Earth and Planetary Science Letters 302 (2011) 247–252

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Owen Fracture Zone: The Arabia–India plate boundary unveiled

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ARTICLE INFO

Article history:
Received 16 June 2010
Received in revised form 6 December 2010
Accepted 10 December 2010
Available online 3 January 2011

Editor: R.D. van der Hilst

Keywords:
plate kinematics
strike-slip faults
pull-apart basins
Arabia–India plate boundary
Owen Fracture Zone

ABSTRACT

We surveyed the Owen Fracture Zone at the boundary between the Arabia and India plates in the NW Indian Ocean using a high-resolution multibeam echo-sounder (Owen cruise, 2009) for search of active faults. Bathymetric data reveal a previously unrecognized submarine fault scarp system running for over 800 km between the Sheba Ridge in the Gulf of Aden and the Makran subduction zone. The primary plate boundary structure is not the bathymetrically high Owen Ridge, but is instead a series of clearly delineated strike-slip fault segments separated by several releasing and restraining bends. Despite an abundant sedimentary supply by the Indus River flowing from the Himalaya, fault scarps are not obscured by recent deposits and can be followed over hundreds of kilometres, pointing to very active tectonics. The total strike-slip displacement of the fault system is 10-12 km, indicating that it has been active for the past ~3 to 6 Ma if its current rate of motion of 3 ± 1 mm yr^{-1} has remained stable. We describe the geometry of this recent fault system, including a major pull-apart basin at the latitude 20°N, and we show that it closely follows an arc of small circle centred on the Arabia–India pole of rotation, as expected for a transform plate boundary.

1. Introduction

The Arabia–India plate motion is currently accommodated along the Owen Fracture Zone (OFZ) in the NW Indian Ocean (Gordon and DeMets, 1989; Matthews, 1966; Whitmarsh, 1979; Wilson, 1965). The OFZ belongs to the large strike-slip plate boundaries like the San Andreas, Dead Sea, North Anatolian and Alpine faults in the continental domain, and the Macquarie Ridge in the oceanic domain (Le Pichon et al., 2005; Lebrun et al., 2003; Mann, 2007; Massell et al., 2000; Stein et al., 1997; Weber et al., 2009). The OFZ is marked by a moderate seismicity and by a prominent bathymetric ridge, the Owen Ridge, up to 2000-m high with respect to the surrounding seafloor (Fig. 1). The Owen Ridge acts as a barrier to turbidites of the Indus deep-sea Fan and prevents their sedimentation towards the west into the Owen Basin (Clift et al., 2001; Mountain and Prell, 1990). As indicated by dextral strike-slip focal mechanisms of earthquakes along the OFZ (Fournier et al., 2001; Gordon and DeMets, 1989; Quittmeyer and Kafka, 1984), the Arabian plate moves northwards slightly faster than the Indian plate at a differential rate of 2 to 4 mm yr^{-1} estimated independently from geodetic (Fournier et al., 2008a) and geological (DeMets et al., 1990, 1994, 2010) data. We recently surveyed the OFZ onboard the *R/V Beautemps-Beaupré* (Owen cruise, 2009) using a high-resolution deep-water multibeam echo-sounder and a 3.5 kHz sub-bottom seismic profiler to identify surficial traces of active faults and characterize the geometry of the fault system in relation with its kinematics. Magnetic and gravity measurements were also routinely acquired.

2. Geometry of the plate boundary

Multibeam bathymetric data reveal an outstanding active submarine fault system between the Beautemps-Beaupré Basin to the south (Fig. 1; Fournier et al., 2008b) and the Dalrymple Trough to the north (Edwards et al., 2008). The fault scarps are well preserved on the seafloor and run at the base of the east-facing escarpment of the Owen Ridge, except at its southern extremity and in its central part where the faults crosscut the ridge (Fig. 1). The fault system is remarkably linear and focused on a single strand along much of its length. Six main fault segments can be identified, apparently uninterrupted over lengths between 60 and 180 km (Fig. 2). The overall geometry of the fault system hereafter described, including releasing and restraining bends, pull-apart basins localized on releasing bends, and basins ending the fault system, is consistent with a dextral strike-slip motion.

We used an oblique Mercator projection with the Arabia–India pole of rotation as pole of projection to test if the trace of the OFZ follows a small circle of the Arabia–India motion (Fig. 2a). In this coordinate system, transform faults should be horizontal straight lines if they strictly follow small circles. The trace of the OFZ is generally

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0012-821X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2010.12.027

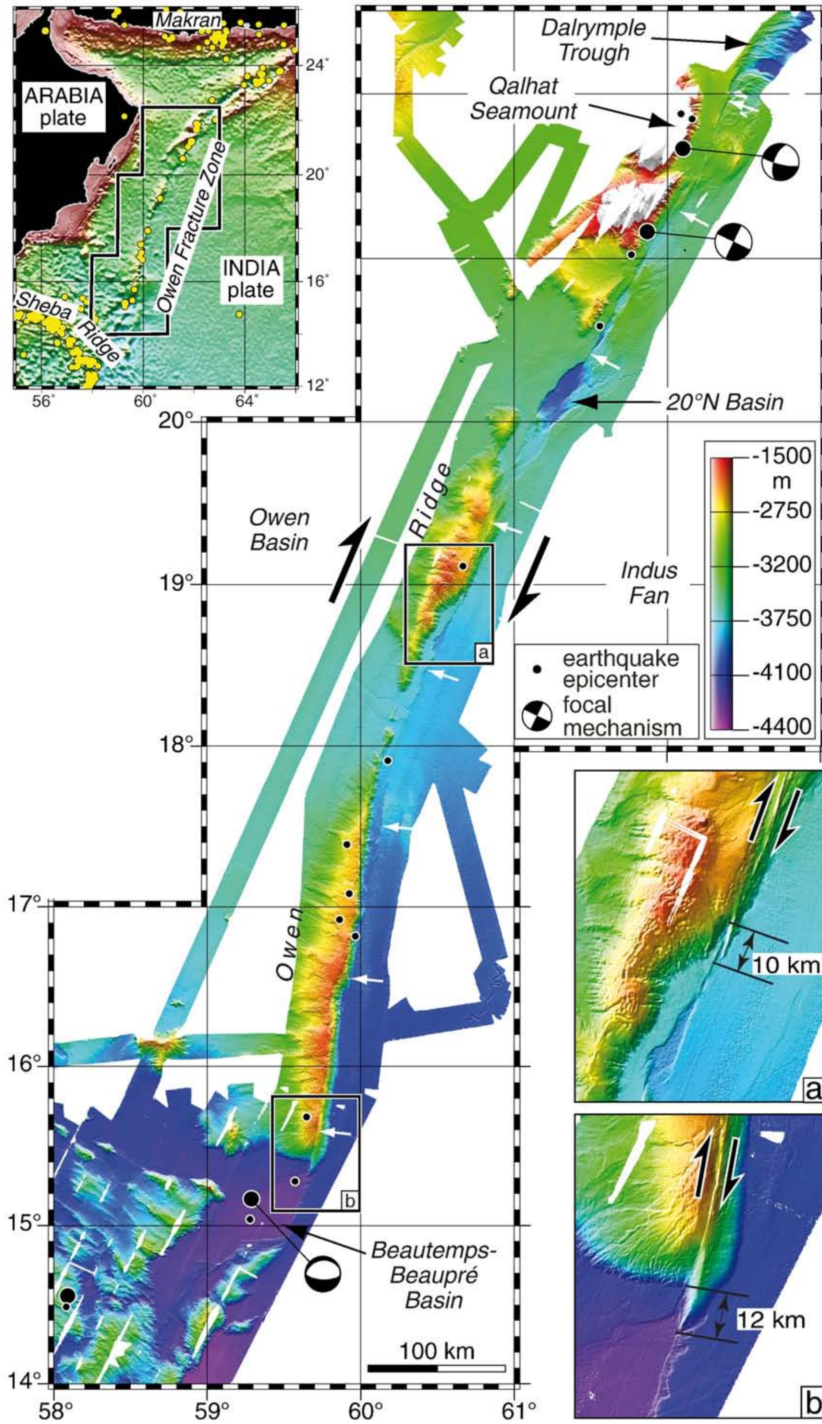

Fig. 1. Active fault scarps of the OFZ mapped with a multibeam echo-sounder can be followed over 800 km from the Beautemps–Beaupré Basin to the Dalrymple Trough (white arrows). The OFZ is bounded to the east by the Indian plate oceanic floor of Paleocene age formed at the Carlsberg Ridge (Chaubey et al., 2002; Royer et al., 2002), overlain by thick deposits (up to 12 km) of the Indus Fan (the second largest deep-sea fan), and to the west by the Owen Basin floored with oceanic crust of poorly constrained age between Late Jurassic and Eocene (Edwards et al., 2000; Mountain and Prell, 1990; Whitmarsh, 1979). The Owen Ridge is made up of three distinct portions separated by two thresholds at 18.2°N and 20°N. The southern ridge is asymmetric with a steep east-facing scarp and a gentle western flank, whereas the central ridge displays a dome morphology elongated in the direction of the Owen fracture zone. The southern and central ridges do not bear any magnetic signal. In contrast, the northern ridge, which rises ~2500 m above the surrounding seafloor and is topped by a flat platform at depths of 400 m below present sea level, is characterized by high amplitude magnetic anomalies attesting to a volcanic origin. It corresponds to the Qalhat Seamount, a volcanic guyot of probable Cretaceous age like the Little Murray Ridge in the Oman Basin (Edwards et al., 2000; Ellouz-Zimmermann et al., 2007; Gaedicke et al., 2002). a) and b) Strike-slip geomorphologic offsets of the active faults reach 10 to 12 km.

parallel to a small circle and is diverted from it between 16.5°N and 20.3°N, where a system of adjacent releasing and restraining bends constituting a paired bend (Mann, 2007) is observed. The releasing bend is made up of two pull-apart basins, a small rhomboidal basin at 18.6°N (see Fig. 1a) and a larger basin at a change in trend of the OFZ at 20°N (see Section 4). Between 16.5°N and 18°N, the fault trace slightly deviates from the direction of the interplate slip vector, leading to the development of a gentle restraining bend. Minor

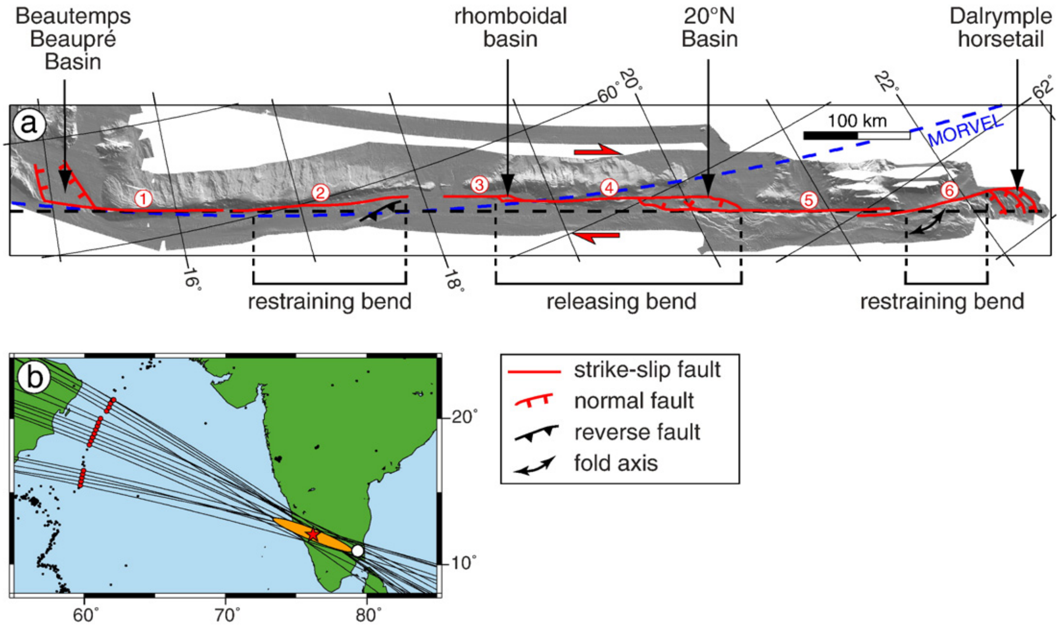

Fig. 2. Two graphical tests confirm that the OFZ is a transform fault. a) On an oblique Mercator map where the pole of projection has been shifted to the Arabia–India rotation pole (12.1°N, 76.2°E; Fournier et al., 2008a), the OFZ is aligned with Eulerian parallels (black dashed line), as expected for a transform fault. Between 16.5°N and 20.3°N, the fault trace is deviated from the horizontal reference line by a paired bend, but returns to it once the bend is passed. A small circle about the closure-enforced MORVEL Arabia–India rotation pole (blue dashed line; DeMets et al., 2010) is parallel to a horizontal straight line south of 18.5°N and diverge increasingly from it north of 18.5°N. Six apparently uninterrupted fault segments are labelled from 1 to 6. b) Great circles perpendicular to the fault trace intersect near the Arabia–India rotation pole (12.1°N, 76.2°E) shown by a red star with its 95% confidence ellipse. The best-fitting MORVEL Arabia–India pole is shown by an open circle (DeMets et al., 2010). The closure-enforced MORVEL Arabia–India pole (−3.2°N, 116.6°E) and the GPS-based Arabia–India pole of Reilinger et al. (2006; 17.7°N, 110.9°E) are located more than 30° toward the east.

compressional structures adjacent to the restraining bend are deduced from the seafloor morphology east of the fault and from the observation of folds and reverse faults in the recent deposits on 3.5 kHz profiles. At the northern end of the OFZ, a second restraining bend associated with folds on the Indian plate side is observed.

To further test the transform motion of the OFZ, we determined the location of the Arabia–India pole from the great circles perpendicular to the fault. As shown in Fig. 2b, the great circles perpendicular to the fault strike, measured out of releasing or restraining bends, intersect close to the rotation pole independently determined from GPS and seismicity data (Fournier et al., 2008a), and close to the best-fitting Arabia–India pole determined from geological data (fault azimuths; DeMets et al., 2010). The closure-enforced MORVEL Arabia–India rotation pole (DeMets et al., 2010), which is located much farther to the east (3.2°S, 116.6°E), predicts right-lateral slip parallel to the OFZ between 15°N and 18.5°N, becoming more and more extensional north of 18.5°N (Fig. 2a). Thus, recent kinematic models agree that the present-day OFZ is a pure strike-slip plate boundary over ~400 km between 15°N and 18.5°N and that, north of 18.5°N, the motion is dominantly strike-slip, but a small component of boundary-normal extensional motion cannot be excluded. MORVEL solution requires a partitioning mechanism north of 18.5°N to accommodate the predicted extensional component of boundary-normal motion, since segments 4 and 5 are pure strike-slip (Fig. 2a). On the other hand, MORVEL prediction is pure strike-slip along segment 6, at the entrance of the Dalrymple horsetail, whereas our model would imply a small component of compression. Non strike-slip components, either extensional or compressional, are expected to be so small that, if distributed over a wide area, they may be difficult to recognize.

3. Age of the active fault system

The active fault system crosscuts the Owen Ridge and offsets it dextrally. The total displacement is well constrained between 10 and 12 km by two strike-slip offsets of morphologic features (Fig. 1a and b). A long-term extrapolation of the GPS-derived slip rate of the OFZ (3 ± 1 mm yr^{-1}) would restore the observed offset in ~3 to 6 Ma. The small finite offset therefore testifies that the present-day fault system initiated recently, most probably during the Pliocene.

The reconstruction of the Arabia–India plate motion from the Somalia-Arabia and Somalia-India plate motion models (Fournier et al., 2010; Merkouriev and DeMets, 2006), indicates that the OFZ rate of motion remained nearly stable since oceanic spreading initiated in the Gulf of Aden 20 Ma ago (Chamot-Rooke et al., 2009). This result implies that, before the development of the present-day fault system, the Arabia–India motion was accommodated by an older fault system, or 'paleo OFZ', inactive since ~3–6 Ma.

The development of the present-day fault system postdates the uplift of the southern and central parts of the Owen Ridge. The onset of uplift of the southern Owen Ridge, related to vertical motions on the paleo OFZ (Weissel et al., 1992), is recorded by the transition from turbidites to pelagic sediments and is precisely dated by drilling of the Early Miocene (19 Ma; Shipboard Scientific Party, 1989; Whitmarsh et al., 1974). The onset of uplift of the Owen Ridge is synchronous of the initiation of seafloor spreading in the Gulf of Aden, constrained by the age of the oldest magnetic anomaly identified (An 6, 19.7 Ma; Fournier et al., 2010).

4. Tectonic record in the 20°N pull-apart basin

The main releasing bend along the OFZ is marked by a 90-km-long pull-apart basin at the latitude of 20°N (Fig. 3). The 20°N-Basin corresponds to a right step-over of 12 km between two master strike-slip faults trending N25°E south of the basin and N30°E north of it. The dimensions of the 20°N-Basin (90 × 12 km) are of the same order than those of the Dead Sea pull-apart basin (132 × 16 km; Ten Brink et al., 1993) along the Dead Sea strike-slip fault on the western side of the Arabian plate. The 20°N-Basin becomes wider (25 km) and deeper

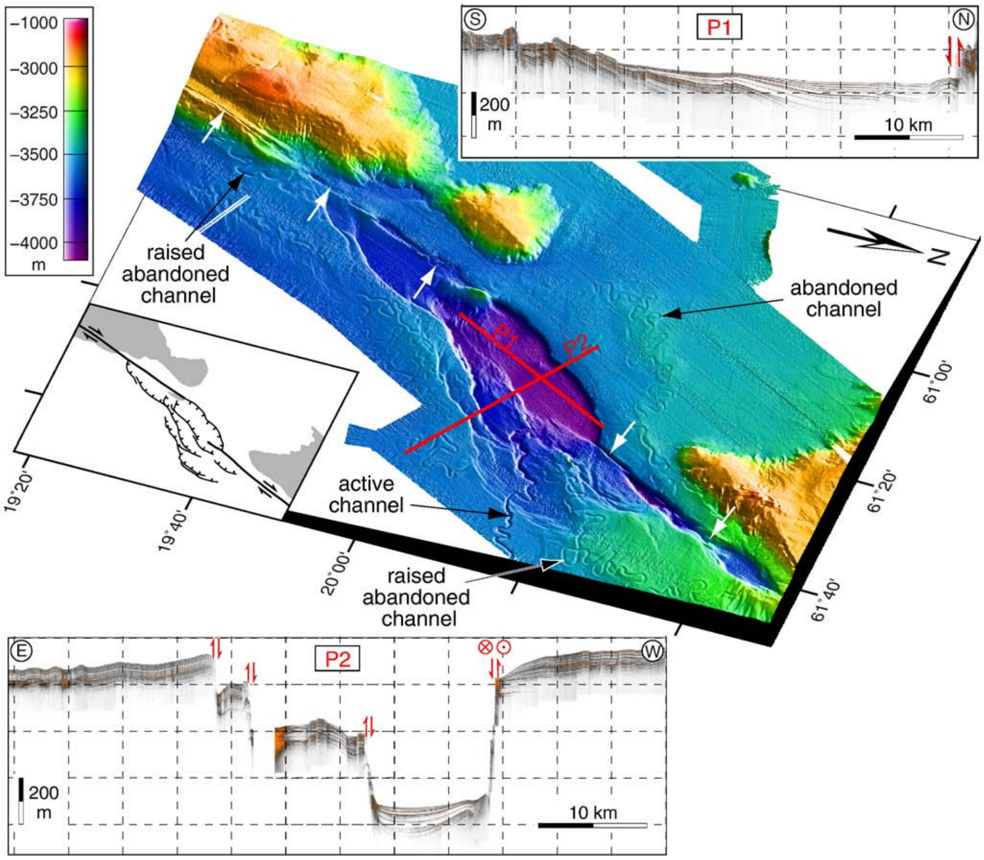

Fig. 3. The 20°N pull-apart basin is located at the main threshold of the Owen Ridge, south of the Qalhat Seamount. The basin is directly supplied in turbiditic deposits by an active channel of the Indus Fan. Two sub-bottom seismic profiles across the basin, along (P1) and perpendicular (P2) to its great axis, show that the turbiditic deposits, characterized on profiles by an alternation of thin highly reflective levels and thick transparent layers, are tilted towards the north due to motion of the border normal fault. White arrows indicate the master strike-slip faults.

(4050 m) to the north, where it is bounded to the west by a master normal fault scarp with a vertical throw of 500 m, and to the east by three normal fault scarps with throws between 100 and 300 m stepping down towards the basin axis (profile P2 in Fig. 3).

The spindle shape of the 20°N-Basin can be compared to pull-apart basins of sandbox analogue models formed in pure strike-slip or transtensional setting (Smit et al., 2008; Wu et al., 2009). The overall geometry of the 20°N-Basin compares closely with pull-aparts developed in a pure strike-slip regime (Wu et al., 2009). In particular, the 20°N-Basin does not exhibit margins of en-echelon oblique-extensional faults, typical of transtensional basins. This observation further confirms that the OFZ is a pure strike-slip feature.

The 20°N-Basin is directly supplied in turbidity–current deposits by an active channel of the Indus Fan (the mouth of the Indus river is 800 km away towards the northeast), which deeply incises the recent deposits (Fig. 3). The channel displays a moderate sinuosity, compared with nearby highly meandering abandoned channels, which attests to a resumption of erosion on a steeper gradient. Similar changes in gradient are evidenced by abandoned channels, raised and tilted in the vicinity of the active faults (Fig. 3), indicating local tectonic uplift provoked by the fault motion. The trace of the active faults bounding the 20°N-Basin is not obscured by turbiditic deposits despite the slow rate of slip of the OFZ. The preservation of normal fault scarps bounding the basin indicates that the rate of vertical (dip-slip) motion along the faults has exceeded the rate of deposition and burial by the sediments of the Indus Fan. The tectonic process is therefore dominant over deposition.

Sub-bottom seismic profiles (3.5 kHz) across the 20°N-Basin show that the basin is asymmetric with a turbidite sequence that becomes thicker towards the north, where the present-day depocentre of the basin is located (profile P1 in Fig. 3). Turbiditic currents feeding the 20°N-Basin could be related to the regional seismicity and/or to the activity of the Indus River in relation with sea-level variations. The basin could thus preserve a record of the seismic activity of the OFZ in its sediments, and possibly of the seismicity of the Makran subduction zone.

5. Terminations of the Owen Fracture Zone

At its both tips, the OFZ terminates into extensional structures associated with basins. To the north, the OFZ ends into the Dalrymple Trough by a system of regularly spaced normal faults that branch from the master strike-slip fault and form a spectacular 30-km-wide horsetail splay (Fig. 4a). The normal faults delineate a series of deep basins (up to 4000 m deep), which constitute the southern part of the Dalrymple Trough. The horsetail splay is indicative of slip dying out gradually towards the northern tip of the OFZ. To the south in contrast, the OFZ terminates abruptly into the Beautemps–Beaupré Basin, a 50-km-wide and 120-km-long basin bounded by two N70-N90°E-trending conjugate master normal faults (Fig. 4b; Fournier et al., 2008b). The basin is characterized by a strong negative gravity anomaly in relation with a thick sedimentary infill of at least 3–4 km. Recent works on the Arabia–India–Somalia triple junction showed that the Arabia–India motion was transferred to the west of the Beautemps–Beaupré Basin along a dextral shear zone, which joins southward the Sheba Ridge axis (Fournier et al., 2010). Numerous landslide scars are observed on the slopes of the Beautemps–Beaupré Basin and the southern Owen Ridge (Fig. 4b and c). Giant landslides, probably triggered by earthquakes along the active fault system, massively impinge the western flank of the Owen Ridge and were evacuated westward in the Owen Basin. Because of their huge volume,

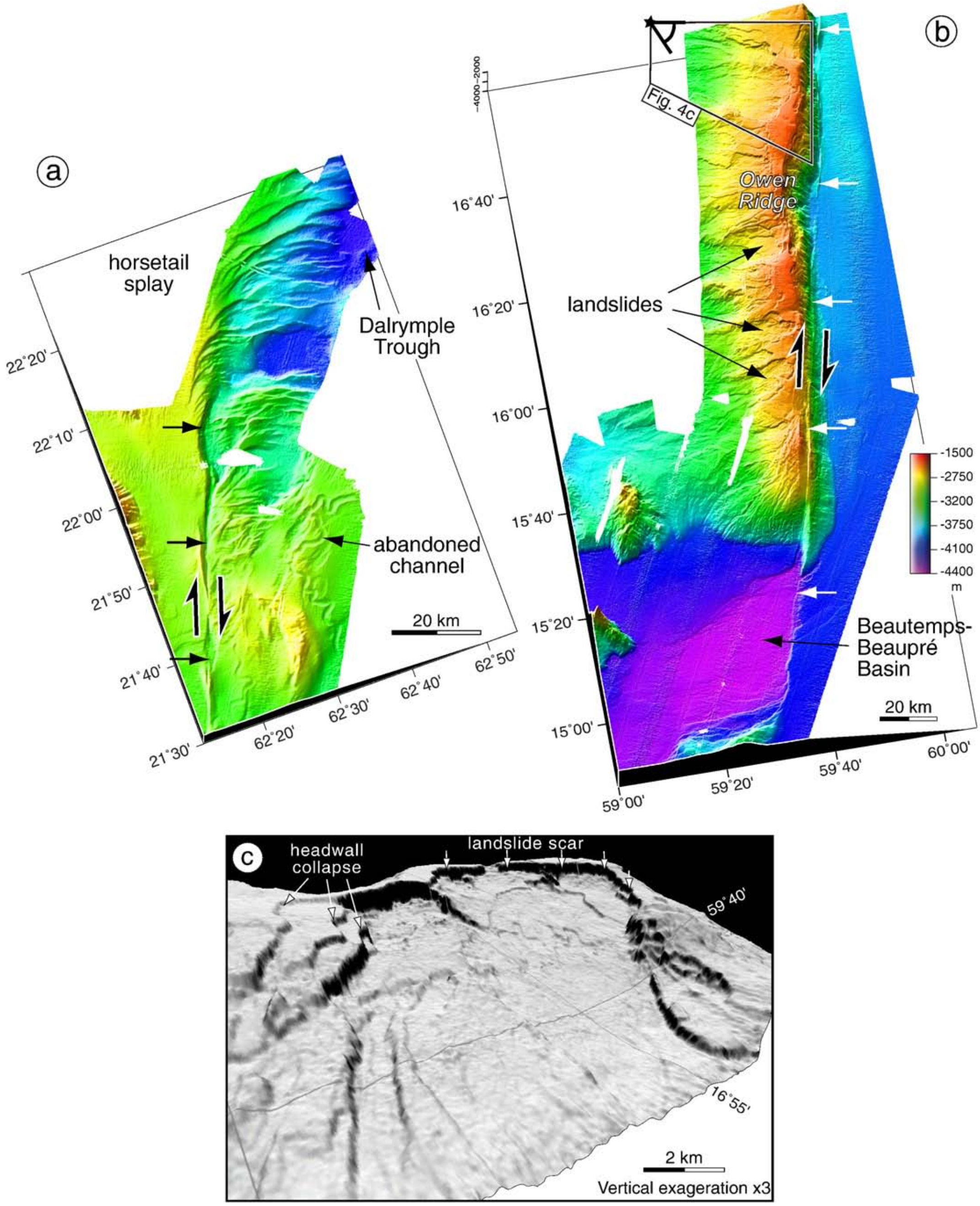

Fig. 4. a) The horsetail splay of the Dalrymple Trough developed in the northern tip-damage zone of the OFZ. Normal faults branch from the master strike-slip fault at low angles, curve progressively and become parallel to the maximum horizontal stress. b) Giant submarine landslides, probably due to strong ground motions from earthquakes of nearby active faults, occurred on western flank of the Owen Ridge and are suspected to have generated tsunami (Heidarzadeh et al., 2008b). c) Perspective view from the northwest of a multi-events generated landslide and related headwall collapses. This landslide removed up to 14 km^3 of material from the pelagic cover of the Owen Ridge (Rodriguez et al., 2010). Location in Figure 4b.

these mass failures represent a potential source of tsunami for the nearby coasts of Oman (Donato et al., 2009; Okal et al., 2006).

6. Conclusion

Our work sheds light on a previously unknown 800-km-long active fault system associated with giant landslides at the Arabia–India plate boundary. These results will motivate a reappraisal of the seismic and tsunami hazard assessment in the NW Indian Ocean (Heidarzadeh et al., 2008a; Okal and Synolakis, 2008). We show that the OFZ is a pure strike-slip boundary between the Arabian and Indian plates. The geometry of the active fault system is probably controlled both by the pre-existing faults of the paleo OFZ and by the topography of the Owen Ridge since the 20°N-Basin is located at the main threshold of the ridge. Extrapolating the present-day slip rate of the OFZ for 3–6 Ma accounts for its total displacement. The initiation of strike-slip motion along the present-day fault system does not coincide with any tectonic event recorded on land in Oman (Fournier et al., 2004, 2006; Lepvrier et al., 2002), but is coeval with a major tectonic reorganization of the Arabia–Eurasia collision from western Turkey to Iran between 3 and 7 Ma (Allen et al., 2004; Axen et al., 2001; Shabanian et al., 2009) deduced from the extrapolation of short-term deformation rates. It is also synchronous with the initiation of extrusion of Anatolia ca. 5 Ma (Armijo et al., 1999) and the onset of seafloor spreading in the Red Sea 4–5 Ma ago (Cochran and Karner, 2007). The lateral transport of the Anatolian lithosphere out of the collision zone could be at the origin of this widespread reorganization, including initiation of the present-day fault system at the Arabia–India plate boundary.

Acknowledgements

We are indebted to the Captain Geoffroy de Kersauson, officers, and crew members of the *BHO Beautemps-Beaupré*, and to the French Navy hydrographers Vincent Lamarre and Yves-Marie Tanguy, and the hydrographic team of the 'Groupe Océanographique de l'Atlantique', for their assistance in data acquisition. We acknowledge the support of SHOM, IFREMER, and INSU-CNRS for the Owen cruise. We thank Thierry Garlan from SHOM for making available bathymetric data of the Fanindien survey. We also thank C. DeMets his insightful review.

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