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Active deformation in Zagros–Makran transition zone inferred from GPS measurements

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SUMMARY
The Bandar Abbas-Strait of Hormuz zone is considered as a transition between the Zagros collision and the Makran oceanic subduction. We used GPS network measurements collected in 2000 and 2002 to better understand the distribution of the deformation between the collision zone and the Makran subduction. Analysing the GPS velocities, we show that transfer of the deformation is mainly accommodated along the NNW–SSE-trending reverse right-lateral Zendan–Minab–Palami (ZMP) fault system. The rate is estimated to 10 ± 3 mm yr⁻¹ near the faults. Assuming that the ZMP fault system transfers the motion between the Makran–Lut Block and the Arabian plate, we estimate to 15 mm yr⁻¹ and 6 mm yr⁻¹, respectively, the dextral strike-slip and shortening components of the long-term transpressive displacement. Our geodetic measurements suggest also a 10–15 km locking depth for the ZMP fault system. The radial velocity pattern and the orientation of compressive strain axes around the straight of Hormuz is probably the consequence of the subducting Musandam promontory. The N–S Jiroft–Sabzevaran (JS) fault system prolongates southwards the dextral shear motion of the Nayband–Gowk (NG) fault system at an apparent rate of 3.1 ± 2.5 mm yr⁻¹. The change from strong to weak coupling for underthrusting the Arabian plate beneath the Zagros (strong) and the Makran (weak) may explain the dextral motion along the ZMP, JS/NG and Neh–Zahedan fault systems which transfer the convergence from a broad zone in the western Iran (Zagros, Tabriz fault system, Alborz, Caucasus and Caspian sea surroundings) to Makran subduction.

Key words: active deformation, collision, GPS, Makran, Subduction, Zagros

1 INTRODUCTION
The present-day N–S convergence between the Arabian and the Eurasian plates is partially accommodated along the Zagros fold and thrust belt and the Oman oceanic lithosphere subduction. The Musandam peninsula-Bandar Abbas-Strait of Hormuz zone, also called the ‘Oman line’, is considered to be the transition between the Zagros continental collision and the Makran oceanic subduction (Kadinsky-Cade & Barazangi 1982) (Fig. 1). The Zendan–Minab–Palami (ZMP) faults accommodate the differential of velocity between the eastern Zagros and western Makran domains. This ZMP fault system runs west of the Makran accretionary wedge up to the Main Zagros Thrust area (MZT). Then, the differential of velocity between the Central Iranian Block (CIB) and the Lut block is taken up by the active Jiroft–Sabzevaran (JS) faults which are considered as the south prolongation of the Nayband–Gowk (NG) strike-slip system (Regard et al. 2004). GPS data in Iran have proved that Arabia converges towards Southeastern Iran at velocity of 23 ± 2 mm yr⁻¹ near the western termination of the Makran subduction (Vernant et al. 2004), less than the time-averaged 36.5 mm yr⁻¹ velocity proposed by the NUVEL 1 model (DeMets et al. 1990). Moreover, Tatar et al. (2002) have shown that Central Zagros accommodates 10 ± 4 mm yr⁻¹ of NNE shortening. Based on a large scale GPS network (Vernant et al. 2004) suggested a right-lateral strike-slip rate of ~11 mm yr⁻¹. This rate is consistent with the recent geomorphic and tectonic analyses suggesting 11–13 mm yr⁻¹ of right-lateral strike-slip motion over the whole ZMP and JS fault systems (Regard et al. 2004, 2005). Based on the comparison of the GPS velocity field deduced from the large scale Iranian Geodetic
Figure 1. Earthquakes in the Zagros Makran transition zone. Seismicity from Engdahl’s catalogue (Engdahl et al. 1998) and Harvard CMT solutions (Harvard University Moment Tensor catalogue (CMT project) and data set available at http://www.seismology.harvard.edu/CMTsearch.html). JS: Jiroft Sabzevaran fault system; ZMP: Zendan–Minab–Palami fault system; NG: Nayband-Gowk fault system; MZT: Main Zagros Thrust.

Figure 2. Simplified structural and tectonic map of the Zagros–Makran transition zone from Regard et al. (2004). Black filled circles indicate the location of the GPS sites. Note the sigmoid shape of the folds in the southeastern Zagros.

2 TECTONIC AND SEISMICITY SETTINGS

The Zagros fold and thrust belt has been an active continental collision since the Neogene. It corresponds to a thick and deformed continental accretionary prism within the Arabian plate. Its southeastern termination coincides with EW-trending folds and thrusts (Blanc et al. 2003) crossed by NNW and NE strike-slip faults (Hessami et al. 2001). The SE Zagros shows very intense but low-magnitude seismicity. This seismicity is limited to the north by the Main Zagros Thrust (MZT) (Fig. 1). Several focal mechanisms are located at 8–14 km depth within the basement (Jackson & Fitch 1981; Baker et al. 1993). They are related to steep reverse faults with EW striking nodal planes and NE–SW-trending left-lateral displacement. To the north, the Central Iranian Plateau (CIP), called also Central Iranian Block, is considered to be a quasi-rigid block on the basis of seismological (Jackson & McKenzie 1988) and GPS observations (Vernant et al. 2004). To the East, the remnant Tethys oceanic lithosphere has been subducted northwards since the Cretaceous beneath the Makran coast, leading to the accretion of a large amount of subaerial and submarine sediments. The present-day seismicity of the Makran is low. Large magnitude events are related to the down going plate at intermediate depths or to superficial large historical earthquakes in eastern Makran (Byrne et al. 1992).

Between the Zagros and the Makran, the ZMP fault system is 20–30 km wide and 250 km long, and it is composed of three parallel faults (Fig. 2). The ZMP faults are linked to the MZT to the north and to the western end of the Makran prism to the south. It lines up with the Arabian continental shelf edge that borders the east side of the Musandam peninsula (Ravaut et al. 1997, 1998). The ZMP fault zone is characterized by strike-slip, oblique reverse and thrust faulting (Regard et al. 2004), and enlarges from a north single fault trace, the Zendan fault, to the south termination, the Zendan and Palami fault zone, which consist of numerous fault segments arranged in a horsetail pattern. Fault-slip analyses indicate a N45° trending compressive stress regime, which is oblique to the N10° trend of the Arabia–Iran convergence rate (Regard et al. 2004). Molinaro et al. (2005) have recently proposed that the MZT and the ZMP fault system are part of a single low-angle fault accommodating essentially dip-slip movement.

80 km to the East of the ZMP fault zone, the JS faults are characterized by a right-lateral strike-slip motion (Regard et al. 2004) similar to that for the Nayband and Gowk faults (Walker & Jackson 2002). The JS faults bend into an NW–SE orientation along the southern limit of the Jaz Murian depression (Fig. 2). Tectonic and geomorphic analyses combined with cosmoneucleide dating have revealed a total right-lateral velocity of 4.7 ± 2.0 mm yr⁻¹ or
6.3 ± 2.3 mm yr\(^{-1}\) for the Minab–Zendan fault system depending on age of fault offsets, and 5.7 ± 1.7 mm yr\(^{-1}\) for the JS fault system (Regard et al. 2005, see Table 3). The velocity of the JS fault system is larger than the 1.5–2.4 mm yr\(^{-1}\) proposed by Walker & Jackson (2002) for the Nayband fault on the base of a dated old volcanic lava flow offset by the fault.

The seismicity is mostly concentrated in the eastern Zagros and between the ZMP fault system and the JS fault zone in the north part of the transition zone (Fig. 1). Earthquakes reported by Kadinsky-Cade & Barazangi (1982) are located in the crust with a northeastward dip at 15–30 km depth, consistent with recent microseismicity studies (Yamini Fard et al. 2003). The focal mechanisms correspond to NE-trending reverse motions. This deep seismicity has been interpreted as a consequence of underthrusting of a wedge of Arabian shelf edge beneath Iranian crust or by the indentation of the Musandam Peninsula (Kadinsky-Cade & Barazangi 1982).

Contrasting with this northern zone, very low seismicity energy is released along the JS and ZMP fault zones. This is particularly the case for the ZMP fault zone south of latitude 27°N where only one teleseismic event (M\(_{W}\) = 5.9) was recorded in 1983 (Harvard University Moment Tensor catalogue (CMT project) and data set available at http://www.seismology.harvard.edu/CMTsearch.html). The focal mechanisms of the upper crustal events near the JS and ZMP fault zones, as for the 1983 earthquake, confirm the right-lateral component of the deformation along these two fault systems (Yamini Fard et al. 2003).

### 3 GPS MEASUREMENTS AND DATA PROCESSING

The GPS network consists of 15 benchmarks over a 300 × 200 km domain spanning the Zagros–Makran transition zone (Figs 2 and 3). The mean distance between sites is 60 km. The network was measured using Ashtech Z12 receivers in 2000 January and again in 2002 January. For both epochs, each benchmark was measured for 48 hr except for a few reference stations permanently installed during the campaign (JASK, MINA, HAJI in 2000 and JASK, MINA, RAZD in 2002).

Data analysis was achieved using the same processing techniques as in Vernant et al. (2004) for the Global Network of Iran. By this way, our regional network will be linked to the Global Network of Iran.

Precise site coordinates were obtained using the GAMIT/GLOBK software packages (Herring 2002; King & Bock 2002). The classical three-step approach (Feigl et al. 1993; Dong et al. 1998) was applied. During the first step, daily solutions are computed from loose \textit{a priori} constraints to all parameters (coordinates, orbital and Earth Orientation parameters) using the doubly differenced phase observations. 16 IGS stations were added to tie our local network to the ITRF2000 reference frame. The short-term precision of the solutions may be estimated by the repeatabilities corresponding to the rms of the independent daily solutions about their mean value. The horizontal repeatabilities was ∼1.7 mm in 2000 and ∼2.6 mm in 2002.

In a second step, a set of coordinates and velocities were estimated from the daily loosely constrained parameters (first step) as quasi-observations in a Kalman filter. The local quasi-observations were combined with quasi-observations at 150 globally distributed IGS stations. The daily global solutions are given by SOPAC from January 1995 to March 2002 (Bock et al. 1997) (solutions available at http://sopac.ucsd.edu). Monthly average global solutions were used during this time when no survey occurred. The last step was devoted to the estimation of a six-parameter transformation (Dong et al. 1998).

At first, GPS velocities and their 95 per cent confidence ellipses are estimated in ITRF2000. Following McClusky et al. (2000) and Vernant et al. (2004), we define a stable European reference frame by minimizing the velocities of 16 IGS stations located in Western Europe and Central Asia (see Table 1 in Vernant et al. (2004), pole coordinates 56.11 ± 1.4°N, −100.79 ± 1.9°E, rate 0.26 ± 0.01 mm yr\(^{-1}\) in ITRF2000 frame). We took into account the temporal and spatial correlation of the GPS noise (McClusky et al. 2000), by adding a coloured noise (random walk equal to 2 mm yr\(^{-1}\)) in estimating the velocities. The GPS velocities relative to ITRF2000 reference and Eurasia are given in Table 1. We chose the Arabia–Eurasia Euler vector published by Vernant et al. (2004) (27.9 ± 0.5°N, 19.5 ± 1.4°E, rate 1.41 ± 0.1 Myr\(^{-1}\)) to estimate the velocities in the Arabian reference plate. GPS velocities deduced from the GPS Global Network of Iran (sites LAMB, JASK, KHAS, ZABO, BAZM, CHAB, KERM, HAR, 1999 and 2001 campaigns) complete our local results (Vernant et al. 2004). The final GPS velocities with respect to Arabia are shown on Fig. 3 (see also Table 1). Very small changes are observed in the estimated velocities when Eulerian poles published by Sella et al. (2002) and McClusky et al. (2003) are used (rms of 0.5 mm yr\(^{-1}\) on the residual velocities).

### 4 GPS HORIZONTAL VELOCITY ANALYSIS

In the Eurasia fixed reference frame, velocities are uniformly oriented N 10° over the transition zone, as attested by the large north
component of the velocities (Table 1). The HAJI velocity is not presented here because its trend is not consistent with the very close RADZ velocity. This discrepancy cannot be explained by the local tectonic conditions and is probably originated from the instability of the HAJI site during the 2000–2002 epoch. JASK is the single site belonging to the Global Network of Iran and to our network. Increasing and densifying the total length of GPS observation for JASK from 1999–2001 to 1999–2000–2001–2002 epoch does not change significantly the velocity estimated during the two epochs (see Table 1 and Vernant et al. 2004). Near the Strait of Hormuz, the site BAGH is characterized by a velocity of 25.3 ± 2 mm yr\(^{-1}\) consistent with velocities of 22.5 and 24.5 mm yr\(^{-1}\) estimated at sites LAMB and BAGH by Vernant et al. (2004) from GPS measurements in 1999 and 2001 of the Iran Global Network. From the coast (BAGH) to the MZT (DENA, RAZD), the rate of shortening is 3.3 mm yr\(^{-1}\) and 3.6 mm yr\(^{-1}\), respectively, between the sites MINA and GHOL.

From the velocities of the sites SORC and GHOL, we estimate 3.1 ± 2.5 mm yr\(^{-1}\) to be the total dextral strike-slip displacement along the north–south JS fault system. Velocities for the eastern coastal sites GENO, SARZ, MINA and POOS are `radially oriented`: the vectors point towards the strait of Hormuz with a maximum at SARZ (7.3 ± 2 mm yr\(^{-1}\)) in a southwest direction. RAZD, DENA, HARA and KERM are characterized by a referenced Arabia velocity of 10 ± 2 mm yr\(^{-1}\) and belong to the southeast extremity of the rigid CIP on the base of the seismological observations (Fig. 1). We have tested this assumption by using the Euler pole of the CIP relative to Eurasia published by Vernant et al. (2004) (23.15 ± 13.2° N, 0.98 ± 1.2° E, rate 0.189 ± 0.1 Myr\(^{-1}\)).

The residual velocities are within the 1σ uncertainties and indicate a small deformation at the SE end of the CIP. We also confirm the eastward increase of the N10° trending shortening rate along the Makran subduction, from 11 ± 2 mm yr\(^{-1}\) for JASK at the western end of the accretionary wedge to 19 ± 2 mm yr\(^{-1}\) for CHAH.

### 5 DISCUSSION

The study area corresponds to a major tectonic discontinuity between the Eastern Zagros mountains and the oceanic Makran subduction zone which accommodate about 50 per cent and 80 per cent, respectively, of the Arabia–Eurasia convergence. In order to better understand the distribution of the horizontal deformation, we adopt a continuous approach to describe the strain rates over the transition zone, being aware of the limits of such assumption when the deformation is localized along faults, as for instance the ZMP fault or JS fault systems. The principal strain rate axes and the rotation rates have been calculated within each triangle from the velocities observed in the corners (Figs 4a and b).

**Table 1.** GPS site velocities and 1σ uncertainties. Longitude (Lon.) and Latitude (Lat.) are given in degrees east and north, respectively. Velocities and uncertainties in mm yr\(^{-1}\). Following Vernant et al. (2004), the Eurasia frame is chosen by minimizing the adjustments to the horizontal velocities of 14 IGS stations located in Western Europe and characterized by a priori zero velocities. The a priori velocities of IGS stations POL2 and KIT3 are fixed to 2 mm yr\(^{-1}\). N and 0.5 mm yr\(^{-1}\).

| Site   | Lon.  | Lat.   | Velocity/Eurasia | Uncertainty | ρ\(^a\) | Velocity/Arabia | Velocity/ITRF2000 |
|--------|-------|--------|-------------------|-------------|--------|----------------|------------------|
|        | E     | N      | E vel.            | N vel.      | E vel. | N vel.         | E vel.           |
| BAGH   | 55.657| 27.000 | 5.14              | 24.77       | 2.08   | 1.79           | 0.030            | 0.90             | 1.00 | 33.52 | 30.90 |
| BAZM   | 60.180| 27.865 | 5.33              | 2.06        | 1.62   | 0.038          | 0.075            | -23.15           | 33.60 | 8.28  |
| CHAB   | 66.694| 25.300 | 1.39              | 7.82        | 1.90   | 1.56           | 0.038            | -4.94            | -18.72| 30.84 | 13.24 |
| DENA   | 56.504| 28.529 | 4.38              | 15.50       | 1.98   | 1.73           | 0.023            | 1.00             | -8.75 | 32.85 | 21.30 |
| FINO   | 55.767| 27.635 | 1.79              | 19.73       | 2.04   | 1.78           | 0.026            | -2.05            | -4.16 | 30.22 | 25.76 |
| GENO   | 56.162| 27.366 | 4.25              | 21.70       | 2.04   | 1.79           | 0.027            | 0.16             | -2.36 | 32.69 | 27.66 |
| GHOL   | 57.217| 28.010 | 2.06              | 16.27       | 1.90   | 1.67           | 0.029            | -1.81            | -8.38 | 30.46 | 22.04 |
| HARA   | 54.608| 30.079 | 1.99              | 15.88       | 1.72   | 1.52           | 0.033            | 0.05             | -7.29 | 30.23 | 22.38 |
| JASK   | 57.767| 25.636 | 2.78              | 14.24       | 1.71   | 1.48           | 0.040            | -2.77            | -10.71| 30.92 | 20.21 |
| KERM   | 57.119| 30.277 | 1.58              | 16.07       | 2.51   | 1.71           | 0.043            | -0.75            | -8.52 | 29.68 | 21.90 |
| KHAS   | 56.233| 26.208 | 5.22              | 24.40       | 1.94   | 1.56           | 0.036            | 0.34             | 0.30  | 33.21 | 30.49 |
| LAMB   | 54.004| 26.883 | 2.99              | 22.30       | 2.02   | 1.58           | 0.031            | -0.06            | -0.02 | 30.88 | 28.79 |
| MINA   | 57.100| 27.160 | 1.36              | 23.36       | 1.89   | 1.64           | 0.030            | -3.05            | -1.22 | 29.72 | 29.18 |
| MOSH   | 57.620| 26.993 | 1.21              | 14.26       | 1.93   | 1.69           | 0.029            | -3.41            | -10.61| 29.48 | 20.02 |
| POOS   | 57.237| 26.379 | 2.58              | 24.18       | 2.01   | 1.75           | 0.029            | -2.37            | -0.48 | 30.83 | 30.07 |
| RAZD   | 55.800| 28.330 | 3.11              | 15.82       | 1.82   | 1.59           | 0.029            | -0.26            | -8.03 | 31.60 | 21.84 |
| SARZ   | 56.946| 27.488 | -1.33             | 19.70       | 1.99   | 1.75           | 0.026            | -5.49            | -4.80 | 27.01 | 25.52 |
| SORC   | 57.884| 27.901 | 1.60              | 13.73       | 1.97   | 1.69           | 0.031            | -2.47            | -11.29| 30.05 | 19.34 |
| ZABO   | 62.517| 31.049 | 0.89              | 0.57        | 1.58   | 1.45           | 0.006            | -2.70            | -27.03| 29.36 | 5.59  |

\(^a\)1σ uncertainties.

\(^b\)Correlation coefficient between the east and the north uncertainties.
Comparison of the seismic, geodetic and tectonic deformation is important for better understanding the style, direction and rate of geological deformation. This approach may be critical since strain rates estimated from earthquake focal mechanisms and GPS velocities are not representative of long-term tectonic deformation, particularly for large active faults. Seismic and geodetic deformation may be compared to estimate the seismic/geodetic strain rate. This ratio was quantified in Iran and Zagros by Jackson & McKenzie (1988) using instrumental and historical seismicity and plate kinematic models. Masson et al. (2005) have recently reestimated this ratio using geodetic strain rates estimated from available GPS data in Iran (Vernant et al. 2004). Densifying the GPS sites in the Zagros Makran transition zone in this work offered a good opportunity to compare style and direction of the geodetic and seismic strain rates. This is particularly interesting for the Zagros fold and thrust belt where earthquakes are mainly localized in the basement whereas geodetic velocities could be rather representative of motion within the sedimentary cover.

The method of analysis was formulated by Jackson & McKenzie (1988) and we refer to Kostrov (1974) for a complete formulation of the relationship between average seismic strain rate tensor and moment tensors of earthquakes occurring in a volume containing active faults. A thickness of 15 km for seismogenic layer is adopted from focal depth estimates (Jackson & McKenzie 1988; Hatzfeld et al. 2003). We take a modulus of rigidity of $3 \times 10^{10}$ Pa. The seismic strain rate is computed for each triangle shown in Fig. 4, using earthquakes from the Harvard centroid moment tensor catalogue for the time period 1976–2004 (depth of earthquakes < 15 km). Because we use a relatively small earthquake data set, Fig. 5 shows geodetic and seismic strain rate axes normalized to the maximum value. This representation allows a comparison of the direction and style of the geodetic and seismic strains, even if the seismic strain is small. In most of the triangles the fix and style of the geodetic and seismic strains are roughly similar. This agreement is particularly noticeable in Zagros (triangles 2, 3, 7, 8), in the JS fault system area (5, 6) and along the ZMP fault system (14). Around the Hormuz Strait a more complex pattern is observed. While the geodetic compressive strain is rotated eastwards, the seismic strain indicates mainly a NS compressive component (10, 11, 12, 13).

The Arabian plate is weakly deformed beneath the Persian gulf as attested by the very low deformation of triangles LAMB–BAGH–KHAS and BAGH–GENO–KHAS. Shortening of the sedimentary cover is mainly accommodated in the Zagros fold belt by an arcuate pattern of folds. Balanced cross-sections across the highly
deformed sedimentary cover in Central Zagros yield a NE-trending shortening rate of 10 mm yr$^{-1}$ since 5 Ma (Blanc et al. 2003), in agreement with our estimation for the present-day shortening velocity. The NS orientation of the geotectonic compressive strain axes are roughly perpendicular to the fold axes (Fig. 4a). The consistency between the geodetic and seismic strain rate tensors in Zagros (see triangles 2, 3, 7, 8 in Fig. 5) indicates a strong mechanical coupling between the folded and thrustsedimented cover and the basement. Many authors pointed out the role of the basement strike-slip faults in the building of the Zagros folds (Berberian 1995; Hessami et al. 2001). In the SE Zagros, Hessami et al. (2001) have depicted two strike-slip fault systems implying that fault-bounded basement blocks and cover may have rotated anticlockwise in the northern part and clockwise in the southern part. The anticlockwise rotations observed for the triangles LAMB–FINO–BAGH, BAGH–FINO–GENO and GENO–SARZ–MINA (Fig. 4b) do not confirm such a hypothesis. In the same area, Aubourg et al. (2004) emphasized the sigmoidal shape of the post Miocene folds (Fig. 2) and explained this trend by the existence of an offshore NE-trending left-lateral shear band. Geodetic survey gives no evidence for such a deformation over the Strait of Hormuz (Fig. 3 and Fig. 4a).

Further East of the Zagros, towards the ZMP and JS fault systems, a rotation of the compressive axis is identified from a roughly NS Zagros orientation to a N45° compressive strain regime (Figs 4a and 5). This shortening fan shaped pattern is also revealed by the orientation of the Neogene and younger folds along the coast line (Fig. 2) and the magnetic fabric of weakly deformed sedimentary rocks from Zagros–Makran zone (Aubourg et al. 2004): the anisotropy of magnetic susceptibility (AMS) shortening direction varies from N350° W in the SE Zagros to N60° towards the Makran zone. The velocities at GENO, SARZ, MINA and POOS are perpendicular to the Neogene and younger fold axes along the coast line and predict compressive structures in the eastern part of the Strait of Hormuz. From sandbox experiments, Dominguez et al. (2000) have analysed stress and deformation of accretionary wedges in response to seamount subduction. They showed that the indentation of the margin occurs above the leading slope of the seamount. Conjugate shear zones associated with strike-slip faults trending oblique to the direction of convergence suggest that compressive stress axes σ1 converges in the wake of the seamount whereas extensional stress axes σ3 tend to parallel the relative plate motion in the wake of the seamount (see Fig. 10 in Dominguez et al. 2000). The NNE-trending structures of the Musandam mountains could act as an ‘elongated seamount’ subducting beneath the Strait of Hormuz in the N10° direction. Therefore, the topography of the Musandam could be the cause of the margin reentrant, as attested by the curvature of the Iranian coastal line and fold axes. This model could also explain the sigmoidal shape of the folds in the southeastern part of the Zagros (Aubourg et al. 2004) and the orientation of compressional axes observed by AMS technique (Aubourg et al. 2004) and by GPS.

Along the ZMP fault system, large clockwise rotations (4–6° Ma$^{-1}$) and strain rates (3–4 10$^{-15}$ s$^{-1}$) are assumed to be lower bounds since the deformation is located over a band width less than 20 km (Fig. 3b). Both strain axes and infinitesimal rotations clearly illustrate the major part of the dextral strike-slip component of the present day motion along the ZMP fault system. Such a result is not compatible with a present-day purely dip-slip movement predicted for the Zendan fault by Molinari et al. (2005). The N45° compressive strain is in agreement with the N60° trend of the seismic compressive component (see triangle 14 in Fig. 15) and the N45° direction of the σ1 stress axis direction estimated by Regard et al. (2004) from fault-slip vector analyses along the ZMP fault system. The transpressive character of the present-day tectonic regime evoked by Regard et al. (2004) is consistent with the distribution of the velocities at sites near the ZMP fault system (Fig. 3): the obliquity of the N10° trending velocity field in the western Makran with respect to the N160° or N140° strikes of the ZMP fault system may generate a displacement perpendicular to the faults. We have shown that the strike-slip motion increases southwards and could be distributed over a large area where the Zendan and Palami faults split in several fault zones around the Jask region (Fig. 2). Regard et al. (2005) propose that the northern part of ZMP fault system accommodates a convergence velocity of 5.6 ± 2.3 or 7.4 ± 2.7 mm yr$^{-1}$ in the direction N11 ± 24° or N13 ± 26°, depending on the shear rate considered for the Zendan fault. They estimate the mean shortening along the northern ZMP fault system to be ~1 mm yr$^{-1}$. Following the GPS results, this shortening is underestimated and may reach ~3 mm yr$^{-1}$. The purely strike-slip motion observed between SARZ and GHOL is not in contradiction with the existence of a reverse component in this area since it is related to the deformation along the Zendan Palami faults. Shortening is clearly observed at SARZ site and may be partly accommodated by the Minab fault.

The ZMP fault zone is paradoxically aseismic in western Makran (Fig. 2). It is possible that the ZMP fault zone experiences aseismic creep at all times or is locked at the present day. In this case, the ZMP fault system could rupture over a large distance with a slip release corresponding to Mx > 7, if the last earthquake occurred as long ago as 1483 (Byrne et al. 1992). Molinari et al. (2005) suggest that the basement is not involved in the deformation of the ZMP fault system. For these authors, the Zendan fault has a shallow low-angle geometry and accommodate mainly dip-slip movement. If the geodetic velocity shows that the first order motion is right-lateral strike-slip for the ZMP system, we cannot exclude that the ZMP fault system could root eastwards as proposed by Molinari et al. (2005).

We have used a block model (Meade et al. 2002; Meade & Hager 2005) to test the effects of a eastward-dipping fault system, and the depth of locking along the ZMP fault system. A very simple model is chosen consisting of three elastic blocks, the Arabian plate, the Central Iranian plateau and the Lut-Makran Block, separated by the MZT, the ZMP and JS fault systems and the southern limit of the Makran wedge. We assume that the MZT and the JS fault systems are vertical and the frontal thrust of the Makran wedge dips northwards at 45° (Ravaut et al. 1997). Our model does not attempt to model the strain distribution over the SE Zagros where the deformation is distributed over the belt. We will focus our analysis on the central part of the ZMP fault system, assuming that the models will be strongly dependent on the mechanical and geometrical properties of the ZMP fault system. The model includes the effect of block rotation and elastic strain accumulation consistent with a simple model of the earthquake cycle. We invert the geodetic data, including the GPS sites on the Arabian plate (Vernant et al. 2004), to compute the Euler vectors of rotation of the blocks. The fault-slip rate at the ZMP fault system boundary is given by the difference of motion between the Arabian plate and the Lut-Makran Block. Using Okada’s (1985) solution, the interseismic elastic effect of each fault segment limiting the blocks is computed. The elastic deformation associated with the ZMP fault system depends on the dip and the locking depth of the faults. Locking depth of 15 km is chosen for all the other segments. Elastic strain associated with the ZMP fault system has been computed along a N70° trending profile located at 26.5°. We have tested various inclinations for the ZMP fault system and the results not presented here indicate that the measured fault parallel velocities cannot be explained by dips of less than
Figure 6. Fault-parallel and fault normal velocities to the ZMP fault system. The azimuth of the faults is N160°. The observed velocities presented in Table 1 have been projected onto a N70° trending profile crossing the ZMP faults at 26.5° N. We use a block model approach (Meade et al. 2002; Meade & Hager 2005) to estimate secular fault-slip rate, geometry and locking depth of the ZMP fault system. We assume that the ZMP faults accommodate the motion between the Arabian plate and the Makran–Lut Block. The block model takes into account the effects of the block rotation and elastic strain accumulation on the velocity. The theoretical velocities are estimated for faults dipping to the east with an inclination of 45°. The plotted curves correspond to locking depth of 5, 10 and 15 km.

At a larger scale, the ZMP, the JS–NG and Neh–Zahedan fault systems transfer the shortening in Iran from the western part where the deformation is widely distributed from the Zagros mountains to the Caspian sea, to the East where the Makran subduction mostly accommodates the deformation.

The tectonic setting in the ZMP transfer zone differs from the JS fault system as it connects the Zagros and Makran wedges whereas the JS one and its northward prolongation, the NG fault system, transfers some deformation from the Makran subduction to the north of Iran. How can we explain the large differential motion along the ZMP fault system? We have proposed previously the possible role of the Musandam Peninsula acting as an indenter of the Arabia into the Iranian crust. Moreover, simultaneous deformation of the continental and oceanic accretionary prisms is partly governed by the frictional property of their associated substrates. Lateral variations in the rheology of the detachments beneath the prisms could result in differential propagation of the deformation front (Cotton & Koyi 2000). Experimental models suggest inflection of the deformation front as a consequence of a faster propagation above a ductile substrate relative to a frictional substrate. Inflection is also accompanied by formation of transpressive folds and faults (see Fig. 12 in Cotton & Koyi 2000). Also, the Makran zone is characterized by a large amount of unconsolidated and saturated water sediments, which may result in a low apparent friction on the detachment and may also explain the aseismic behaviour of the western Makran (Byrne et al. 1992). However, our GPS results do not bring evidence of a rapid southward propagation of the Makran prism.

3.1 ± 2.5 mm yr⁻¹ dextral strike-slip motion along the JS fault system results only from SORC and GHOL sites and, therefore, suffers from large uncertainty. Nevertheless, this result is apparently consistent with the 1.5–2.4 mm yr⁻¹ velocity for the NG fault system (Walker & Jackson 2002). However, the displacement has been estimated, respectively, at 50 km (GHOL) and 10 km (SORC) on both sides of the JS fault system. Assuming that JS fault system is presently locked, we estimate an interseismic loading rate probably lower than the long-term rate of the strike-slip motion. Therefore, our result does not conflict with the 5.7 ± 1.7 mm yr⁻¹ slip rate estimated by Regard et al. (2005).

Regard et al. (2005) evaluate the global velocity between the Musandam peninsula and the Jaz Murian to 11.2 ± 3.9 or 13.0 ± 3.9 mm yr⁻¹ with a N10° trending. It is paradoxical that this estimation is lower than the 15 mm yr⁻¹ given by the block model for the ZMP fault system only. We propose here a simpler explanation assuming that the shear velocity along the ZMP increases southwards from the MZT to the western Makran: the northern fault segments analysed by Regard et al. (2005) are roughly oriented N140° resulting in a lower strike-slip motion. The GPS right-lateral strike-slip velocities of GOHL with respect to SARZ (5.1 ± 2 mm yr⁻¹) and MINA (6.3 ± 2 mm yr⁻¹) confirm this assumption.

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6 CONCLUSIONS

On the basis of the GPS observations reported in this paper, the deformation between the Zagros and Makran mainly corresponds to a transpressive regime, with a right-lateral strike-slip motion close to the ZMP fault zone at velocity of 10 ± 3 mm yr⁻¹ which is the most important relative displacement rate observed by GPS on a single fault system in Iran. Using a simple block model, we have shown that the observed velocities are in agreement with a long-term motion between Arabian plate and the Makran–Lut Block of 15 mm yr⁻¹ for the strike-slip component and 6 mm yr⁻¹ for the shortening component on the ZMP fault system. This displacement is accompanied by right-lateral strike-slip motion along the JS fault zone at velocity of 3.1 ± 2.5 mm yr⁻¹. However, our GPS sites are too sparse to predict if the segments of the ZMP fault system are creeping aseismically or if they may rupture in large earthquakes (Ms > 7) with long recurrence times. Further GPS measurements on dense networks and INSAR investigations along the faults zone will allow us to address this question. We propose that the radial GPS velocities observed along the coastal line probably reflects the mechanical impact of the subducting Musandam Peninsula on the shortening fan pattern around the Strait of Hormuz.

At regional scale, the right-lateral motion along the ZMP may not be completely explained by local tectonic considerations. This fault system participates in the large dextral shear motion in eastern Iran, involving the JS–NG and Neh–Zahedan fault systems. These fault systems accommodate the shortening distributed on a broad deformation zone in the western Iran (Zagros, Alborz, Caspian sea, Kopet Dagh) whereas the convergence is mostly localized along the Makran subduction in the eastern part. Right-lateral strike-slip motion of NG and Neh–Zahedan fault systems remain poorly quantified and must be measured by GPS in order to better understand the distribution of right-lateral shear occurring on the borders of the Lut Block up to the Doruneh fault.

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