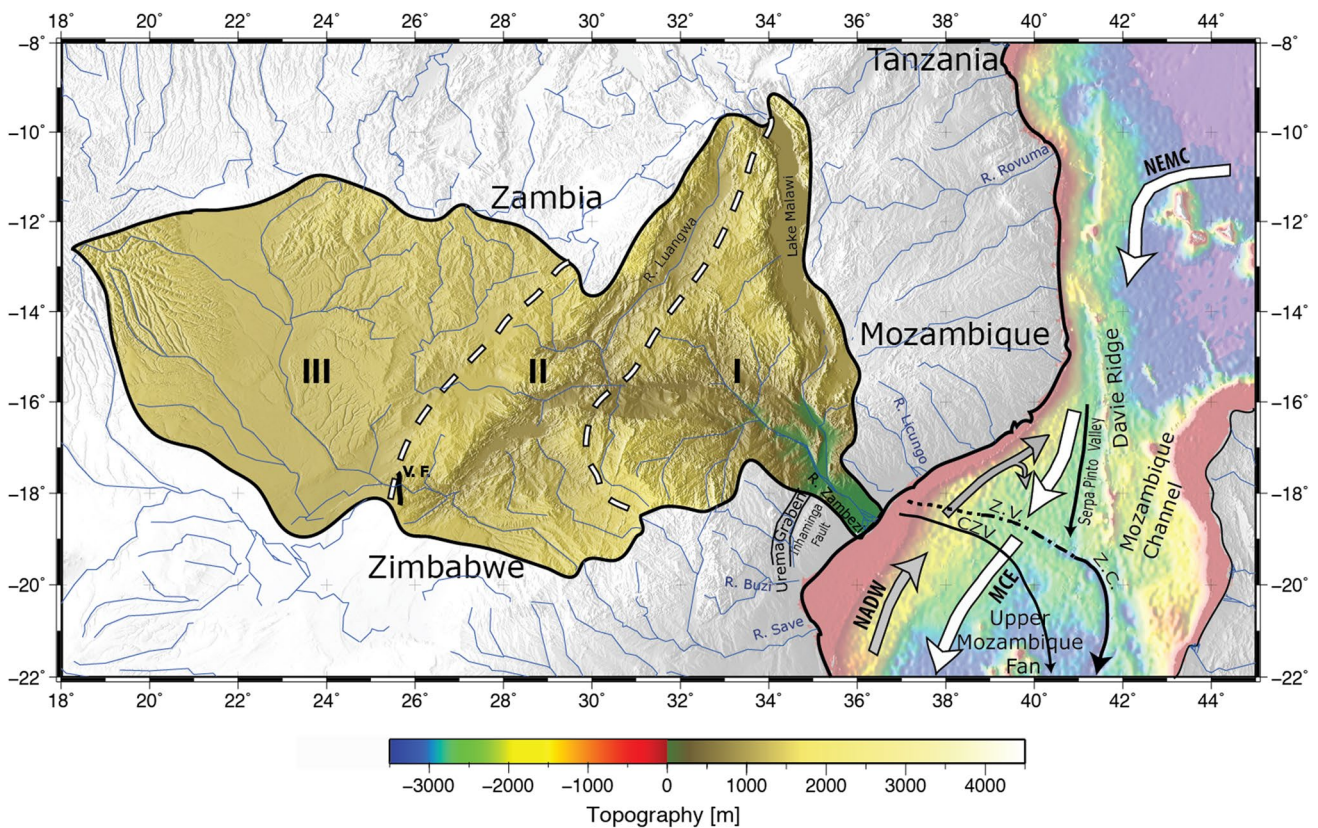

Fig. 2 Map of the present-day catchment of the Zambezi River and oceanic circulation in the basin. The Catchment area is divided into 3 parts, i.e. lower (I), middle (II) and Upper (III). The middle catchment area was captured during the Late Cretaceous Uplift while the upper catchment area that previously drained into the Limpopo Basin further south, joined the Zambezi River during the Pliocene–Pleistocene uplift. A branch of the North East Madagascar Current (NEMC) flowing along the northern margin of Madagascar enters the Mozambique Channel where southward flowing anti-cylonic eddies (MCE) dominate the channel (*white arrow*). A weak Antarctic Intermediate Water and North Atlantic Deep Water (NADW) current flow northwards along the Mozambican margin (*grey arrow*)

Fig. 3 Location of the seismic lines used in this study. The Sofala-Zambesia Bank (SZB) forms a prograding sequence over the Zambezi Delta Depression (ZDD). The age constraints for seismic horizons are derived from well-data Zambezi-1 (Z-1) and Zambezi-3 (Z-3) that lie on profile BGR07-205
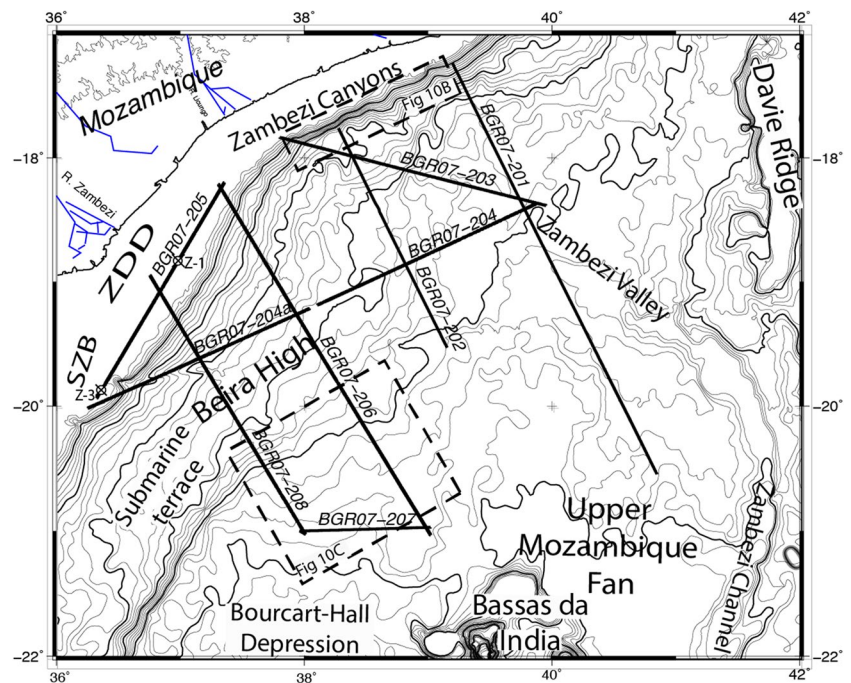
levee flanks. The deep channel is filled in with well-stratified sediment deposits.

Since Late Miocene, a significant part of the sediment load from the Zambezi was delivered via the Zambezi Valley directly to the Mozambique fan in the deeper basin by bypassing the shelf. The morphology of the Zambezi Channel (Figs. 1, 3) is very well defined in GEBCO bathymetry. Contrary to the previous study of Droz and Mougenot (1987), seismic profiles (Figs. 4, 5, 6, 9) and ship-borne swath bathymetry (Fig. 10) reveal several tributary valleys and canyons that merge into a sing Para_FL le valley around 40°E (referred to as Zambezi Valley) where it starts to resemble a channel-levee system (referred to as Zambezi Channel) with thick sediment deposits on either side. The valley erodes the Miocene and younger sediments and is characterized by steep walls and slope failures. The valley itself appears to be in-filled with chaotic or sheeted sediment deposits (Fig. 9). Several closely spaced canyons (Zambezi Canyon) originating on the shelf slope sharply incise the seafloor (Figs. 5, 6, 10) and merge into subtle valleys on the continental rise.

Discussion

In the following section, we describe the evolution of the turbidite systems of the Upper Mozambique Fan chronologically starting from Late Cretaceous until present. The controls on the architecture of the turbidite system are simultaneously discussed.

Table 2 Generalized stratigraphy of the Mozambique basin (modified from De Buyl and Flores 1986) and seismic stratigraphy adapted from Castelino et al. (2015) used in this study

| Seismic Unit	Age	Composition/ Formation (Fm)	Litho-logy	Event/ Environment
MBSU-6	Holocene / Pleistocene	Deltaic Complex - Sand		Onshore Tectonic uplift-ongoing
MBSU-5	Miocene / Oligocene	Jofane Fm / Temane Fm		Onshore tectonic uplift / Sea level lowstand
MBSU-4	Eocene / Paleocene	Cheringoma Fm / Inharrime Fm		reduced sediment influx
MBSU-3	Upper Creatceous	Grudja Fm / Upper Domo Shales		Bottom current onset onshore Tectonic Uplift
MBSU-2	Lower Cretaceous	Domo Sands / Lower Domo Shales / Maputo Fm (Sena Fm)		
MBSU-1	Late Jurassic	Continental red beds		Enclosed basin Terrigenous deposits
Basement	Middle-Late Jurassic	Karoo igneous		Rifting-Gondwana Break up
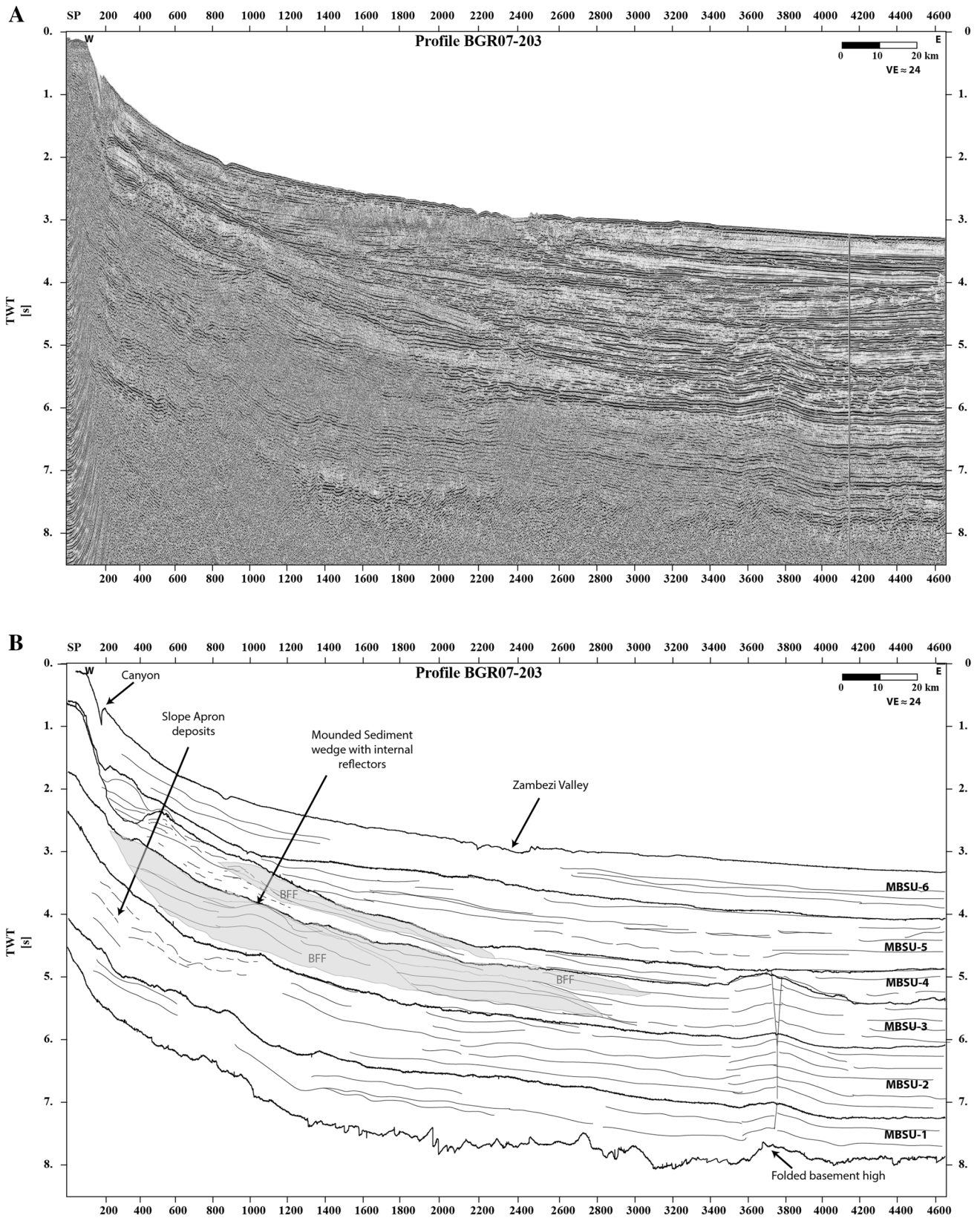
Fig. 4 **a** Uninterpreted seismic profile of BGR07-203. **b** Line drawing of seismic line BGR07-203. Sediment mounds associated with slope-apron submarine fan deposits are observed in the section. Shelf incising canyons are located on the seafloor. Seismic stratigraphy MBSU-1–MBSU-6 used in all figures is described in Table 2
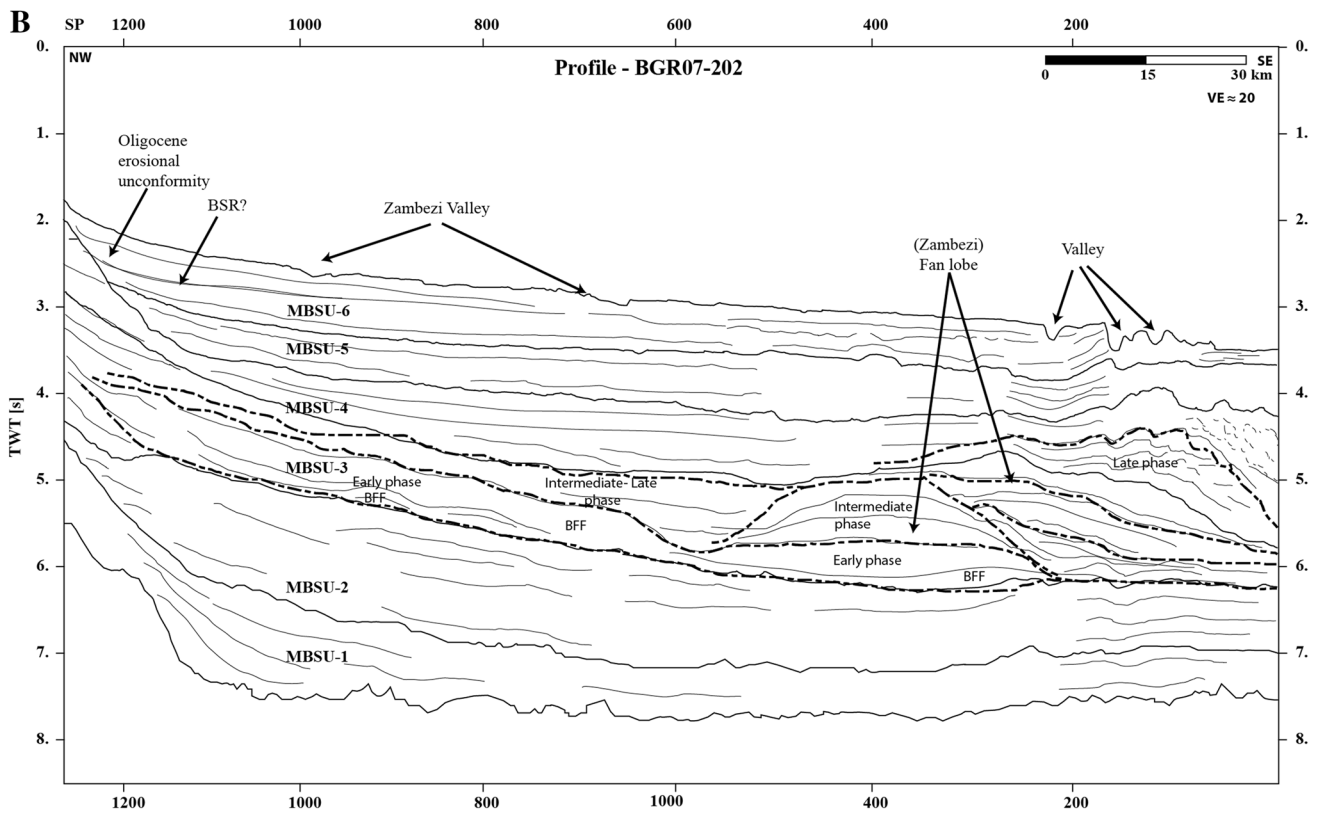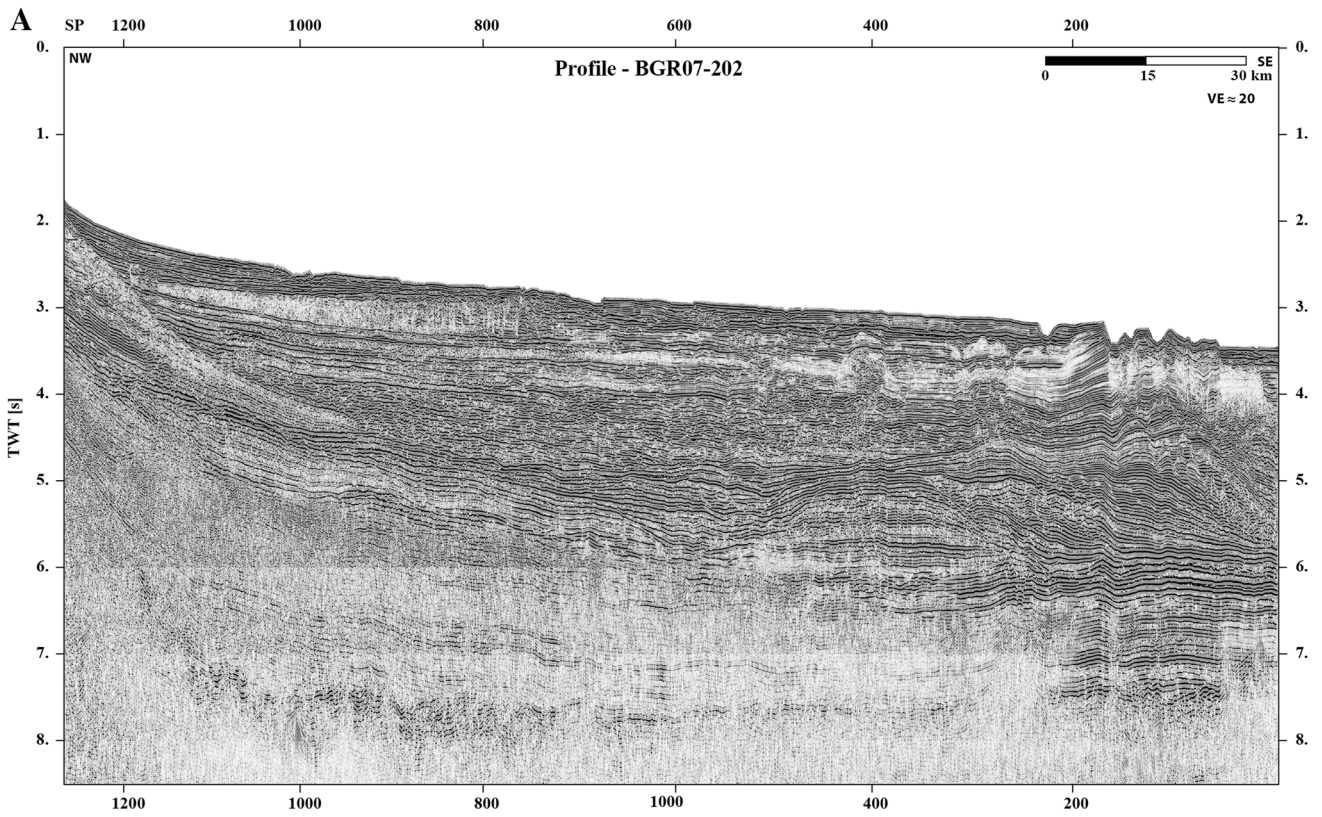
◀**Fig. 5** **a** Uninterpreted seismic profile of BGR07-202. **b** Line drawing of interpreted seismic profile BGR07-202 (modified from Castelino et al. 2015). Most of MBSU-3 unit comprises of fan lobes. During the early phase when tectonic activity triggers fan development, the lobes have comparable development. During the later phase when sediment supply is the primary control, the right (southwestern) lobe accumulates faster and migrates southwards under the influence of bottom currents. The seafloor is incised by valleys at several locations that transport sediment load from the shelf into the channel

Controls on Late Cretaceous—Eocene fan development

Partridge and Maud (1987) inferred epeirogenic uplift of southern Africa by about 1000 m around ~90 Ma on the basis of onshore landscape analysis. This has been subsequently corroborated by apatite-fission track analysis of samples along the Atlantic margin in Nambia and South
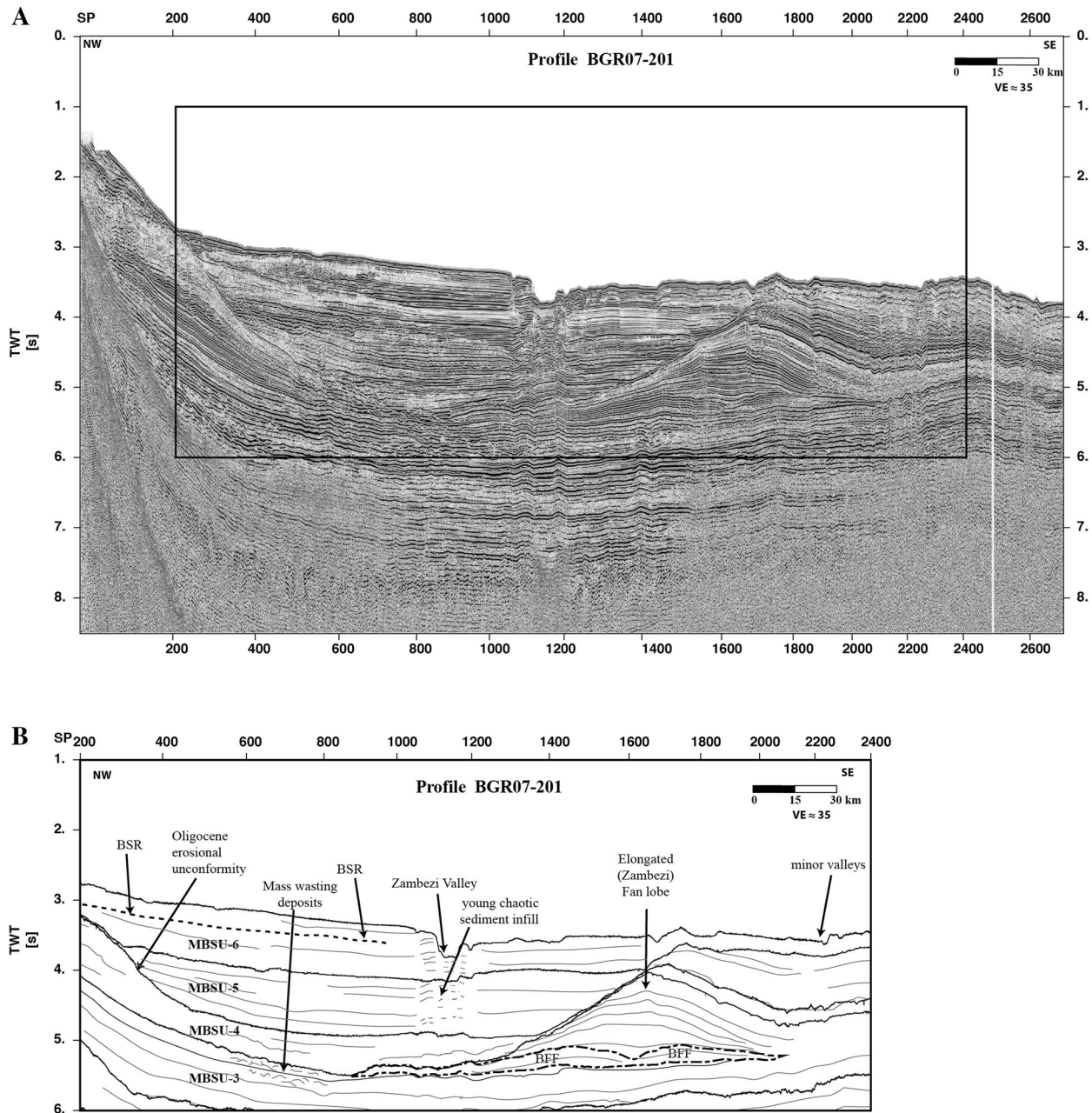

Fig. 6 **a** Uninterpreted seismic profile of BGR07-201. The black box indicates the extent of the interpreted section. **b** Line drawing of interpreted seismic Profile BGR07-201 (modified from Castelino et al. 2015). Submarine fan development begins in unit MBSU-3 (Late Cretaceous) where mass wasting deposits are followed by development of Basin Floor Fans (BFF). The Zambezi valley that fed the Upper Mozambique Fan is characterized by steep walls, slope failure faults and chaotic sediment infill. BSR (*Bottom* Simulating Reflector) along the profile is identified on the continental rise indicating the presence of gas hydrates and free gas below it
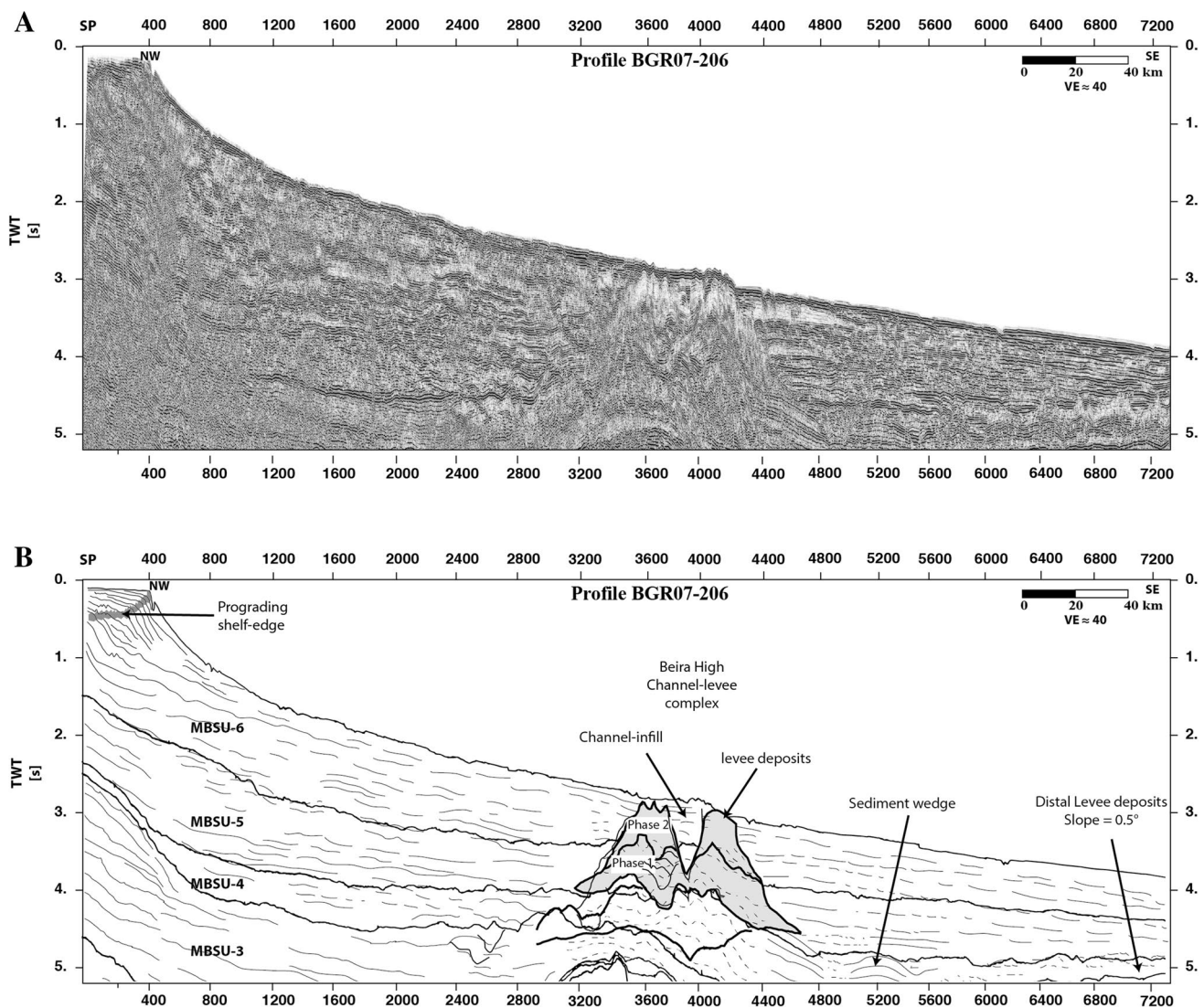
Fig. 7 a Uninterpreted seismic profile of BGR07-206. **b** Line drawing of seismic line BGR07-206. The top-MBSU-4 reflector outlines several incised valleys that are filled with younger sediments. The massive Channel-valley complex above Beira High is illustrated in a grey shade

Africa (Brown et al. 2014; Wildman et al. 2016) and along the Malawi Rift system and in northern Mozambique (Daszinnies et al. 2009; Emmel et al. 2011), where fission track analysis show distinct period of cooling in the Late Cretaceous around ~75 Ma. This uplift could have resulted in a regional change in sea level affecting at least the shelf region over a relatively short time span. Nelson et al. (2011) use precise radiocarbon dating to report how rapid Holocene sea level changes result in the formation of mass transport deposits globally. The presence of Cretaceous mass transport deposits along the Mozambican continental shelf (e.g., Fig. 6-SP 500–800; 5–5.5 s) is consistent with the idea of regional sea level change at that time or alternatively, to seismicity due to onshore uplift. Besides these slope failures, basin floor

fans developed at the continental rise where they were fed by shelf canyons and gullies with sediments eroded from the shelf. We refer to the mass wasting deposits and basin floor fan (BFF) development as early phase of fan development that is controlled by tectonic activity (Figs. 4, 5, 6). The seismic lines of our study cover only the lower fan deposits. Onshore studies based on well data show the presence of fan deposits (De Buyl and Flores 1986; Nairn et al. 1991; Salman and Abdula 1995) that indicate the Palaeocene–Eocene shelf and Zambezi Fan were located much further landwards than today's (Fig. 11a). The Late Cretaceous uplift was accompanied by large-scale denudation of the African surface and a growing Zambezi catchment area (Fig. 2), which led to increased sediment material transport. Contemporaneous increases
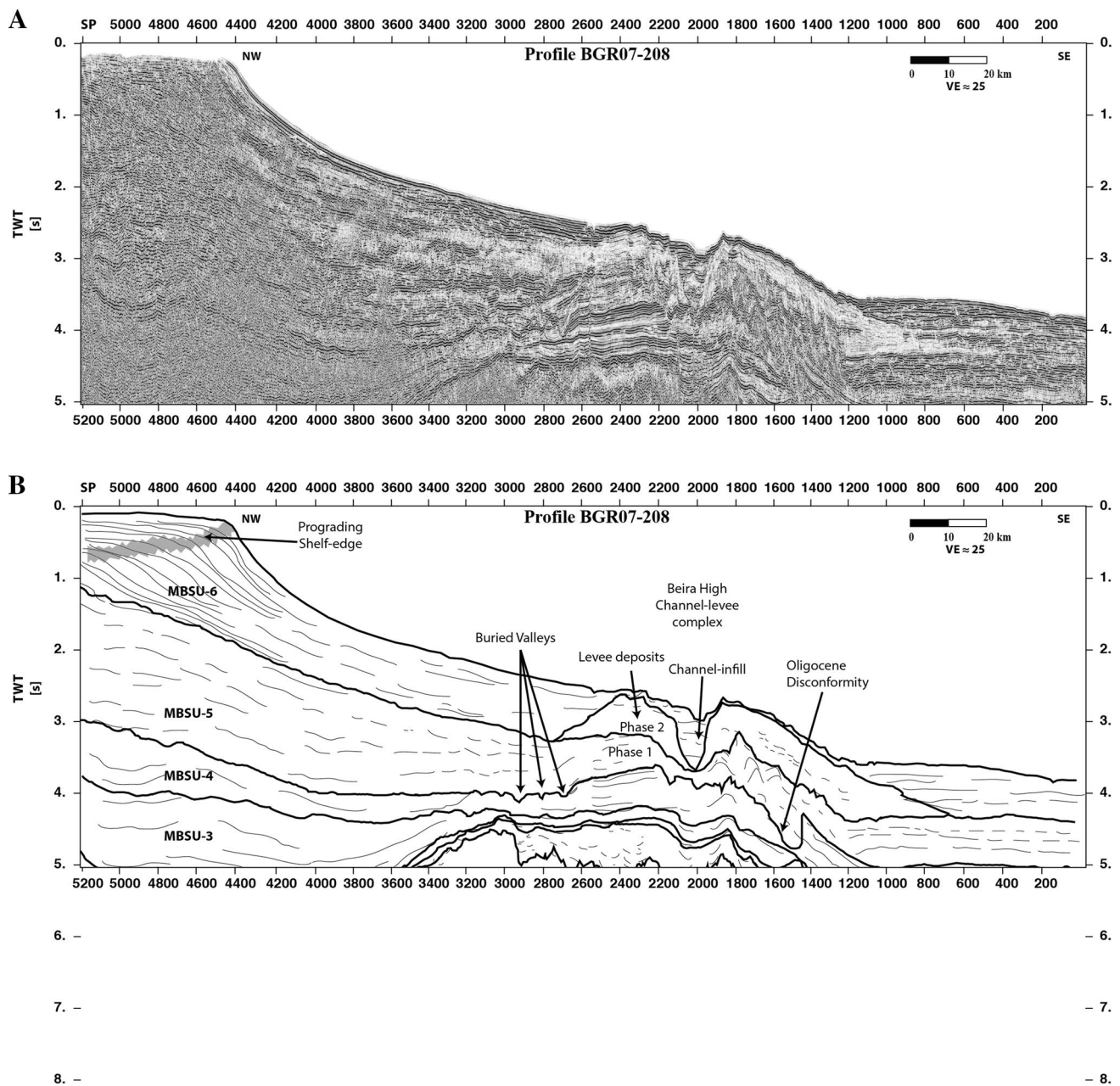
Fig. 8 a Uninterpreted seismic profile of BGR07-208. **b** Line drawing of seismic line BGR07-208 showing the continuation of the Channel-valley complex above Beira High. The top reflector of MBSU-4 is strongly eroded unconformity and younger chaotic sediments fill the erosive topography. To the east, deep-sea sedimentation on laps the levee deposits

in sedimentation rates in other southern African margin depocentres (e.g., Orange River Delta (Rouby et al. 2009), Outeniqua Basin (Tinker et al. 2008) and Limpopo Delta (Said et al. 2015)) are also attributed to Late Cretaceous uplift. In Namibia, up to 1 km on the Atlantic margin and 4.5 km inland have been eroded (Wildman et al. 2016). Similar denudation has been reported in northern Mozambique and in the Zambezi catchment area (Daszinnies et al. 2009; Partridge and Maud 1987).

The average sedimentation rate in the Mozambique Basin increased almost two fold during this period, peaking at in excess of 75 mm/kyear. Previous studies have shown that the consequent increase in sediment influx (Castelino et al. 2015; Walford et al. 2005) led to the deposition of upper or middle–fan deposits over the older deposits of the lower fan as it grew further out into the channel until the Eocene (Fig. 4). We refer to these deposits as the 'Late phase' of fan development where sedimentation

volume and type is the primary control on the fan deposits. Upslope, the south-western (right) fan lobe shifted southwards by discrete steps while accumulation on the north-eastern lobe was significantly less (Figs. 5, 6). This can be interpreted as a complex product of shelf margin build-up moving landward after the post-uplift subsidence and the influence of north–south bottom current.

Oligocene–Miocene turbidite system over Beira High

By the end-Eocene, planation of the South African topography, whose result is referred to as the Post African I surface (Partridge and Maud 1987), deprived the African rivers of sediments. In the offshore seismic data, this might be documented by the base Oligocene (Top MBSU-4) reflector unconformity, which relates to a hiatus and global eustatic sea level fall after Eocene to mid-Oligocene times (Figs. 4, 5, 6, 7, 8). In this period, the delta foreset retreated landwards by almost 100 km as the shelf in the ZDD became subaerially exposed (De Buyl and Flores 1986; Droz and Mougenot 1987). Sedimentation rates were almost negligible in the shelf region. Consequently, a significant quantity of sediments on the shelf and the submarine terrace over Beira High were eroded by incising canyons and valleys in the ZZD and most likely transported to the mouth of the valley in the deeper basin. After the marine regression phase, sediment input into the basin was revived by renewed elevation of African surface topography by 150–300 m during the Miocene (Burke 1996; Burke and Gunnell 2008; Castelino et al. 2015; Partridge and Maud 1987; Walford et al. 2005). Uplift along the Ovambo–Kalahari–Zimbabwe Axis rejuvenated the southern African drainage network, initiating a new cycle of erosion in the continental interior and accompanying increased sediment discharge in the Limpopo and Congo deltas (Moore et al. 2009; Roberts and White 2010; Said et al. 2015). On the Mozambique Fan, too, topset reflector patterns and well-developed clinoforms at the shelf edge indicate an increase in sediment supply and accommodation space by subsidence and sediment compaction (Fig. 7- SP 0-800, 0–1.5 s TWT; Fig. 8-SP 5200–4100, 0–1.5 s TWT). However, the sediment volume flux outpaced the increase in accommodation space resulting in strong prograding sequences and outbuilding of the system. The chaotic and discontinuous character of sediment deposition and development of multiple channels indicates a high-energy environment. During the subsequent phase, a massive channel levee complex formed over Beira High (Fig. 7,8; Phase 2) with a deep channel. We associate this change in depositional regime to Middle-Miocene reactivation of the northwest - southeast oriented Inhaminga fault system that cuts the older northwest–southeast Zambezi Graben, producing topography that diverted the sediment load of the Zambezi further south over Urema Graben towards Beira for a short period of time (De Buyl and Flores 1986; Flores 1973) (Fig. 11c). The change in the deltaic environment due to sediment supply from further south triggered the development of the Beira High Channel-Levee Complex. Numerical and experimental models show that the initiation of channel-levee systems requires specific combinations of grain size, slope, and a mechanism for the production of regular turbidity currents at the mouths of canyons (Imran et al. 2002, 1998). Palaeo-climatic studies indicate shifting African monsoon-like conditions along the eastern and southeastern African Margin during Late Neogene (Maslin and Christensen 2007), implying strong seasonal variation in precipitation that could have acted to produce turbidity currents. Activity in the channel ceased or reduced when
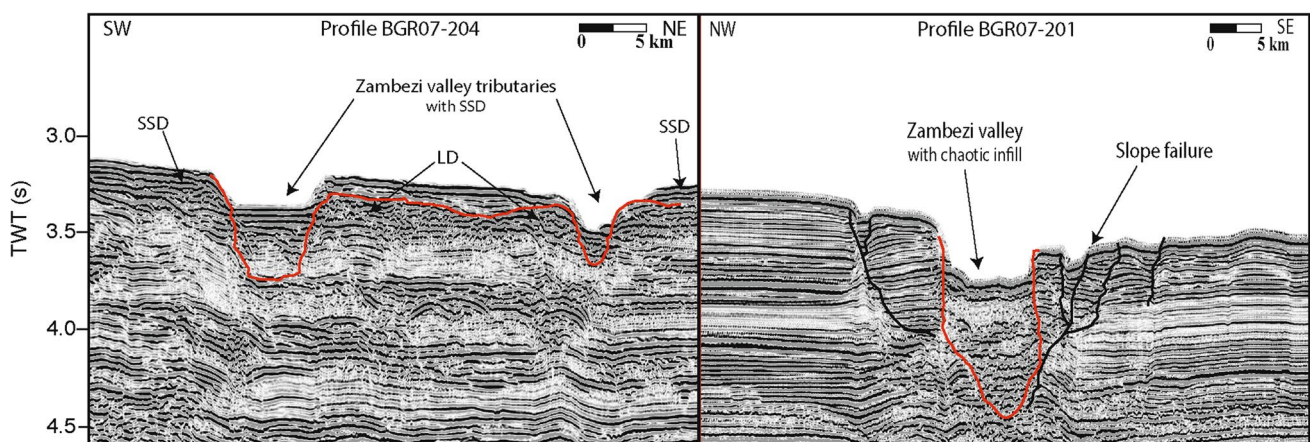

Fig. 9 Seismic profiles across the Zambezi Valley (*right*) and its tributaries (*left*) in the Mozambique Basin are outlined in *red*. The sidewalls of the tributaries are oversteepened and are infilled with chaotic sediment deposits overlain by sheeted sediment drape. The Zambezi Valley flanks show several faults related to slope failure. *LD* levee deposits, *SSD* sheeted sediment drapes

Fig. 10 a Bathymetric map of
the Mozambique Basin showing
ship-borne multibeam data
acquired during the expedi-
tion with GEBCO 2014 in
the background. **b** Ship-borne
bathymetry along the conti-
nental slope in the north shows
several canyons indenting the
seafloor. **c** Submarine valleys
at the base of the submarine
terrace that provides pathways
for the sediment load to directly
bypass the shelf
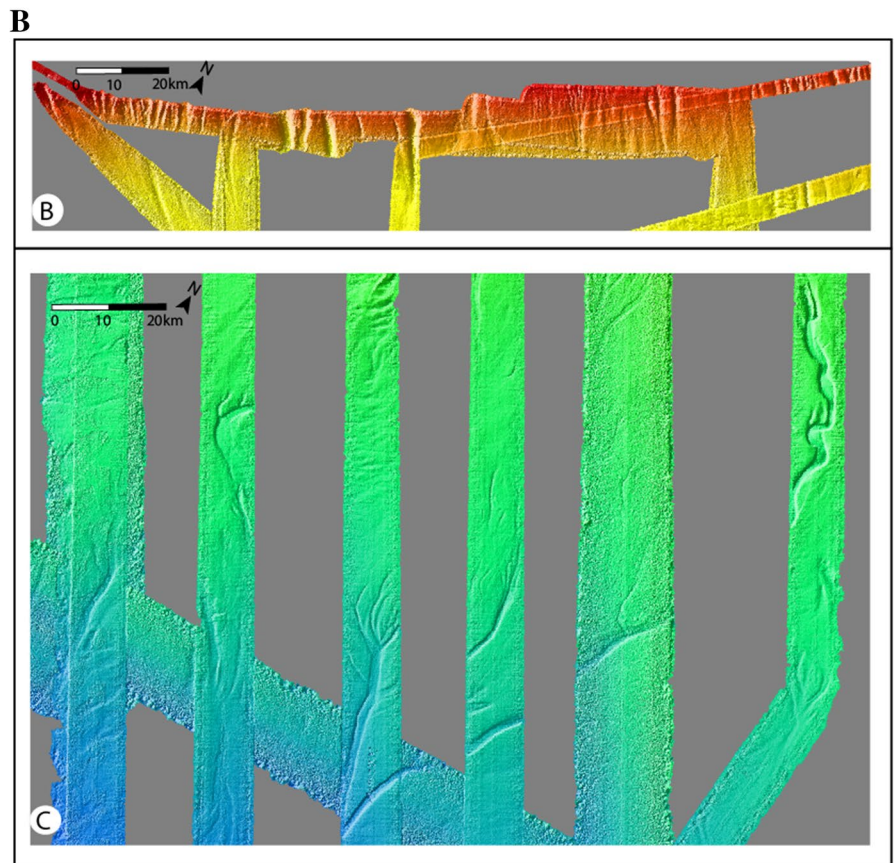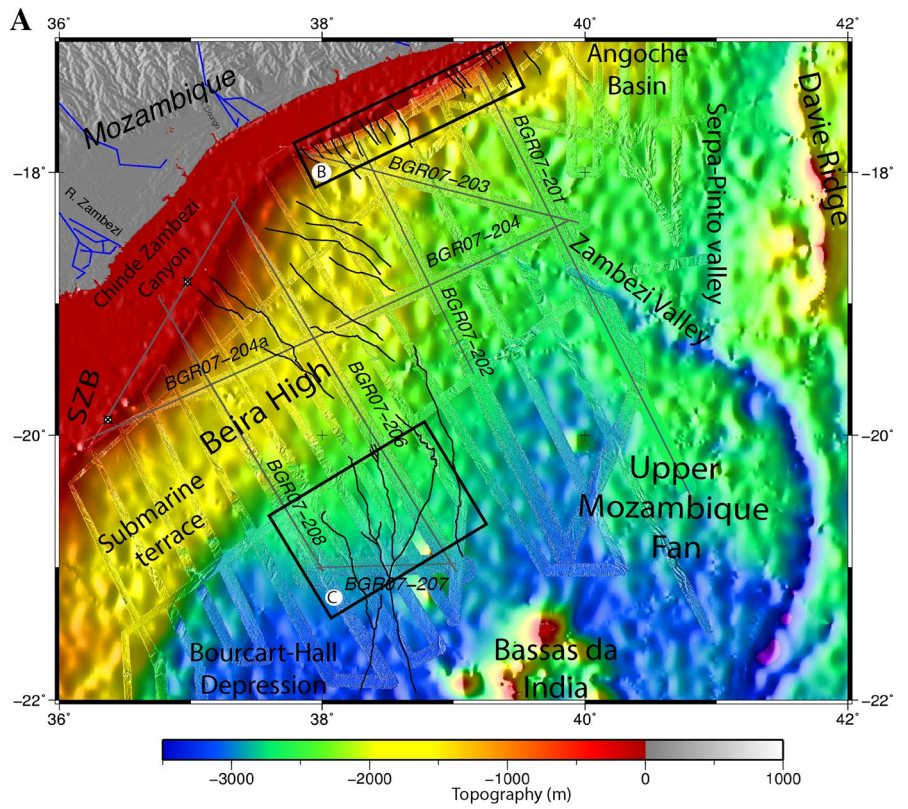
the course of the Zambezi was later restored close to its present-day position. The channel was subsequently filled with well-stratified sediments under low energy conditions or a subsequent wavering phase of the turbidite system.

Late Miocene–Pliocene/Pleistocene development of the Zambezi Channel system

The Zambezi Valley (Figs. 6, 9) has incised through Miocene sediment packages, implying its sedimentary system is not older than Miocene. Using our profiles, it is difficult to make observations that enable us to precisely date the onset of turbidity current activity in the Zambezi Valley during the Miocene. However, further down the channel, Droz and Mougenot (1987) found that the Serpa-Pinto Valley (Fig. 1) deposits of Oligocene-Early Miocene age underlie the Zambezi Channel deposits. This would constrain the age of Zambezi valley to around the middle Miocene or later, to coincide with East African rifting onshore Mozambique and the Zambezi's adoption of its present-day course. In this case, the sediment load that was previously transported over Beira Channel-Levee system would have subsequently diverted north along the shelf before being flushed down the Zambezi canyons and valley and into the Zambezi Channel where it is deposited as levee deposits.

Chaotically-stratified sediments overlain by sheeted drapes that fill the valley (Fig. 9) suggest reduced turbidity current activity in the present-day valley. This supports Droz and Mougenot's (1987) attribution of the absence of Pliocene sediments on the levee further south (Kolla et al. 1980b) to reduced activity, rather than erosion by deep water currents, in the channel. Canyons may achieve stability through successive slumps (Coleman et al. 1983) or by waning turbidity current activity. Following this rationale, slump deposits or fine pelagic and hemi-pelagic sediments gradually fill canyons. The chaotic sediments sediment deposits in the valley observed in the profiles (Fig. 9) are most likely slump deposits related to stabilization of the system with only a small fraction of the sediment load discharged by the rivers being deposited as sheeted drapes post-stabilisation. On the other hand, sedimentation rates in the basin have continuously increased since Miocene times (Castelino et al. 2015; Walford et al. 2005), accompanying continental uplift by almost 1000 m and doubling of the Zambezi catchment area (Walford et al. 2005). In line BGR-203, shallow valley incisions filled with sediments are observed that could be upslope manifestations of the Zambezi Valleys. However, the continuations of these valleys are beyond the resolution of the bathymetry. The last 20,000 years of have been strongly affected by sea level rise and flooding of the shelf transporting sediment further northwards on the shelf (Schulz et al. 2011; Van der Lubbe et al. 2014; Wiles et al. 2017). If similar conditions also existed during the Pliocene then canyons would have been starved of sediments during sea level lowstand causing the inactivity in the Zambezi Valley.

Present-day source to sink pathway

Sedimentation rates in the Zambezi delta inferred from isochore maps show a recent increase in the sediment load of the Zambezi to in excess of 200 mm/kyear averaged over last 5 Ma (Castelino et al. 2015; Walford et al. 2005). Higher sedimentation rates (750–900 mm/kyear) are observed in the sediment cores on the shelf slope in front of the Zambezi mouth and lower rates (>500 mm/kyear) further north since 20,000 b.p.(Van der Lubbe et al. 2014). The associated sediment transport pathways over the shelf to the deeper basin are unfocused and difficult to determine (Schulz et al. 2011). This lack of stability is related to sea level rise and subsequent flooding of the shelf since LGM when parts of the shelf were sub-aerially exposed and the sediments were transported via gullies and canyons directly to the deeper basin. Beiersdorf et al. (1980) show graben-like structures that are filled with Pliocene sediments on the shelf in the Zambezi Delta. While significant quantities of sediment are deposited on the shelf, it is suspected that sediments are also transported to the Upper Mozambique Fan via the re-excavated Chinde-Zambezi Graben (Droz and Mougenot 1987) (Fig. 10). The presence of Pliocene sediments lead Droz and Mougenot (1987) to suggest that this graben trapped sediments and starved the Zambezi canyon that fed the Zambezi valley. Seismic profiles (Figs. 4, 5, 6) and new bathymetry data (Fig. 10b) show the presence of several closely spaced canyons along the shelf north of the Zambezi mouth and northwest-southeast oriented valleys originating close to the shelf and meandering southwards east of Beira High (Fig. 10c). This supports the recent hypothetical models that propose a northward transport of a significant fraction of sediment load over the shelf based on short sediment core data (Schulz et al. 2011) and a compartmentalized tripartite regime supplying sediments into the Angoche Basin, the Bourcart-Hall Depression and the Zambezi Valley-Channel (Wiles et al. 2017). This study along with other recent studies supports the hypothesis of Droz and Mougenot (1987) that a large fraction of the sediments bypass the shelf and flow south directly into the Mozambique Channel. This valley meanders at the base of the slope where the gradient of the slope changes before entering the Bourcart-Hall Depression west of the Bassas da India and Europa islands (Fig. 10c).

Role of oceanic circulation

It is worthwhile to note the presence of fully developed channel-levee systems flanked by thick (almost 2 s TWT)
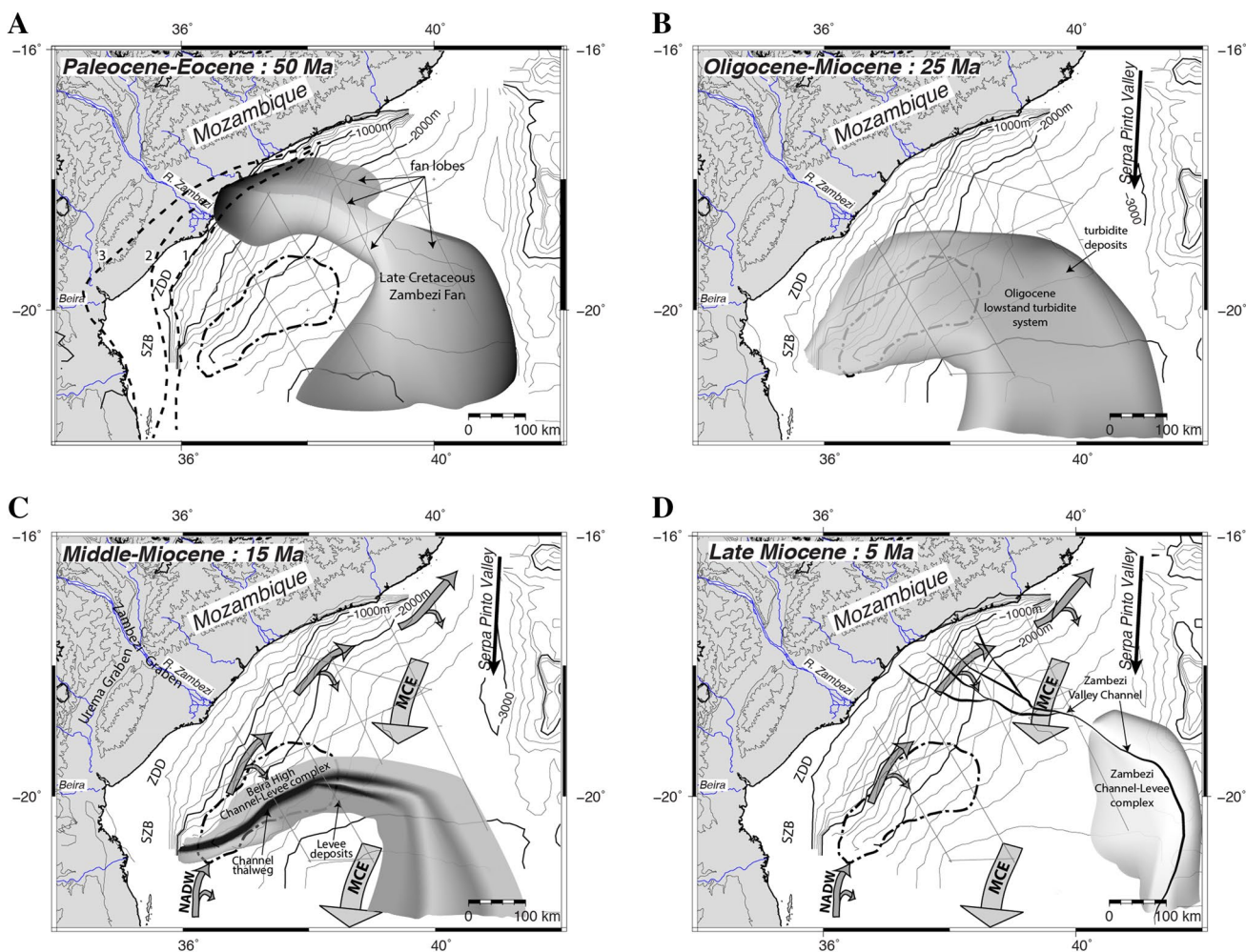
Fig. 11 The hypothesized schematic sketch of the submarine fans and turbidite systems in the Mozambique Basin showing the minimum extent of turbidite deposits (*grey* shades) and their feeding canyons and valleys (*black*). The size and geometry are interpreted from seismic profiles. The contour lines (depth in meters) show the palaeo-bathymetry for the given age (Castelino et al. 2016) **a** Minimum extent of the Zambezi Fan during Paleocene–Eocene. The fan consists several fan lobes are stacked on top each other that migrates southwards around Beira High (*dash-dot line*). The *dashed lines* indicate retreating palaeo-shelf edge (Salman and Abdula 1995) 1- Paleocene; 2- Early Eocene; 3- Middle-Late Eocene. **b** Turbidite system during Late Oligocene -Early Miocene switched further south.

Reworked shelf sediments are transported downslope by valleys and subsequently filled and covered by younger Miocene sediments. **c** Beira High Channel-Levee complex that was fed by the Zambezi River when it was diverted over Urema Graben during middle-Miocene. *Dark shading* indicates thalweg of the channel. **d** Pathways of the Zambezi Valley feeding the Upper Mozambique Fan during Late Miocene. Location and orientation of bottom currents i.e., Antarctic Intermediate Water and North Atlantic Deep Water (NADW) and Mozambique Channel Eddies (MCE) that may have influenced channel-levee complex inception are indicated with *grey arrows*. *SZB* Sofala-Zambesia Bank, *ZDD* Zambezi Delta Depression

levee deposits over Beira High during Miocene and Zambezi Channel, during middle-late Miocene and their absence or poor development on other valleys during other times. Numerical and analogue models for investigating the role of turbidity currents in channel-levee inception have neglected the effects of contourite currents (Imran et al. 2002, 1998). In the experimental set-up, the reflection of the sufficiently fine-grained sediment load from the back wall inhibited the process of self-channelization by polluting the ambient water conditions and disturbing sediment

deposits (Imran et al. 2002) implies that the process can be easily disturbed. Both the channel-levee systems in the Central Mozambique Basin are oriented along or slightly oblique to the direction of present-day bottom currents that sweep over them i.e. the almost northward flowing NADW and AAIW over Beira high (1500–2400 m) and the southward flowing MCE over the Zambezi Channel (Fig. 2). This suggests that similar bottom currents, if active in the Miocene, would not have significantly interfered with the processes by which turbidite currents led to the inception

and development of channel-levee complexes. Without ruling out other factors on other valleys, the Late Neogene-Quaternary feeder canyons and valleys on the continental rise are oriented almost perpendicular to the direction of bottom current propagation (NADW). It is possible that NADW inhibits self-channelization on these features despite the presence of deep incising canyons, surging turbidite loads, and steep slopes. The formation of an intermediate submarine terrace seaward of the shelf at depth range of 1000–2400 m can be attributed to dispersal of sediment overspill by northward flowing bottom currents (NADW) (Fig. 11). This also partially explains why the Zambezi Valley has such poorly developed levee deposits (~0.25 s TWT) (Fig. 9) and why the Zambezi Channel-levee complex is observed beyond 41°E where the system turns south and into the same direction as the MCE.

Conclusions

The Mozambique Fan turbidite complex is a product of several ancient and modern turbidite systems originating from the southeast African and Madagascan continent over tens of millions of years. The development of the submarine Zambezi Fan in the Mozambique Basin since the Late Cretaceous makes it one of the oldest identified depositional systems. Based on timing coincidences, onshore tectonic activity and associated uplift is the apparent mechanism and primary control on the development of the deep sea fan. Episodes of tectonic uplift during Late Cretaceous and Miocene and associated sea level change, and reactivation of rift systems has had a significant impact on the sediment delivery pathways. The increase in sediment supply into the basin, which is also a consequence of tectonic activity, has a delayed impact of a few million years on the development of turbidite system.

We identified two additional ancient turbidite systems in the basin in addition to the one ancient identified by Droz and Mougenot (1987) and present some more evidence regarding unknown aspects of the present-day turbidite system connected to the Zambezi River. The ancient systems exhibit two or more active phases controlled by tectonic activity and sediment supply during its development. From Late Cretaceous to Eocene, the Zambezi Fan developed in response to tectonic activity onshore. The early phase appears to be an instantaneous response to local sea level change. During the subsequent phase, the fan grew and prograded by increased sediment influx in to the basin. The effect of bottom currents on the dispersal of the fan is very significant in the deeper basin where the influence of turbidity currents begin to wane.

From Oligocene- to middle Miocene, the sediment supply migrated south over Zambezia-Sofala Bank. The early

phase is related to the eustatic sea level change during mid-Oligocene when several canyons eroded the shelf and submarine terraces. The subsequent uplift of Africa revived sediment input in the basin resulting in prograding clinoforms on the shelf edge. Reactivation of the Inhaminga fault system during middle Miocene changed the course of the Zambezi over the Urema Graben and resulted in the development of the Channel-Levee system over Beira High.

Ongoing rifting along the Urema Graben restored the Zambezi to its present-day orientation and significant amounts of sediments were transported northwards along the shelf by nearshore drifts where they bypassed the shelf slope and continental rise before being flushed down the Zambezi Canyon-valley system into the abyssal plains of the Mozambique Channel. Presently, the turbidite system is compartmentalized in a tripartite regime controlled by sea level variations with sediment load distributed along the entire shelf before being dispersed into the basin by valleys that extend over the submarine terrace between Zambezi Valley, Beira High and Bassas da India Island.

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