In situ evidence for dextral active motion at the Arabia–India plate boundary

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The Arabia–India plate boundary—also called the Owen fracture zone—is perhaps the least-known boundary among large tectonic plates[1–6]. Although it was identified early on as an example of a transform fault converting the divergent motion along the Carlsberg Ridge to convergent motion in the Himalayas[7], its structure and rate of motion remains poorly constrained. Here we present the first direct evidence for active dextral strike-slip motion along this fault, based on seafloor multibeam mapping of the Arabia–India–Somalia triple junction in the northwest Indian Ocean. There is evidence for ∼12 km of apparent strike-slip motion along the mapped segment of the Owen fracture zone, which is terminated to the south by a 50-km-wide pull-apart basin bounded by active faults. By evaluating these new constraints within the context of geodetic models of global plate motions, we determine a robust angular velocity for the Arabian plate relative to the Indian plate that predicts 2–4 mm yr^{-1} dextral motion along the Owen fracture zone. This transform fault was probably initiated around 8 million years ago in response to a regional reorganization of plate velocities and directions[8–11], which induced a change in configuration of the triple junction. Infrequent earthquakes of magnitude 7 and greater may occur along the Arabia–India plate boundary, unless deformation is in the form of aseismic creep.

Physiographically, the Arabia–India plate boundary consists of a curved and almost continuous topographic ridge called the Owen Ridge[12] (Fig. 1a). The Owen Ridge trends parallel to, and is bounded on its eastern side by, the Owen fracture zone (OFZ). From correlations of seismic profiles with Deep Sea Drilling Project drillings, the uplift of the Owen Ridge was dated as Early Miocene[12] and was related to vertical motions on its eastern bounding fault (hereafter referred to as the 'old' OFZ). The OFZ terminates northwards into the Dalrymple Trough. Southwards, it connects with the Carlsberg and Sheba ridge system at the Aden–Owen–Carlsberg (AOC) triple junction[13]. Earthquake focal mechanisms indicate dextral strike-slip motion[3,4]: Arabia is currently moving northward more rapidly than India with respect to Eurasia. With a rate estimated as 2 mm yr^{-1} (refs 5,6), the OFZ is one of the slowest plate boundaries on Earth. Space geodesy models (GPS) have been unable to unambiguously detect this slow motion so far, and conflicting solutions have been proposed for the relative India–Arabia motion, with opposite senses of slip along the OFZ[14–18]. Two recent solutions predict dextral shear with different amounts of extension[16,17] (see Supplementary Information, Table S1).

In October 2006, aboard the R/V Beautemps-Beaupré, we mapped the AOC triple junction and the southern extremity of the OFZ using a Kongsberg-Simrad EM120 deep-water multibeam echo-sounder. Sea-bottom reflectivity coverage, magnetic, gravity and sub-bottom (3.5 kHz) profiles were acquired simultaneously. The survey aimed at elucidating the configuration of the plate boundaries and the kinematic evolution of the triple junction. We focus here on the southern extremity of the OFZ, where we discovered a recently formed major active fault.

Multibeam sounding data show that the axial rift of the slow-spreading Sheba Ridge is bounded by normal fault escarpments (Fig. 1b). The rift valley deepens progressively toward the southeast, where it connects to the Owen transform fault (OTF). The northern boundary of the Somalia plate is thus well defined by the Sheba Ridge and the OTF.

In contrast, the Arabia–India plate boundary is poorly delineated. The OFZ is made up of a sinuous segment to the south and a rectilinear segment to the north (Fig. 1b). The sinuous segment corresponds to the seismically quiet segment of the OFZ and does not show any evidence of active deformation on the multibeam map or on 3.5 kHz profiles. It separates two oceanic lithospheres of different ages and depths originated at the Carlsberg and Sheba ridges, respectively, and may correspond to the fossil trace of the OTF. The rectilinear segment of the OFZ consists of an active strike-slip fault trending N10° E $\pm$ 3°, which cross-cuts and offsets the southern extremity of the Owen Ridge (Fig. 2a). The rectilinear trace of the fault indicates that the fault plane is nearly vertical. Surprisingly, the active fault is not located at the foot of the east-facing 2,000-m-high escarpment of the Owen Ridge, as suggested by earlier seismic profiles[12], but almost on top of it. There is no evidence of active deformation at the foot of the escarpment and therefore the whole Arabia–India relative motion seems currently accommodated along the active fault (however, the active fault might reactivate an ancient fault zone at depth). The fault shows a right-lateral apparent horizontal offset of 12 $\pm$ 1 km and no noticeable vertical offset (Fig. 2b). To the south, the fault

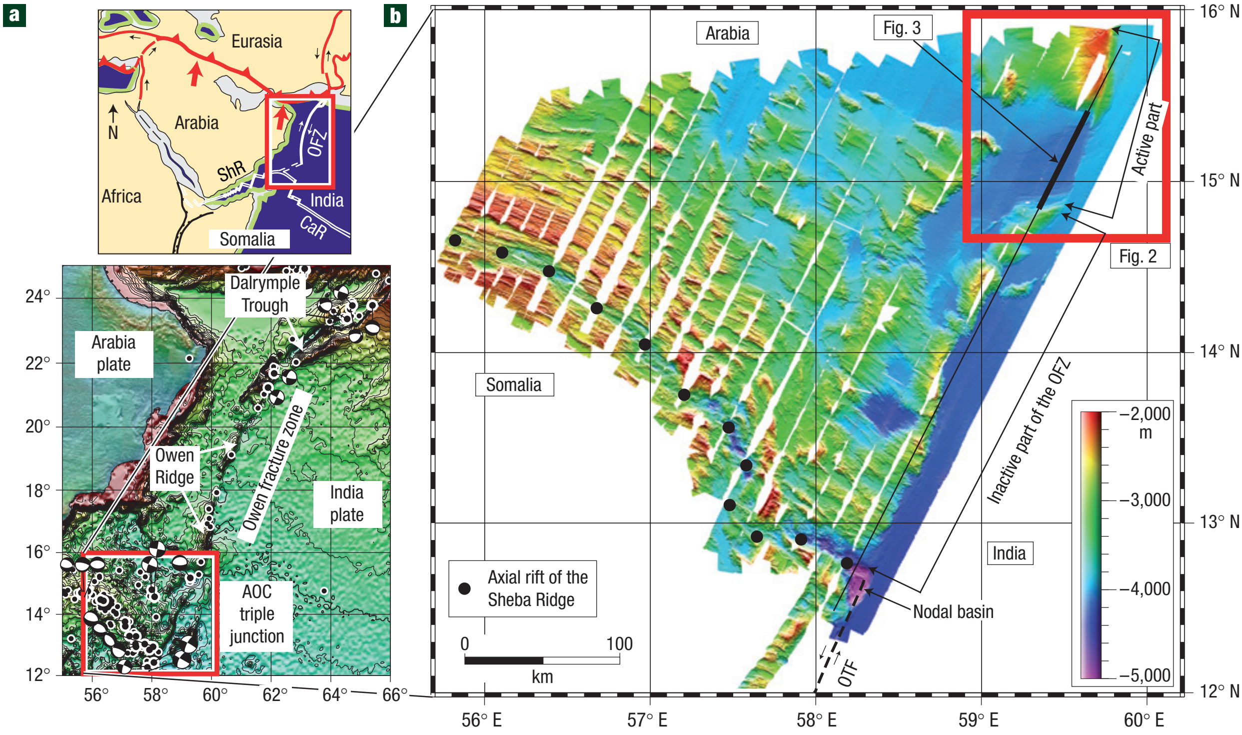

Figure 1 Location map and bathymetry of the OFZ and Arabia–India–Somalia triple junction. **a**, Satellite altimetry data[30], shallow seismicity between 1964 and 2004 (ref. 20) (focal depth < 50 km; magnitude > 2) and all available earthquake focal mechanisms for the AOC triple junction. The inset shows the geodynamic framework of the triple junction. CaR: Carlsberg Ridge. OFZ: Owen fracture zone. ShR: Sheba Ridge. **b**, Multibeam bathymetry of the triple junction mapped during the AOC cruise in 2006. The Sheba Ridge shows a typical slow-spreading ridge morphology with a well-developed axial rift bounded by normal faults stepping down toward the volcanic axis. The axial rift is sinuous, not segmented by transform faults, and deepens progressively toward the southeast and then connects to the Owen transform fault (OTF) through a deep nodal basin.

terminates in a ∼50-km-wide pull-apart basin bounded by N70° E to N90° E-striking normal faults (Fig. 2b,c). Active normal faulting in the basin is attested by seismicity: a magnitude 5.5 (m_b) extensional earthquake occurred exactly at the northern edge of the basin (Fig. 2c).

3.5 kHz profiles across the basin show numerous normal faults offsetting the youngest turbiditic deposits transported by tributaries of the Indus cone (Fig. 3). The two border normal faults show vertical throws of about 100 m. Numerous smaller normal faults with throws of about 10 m are observed in the southern part of the basin. The basin is characterized by a strong negative gravity anomaly of ∼100 mGal with respect to the surrounding crust (Fig. 3). Two-dimensional forward gravity modelling indicates that the gravity low can be explained by a combination of low-density sedimentary infill and low-density mantle below, possibly hot asthenosphere. A realistic model with a sediment thickness of 3–4 km yields a minimum finite stretching of 10 km, which is about the same as the 12 km total offset along the strike-slip fault.

The Arabia–India plate boundary terminates into the pull-apart basin some 250 km north of the Sheba Ridge. Multibeam and seismicity data do not provide evidence for a localized plate boundary that would connect the OFZ and the pull-apart basin to the Sheba Ridge. The present-day AOC triple junction therefore appears as a diffuse deformation zone (inset in Fig. 4). Before the initiation of the strike-slip fault and the development of the pull-apart basin, the southern sinuous segment of the OFZ was probably active (as part of the 'old' OFZ) and accommodated the Arabia–India dextral relative motion inferred from magnetic data from the Sheba and Carlsberg ridges[4]. The AOC triple junction was then located at the junction of the old OFZ, the Sheba Ridge, and the OTF with a fault–fault–ridge (FFR) geometry (inset in Fig. 4). Because this kind of triple junction is often unstable, it was probably abandoned when a change of the Arabia–India kinematics caused the activation of the strike-slip fault and pull-apart basin. Since then, an ultraslow divergent boundary has been developing in the pull-apart basin and might join the Sheba Ridge in the future to reach a more stable ridge–ridge–ridge triple junction[13]. At present, deformation is not clearly localized between the pull-apart basin and the Sheba Ridge, and the current configuration of the triple junction might correspond to a transient state preceding the birth of a new plate boundary. Estimating the timing of the change of configuration of the AOC triple junction requires determination of the slip rate along the active fault.

Data available for determining the rate of motion along the OFZ are scarce. In NUVEL-1 (ref. 5), two transform fault azimuths obtained from conventional sounding profiles[1] and six earthquake slip vectors were used to constrain the Arabia–India pole (Fig. 4). A dextral motion of 2 mm yr^{-1} along the Owen fracture zone was found, significantly lower than previous solutions[4,19].

The latest published geodetic solutions span a range of predictions for the motion along the OFZ including sinistral shear[14,18], dextral transpression[15] and dextral transtension[16,17]. We tested whether the latest solution for the International Terrestrial Reference Frame (ITRF2005) yields a more robust solution (see the Methods section and Supplementary Information). The resulting rotation pole (P1) predicts a pure strike-slip motion along the

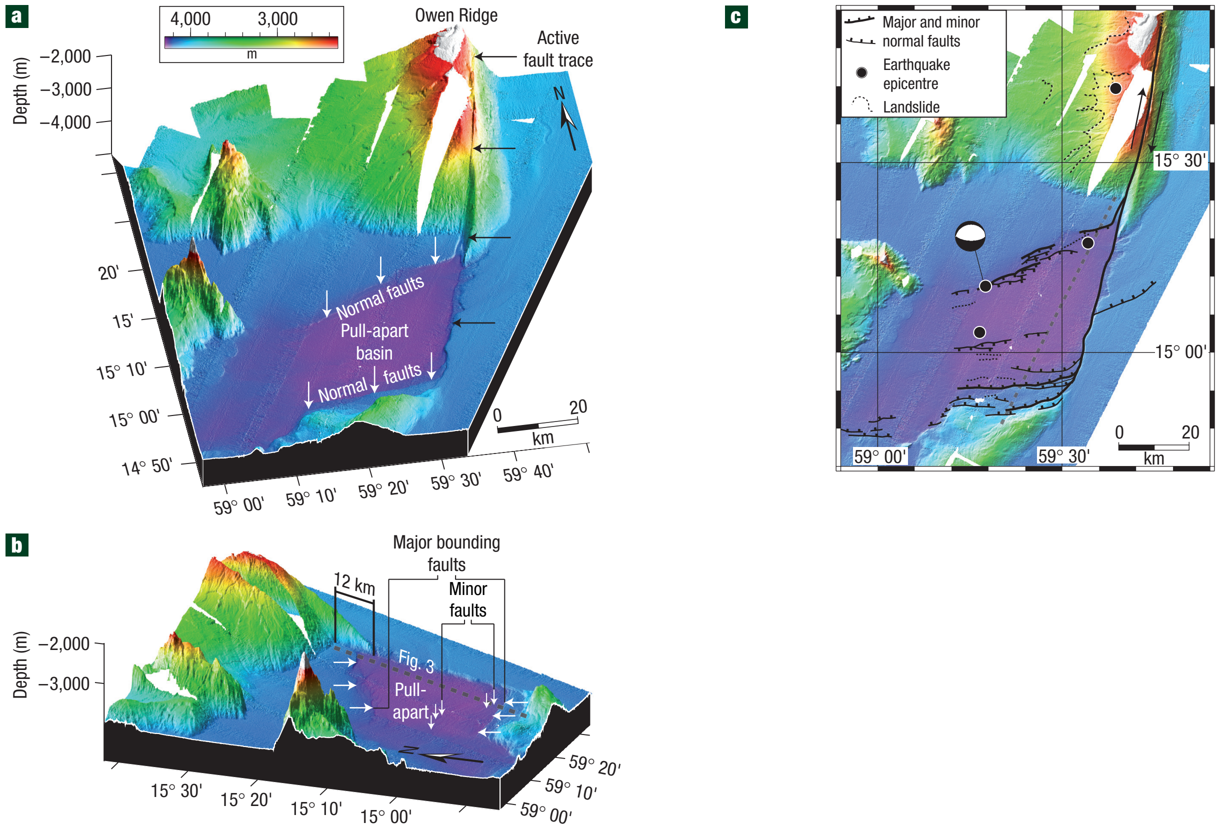

Figure 2 Three-dimensional and map views of the active fault discovered at the southern extremity of the OFZ (location in Fig. 1b). a, The N10° E-trending fault cross-cuts the Owen Ridge and terminates to the south in a pull-apart basin bounded by N70° E to N90° E-trending normal faults. **b**, The total displacement along the fault is determined from the right-lateral 12 km ±1 geomorphologic offset of the Owen Ridge. **c**, The fault activity is attested by shallow seismicity in the basin and by the extensional focal mechanism (Harvard CMT, 12 September 1990) of an earthquake on the northern bounding fault. The southward steeply dipping nodal plane of the earthquake focal mechanism probably corresponds to the bounding fault plane.

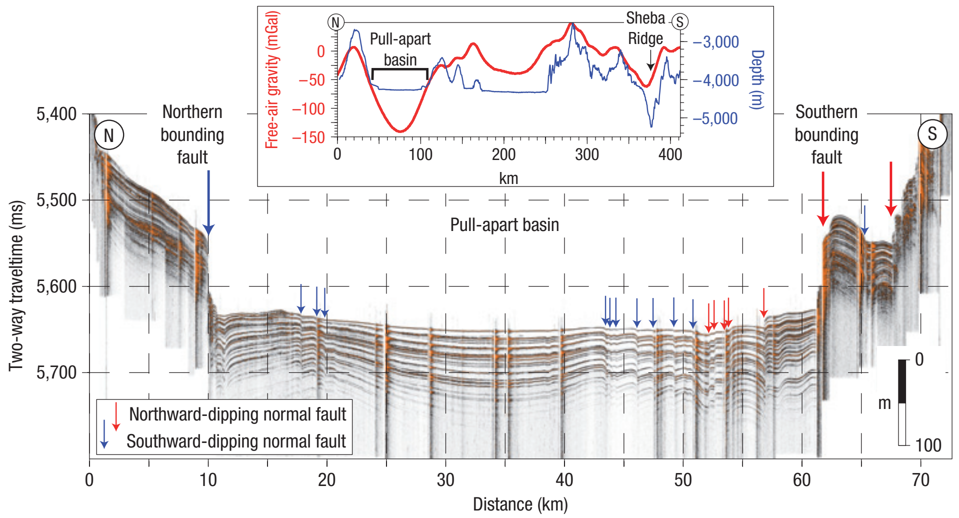

Figure 3 3.5 kHz seismic profile across the pull-apart basin (location in Figs 1b and 2b). The present-day depocentre is delineated by numerous normal faults in the southern part of the basin. The inset shows the free-air gravity profile across the basin and the northern flank of the Sheba Ridge (location in Fig. 1b). The basin is not in local isostatic equilibrium. The gravity minimum is offset southwards by about 5 km with respect to the basin centre, suggesting an asymmetrical infill with a greater basement depth to the south, in agreement with the high density of normal faults to the south. The main characteristics of this previously unknown basin—total width of 50 km, finite stretching of ∼12 km, sediment thickness of 3–4 km, asymmetric infill—make it an equivalent in the oceanic domain of the Corinth continental rift.

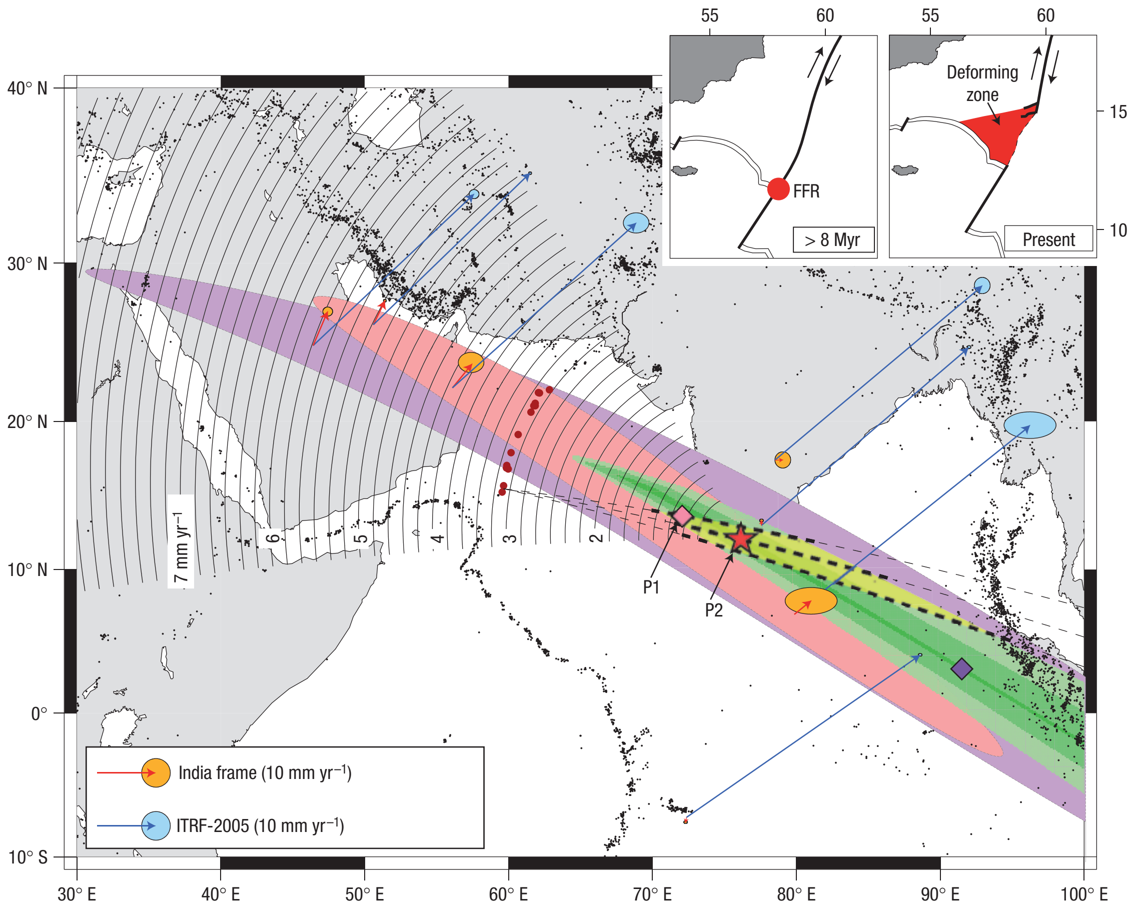

Figure 4 Arabia–India GPS kinematics. Blue and red arrows show the ITRF2005 solution in the original and India-fixed reference frames with 95% confidence ellipses. The best geodetic P1 (pink) and NUVEL-1A (purple) India–Arabia rotation poles are shown with their 95% confidence ellipsoids. Red dots show earthquake epicentres[20] along the OFZ used to map regions of allowable India–Arabia poles (green regions) with four-, six- and eight-sigma errors on epicentre positions. Dashed lines delimit the region where the poles fit the azimuth of our new fault (yellow region). The red star shows the best pole P2 using earthquakes, fault azimuth and GPS at Bahrein station. The predicted rate on the OFZ is 3.2 ± 1.2 mm yr^{-1} (thin circles). The black dots are earthquake epicentres (shallow seismicity between 1964 and 2004). The inset shows the configuration of the AOC triple junction before (left) and after (right) the development of the strike-slip fault and pull-apart basin.

OFZ of 2.7 ± 1.7 mm yr^{-1}. The predicted azimuth of motion along the newly mapped, N10° E-striking, active fault is N7.5° E. This azimuth is more accurate than any of the previous models, NUVEL-1A (N18.5° E) included. The rate is consistent with the shear component in ref. 17, which used many more sites in the Arabian plate. However, our new pole does not predict the proposed extension component.

The location of the rotation pole can be independently determined from the earthquakes which occurred along the strike-slip portion of the OFZ between 15° N and 22° N latitudes, where it closely follows a portion of a small circle[13] over ~700 km. Using the relocated positions of these earthquakes[20], we produce a set of acceptable poles for India–Arabia motion (see the Methods section). Only a small fraction of these acceptable poles satisfy the N10° E$\pm$3° azimuth of the active fault. We use this additional constraint to derive our best pole (P2 in Fig. 4).

Thus, three independent datasets (multibeam bathymetry, earthquakes focal mechanisms and space geodesy) indicate that the India–Arabia boundary is a right-lateral transform fault that closely follows a small circle centred on a nearby pole of rotation. Combining all the available data, our best estimate of the present-day motion predicts a rate of 3 mm yr^{-1} along the OFZ.

To determine the onset of motion along the active fault, we examine the recent evolution of the Arabia–India motion. The comparison of GPS motions with NUVEL-1A motions suggests that the Arabia–Eurasia relative motion might have slowed down by as much as 30% during the past 3 Myr (refs 18,21). During the same period, the India–Eurasia relative motion seems to have decreased in the same proportion[15,22,23]. Because the Arabia–India relative motion is small, any change in motion of one of the two plates could have dramatic consequences for the OFZ, for instance a change in the sense of slip. Our structural interpretation of the AOC cruise data shows that right-lateral shear has prevailed along the OFZ for the past million years, long enough to form the pull-apart basin: we found no evidence for recent inversion tectonics. Moreover, the Arabia–India instantaneous rate that we obtain from GPS data (3 mm yr^{-1}) is not significantly different from the NUVEL-1A rate obtained for the past 3 Myr (2 mm yr^{-1}). The simplest interpretation is that India–Arabia motion remained close to this value at least during the past 3 Myr. In a constant-rate model, the age of the fault—obtained by dividing its finite offset (12 km) by the mean rate of motion (2–4 mm yr^{-1})—would be 3–6 Myr. Although such a young age cannot be ruled out, it is significantly younger than the age of the latest major kinematic reorganization, which occurred in the Indian Ocean ~8 Myr ago[8]. This age corresponds to the onset of intraplate deformation in the India–Australia plate dated at 7.5–8 Myr by ODP drillings[9], which is coeval with the rise of the Tibetan plateau to its maximum elevation[10,11]. It also coincides with a kinematic change bracketed between 11 and 9 Myr along the Carlsberg Ridge[8]. Since then, magnetic data along the Carlsberg and Sheba ridges indicate a steady motion between the Somalia–India and Somalia–Arabia plates, respectively[8,24]. An alternative to the constant rate model is a progressively increasing rate from 0 to 3 mm yr^{-1} starting some 8 Myr ago. This scenario is still compatible with the GPS and NUVEL-1A rates and would agree better with the regional tectonics.

These new findings have implications for seismic hazard and earthquake recurrence along the Arabia–India boundary. The OFZ seismicity reported for the past 40 years is negligible. Breaking the 120-km-long fault segment that we mapped would require a $M_w > 7$ earthquake if the recurrence interval were 10^2 years[25], and several earthquakes of this size would be required to break the entire fault. Yet, the centennial earthquake catalogue[26], supposed to be complete down to magnitude 7 earthquakes, does not report any significant event along the OFZ. Our interpretation is that the OFZ shares some of the characteristics of intraplate faults, such as small slip rate, small cumulative slip and large recurrence interval ($>10^3$ years). Infrequent but large earthquakes may then be expected, similar to the large (M_w7.9 and M_w7.6) strike-slip earthquakes that occurred in the intraplate setting in the Indian Ocean[27,28].

METHODS

KINEMATIC ANALYSIS

Available Arabia–India Euler poles are shown in Supplementary Information, Fig. S1 and listed in Supplementary Information, Table S1, together with their predictions at the location of the newly mapped fault. GPS measurement campaigns are generally dedicated to only one of the two plates, so that in many studies the Arabia–India motion is a poorly constrained by-product of the realization of the solution into a global reference frame using IGS continuous sites (cGPS). In October 2006, IGN made available the latest solution for the International Terrestrial Reference Frame (ITRF2005, available at http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005.php). The level of data accuracy is unprecedented and compensates for the limited number of sites (for example, the 53 site velocities located onto rigid Eurasia have a mean residual vector of 0.4 mm yr^{-1}). We first determined the Arabia-ITRF2005 (three permanent sites) and India-ITRF2005 (four permanent sites) poles of rotation and associated variance–covariance matrices, and combined them to obtain the motion of Arabia with respect to India (pole P1, see Supplementary Information, Table S1). One of the Indian stations (Diego Garcia) may arguably be located within the India–Australia deformation zone, but it is close enough to the India–Australia pole of rotation[29] to be included in the Indian set. Apart from the Colombo station (Sri Lanka), which has not been measured for a long time, the three other Indian sites have a mean residual of 0.5 mm yr^{-1}. The velocities of Arabian stations in the Indian reference frame are between 4 and 6 mm yr^{-1}. The rotation pole P1 predicts a pure strike-slip motion along the OFZ of 2.7 ± 1.7 mm yr^{-1}.

Multibeam data show that the OFZ is a pure strike-slip fault between 15° N and 16° N, and, at the other end of the fracture zone, one focal mechanism between 21° N and 22° N (Harvard CMT, April 7, 1985) indicates a dextral strike-slip motion along a N26° E-trending vertical fault plane. Between 16° N and 21° N, the OFZ follows a portion of a small circle. The simplest interpretation is that the entire segment located between 15° N and 22° N is a predominantly strike-slip fault, with a motion gradually reorienting from N10° E in the south to N30° E in the north. Earthquakes along this strike-slip portion of the OFZ (red dots in Fig. 4) were used to map regions of allowable India–Arabia poles (green regions) using a simple rejection criterion: the pole was rejected if the distance of one earthquake from the best small circle was greater than the location error. The errors given in the catalogue[20] are small (4–18 km) and the retained rejection criterion is drastic. Keeping poles that fit the azimuth of our newly mapped fault within its uncertainty (N10° E $\pm$ 3°) enables us to narrow the area of acceptable poles. The best pole P2 (red star in Fig. 4) located at 12.1° N and 76.2° E ($-0.102°$ Myr^{-1}) was determined using earthquakes, fault azimuth and GPS at the Bahrein station (smallest uncertainty of the Arabian vectors).

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