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Research paper

Tracking the paleogene India-Arabia plate boundary

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ABSTRACT

The location of the India-Arabia plate boundary prior to the formation of the Sheba ridge in the Gulf of Aden is a matter of debate. A seismic dataset crossing the Owen Fracture Zone, the Owen Basin, and the Oman Margin was acquired to track the past locations of the India-Arabia plate boundary. We highlight the composite age of the Owen Basin basement, made of Paleocene oceanic crust drilled on its eastern part, and composed of pre-Maastrichtian continental and oceanic crust overlaid by ophiolites emplaced in Early Paleocene on its western side. A major fossil transform fault system crossing the Owen Basin juxtaposed these two slivers of lithosphere of different ages, and controlled the uplift of marginal ridges along the Oman Margin. This transform system deactivated ~40 Myrs ago, coeval with the onset of ultra-slow spreading at the Carlsberg Ridge. The transform boundary then jumped to the edge of the present-day Owen Ridge during the Late Eocene-Oligocene period, before seafloor spreading began at the Sheba Ridge. This migration of the plate boundary involved the transfer of a part of the Indian oceanic lithosphere formed at the Carlsberg Ridge to Arabia. This Late Eocene-Oligocene tectonic episode at the India-Arabia plate boundary is synchronous with a global plate reorganization event corresponding to geological events at the Zagros and Himalaya belts. The Owen Ridge uplifted later, in Late Miocene times, and is unrelated to any major migration of the India-Arabia boundary.

1. Introduction

The Zagros and Himalaya mountain belts are the most prominent reliefs built by continental collision. They respectively result from Arabia and India collision with Eurasia. It has been suggested that convergence motion at mountain belts induced most of the plate reorganization events in the Indian Ocean during the Cenozoic (Molnar et al., 1993; Patriat et al., 2008; Hatzfeld and Molnar, 2010). Although critical for paleogeographic reconstructions (Cande et al., 2010; Gibbons et al., 2013, 2015), the way transform motion between Arabia and India was accommodated since its inception ~90 Myrs ago remains poorly understood. Similar to the Andrew-Bain transform in the SW Indian Ocean (Ligi et al., 2002; Sclater et al., 2005), the India-Arabia plate-boundary is a case of long-lived transform that has been active since the Late Cretaceous. It thus provides a good case study to investigate the role of major kinematic events over the structural evolution and the successive migration of a long-lived transform system.

The present-day India-Arabia plate boundary is a 800-km-long strike-slip fault known as the Owen Fracture Zone (OFZ hereafter) (Fig. 1; DeMets et al., 2010; Fournier et al., 2011). The OFZ runs along the Owen–Murray Ridge system, a series of prominent bathymetric highs located between 60°E–62°E that currently isolate the Owen Basin to the west from the Indus turbidite system to the east. The OFZ differs from the Owen Transform (i.e., the India/Somalia boundary), which offsets the Carlsberg and Sheba Ridges over 250 km (Fig. 1). The OFZ sensu stricto (i.e. the present-day active trace) is Plio-Pleistocene in age (3–6 Ma) according to kinematic and structural studies (Fournier et al., 2008a,b; 2011; Rodriguez et al., 2011, 2013b; 2014b). This age drastically contrasts with the age of the India-Arabia relative motion, assumed to begin at ~84–92 Ma in most reconstructions, i.e., the age of ~N–S opening of the Mascarenes Basin between Madagascar and the India–Seychelles block (Besse and Courtillot, 1988; Bernard and Munschy, 2000; Seton et al., 2012 and references herein). It raises the question of the location and the structure of the pre-Pliocene

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India-Arabia plate boundary.

According to magnetic anomalies recorded in the Arabian Sea (Sheba and Carlsberg Ridges; Merkouriev and DeMets, 2006; Fournier et al., 2010), the India-Arabia plate boundary ran along the Owen–Murray Ridge since at least ~20 Ma, possibly accommodating about 80 km of relative motion (Chamot-Rooke et al., 2009). Strike-slip tectonics prior to the emplacement of the OFZ is inferred on the basis of the identification of a fracture zone immediately to the east of the Owen Ridge and the fanning configuration of Miocene sediments at the top of the ridge (Rodriguez et al., 2014a). The Plio-Pleistocene OFZ observed on the seafloor is the latest stage of structural evolution of this strike-slip system, older Miocene traces being buried under the Indus fan (Rodriguez et al., 2011, 2014a,b).

Conflicting views have been proposed with regards to the location of the India-Arabia boundary prior to the onset of seafloor spreading in the Gulf of Aden in the Early Miocene (Fig. 2) (Whitmarsh, 1979; Mountain and Prell, 1990; Edwards et al., 2000; Royer et al., 2002). Whitmarsh (1979) and Gaina et al. (2015) postulated that the India-Arabia plate boundary remained close to its present-day location since Late Cretaceous times, whereas Mountain and Prell (1990) proposed that Paleogene strike-slip motion took place at the edge of the Oman margin. Paleogeographic reconstructions based on magnetic anomalies also suggest the plate boundary was located in the Owen Basin during Paleogene (Royer et al., 2002). Although critical to unravel the past locations of the India-Arabia plate boundary, the structure of the Owen Basin has been scarcely documented, with preliminary works by Mountain and Prell (1990) and Barton et al. (1990).

About 5000 km of seismic lines crossing the Owen Basin, the Owen Ridge, and the OFZ were acquired (Fig. 3 a,b). Seismic lines are tied with the DSDP and ODP drillings available in the area to define the stratigraphic framework of the basin and the age of the deformation episodes. The objective of this study is to locate and describe the structure of the India-Arabia plate boundary prior to Miocene, with a particular emphasis over the Paleogene period, i.e., the period of separation of Arabia from Africa (McQuarrie et al., 2003).

2. Material and methods

The dataset presented in this study was acquired onboard the BHO Beautemps-Beaupré (a ship of the French Naval Hydrographic and Oceanographic Service) during the OWEN and OWEN-2 surveys in 2009 and 2012, respectively. Seismic reflection profiles were acquired using the high-speed (10 knots) seismic device designed by GENAVIR. The source consists in two GI air-guns (one 105/105 c.i. and one 45/45 c.i.) fired every 10 s at 160 bars in harmonic mode, resulting in frequencies ranging from 15 to 120 Hz. The receiver is a 24-channel, 600-m-long seismic streamer, allowing a common mid-point spacing of 6.25 m and a sub-surface penetration of about 2 s two-way travel time (TWT). The processing consisted of geometry setting, water-velocity normal move-out, stacking, water-velocity f-k domain post-stack time migration, bandpass filtering and automatic gain control. All profiles are displayed with a vertical exaggeration of 8 at the seafloor. Reflectors picked on seismic profiles have been selected on the basis of seismic discontinuities that either reflect lithological changes, stratigraphic hiatuses or

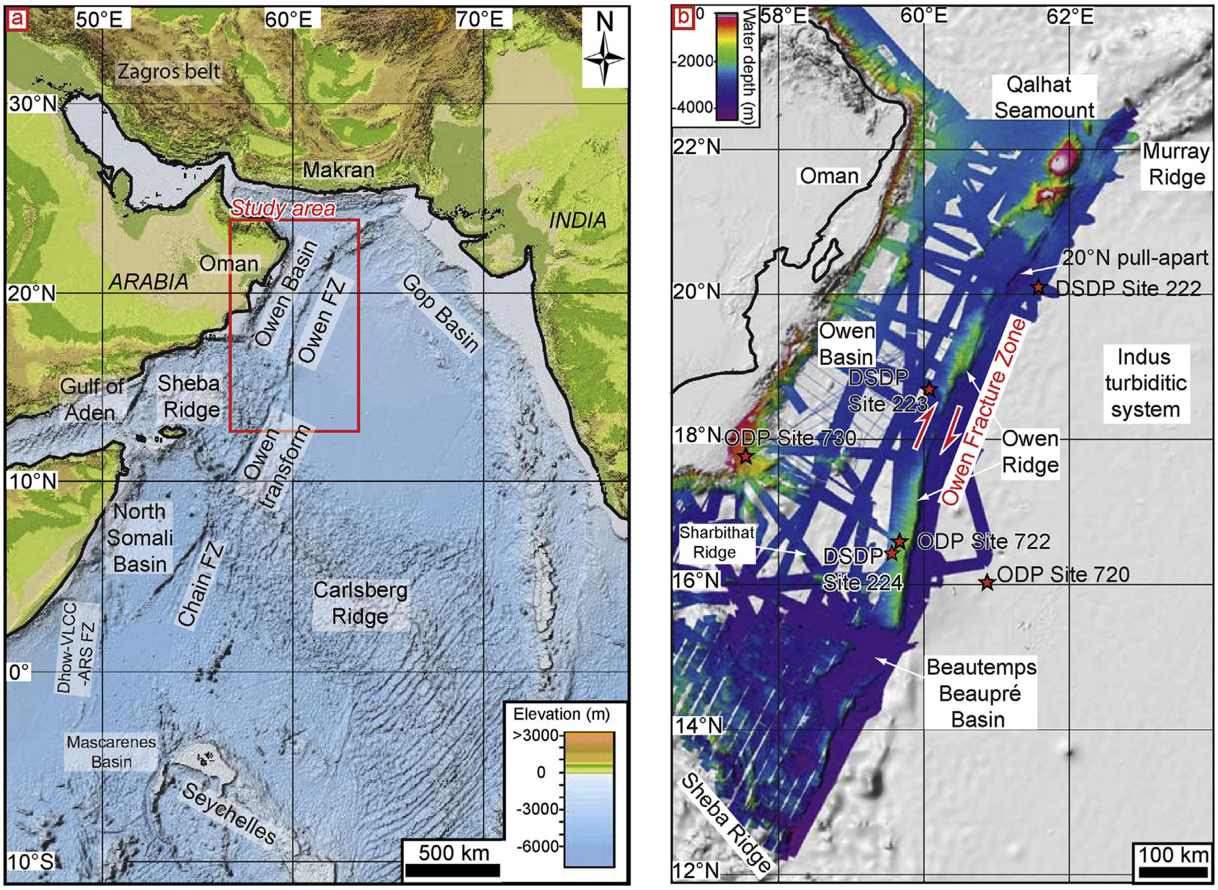


Fig. 1. a) General map of the western Indian Ocean (FZ: Fracture Zone); b) Multibeam bathymetry of the Owen Basin, compiled with SRTM topography at 30 (Becker et al., 2009).

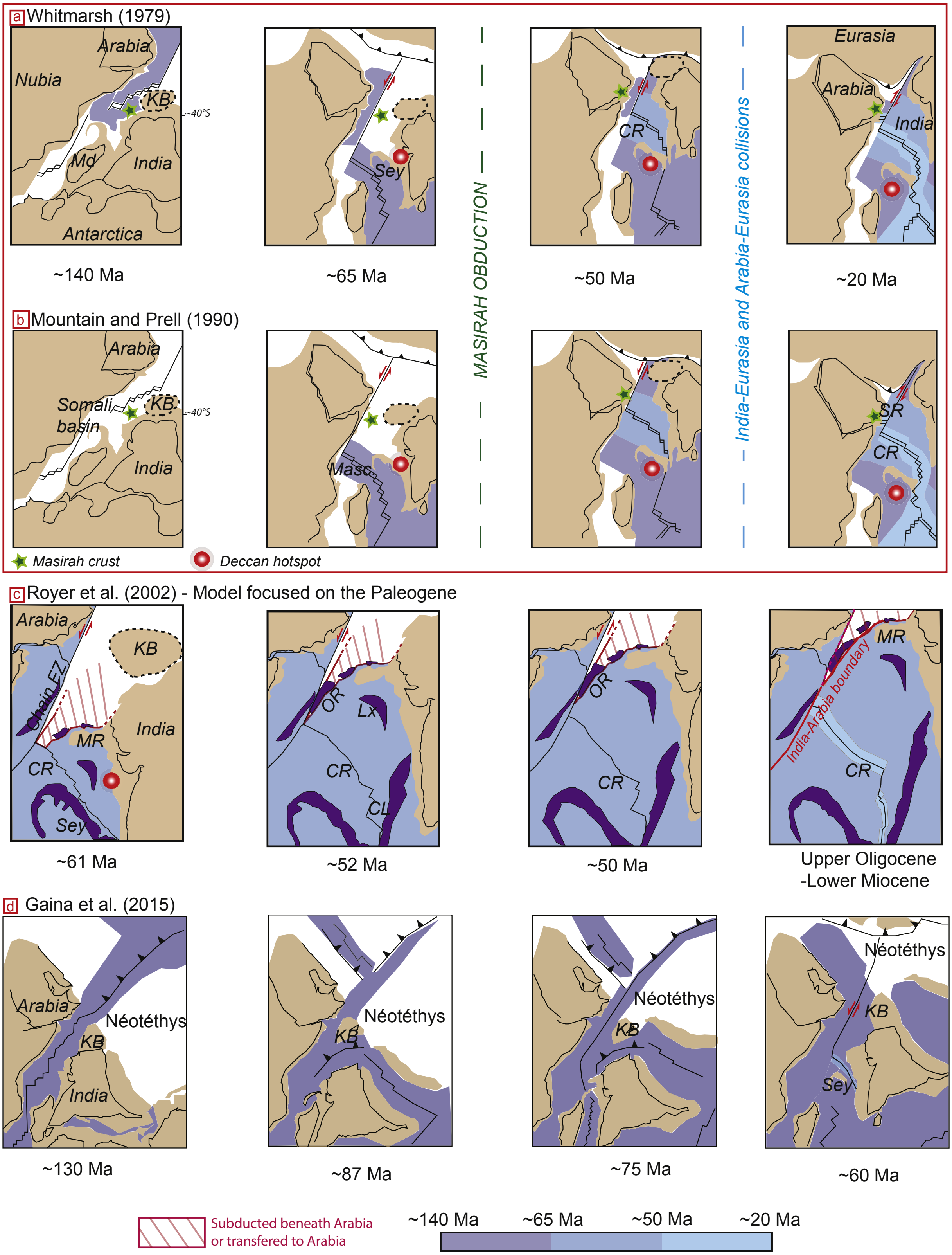


Fig. 2. Reconstructions of the India-Arabia relative motion since Tithonian times according to a) Whitmarsh (1979), b) Mountain and Prell (1990), c) Royer et al. (2002); and d) Gaina et al. (2015). The first reconstruction assumes that the India-Arabia plate boundary remained close to its present-day location since Late Cretaceous times, while the second one hypothesizes that the plate-boundary was located further west along the Oman margin during Paleogene times, and then jumped to its present-day location in the Early Miocene. By contrast, paleogeographic reconstructions (c) from Paleocene to Oligocene based on magnetic studies (Royer et al., 2002) imply a location of the Paleogene India-Arabia plate boundary within the Owen Basin. Hatched areas represent the piece of Indian lithosphere transferred to Arabia in Oligocene times. (d) Reconstructions of Gaina et al. (2015) highlighting a subduction zone between India and the Kabul block. The location of the India-Arabia plate boundary is similar to the model of Whitmarsh (1979). CL:Chagos Lacadive Ridge; CR: Carlsberg Ridge; KB: Kabul Block; Lx: Laxmi Ridge; Masc.: Mascarene spreading center; Md: Madagascar; MR: Murray Ridge; OR: Owen Ridge; Sey: Seychelles; SR: Sheba Ridge.

tectonic deformation. Seismic profiles are tied with drilling sites available in the Arabian Sea from DSDP and ODP legs (Shipboard Scientific Party, 1974, 1989).

3. Geological background

The Owen Basin is a ~200-km-wide basin located between the Oman margin and the Owen Ridge (Fig. 3). The Owen Ridge is a SSW-NNE trending ridge system composed of three major segments: the Southern Owen Ridge, the Central Owen Ridge, and the Qalhat Seamount (Fig. 1), which is a volcanic guyot (Fournier et al., 2011; Rodriguez et al., 2012). The sharp, SSW-NNE trending Oman margin is overlaid by ophiolites exposed at the location of Ras Madrakah, Ras Jib'sch, and the Island of Masirah (Fig. 3a). To the south of the Owen Basin, the Sharbithat Ridge marks the transition with the Sheba spreading ridge system (Fig. 3a). To the north, the Owen Basin enters in the Makran Subduction Zone.

3.1. Geological history of the Arabian Sea

The record of magnetic anomalies (Fig. 4) related to the onset of oceanic spreading at the Carlsberg Ridge began about 63 Ma ago (C28), in response to a transition in the Deccan hotspot activity following the episode of Seychelles–India breakup and the formation of the Gop Basin (Minshull et al., 2008; Yatheesh et al., 2009; Calvès et al., 2011; Armitage et al., 2011). A continuous record of magnetic field inversions revealing paleo-propagators is available from chrons 28 to 20 (i.e., from ~60 to 42 Ma) (Fig. 4; Chaubey et al., 1998, 2002; Dyment, 1998; Royer et al., 2002). The 15 cm yr^{-1} – 5 cm yr^{-1} slowdown of seafloor spreading at the Carlsberg Ridge first estimated at chron 24–25 (i.e. ~54–56 Ma; Patriat and Achache, 1984; Molnar and Stock, 2009), has recently been re-evaluated at ~47 Ma (Cande and Patriat, 2015; Matthews et al., 2016). A change of plate motion direction is still recorded at 56 Ma, but it is unrelated to the India-Eurasia collision (Cande and Patriat, 2015). A period of ultra-slow spreading well recorded in the Arabian Sea then occurred from chrons 18 to 7 (i.e., from ~40 to 24 Ma) (Fig. 4; Merkouriev et al., 1996). It is marked by drastic and abrupt changes (in the order of 30°) in the mean spreading direction starting at 40 Ma (Merkouriev et al., 1996). Another kinematic change is recorded between chron 7 and 6 (~24–20 Ma), which is synchronous with the beginning of seafloor spreading at the Sheba Ridge (Fournier et al., 2010).

Due to uncertainties in the configuration of Greater India prior to collision with Eurasia (Ali and Aitchison, 2008), and the number of subduction zones (Guillot and Replumaz, 2013), several interpretations of changes in Carlsberg Ridge spreading rate and direction are possible. The kinematic change recently corrected to 47 Ma (Cande and Patriat, 2015) is roughly synchronous with the record of ultra-high pressure metamorphism at Tso-Morari in the

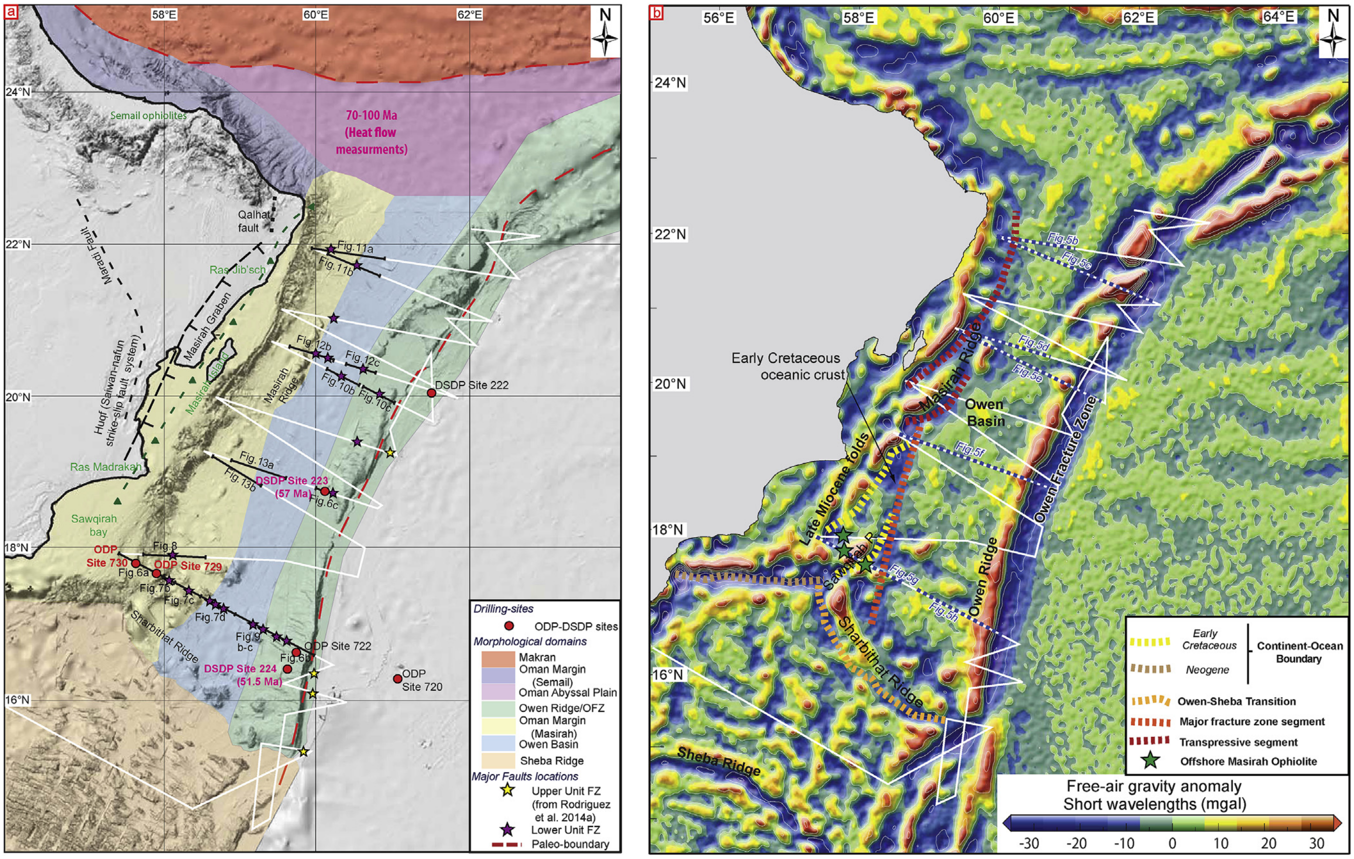


Fig. 3. a) Shaded bathymetric map of the Owen Basin. The Owen Basin area is divided in three morphological domains: the Oman margin, the Owen Basin, and the Owen Ridge. The Oman margin originates from Gondwanaland breakup in Late Jurassic times, and used to be a transform margin. The Owen Basin is a part of the oceanic lithosphere formed by the Carlsberg Ridge transferred to the Arabian Plate subsequently to a migration of the India-Arabia plate boundary during Oligocene. The Owen Ridge forms a series of bathymetric highs uplifted in Late Miocene. Stars represent the location of the major faults identified in this study; yellow stars represent faults active during the deposition of the Upper Unit, and purple stars represent faults possibly active during the deposition of the Lower Unit. Location of seismic profiles presented in this study. b) Free-air gravimetric map of the Owen Basin, with a Fourier pass-band showing wavelengths in the order of ~100 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

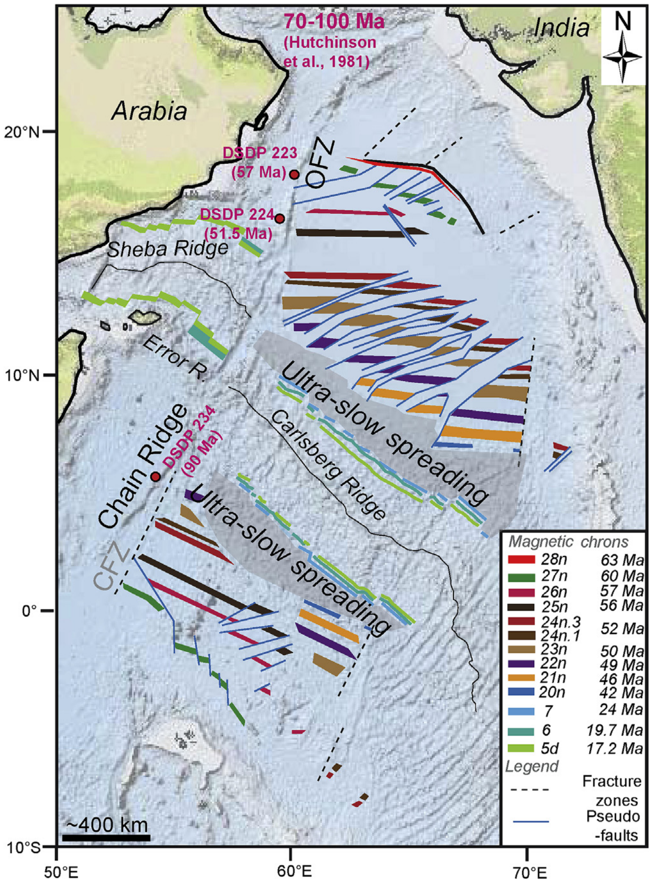


Fig. 4. Magnetic anomalies map over the Arabian Sea, modified from Merkouriev et al. (1996), Chaubey et al. (2002), and Royer et al. (2002), and ages of basement from deep-sea drillings. Ages of chrons are from Cande and Kent (1995). Note that the distance between 51.5 and 57 Ma-old basements in the Owen Basin is roughly the same as the distance between anomalies 24n3 and 25n in the Arabian Sea, i.e. ~250 km. CFZ: Chain Fracture Zone.

Himalayan Belt (de Sigoyer et al., 2000; Guillot et al., 2008) and may record the India-Eurasia collision. In this framework, the episode of ultra-slow spreading between 40 and 24 Ma may be the consequence of break-off events of the Neotethysian slabs beneath the Zagros (Agard et al., 2011) and the Himalayan belts (Khon and Parkinson, 2002).

An alternative scenario is to consider the ~47 Ma slowdown of spreading rate (Cande and Patriat, 2015) as the result of the collision of an island arc separated from Greater India (the Kohistan-Ladakh Arc) with Eurasia (Khan et al., 2009; Bouilhol et al., 2013; Gibbons et al., 2015). In the latter case, the ultra-slow spreading episode starting around 40 Ma would correspond to the beginning of the collision of the northern Indian passive margin with Eurasia. Finally, van Hinsbergen et al. (2012) proposed that collision between India and Eurasia only started around 25 Ma, earlier stages being related to collision of terranes detached from Greater India with Eurasia.

The change in spreading rate and direction starting at 24 Ma corresponds to a global plate reorganization event (Patriat et al., 2008), whose interpretation depends on the paleogeographic reconstructions mentioned above. This 24 Ma plate reorganization event may have been either triggered by Arabia-Eurasia collision (McQuarrie and van Hinsbergen, 2013) or a major change at the India-Eurasia collision (slab break-off or final step of the collision; van Hinsbergen et al., 2012).

Subsequent to the ~47 Ma slowdown of Carlsberg spreading rates (Cande and Patriat, 2015), the India-Arabia relative motion remained sinistral (over ~1000 km of shear offset) prior to the opening of the Gulf of Aden, India traveling fast towards Eurasia while Arabia was still attached to Africa (Besse and Courtillot, 1988; Royer et al., 2002). The rifting of the Gulf of Aden began around 33 Ma (Bosworth et al., 2005; Leroy et al., 2010), and was probably enhanced by the development of the Afar hotspot at ~30 Ma (Bellahsen et al., 2003).

3.2. Previous reconstructions of the India-Arabia relative motion

Because the identification of magnetic anomalies recorded over the Owen and North Somali Basins is ambiguous, the age and the origin of the lithosphere in the Owen Basin and the Makran subduction zone, together with the precise amount of relative motion accommodated by the India-Arabia boundary during the Paleogene, remain debated (Edwards et al., 2000; Smith et al., 2013). Thermal flux analysis (Hutchison et al., 1981) concluded that an oceanic lithosphere of Upper Cretaceous age was lying in the northernmost part of the Owen Basin at the entrance of the Makran subduction zone (Fig. 4, Hutchison et al., 1981).

3.2.1. Reconstructions of Whitmarsh (1979)

First paleogeographic reconstructions from Whitmarsh (1979) suggest that the India-Arabia plate boundary remained close to its present-day location since transform motion initiated between India and Arabia ~90 Ma (Fig. 2a). Part of the Owen Basin may thus share a common origin with its conjugate North Somali Basin (Fig. 1). The North Somali Basin used to be connected with the West Somali Basin by a set of transform faults referred as the Dhow-VLCC-ARS complex (Cochran, 1988). The North Somali Basin appears to be the third of a series of oceanic basins separated by long transform faults (>2000 km for the Davie transform) created during Mesozoic relative motion between West and East Gondwanaland (Cochran, 1988; Gaina et al., 2015). However, the Paleocene age of the oldest sediments drilled at the Owen Ridge (Figs. 3 and 4) (Shipboard Scientific Party et al., 1989; Mountain and Prell, 1990) and depth to basement do not support the Jurassic-Early Cretaceous age inferred by comparison with the East-African margin (Whitmarsh, 1979).

3.2.2. Reconstructions of Mountain and Prell (1990)

In this second model (Fig. 2b), the India-Arabia plate boundary initially laid ~200 km west of its present-day position, and shaped the East Oman margin, which is considered as a fossil transform margin (Mountain and Prell, 1990). In the meanwhile, the Mascarene Basin opened (~65–90 Ma; Bernard and Munschy, 2000) and the Carlsberg Ridge developed (since ~63 Ma) (Fig. 2b). The India-Arabia plate boundary then jumped to its present-day position about 20 Ma ago, when seafloor spreading started at the Sheba Ridge. This inferred jump of the India-Arabia plate-boundary marks the deactivation of strike-slip motion along the Oman margin, and is supposed to trigger the Owen Ridge uplift (Mountain and Prell, 1990). This model implies a Late Cretaceous-Early Paleocene age for the Owen Basin (age between 51 and 57 Ma supported by drillings, Mountain and Prell, 1990), formed at a spreading center subsequently subducted in the Makran subduction zone. The reconstruction of Mountain and Prell (1990) implies that the crust of the Masirah Ophiolites located on the Oman Margin would be Late Cretaceous in age. However, subsequent works (see section 3.3) showed that the Masirah Ophiolites are composed of Tithonian oceanic crust (Peters and Mercolli, 1998) and that the Owen Ridge uplifted in Late Miocene without any major migration of the India-Arabia boundary (Rodriguez et al., 2014a, b).

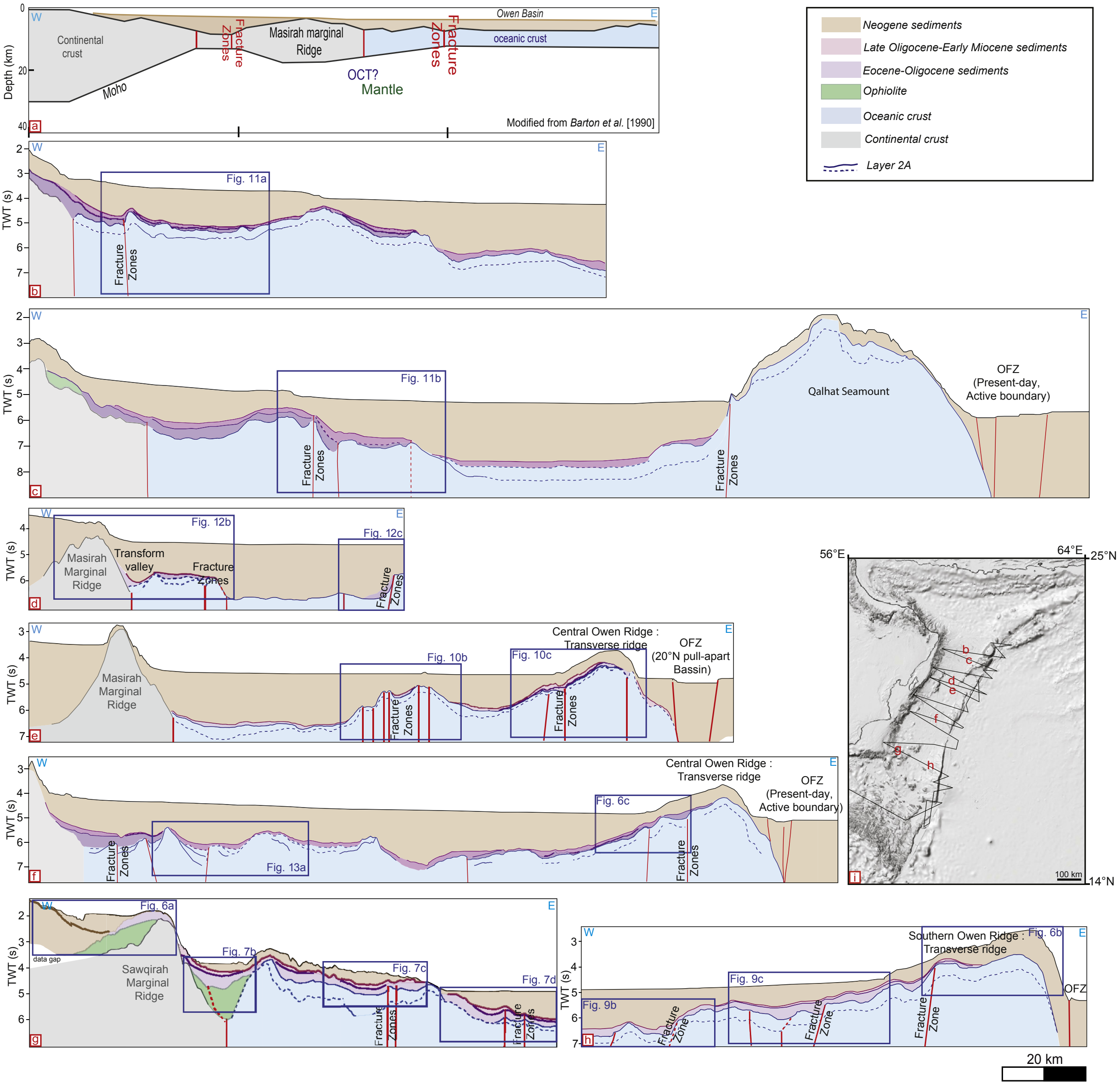


Fig. 5. a) Deep-structure of the Owen Basin deduced from wide-angle seismic data (Barton et al., 1990), see Fig. 3a for location. OCT: inferred ocean-continent transition. b) to h): Simplified picking of large scale seismic profiles, and locations of close-views of seismic profiles displayed hereafter. i) Location of seismic profiles, same as Fig. 3.

3.2.3. *Reconstructions of Royer et al. (2002).*

Reconstructions by Royer et al. (2002) are supported by the record of magnetic anomalies over the Arabian Sea (Figs. 2c and 4). In contrast with those by Whitmarsh (1979), these reconstructions show that the present-day OFZ cannot be the conjugate of the Chain Fracture Zone (India–Somalia boundary) prior to the opening of the Gulf of Aden. This is in agreement with the Pliocene age of the OFZ, which is a much younger generation of the India-Arabia plate boundary than the Chain Fracture Zone (Fournier et al., 2008, 2011; Rodriguez et al., 2011, 2013b, 2014b). According to Royer et al. (2002), the conjugate of the Chain Fracture Zone must cut obliquely through the Owen Basin. Indeed, considering the India-Arabia plate boundary at its present-day location for the entire Cenozoic time span would imply a major subduction zone (i.e., India beneath Arabia) in the area of the Murray Ridge between chrons 27 and 20. Subduction zone is not supported by seismic profiles or potential field data (Edwards et al., 2000, 2008; Calvès et al., 2011), but may be suggested by the supra-subduction zone geochemical signature of mantle peridotites at the Murray Ridge (Burgath et al., 2002).

3.2.4. *Reconstructions of Gaina et al. (2015)*

Gaina et al. (2015) proposed a location of the India-Arabia plate boundary similar to Whitmarsh's model (Fig. 2d). Their reconstruction infers a subduction zones in the Late Cretaceous- Early Paleocene (Fig. 2d) to account for ophiolites in Eastern Pakistan, whose emplacement was related to the dynamics of the India-Arabia motion. A fossil slab is inferred from tomography of the mantle. They further attempted to model some of the magnetic anomalies recorded in the Owen Basin, leading to a scenario of

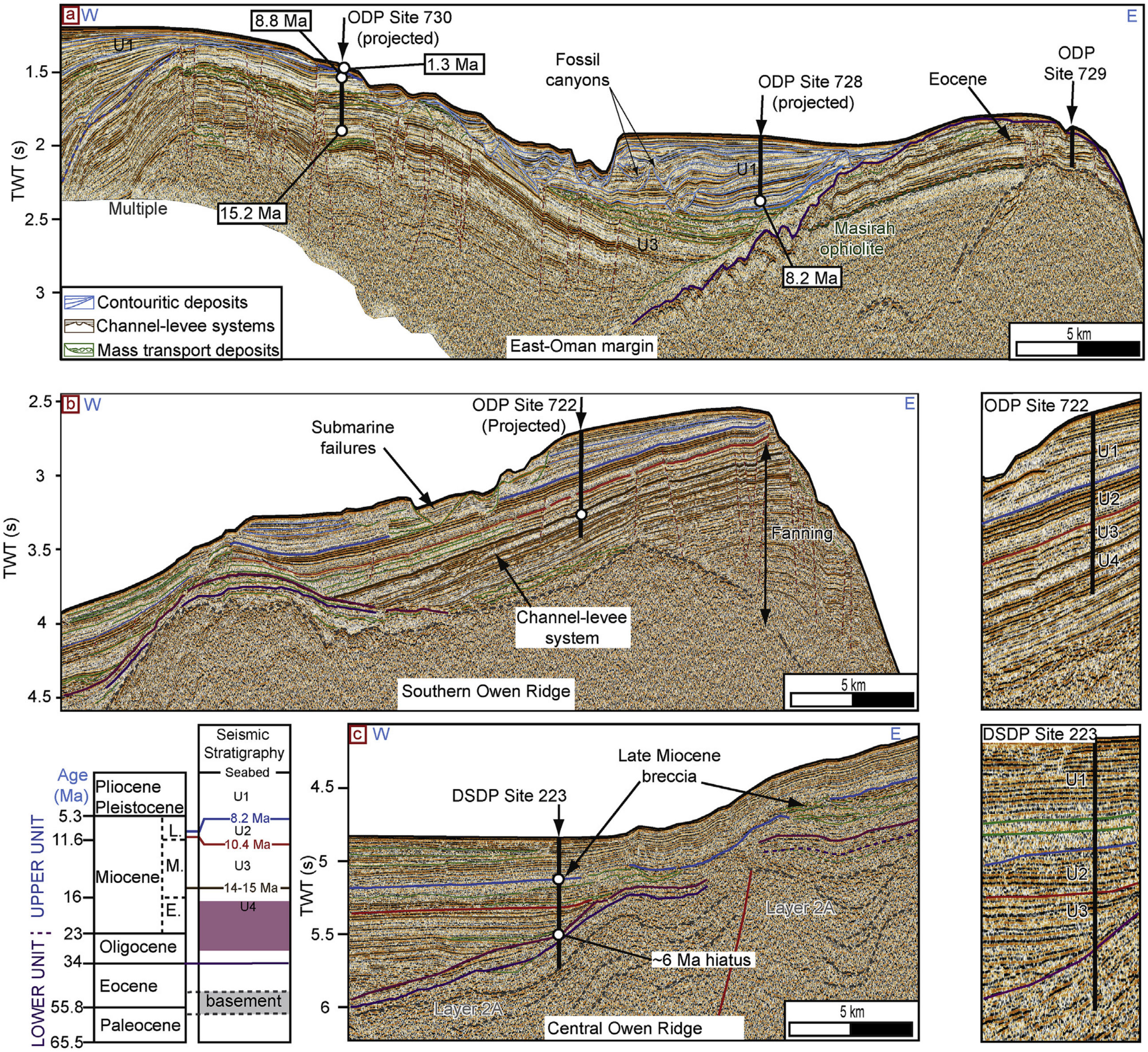


Fig. 6. Seismic profiles crossing a) the Oman Margin, b) the Southern Owen Ridge, c) the Central Owen Ridge (see Fig. 3 for location). Insets show close-views of the seismic profiles in the area of deep-sea drilling (ODP and DSDP) locations. The stratigraphic framework is summarized on the lower left hand corner. The Owen Basin stratigraphy is divided in two major units: the Lower Unit (Paleocene-Uppermost Oligocene) and the Upper Unit (Early Miocene to Present). The Upper Unit itself is divided in 4 sub-units relative to Miocene sedimentary and tectonic events described in detail in Rodriguez et al., 2014a. Profile a) displays a Late Miocene anticline that is overlapped by an 8 Ma-old contouritic drift. An Upper Eocene unconformity and Masirah Ophiolites are also observed. Profile b) shows a W–E seismic profile crossing the Southern Owen Ridge at the location of ODP Site 722. The basement, drilled at DSDP sites, consists of 51–57 Ma-old basaltic lamprophyres. A major unconformity is observed on the western side of the ridge, where Early Miocene turbidite deposits (sub-unit 4) onlap Oligocene deposits drilled at DSDP Site 224. The top of sub-unit 4 corresponds to a pelagic layer previously interpreted as the facies transition related to the ridge uplift and ends at 14 Ma. The overlying sub-unit 2 and 3are composed of pelagic chalk and ends at 8.2 Ma. Sub-unit 1 is composed of pelagic ooze and chalk, and dissected by landslides. c) shows an W–E seismic profile crossing the Central Owen Ridge. A major unconformity, corresponding to a hiatus of 6 Ma, has been drilled at DSDP Site 223, together with Upper Miocene mass transport deposits. Same horizontal scale for all profiles.

NW–SE opening between 84 and 74 Ma. In this framework, no major migration of the India-Arabia plate boundary occurred since ~90 Ma.

3.3. *The Oman margin*

3.3.1. *The Masirah obduction*

Eocene limestone deposits unconformably overly the Masirah ophiolites (Immenhauser, 1996), whereas Upper Cretaceous (Maastrichtian) formations are folded in the Batain Plain to the north-east of Oman (Schreurs and Immenhauser, 1999). This set of observations indicates a Late Cretaceous-Early Paleocene age of the obduction of the Masirah ophiolites over the East-Oman continental margin (Immenhauser et al., 2000), distinct from the obduction of the Semail ophiolites (remnants of the Neotethys Ocean) in Campanian times (Searle and Cox, 1999). Paleomagnetic studies show that the accretion of the Masirah oceanic crust occurred at latitudes ~30–50°S (Fig. 2) (Gnos and Perrin, 1997) during Tithonian-Berriasian (~140–145 Ma) according to radiometric ages (Peters and Mercolli, 1998). The oceanic lithosphere exposed at Masirah Island thus corresponds to a piece of the Indian Ocean formed during the very early stages of Gondwanaland breakup and the opening of the Somali Basin (Fig. 2a and b; Peters and Mercolli, 1998). A large northward motion of the Masirah oceanic crust is therefore necessary prior to the Masirah obduction, which lead Gnos and Perrin (1997) and Gnos et al. (1997) to assume that Masirah ophiolitic body used to be a part of the Indian plate. Some reconstructions however highlight the possibility that the Masirah ophiolites derived from a proto-Owen Basin attached to Arabia (Gaina et al., 2015).

3.3.2. Strike-slip motion along the Oman margin

A past location of the India-Arabia plate boundary close to the Oman Margin would have implied significant strike-slip tectonics during Cretaceous. Several left-lateral strike-slip features active during Santonian-Campanian times are observed, including the Sawain-Nafun Fault System (Fig. 3a) in the Huqf desert (Shackleton and Ries, 1990; Pilcher et al., 1996), the Maradi Fault Zone (Filbrandt et al., 2006) and the Jebel Ja'alan-Qalhat Fault System in the north-east of Oman (Filbrandt et al., 1990). Offshore, Mountain and Prell (1990) hypothesized the presence of flower-structures on low-quality seismic lines collected on the Oman Platform (Sawqirah Bay), subsequently referred as the Masirah Transform in the literature (Loosveld et al., 1996). The deep structure of the Owen Basin basement revealed by seismic refraction data (Fig. 5a, Barton et al., 1990) displays juxtaposed blocks with abrupt changes in crustal thickness (Fig. 5a), a feature commonly observed along transform margins. The width of the continental margin is less than 100 km (Fig. 5a). Barton et al. (1990) proposed that the Masirah obduction initiated at a Late Cretaceous transform boundary. A Late Cretaceous strike-slip activity is also reported along the Somali margin from industrial data (Bosselini, 1986).

The geological record does not document whether strike-slip tectonics was continuous along eastern Africa (off Somalia and Arabia) or whether it was interrupted (similar to the Cascadia subduction between the San Andreas and Queen Charlotte transform boundaries between the North America and Pacific plates).

3.3.3. The Owen Ridge uplift

A major, ~2000 m episode of seafloor uplift of the Oman margin, related to the development of broad anticlines, started at 8.2–8.8 Ma according to ties with ODP Site 730 (Fig. 6a, Rodriguez et al., 2014a). Consistently, the uplift of the Owen Ridge is marked by a 8-9 Myr-old erosive surface (dated at ODP Site 722) corresponding to the onset of large submarine failures (Fig. 6b) and a coeval fanning sequence of Indus turbidites (Rodriguez et al., 2012, 2013a, 2014a). Consequently, the Owen Ridge did not act as a major topographic barrier for Indus sedimentation during most of the Miocene period.

Earlier works (Whitmarsh et al., 1974; Whitmarsh, 1979) proposed the uplift of the Owen Ridge was related to a regional angular unconformity between Oligocene pelagic chalk and Early Miocene turbidites drilled at DSDP Site 223 at the western side of the Owen Ridge (Figs. 4 and 6c). Mountain and Prell (1990) subsequently suggested a depositional origin for this angular unconformity, i.e., a simple transition from Oligocene pelagics to Early Miocene turbidites as Indus turbidites flooded the Owen Basin. Therefore, this unconformity does not mark the uplift of the Owen Ridge (Mountain and Prell, 1990; Rodriguez et al., 2014a, 2014b).

The uplift of the Owen Ridge took place in the framework of a general kinematic change identified throughout the Indian Ocean in the Late Miocene (Wiens et al., 1985; Chamot-Rooke et al., 1993; Henstock and Minshull, 2004; DeMets et al., 2005; Merkouriev and DeMets, 2006; Delescluse and Chamot-Rooke, 2007; Delescluse et al., 2008; Molnar and Stock, 2009; Bull et al., 2010; Rodriguez et al., 2014a, 2014b).

4. Stratigraphic framework

The Arabian Sea was drilled during DSDP 23 and ODP 117 legs (Figs. 1, 3 and 4) (Shipboard Scientific Party, 1974, 1989). The Indus abyssal plain mainly is mainly floored by turbidites alternating with pelagic deposits, with well-developed channel-levee systems since the Middle Miocene (ODP Site 720 and DSDP Site 222; Shipboard Scientific Party, 1974, 1989; Clift et al., 2001, 2002).

Only one drilling site (DSDP Site 223, location in Figs. 3 and 4) is available in the Owen Basin at the latitude of the central segment of the Owen Ridge. There, the basement is composed of trachybasaltic lamprophyres. Several stacked lava flows (belonging to layer IIA) are observed on seismic lines (Figs. 6–13) in the oceanic parts of the Owen Basin. Four drilling sites are located on the southern segment of the Owen Ridge, including ODP Site 722 and DSDP Site 224 (the latter penetrating down to the basement; see Figs. 3 and 4 for location). Unfortunately, submarine landslides (Rodriguez et al., 2012, 2013a) make difficult any reliable detailed correlation of the seismic stratigraphy with that of the Owen Basin.

Eight ODP drilling sites are available on the Oman Margin at the latitude of the Sharbithat Ridge, the deepest reaching the Middle Miocene (ODP Site 730; see Figs. 3 and 4 for location). ODP Site 729 is located off the Sawqirah Bay and sampled a major unconformity between Eocene and Pleistocene sediments (Fig. 6a). Large-scale stratigraphic correlations are difficult because of the steep slopes of the margin, however some events can be clearly recognized on the basis of erosion surface and unconformities that can be correlated from the margin to the basin. The stratigraphic framework of the Owen Basin is divided in two major units according to differences in their seismic character and a regional angular unconformity.

4.1. Lower unit (Paleocene to Late Oligocene)

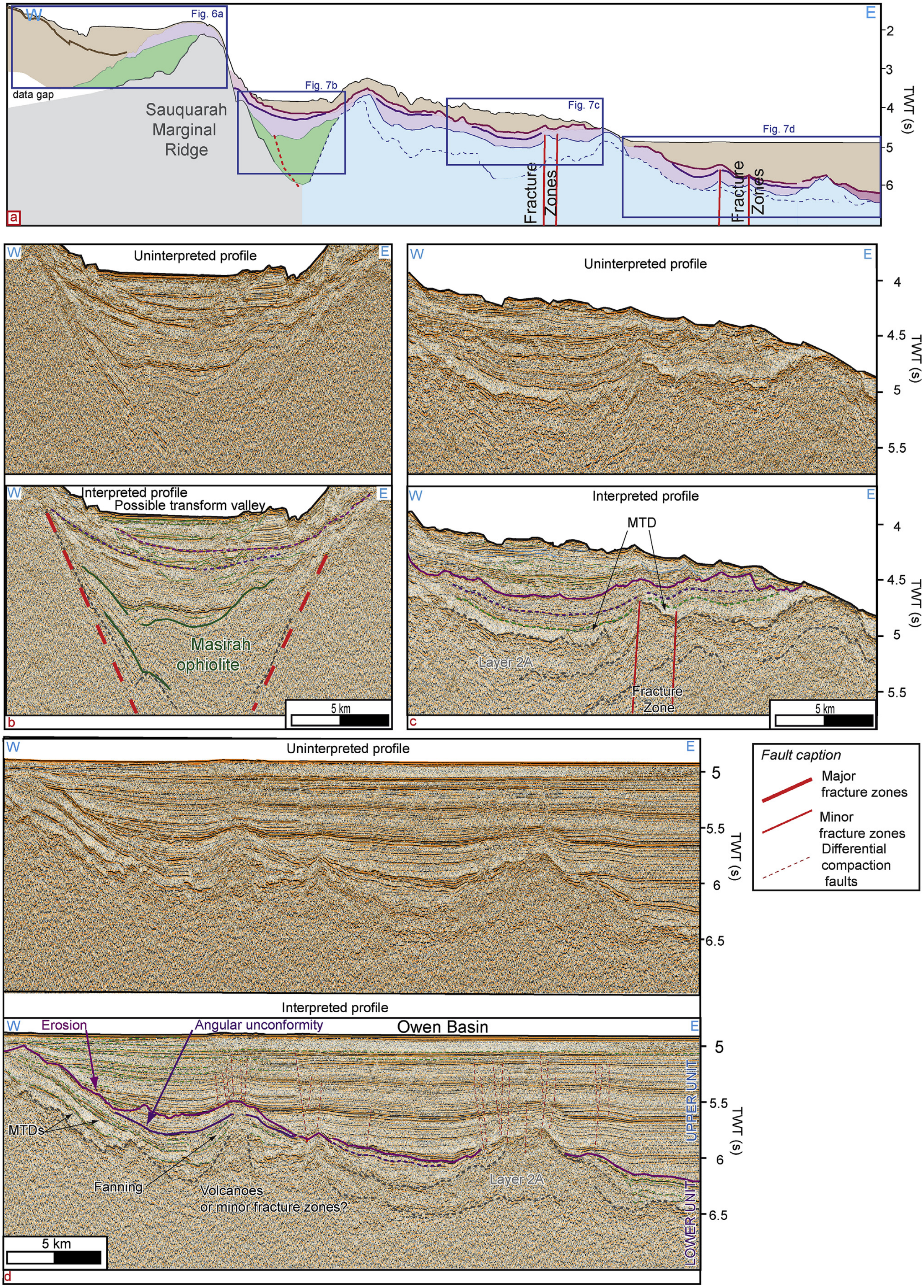
A Paleocene to Oligocene unit, composed of nanno-chalk and claystone, was drilled at DSDP Sites 223 and 224 and forms the pelagic blanket of the Owen Basin substratum (Figs. 6–13; Shipboard Scientific Party, 1974). At DSDP Site 223, on the western flank of the central Owen Ridge (Fig. 6c), the thickness of the Lower Unit is ~220 m, the Oligocene section representing only ~50 m of sediments (Shipboard Scientific Party, 1974).

Mass Transport Deposits (MTD hereafter) are characterized by a typical chaotic to transparent seismic facies and locally sampled at DSDP Site 224. Numerous MTD are observed at the edge of basement flanks (especially at the latitude of the Southern Owen Ridge; Figs. 6b and 9), and produce large thickness variations within the Lower Unit.

The thickness of the Lower Unit is larger in the vicinity of the Oman margin (Fig. 7d), which probably reflects the terrigenous input from the margin. On the platform, Eocene limestones drilled at ODP Site 729 (Figs. 4 and 6a) indicate a shallow-water context of deposition and are very similar in nature with the limestones overlying the Masirah Ophiolites on land (Peters et al., 1995). An angular unconformity (picked in dark purple) is identified within the Lower Unit all along the edge of the east Oman margin. It laterally merges with the younger regional unconformity in the Owen Basin that seals the Lower Unit (picked in light purple (in the web version)) (Figs. 7d, 8 and 11–13).

4.2. Late Oligocene-Early Miocene Angular unconformity

Late Oligocene turbidites drilled between two basement highs at the southern ridge indicates the time the Indus deposits started to flood the Owen Basin (DSDP Site 224, Shipboard Scientific Party, 1974). The biostratigraphic dating of the turbidite layer


a
W
E
Fig. 6a
Fig. 7b
Fig. 7c
Fig. 7d
data gap
Sauquarah Marginal Ridge
Fracture Zones
Fracture Zones
TWT (s)
2
3
4
5
6
b
Uninterpreted profile
Interpreted profile
Possible transform valley
Masirah ophiolite
5 km
c
Uninterpreted profile
Interpreted profile
MTD
Layer 2A
Fracture Zone
5 km
4
4.5
5
5.5
TWT (s)
d
Uninterpreted profile
Interpreted profile
Owen Basin
Erosion
Angular unconformity
MTDs
Fanning
Volcanoes or minor fracture zones?
Layer 2A
UPPER UNIT
LOWER UNIT
5 km
5
5.5
6
6.5
TWT (s)
Fault caption
Major fracture zones
Minor fracture zones
Differential compaction faults

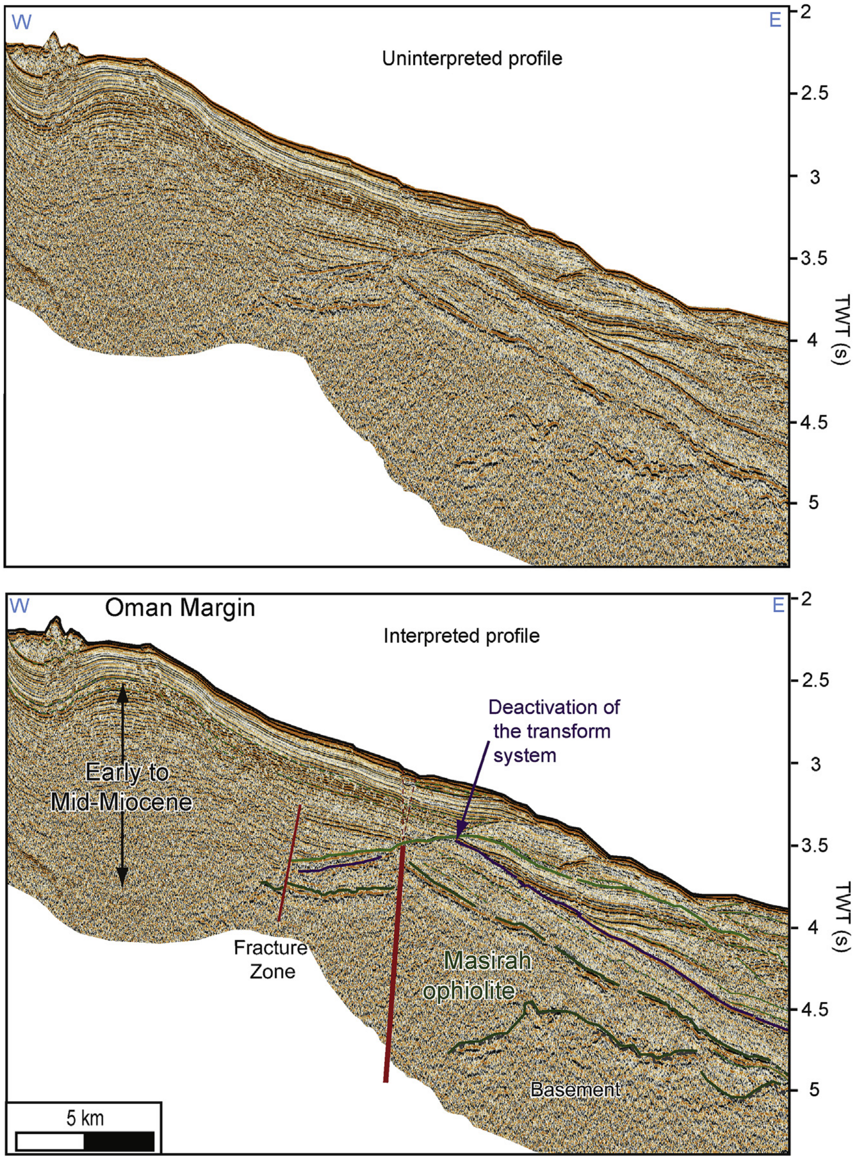


Fig. 8. Seismic profile shows the Masirah ophiolitic body offset by a fracture zone; and the Late Miocene episode of folding.

immediately overlying the unconformity at DSDP Sites 223 and 224 gives ages of 14 and 19.6 Ma, respectively (Fig. 6, Shipboard Scientific Party, 1974). It highlights the strong diachronicity of the unconformity over the Owen Basin (Latest Oligocene to Early Middle Miocene). Along the Oman margin, the Lower Unit is incised by an erosion surface merging downslope with the angular unconformity described above (Fig. 7d). The erosion surface is characterized by truncated reflectors and V-shaped incisions typical of erosion by turbidite canyons (Fig. 7d). This surface of erosion was drilled at ODP Sites 726 and 729 (Shipboard Scientific Party et al., 1989), where it cuts into Eocene limestones and it is sealed by Pleistocene deposits (Fig. 6a). The seismic profile displayed in Fig. 6a crossing the Oman platform shows that reflectors older than 15 Ma (according to correlation with ODP Site 730) terminate as onlaps on the erosion surface. It is difficult to correlate this erosion surface to stratigraphic events described on land in the absence of precise dating by drillings. The fact it merges laterally with the Late Oligocene-Early Miocene unconformity drilled in the Owen Basin (DSDP Site 223) suggests that the erosion surface may correspond to the major emersion of the Arabian continent recorded in the upper part of the Dhofar group (Mughsayl Formation, ~19 Ma), that marks the end of the synrift phase in the Gulf of Aden (Platel et Roger et al., 1989; Roger et al., 1989; Carbon, 1996; Lepvrier et al., 2002; Huchon and Khanbari, 2003; Fournier et al., 2004;

Fig. 7. a) Simplified line drawing of the seismic profile detailed in close-views b–d; b–e) Seismic profiles acquired in the southern part of the Oman margin (see Fig. 3 for location, and Fig. 5 for a general view). Seismic profile b) shows the structure of the edge of the Sawqirah Ridge, which looks similar to a transform valley. A chaotic body is interpreted as a fragment of the Masirah Ophiolite, but it may also be a large MTD. Seismic profile c) shows abrupt and sharp offsets of sediments composing the Lower Unit interpreted as fracture zone traces. The erosive surface sealing the Lower Unit is also observed. Seismic profile d) shows an angular unconformity (picked in dark purple) related to a tectonic episode. The Upper Unit is composed of turbidites and MTDs and is affected by differential compaction structures localized at the edge of basement high, interpreted either as small fracture zone offsets or volcanoes. Same horizontal scale for all profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

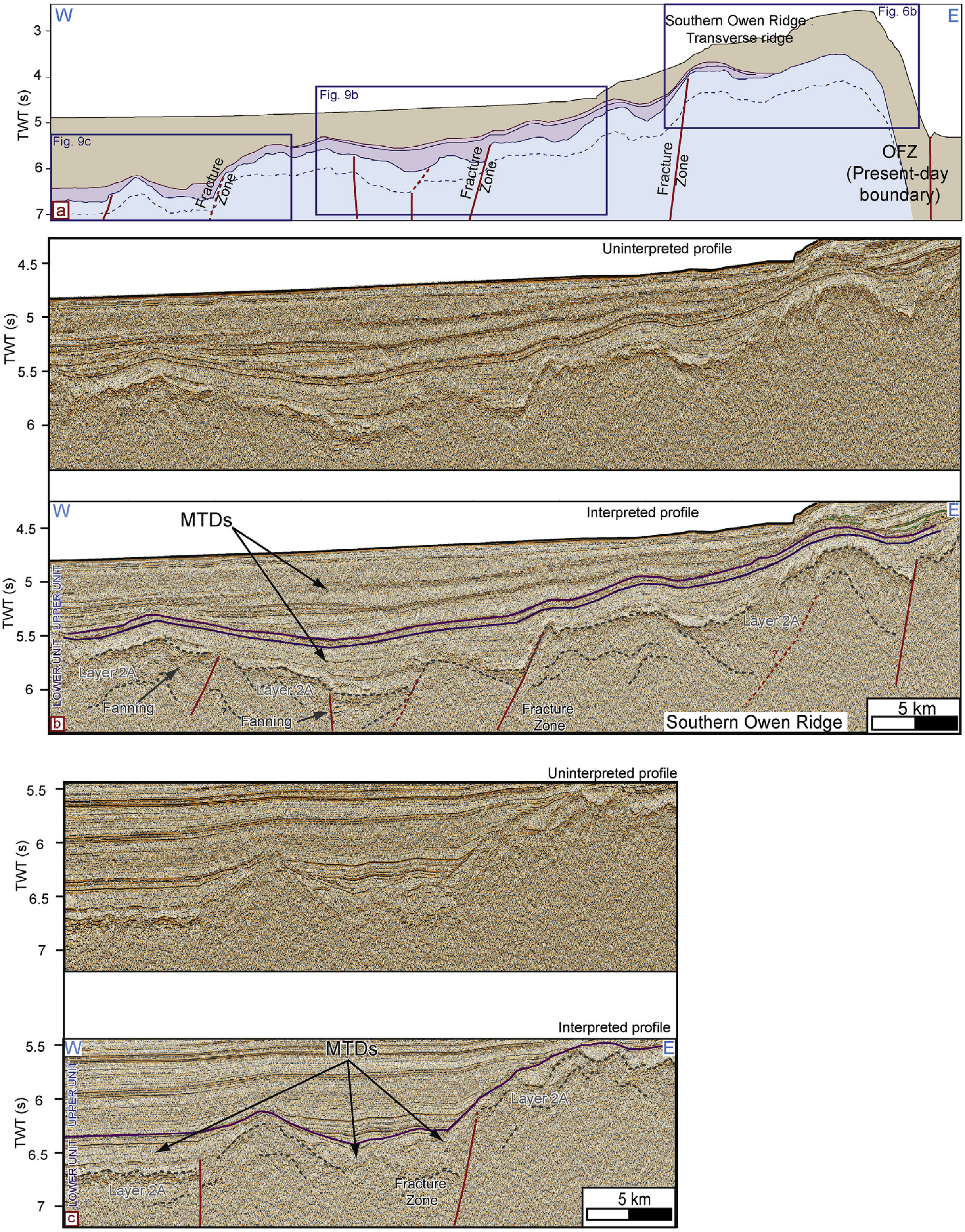


Fig. 9. a) Simplified line-drawing of a seismic line crossing the southern Owen Ridge. Seismic Profiles b) and c) show the western side of the Owen Ridge, and abrupt basement offsets representing potential remnants of a Paleocene-Eocene fracture zones (recorded by the fanning configuration of lavas in layer 2A). MTDs: mass transport deposits. See Fig. 3 for location. Same horizontal scale for all profiles.

Bellahsen et al., 2006; Leroy et al., 2010; Robinet et al., 2013).

4.3. *Upper unit (Latest Oligocene to present)*

Well-developed channel-levee systems, typical of turbidite sedimentation, are observed within the Upper Unit around the

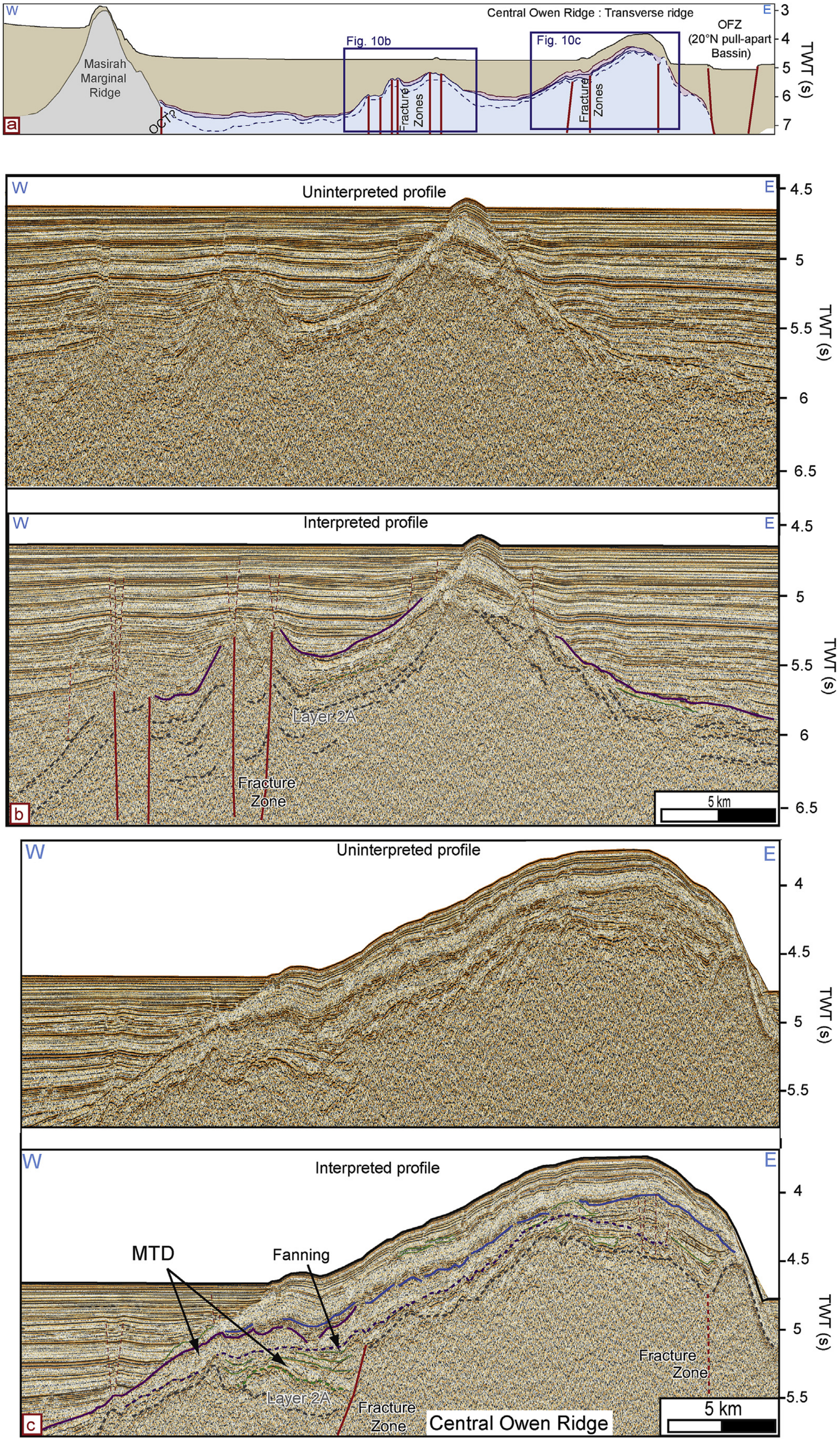


Fig. 10. a) Simplified line-drawing of a seismic profile crossing the entire Owen Basin at the latitude of the Central Owen Ridge. Seismic profiles b) and c) show abrupt and sharp sub-vertical offsets interpreted as traces of a Paleogene fracture zone close to the present-day central Owen Ridge. Profile c) highlights a particular fanning configuration in the MTDs coming from the central ridge. See Fig. 3 for location. Same horizontal scale for all profiles.

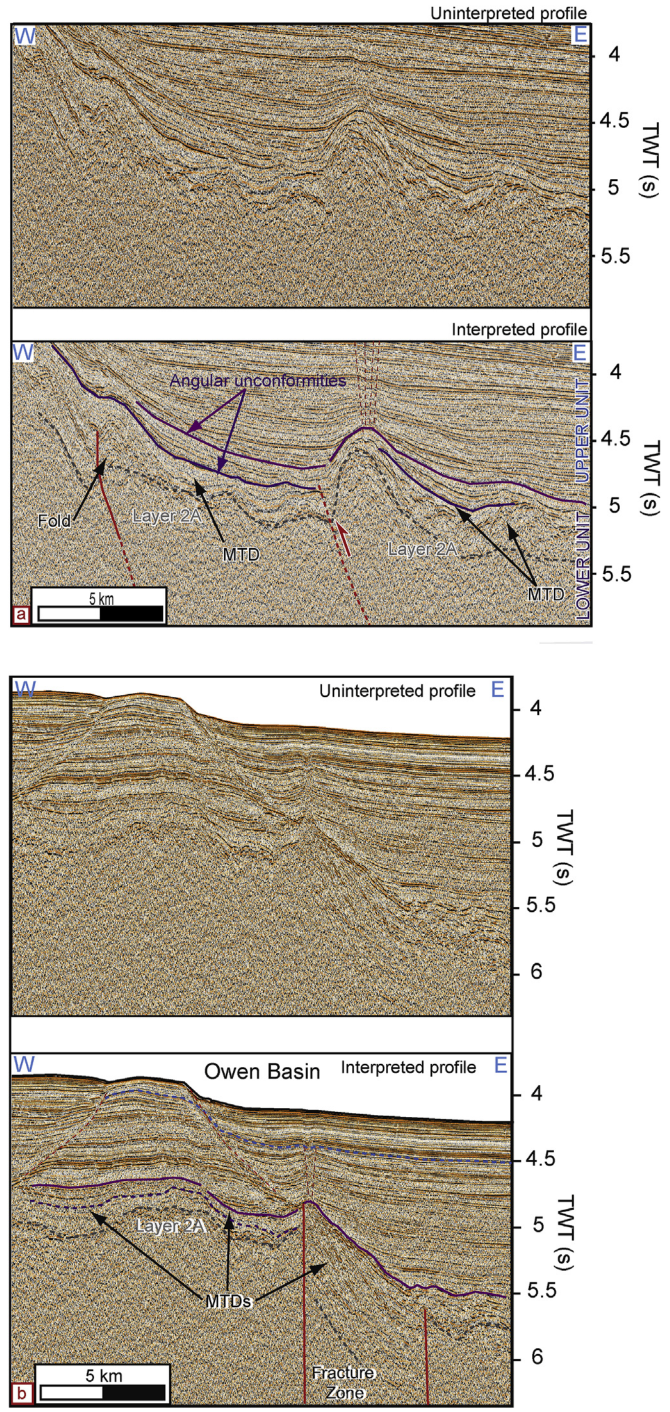


Fig. 11. Seismic profiles crossing the edge of the section of the north eastern Oman margin oriented 15°NE (see Fig. 3 for location). Profile a) shows a fold rooted on a reverse fault, indicating an Oligocene episode of compression. Profile b) shows the abrupt tilt of the Lower Unit sediments towards the Owen Basin, along a vertical fault interpreted as a trace of a fracture zone. Same horizontal scale for all profiles.

latitude of 20°N in the Owen Basin (Fig. 12). As evidenced by channel-levee systems that are still well expressed on the seafloor of the Owen Basin (Rodriguez et al., 2011), the topographic low at the latitude of 20°N used to be a major gateway with the Indus deep-sea fan. This gateway was cut off in the Pliocene (~3 Ma) when the OFZ settled as a topographic barrier forming deep pull-apart basins (Figs. 1 and 5) (Fournier et al., 2011; Rodriguez et al., 2011, 2013b, 2014b). It is consistent with Indus turbidites recognized in the Oman abyssal plain prior to the uplift of the Murray Ridge (Gaedicke et al., 2002a,b; Ellouz Zimmerman et al., 2007). Most of the channel-levee complexes observed in the Owen Basin thus originate from the Indus fan (Fig. 12). The connection between the Indus Fan and the Owen Basin was enhanced by the increase in the Indus sedimentation since the Early-Middle Miocene observed by Clift et al. (2001) and Clift and Gaedicke (2002) in response to the Himalayan uplift and the onset of the Asian monsoon.

Drillings of the Miocene interval at the Oman margin (Fig. 6a; ODP Sites 728 and 730) mainly document pelagic chalk sequences separated by slump deposits and thin (<10 m) calcareous turbidites (Shipboard Scientific Party et al., 1989). These deposits were mostly trapped by the Masirah Ridge (described in Section 5) excepted in areas where the Masirah Ridge was low.

The Upper Unit is also characterized by large MTDs interfingered between turbidite and pelagic deposits (Figs. 6, 7 and 9). The distribution of MTDs within the Upper Unit in the Owen Basin varies according to the source of the sedimentary material, namely the Oman Margin or the Owen Ridge. The most voluminous MTDs, as shown in Fig. 9, comes from the southern segment of the Owen Ridge since the Late Miocene (Rodriguez et al., 2012, 2014a). Large MTDs coming from the Oman Margin are widely distributed in the Owen Basin (Fig. 7), except at the latitude of the Masirah Ridge, where they are trapped (Fig. 5d, e and 12). Contouritic drift architectures, indicating interaction between sediment and deep-sea currents (Faugères et al., 1999; Faugères and Mulder, 2011; Rebesco et al., 2014), are also observed within the Upper Unit along the Oman Margin (e.g., Fig. 6a). Stratigraphic details of the Upper Unit (signification of subunits U1–U4) can be found in Rodriguez et al. (2014a).

5. Tectonics of the owen basin and its borders

5.1. *Diagnostic features of fracture zones on seismic profiles*

In this section, we describe the structure of the Owen Basin and its borders, with particular emphasis on structures that may be good candidates for the fossil India-Arabia plate boundary. We discriminate whether fossil structures identified on seismic profiles result from the transform boundary activity or other processes on the basis of the criteria below. At the lithospheric scale, transform boundaries form vertical planes juxtaposing lithospheric plates with more or less pronounced differences in age and density. Transform boundaries are commonly localized within narrow and elongated valleys, bounded on at least one side by an asymmetric ridge of flexural origin, with a steep slope facing the valley and a more gentle slope outwards (Fig. 14). Although the slopes created by transform reliefs are among the steepest encountered on Earth, they are far from strictly vertical because of erosion related to submarine landslides (Basile and Allemand, 2002), sometimes observed at the edge of steep transform margin slopes. Discriminating between fracture zones with small vertical offsets and small fossil volcanoes is sometimes difficult within the oceanic basement. Continent-ocean transforms commonly display uplifted reliefs referred as marginal ridges or terraces (Fig. 14). The origin of marginal ridges or terraces is not well understood and can result from a complex pattern of transpressive deformation along a transform margin and/or from erosive processes controlled by the transform fault (as exemplified by studies on the Queen Charlotte Transform; Barrie et al., 2013; Harris et al., 2014; Rohr, 2015; Tréhu et al., 2015). In areas of turbidite sedimentation, strike-slip faults generally produce positive or negative flower-structures, either in response to transpressive or transtensive stress regime. Basement highs related to fractures control the pattern of differential

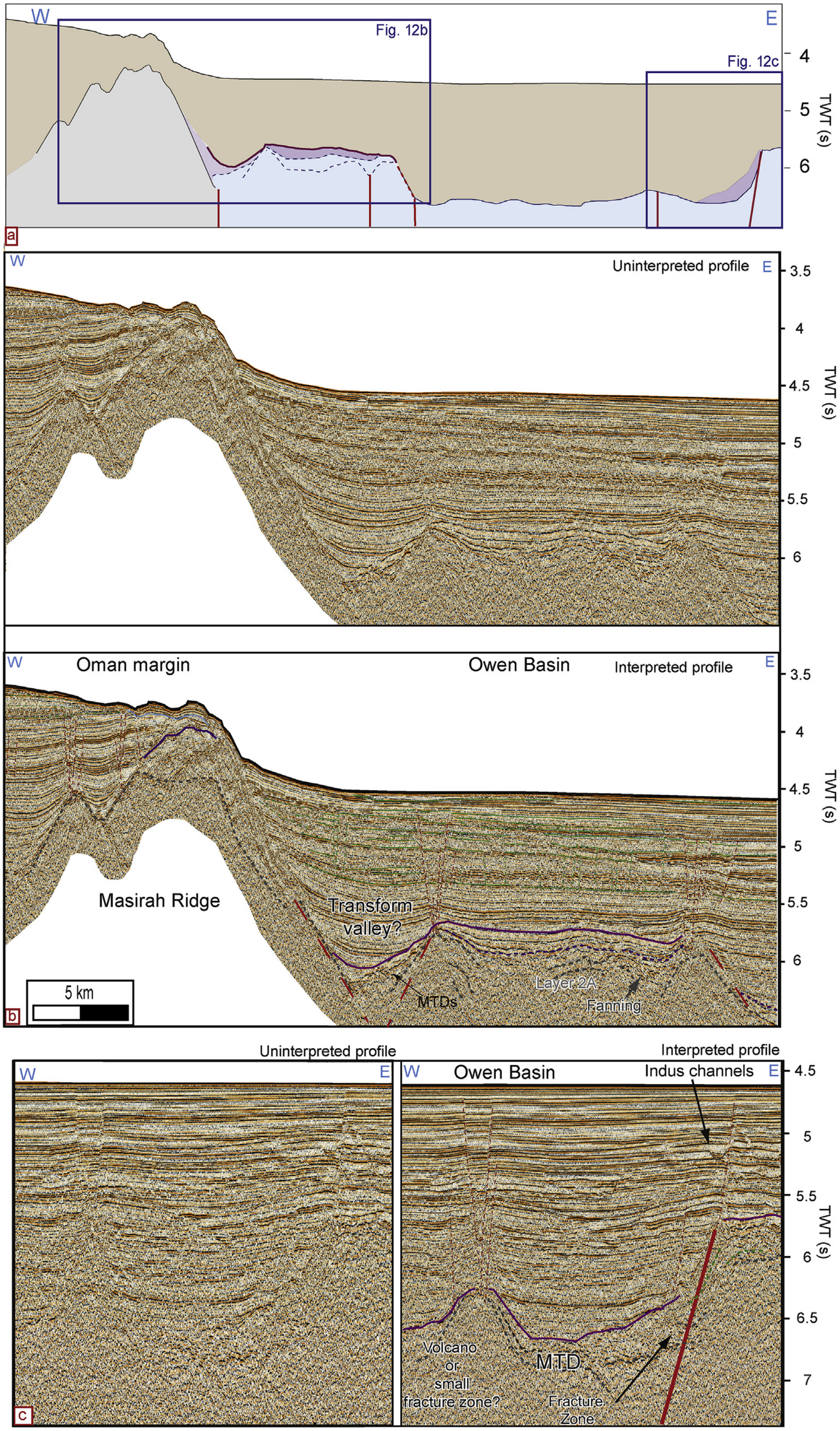


Fig. 12. Line drawing of a seismic section crossing the Masirah Ridge to the edge of the 20°N Basin. Seismic profile b) shows the Masirah Ridge and differential compaction structures in the Owen Basin. A graben, corresponding potentially to a transform valley, is observed at the foot of the Masirah Ridge. Profile c) shows a large vertical offset of the basement interpreted as a fracture zone. It also shows differential compaction structures, and turbidite channel levees coming from the Indus Fan. See Fig. 3 for location. Same horizontal scale for all profiles.

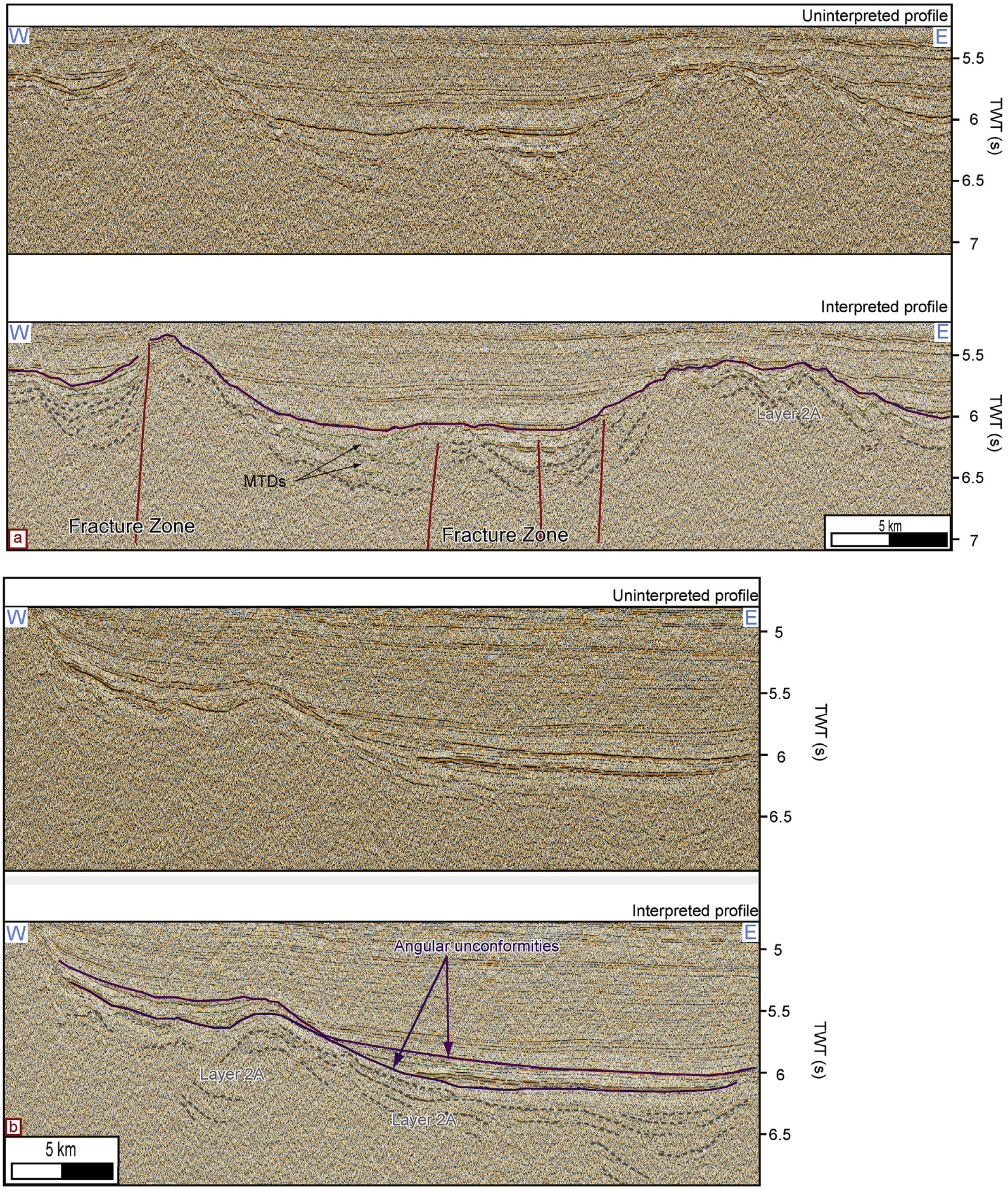
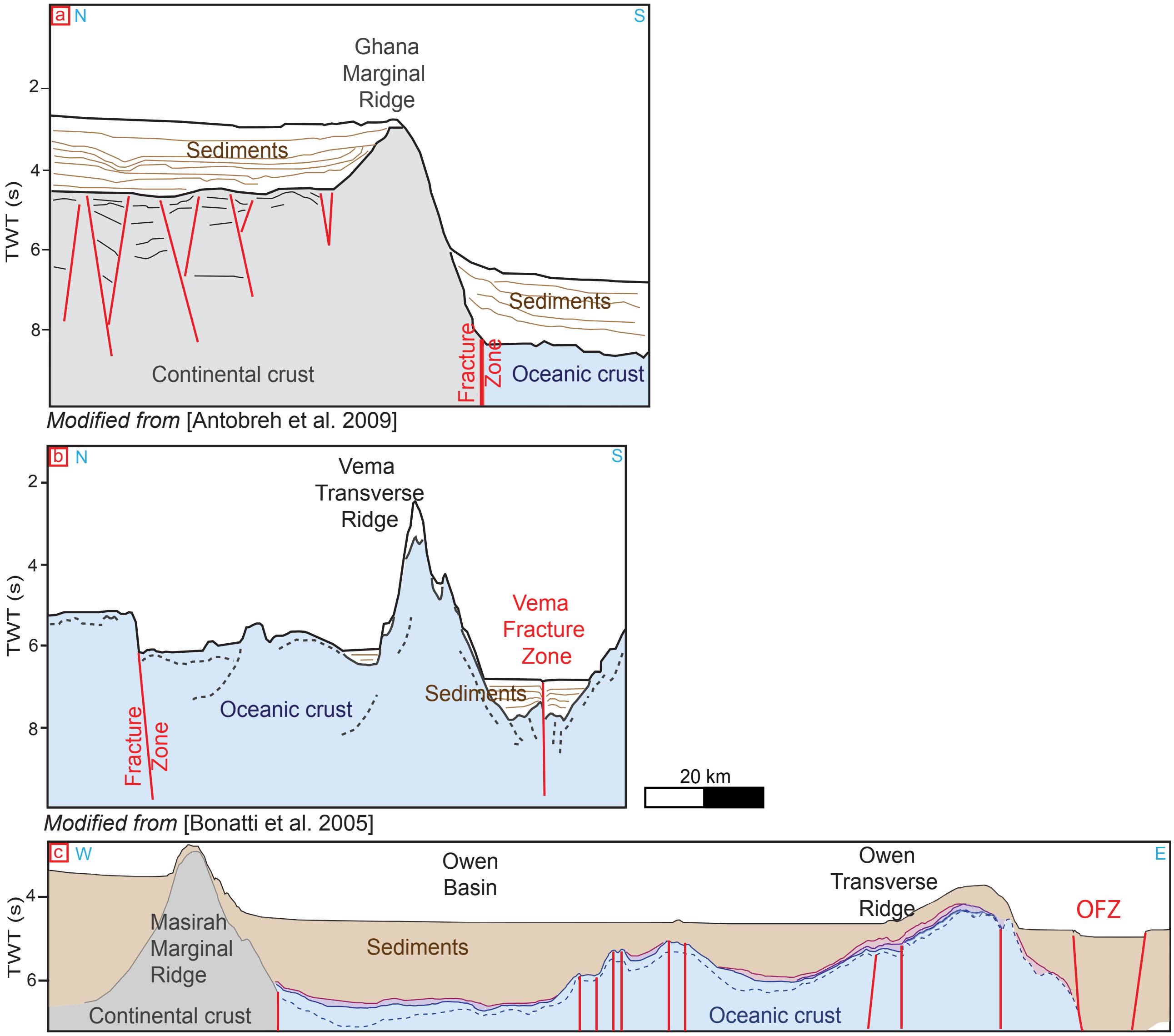


Fig. 13. Seismic profile a) highlights the uneven character of the Owen Basin basement. Possible fracture zones are underlined by the fanning configuration of MTDs. Seismic profile b) shows the regional angular unconformity separating the Lower Unit from the Upper one, and the regional unconformity corresponding to the deactivation of the Paleocene-Eocene transform boundary. See Fig. 3 for location. Same horizontal scale for all profiles.

compaction in the overlying sedimentary cover (e.g., Cartwight, 1994; Wilson, 2000).

5.2. Structure of the Oman margin and offshore Masirah ophiolites from seismic data

The east Oman platform is characterized by a large anticline system, which started to grow at 8.2–8.8 Ma at ODP Site 730 (Figs. 6a and 8), coeval with the uplift of the Owen Ridge. This Late Miocene episode of deformation and its regional effects are described in detail in Rodriguez et al. (2014a, 2014b). We note that the Masirah Transform previously defined by Mountain and Prell (1990) is not recognized, and actually corresponds to canyon incisions cutting through the Oman platform filled-in by a contouritic drift (Fig. 6a). Here we focus on the pre-Miocene structures of the Oman Margin.



Modified from [Antobreh et al. 2009]

Modified from [Bonatti et al. 2005]

Fig. 14. Examples of the diagnostic features of a transform plate boundary on seismic profiles, to be compared to general sections of the Owen Basin displayed in Fig. 5 a) Simplified line-drawing of a seismic line crossing the Ghana-Ivory Coast Marginal Ridge and b) of a seismic line crossing the Vema Transform. c) Simplified line drawing of a profile crossing the Owen Basin. End-members reliefs associated to transform boundaries encompass several thousands of meters reliefs (such as the transverse ridges of the Romanche Transform (Bonatti et al., 1994; Gasperini et al., 1997, 2001), the Shackleton Transform (Livermore et al., 2004), or the Barracuda Ridge (Pichot et al., 2012) in the Atlantic Ocean) or relatively modest reliefs (in the order of tens or hundreds meters) commonly observed at fracture zones.

Between 20°N and 21°N, the morphology of the Oman continental slope is characterized by the Masirah Ridge oriented ~ N25–30°E (Figs. 4 and 5) (Barton et al., 1990). It forms a horst structure up to ~1500-m-high with respect to the Owen Basin seafloor. The basement of the Masirah Ridge is partly buried under sediments and extends between 19°N and 21°50′N on seismic lines. The Masirah Ridge corresponds to continental lithosphere according to seismic refraction data (Fig. 5a; Barton et al., 1990). A similar prominent horst is observed at the latitude of the Sharbithat Ridge on Fig. 6a, although its bathymetric expression has been smoothed by subsequent sedimentation trapped on its western side. Because located off the Sawqirah bay, this ridge is hereafter referred as the "Sawqirah Ridge". The horst-pattern of the Masirah and Sawqirah Ridges (Figs. 6, 7 and 12) is similar to the marginal ridge observed along the Ghana-Ivory coast margin (Mascle et al., 1988; Basile et al., 1993; Lamarche et al., 1997; Clift and Lorenzo, 1999). Conspicuous graben structures, bordered by abrupt basement highs, are observed at the edge of the Masirah (Fig. 12) and the Sawqirah Ridges (Fig. 7b). Moreover, the basement exhibits strong offsets (~0.4 s TWT) in front of the Masirah Ridge (Fig. 12). The pattern of basement offsets at the edge of the Masirah-Sawqirah ridges looks like the transform valley identified along the Ghana-Ivory margin (Basile et al., 1993), and may indicate fossil strike-slip activity. Unfortunately, the penetration of the OWEN-2 seismic dataset is not deep enough to further buttress this hypothesis.

An acoustically chaotic body with an irregular thickness lies on the western flank of the Sawqirah Ridge (Fig. 6a), and at the foot of the continental slope (Figs. 7b and 8). It is overlaid by the same Eocene limestones observed on Masirah Island (ODP Site 729), and is therefore interpreted as the offshore prolongation of the Masirah ophiolitic body (Mountain and Prell, 1990). Considering that the obduction occurred in Late Cretaceous-Early Paleocene times (Immenhauser et al., 2000), the identification of offshore pieces of the Masirah Ophiolites implies that the basement at the edge of the

Oman margin is at least Cretaceous in age (and probably older).

Several fault offsets are observed along the edge of the Oman margin. Masirah ophiolites are also locally faulted with offset of 0.2 s TWT (Fig. 8). At the foot of the Sharbithat Ridge, the basement and the overlying sediments are tilted and offset by two vertical faults (Fig. 7), outlined by a 0.2 s-thick MTD offset vertically by 0.3 s (TWT).

An ambiguous feature is observed between latitudes 21°30′N and 22°30′N, where the Oman Margin trends ~ N15°E (Fig. 11). There, an anticline structure, bordered by fanning sedimentation in the Lower Unit, possibly roots on a steep-dipping reverse fault (Fig. 11). An alternative is to consider the conic shape as the result of volcanism, but the flat base of the volcano is not observed.

The stratigraphic record helps to unravel the uplift age of the Masirah-Sawqirah marginal ridges uplift. The westward tilt of the Masirah Ophiolites lying on the Sawqirah Ridge and the associated Eocene sedimentary cover (Fig. 6a), as well as the incision of the Sawqirah Ridge by an erosive surface unconformably overlain by Miocene turbidite sediments (Fig. 6a), recorded the uplift of the Sawqirah Ridge. At the edge of the margin, the uplift episode is recorded by the angular unconformity observed within the Lower Unit (picked in dark purple in Figs. 7–13).

The layer of Oligocene sediments drilled at DSDP Site 223 beneath the unconformity between the Lower and Upper Units and above the dark purple unconformity is very thin (50 m). Therefore, the dark purple unconformity is probably Middle-Late Eocene (i.e., ~40 Ma) in age, but offshore stratigraphic constrains are quite scanty in this area. The onland stratigraphic record in the southeast Oman margin documents an uplift ending at the Lutetian-Bartonian boundary (~40.4 Ma) (Robinet et al., 2013). Consistently, transpression is also recorded on land along the Qalhat Fault (to the northeast of the Oman sultanate) between Thanetian-Ypresian (Jafnayn Formation; 48–58 Ma) and Burdigalian times (Thawah Formation; 16–20 Ma) (Carbon, 1996). The uplift of the Masirah-Sawqirah marginal ridges thus occurred in Eocene times, and ended around 40 Ma.

5.3. Structure of the owen basin from seismic data

The basement of the Owen Basin displays buried reliefs up to 1.5 s (TWT) high with respect to the surrounding basement, associated with abrupt sub-vertical fault offsets. The deformation affects the sediments of the Lower Unit (Figs. 7, 10, 12 and 13) that are tilted on the flanks of the sub-vertical faults. These basement offsets are interpreted as an oceanic transform/fracture zone fabric. The basement of the Owen Basin also forms several symmetric and narrow buried reliefs up to ~0.5 s TWT high (with respect to the surrounding substratum) (Figs. 7, 10 and 12). These basement offsets can be interpreted either as an oceanic transform/fracture zone fabric, or extinct volcanoes (both interpretations being not exclusive). Structures composed of multiple and steep fault strands merging in one single fault at depth are characteristic of the Upper Unit in the Owen Basin (and the Oman margin) (Figs. 7–13). The throw at individual faults increases at depth, which indicates long-lived structures. Their location systematically coincides with abrupt and sharp basement offsets described above. These structures result from differential compaction, unrelated to active tectonics.

5.4. Structure of the Owen Ridge from seismic data

The basement of the Owen Ridge displays strong reflectors on the seismic data set, with chaotic hyperbolae, corresponding to trachybasalts of Late Paleocene age (Shipboard Scientific Party, 1974). The basement of the southern, central, and buried segments of the Owen Ridge displays on its western side strong offsets, with apparent dip ranging between 20 and 45°, delineating 5-20-km-wide areas (Figs. 6c, 9 and 10). These basements offsets are commonly associated with chaotic deposits at their edge corresponding to the collapse of their flanks. These basement offsets are very similar to the fracture zones formed in the prolongation of transform offsets at the Carlsberg Ridge during Paleogene (Gaedicke et al., 2002a). These observations suggest that the proto-Owen Ridge used to be a bathymetric ridge associated to a fracture zone system prior to its uplift in the Late Miocene (Rodriguez et al., 2014a).

Because pelagic sedimentation rates are too slow and submarine failures smooth fault scarps, the Lower Unit sedimentation does not provide favorable conditions for recording the deformation. Nevertheless, fanning configurations within lava flows composing the layer 2A (51–57 Ma-old; Shipboard Scientific Party, 1974) recorded the tectonic activity of half-grabens at the southern (Fig. 9) and the central ridge (Figs. 6c and 10). MTDs removing the sedimentary cover are trapped at the edge of half-graben structures and locally display a fanning configuration (e.g., at the Central Owen Ridge, Fig. 10), although indications of tectonic activity remain ambiguous.

Defining the basement of the Owen Basin from the foot of the Masirah-Sawqirah Ridges to the Owen Ridge as a ~6-km-thick oceanic crust would be in good agreement with the crustal structure of the Owen Basin (Fig. 5a) deduced by Barton et al. (1990) from seismic refraction studies. However, the identification of the nature of the basement based on seismic data alone may be ambiguous, as extended continental crust and oceanic crust may share similar properties on this type of dataset (Welford et al., 2015; Delescluse et al., 2015).

5.5. Structure of the owen basin and its borders from gravity field analysis

The trend of transform systems remains difficult to determine because of the scarcity of the seismic and magnetic profiles in the Owen Basin. Linear gravity anomalies are observed in the gravity field close to the margin (Fig. 3b), but they may originate from the addition of several contributions, including the steep bathymetric step as well as Moho step, plus local anomalies of crustal origin. We filtered the free-air gravity to keep the shortest wavelengths. Since they seem to follow the trend of the marginal ridges, these short wavelengths anomalies may be used as a guide to map major lineaments at the edge of the Oman margin, where some of the sub-vertical fault offsets have been identified (Figs. 7, 8 and 11). Lineaments along the northern part of the east Oman margin (between 20° and 22°30′N) outline the transpressive segments of the Paleogene India-Arabia plate boundary. Along the southern segment (18°N–20°N), the marginal ridges roughly trend N20°E–N30°E, but a N–S lineament (highlighted by a dotted orange (in the web version) line in Fig. 3b) is recognized along the southern segment of the margin. Another lineament (highlighted by a yellow dotted line in Fig. 3b) may correspond to the ocean-continent boundary of the proto-Owen Basin formed in the Early Cretaceous.

The free-air gravity anomaly map (Fig. 3b) does not display any obvious trace of the oceanic fabric in the Owen Basin (as observed for example in the Amirante Basin, Gaina et al., 2015). The lack of major fracture lineament is also a characteristic of the free-air gravity field in the Arabian Sea, east of the OFZ. In the Arabian Sea, the absence of clear fracture zone lineament on the free-air gravity is due to a complex system of propagating ridges during the Paleogene (Chaubey et al., 2002) buried beneath a thick sedimentary column, in relation with the high sedimentation rates of the Indus Fan (Clift et al., 2002). Vertical offsets identified on seismic profiles in the Owen Basin and on the western flank of the Owen Ridge probably represent minor fracture zones related to the transform fabric.

6. Discussion

6.1. Revised geological history of the India-Arabia plate-boundary (Paleocene-Miocene)

The observations above bring new geological constraints for the history of the India-Arabia plate boundary:

1) The east Oman margin displays the characteristics of a fossil transform margin, with the ocean-continent transition lying at the eastern edge of the Masirah-Sawqirah Ridges. The Masirah-Sawqirah ridges correspond to marginal ridges typical of transform margin. The structure of the Owen Basin is characterized by oceanic fracture zones related to the oceanic fabric of the Carlsberg Ridge. The proto-Owen Ridge used to be a relief associated with one of these fracture zones. This structure is in agreement with wide-angle seismic interpretation of Barton et al. (1990) (Fig. 5a).
2) The uplift of the marginal ridges occurred in Paleocene-Eocene times, and ended at ~40 Ma. A regional unconformity (picked in dark purple (in the web version)) marks the end of the uplift, and the deactivation of the fossil India-Arabia plate boundary in the Owen Basin. The transpressive deformation associated with the uplift of the marginal ridge is also recognized at the northern segment of the Oman margin (Fig. 11).
3) The observation of the Masirah ophiolites lying at the edge of the Oman margin indicates that the substratum is at least Late Cretaceous in age. This observation is in agreement with seismic studies of Beauchamp et al. (1995) showing tilted blocks under the Masirah Ophiolites, most probably related to Gondwana break-up during Late Jurassic-Early Cretaceous. It contrasts with the inferred Paleogene age of the substratum in the vicinity of the Owen Ridge. The Owen Basin is thus composed of pieces of oceanic lithosphere of different ages.
4) Seismic profiles document the inception of transform motion on the eastern side of the Owen Ridge at least 20 Ma, and indicate a narrow strike-slip boundary (Rodriguez et al., 2014a). Transform motion may have existed at this location prior to the Early Miocene, but it could not be detected due to the limited penetration of seismic profiles. Consistently, there is no tectonic activity in the Owen Basin and the Oman margin during the Late Eocene-Late Miocene time span. Indeed, the uplift of the Owen Ridge occurred in the Late Miocene (not in the Early Miocene as proposed by Mountain and Prell, 1990) and is unrelated to any major migration of the India-Arabia plate-boundary (Rodriguez et al., 2014a, 2014b).

Critical points to investigate with regards to the past locations of the India-Arabia plate boundary are the composite age of the Owen Basin (pre-Maastrichtian in the west, Paleocene-Eocene in the east) and the location of the spreading center at the origin of the basin (subducted beneath the Makran or located elsewhere?). The geological reconstruction of the India-Arabia relative motion must also explain the Tithonian age of the oceanic crust exposed at Masirah.

6.2. The India-Arabia plate boundary during the Paleocene-Eocene

A way to solve the paradox of the composite age of the Owen Basin is to consider that it reflects the juxtaposition of oceanic slivers of different ages by a transform system deactivated in Eocene times (i.e., ~40 Ma, uplift of the marginal ridges and transpression at their edge).

The transform system running at the edge of the marginal ridges (Fig. 3b) between 20° and 22°N is the best candidate for the Paleocene India-Arabia plate boundary (Fig. 11). It roughly fits the location of the conjugate of the Chain Fracture Zone during Paleocene-Eocene times deduced from reconstructions of Royer et al. (2002) (although Cande et al. (2010) suggested that slight adjustments should be done). The predicted trend of the conjugate of the Chain Fracture Zone is also in good agreement with the ~N15–20°E trend of the Oman margin between latitudes 21°30′N and 22°30′N. However, the trend of the Sawqirah-Masirah marginal ridges is ~N25–30°E, which represents a difference of ~10–15° with the inferred direction of the Paleocene-Eocene boundary. This difference in trend may have favored transpressive tectonics and therefore the uplift of the marginal ridges.

According to the reconstructions of Royer et al (2002, Fig. 2c), the amount (~800 km) of Indian oceanic crust accreted at the Carlsberg Ridge by the end of Eocene was large enough to form the Owen Basin (Figs. 3 and 4; Shipboard Scientific Party, 1974). Moreover, the distance between drilling sites DSDP 223 and 224, where basement rocks of 57 and 51.5 Ma have been respectively drilled, is roughly the same as the distance (i.e. ~250 km) between the magnetic anomalies 24 (52 Ma) and 25 (56 Ma) recorded in the Arabian Sea further east (Fig. 4), pointing out similar spreading rates at the origin of these basins. The main implication is that the Owen Basin was mostly formed by the Carlsberg Ridge. This interpretation rules out an origin from a now subducted spreading center as previously proposed by Mountain and Prell (1990). The eastern jump of the India-Arabia boundary from the edge of the Oman transform margin to a former oceanic transform fault in the vicinity of the Owen Ridge implied an episode of transfer of a large piece of the Indian oceanic lithosphere to the Arabian Plate (Fig. 15). In this framework, the Tithonian oceanic lithosphere at the origin of the Masirah Ophiolites was subducted under the Makran subduction zone, while the Carlsberg Ridge accreted new oceanic seafloor to the south.

Our model also implies the Owen Basin seafloor opened in a ~N–S direction, in contrast with the more or less E–W opening proposed by the magnetic anomalies identification of Gaina et al. (2015). The difference between the age of the basement of the eastern part of the Owen Basin determined by the model of Gaina et al. (2015) and the dating of the lava flows or the oldest pelagic sediment (Mountain and Prell, 1990) is of at least 17 Myr and more than 23 Myr in the southern part of the basin. Although the lava flows drilled in the Owen Basin are not typical MORB lavas, trachybasalts are commonly observed at oceanic propagators (Sinton et al., 1983) similar to the Carlsberg Ridge in the Paleogene (Chaubey et al., 2002), and their age is not necessarily very different from the age of the seafloor. In addition, an unexplained decrease in the intensity of magnetic anomalies formed during the Paleogene at the Carlsberg Ridge is observed close to the OFZ, but magnetic anomalies can still be related to the Carlsberg Ridge fabric (Chaubey et al., 2002; Royer et al., 2002). Therefore, the scarcity of available magnetic profiles precludes a unique identification of magnetic anomalies in the Owen Basin. The hypothesis of a N–S fabric for the eastern part of the Owen Basin remains to be evaluated.

6.3. The India-Arabia plate boundary during the late eocene - oligocene

The onset of ultra-slow spreading at the Carlsberg Ridge ~40 Ma ago (chron 18) was accompanied by a drastic change in the spreading direction (~30° clockwise rotation) (Merkouriev et al., 1996). This change implies a 30° clockwise rotation of the

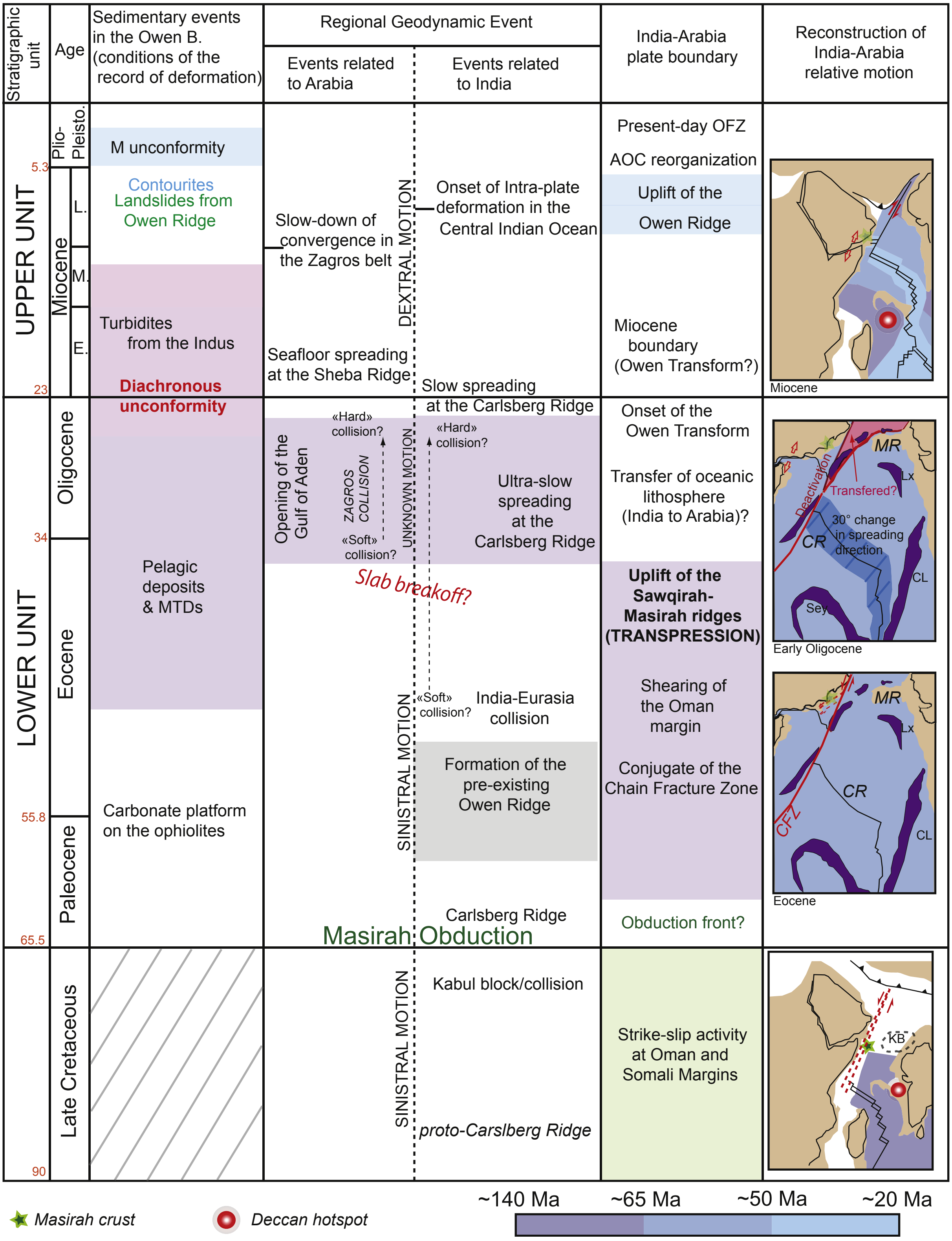


Fig. 15. Synthesis of the India-Arabia relative motion geological history since Late Cretaceous times, and summary of the new geological framework proposed in this study, involving a transfer of a part of the Indian plate to the Arabian plate in Oligocene. Reconstructions modified from Royer et al., 2002. CFZ: Chain fracture zone; CL: Chagos Lacadive Ridge; CR: Carlsberg Ridge; KB: Kabul Block; Lx: Laxmi Ridge; Md: Madagascar; MR: Murray Ridge; OR: Owen Ridge; Sey: Seychelles; SR: Sheba Ridge.

Paleocene-Eocene India-Arabia plate-boundary (i.e., the conjugate of the Chain Fracture Zone determined by Royer et al., 2002). The 30° rotation of the conjugate of the Chain Fracture Zone fits with a relocation of the India-Arabia boundary in the vicinity of the present-day Owen Ridge (Fig. 15). Moreover, the onset of ultra-slow spreading is coeval with the end of an episode of uplift of the Oman margin at the Lutetian-Bartonian boundary (~40.4 Ma) (Robinet et al., 2013), which could correspond to the abandonment of the Paleocene-Eocene plate boundary.

The magnetic anomaly 7 (24 Ma) marks not only a change in the spreading direction of the Carlsberg Ridge, but also a global kinematic change recognized at the Southwest Indian Ridge, in the Atlantic, and the Pacific oceans (Patriat et al., 2008). It indicates the minimal age of the Owen Transform (between the Sheba and Carlsberg Ridges). In this framework, the formation of the eastern part of the Sharbithat Ridge and its conjugate, the Error Ridge, are linked to the earliest stage of seafloor spreading at the Sheba Ridge (Stein and Cochran, 1985).

The precise location of the India-Arabia plate boundary and the precise timing of the migration during Oligocene times remain unknown. The Owen Basin does not display any trace of Late Oligocene activity of transform faults, and we do not observe any trace of transform activity older than Early Miocene at the Owen Ridge, but it may be due to the limited penetration of the available seismic lines. Because the Oligocene is thin (<50 m) or absent in most places of the Owen Basin, it is also possible that the tectonic activity of a fossil India-Arabia boundary was not recorded. It is even possible that Arabia and India were coupled during most of Oligocene times (similar to the Indo-Australian plate; Copley et al., 2010), prior to the clear separation of Arabia from Nubia at ~25 Ma (McQuarrie et al., 2003). Episodic coupling between India and Arabia may be a transient step during reversal of India-Arabia relative motion from sinistral (until ~40 Ma) to dextral (since 20 Ma).

6.4. *Origin of the India-Arabia boundary reorganization around 40 Ma*

A plate reorganization event occurred around 35–40 Ma in the Indian Ocean, expressed by the deactivation of seafloor spreading in the Wharton basin, the subsequent coupling of India and Australia in a single, Indo-Australian plate, and acceleration of seafloor spreading between Australia and Antarctica (Liu et al., 1983; Copley et al., 2010; Jacob et al., 2014). The direction of spreading at the Carlsberg, Central Indian and East Indian Ridges rotated eastward in response to this kinematic change and stress field reorientation (Merkouriev et al., 1996; Jacob et al., 2014; Müller et al., 2014). The deactivation of the Paleocene-Eocene India-Arabia plate-boundary around 40 Ma, as well as the onset of ultra-slow spreading at the Carlsberg Ridge may also reflect this global reorganization in the western Indian Ocean. This plate reorganization event probably occurred in response to a major geodynamic event related to the India-Eurasia or Arabia-Eurasia collisions surrounding the Indian Ocean.

However, uncertainties remain in the geological history of these collisions zones (Fig. 15), i.e. the timing of slab break-off events, the timing of the "hard-collision" stage, and the exact shape of the Greater India and Arabia prior to collision with Eurasia (Jolivet and Faccenna, 2000; Ballato et al., 2011; Wrobel Daveau et al., 2010; Mouthereau et al., 2012; van Hinsbergen et al., 2012; McQuarrie and van Hinsbergen, 2013; Gibbons et al., 2015). The identification of the precise tectonic driver of the plate reorganization event is therefore difficult. The rough synchronicity of slab break-off events around 40 Ma beneath both the Zagros and Himalayan belts makes the Indonesian subduction zone the only source of strong slab-pull forces at that time.

7. Conclusions

This study highlights how the Oman passive margin, formed by rifting processes in Tithonian, was turned into a transform margin in the Late Cretaceous-Paleogene. Since Paleocene times, the India-Arabia plate-boundary principally reacted to a major plate reorganization event at the end of the Middle Eocene. A major uplift episode along the east Oman margin formed the Masirah and Sawqirah marginal ridges during the Early Eocene. The Paleocene-Eocene boundary deactivated and subsequently migrated ~200-km east, probably during Late Eocene-Oligocene times. The migration of the India-Arabia plate boundary is unrelated with the uplift of the Owen Ridge, which occurred later in the Late Miocene (Rodriguez et al., 2014a). The composite nature of the Owen Basin results from the juxtaposition by a major transform boundary of a part of the Paleocene-Eocene oceanic lithosphere formed at the Carlsberg Ridge with the Mesozoic margin of Arabia affected by the Masirah obduction. The transform boundary was probably the conjugate of the Chain Fracture Zone according to reconstructions of Royer et al. (2002). The Oligocene plate boundary reorganization involved the transfer of a piece of the Paleocene-Eocene oceanic lithosphere of the Indian Plate to the Arabian Plate. The transfer of a piece of the Paleogene Indian plate to Arabia solves the inconsistencies of the previous reconstructions (Whitmarsh, 1979; Mountain and Prell, 1990).

The Oman margin therefore displays several characteristics of a transform margin, including marginal ridges, steep slopes (~10° in some areas), and a less than 100-km-wide ocean-continent transition. Although the present-day structure is similar to transform margin in the Atlantic Ocean (Greenroyd et al., 2008), most of the transform margin characteristics were acquired after the initial episode of rifting in the Tithonian (i.e., formation of the marginal ridges in the Middle Eocene, reactivation of the margin in the Late Miocene). The ocean-continent transition is the result of the juxtaposition of the oceanic part of the Owen Basin with the Oman continental margin by the Paleogene India-Arabia plate boundary, but does not reflect the initial width of the proto-Owen Basin formed in the Tithonian. The initial ocean-continent transition of the Tithonian passive margin is not observed anymore in the northern part of the basin (20°–22°N) and has been probably subducted at the Makran subduction zone. The steepest slopes reflect the Late Miocene episode of reactivation, which is unrelated to transform tectonics (Rodriguez et al., 2014a).

Nevertheless, the mode of obduction of the Masirah ophiolites, the mechanism of development of the marginal ridges along the Oman margin, and the identification of magnetic anomalies in the Owen Basin need to be further studied to fully validate the paleogeographic reconstructions proposed in this study.

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