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The present-day deformation of the central Zagros from GPS measurements

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[1] In 1997 and in 2000, we measured the distances between 14 geodetic benchmarks across the central Zagros mountain belt. The results show that about 10 mm/yr of shortening in the central Zagros is distributed across the mountain belt. This shortening corresponds to roughly 50% of the total convergence between Arabia and Eurasia and is consistent in direction. The Persian Gulf does not deform significantly. The Main Zagros Reverse Fault is not an active kinematic boundary. The internal deformation of the folded belt is rather homogeneous, at the scale of our survey, which does not allow us to detect any individual active blind fault. However, the strain pattern suggests that N-S dextral strike slip faults may accommodate part of the deformation. **INDEX TERMS:** 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 1243 Geodesy and Gravity: Space geodetic surveys; 8107 Tectonophysics: Continental neotectonics; 8102 Tectonophysics: Continental contractional orogenic belts. **Citation:** Tatar, M., D. Hatzfeld, J. Martinod, A. Walpersdorf, M. Ghafari-Ashtiany, and J. Chéry, The present-day deformation of the central Zagros from GPS measurements, *Geophys. Res. Lett.*, 29(19), 1927, doi:10.1029/2002GL015427, 2002.

1. Introduction

[2] The Zagros mountain belt is approximately 1500 km long, 250–400 km wide, and runs from eastern Turkey, where it connects to the North- and East-Anatolian faults, to the Oman Gulf, where it dies out at the Makran subduction zone (Figure 1a). The Zagros accommodates part of the convergence between Arabia and Eurasia. Based on the indirect closure of the relative motion between the Arabia, Africa and Eurasia circuits, the NUVEL 1A model [DeMets *et al.*, 1994], predicts a roughly N-S, 30–40 mm/yr convergence between Arabia and Eurasia. The present-day shortening accommodated by the Zagros mountain belt has been deduced so far from (1) a reconstruction of the velocity vectors between Eurasia-Arabia-Iran, based on focal mechanism slip vectors, which gives a loose value of 10–15 mm/yr [Jackson and McKenzie, 1988] and (2) an uplift rate of ~1mm/yr measured from geomorphological observations

which suggests a shortening rate of 10 mm/yr [Falcon, 1974]. The seismic energy release in the Zagros does not explain more than 10% of the total deformation [Jackson and McKenzie, 1988] and the Arabia-Eurasia vector [DeMets *et al.*, 1994] systematically misfits the slip vectors of the earthquakes mechanisms located in western Zagros.

[3] The Zagros mountain belt lies on the former Arabian passive margin which is covered by up to 10 km of Cambrian to Miocene sediments [e.g. Stocklin, 1974; Haynes and McQuillan, 1974; Stoneley, 1981]. These sediments contain several thick layers of evaporite which cause decoupling of the surface deformation from the basement faults. During the Mesozoic, the Zagros has experienced a major episode of convergence, mostly accommodated by the Main Zagros Reverse Fault (MZRF) [Stocklin, 1974; Stoneley, 1981]. A second episode of deformation during the Neogene led to the folding that affected the Simple Fold belt located between the MZRF and the Persian Gulf. There is no direct measurement of the amount of relative displacement across the MZRF during the Mesozoic. Falcon [1974] estimates that 50 km of shortening has been accommodated by the Simple Fold belt during the last 5 My, which is consistent with a rate of 10 mm/yr.

[4] Several faults, or major discontinuities, are identified in the central Zagros (Figure 1b). Using the terminology proposed by Berberian [1995], the Main Recent Fault is an active right lateral strike-slip fault which follows the MZRF. This active fault is observed mostly in the northern part of the Zagros [Tchalenko and Braud, 1974; Ricou *et al.*, 1977]. There, near Dorud (Figure 1a), the Main Recent Fault offsets the MZRF of about 200 km, which would indicate a slip rate of 40 mm/yr, assuming that it has been active since 5 My. The Dorud fault segment is seismically very active [Tchalenko and Braud, 1974; Berberian, 1981]. Ricou [1974] and Ricou *et al.* [1977] suggest that the Main Recent Fault has also been active, during the Quaternary, further to the Southeast in the area of Neyriz (Figure 1a), with a total horizontal slip of about 20 km, but this southern segment is not seismically active.

[5] Clearly, the Zagros is not a linear belt experiencing pure NE-SW shortening, since an important component of strike-slip motion is observed on the Main Recent Fault in the north-western part of the chain but not southeast of Neyriz. This difference between North and central Zagros may result from the existence, within the folded belt, of NS-trending dextral strike-slip faults. The largest of these faults is the Kazerun fault responsible for a 140 km right lateral offset affecting lower Miocene terranes which implies a rate of 15 mm/yr [Berberian, 1981, 1995]. Recent earthquakes whose mechanisms show right lateral strike slip motion [Baker *et al.*, 1993] are located on the Kazerun fault. To the

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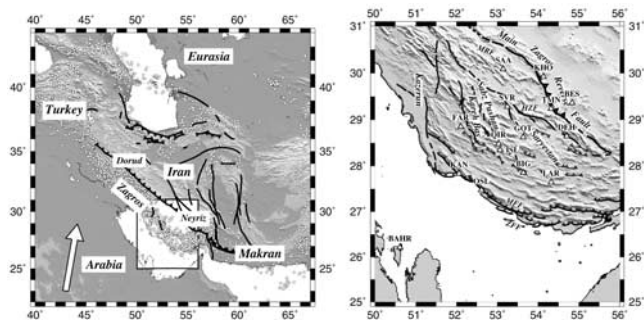


Figure 1. (a) Seismotectonic map of Iran. Iran is located between the Arabian and Eurasian plates. The arrow represents the 35 mm/yr NUVEL 1A motion of Arabia relative to Eurasia [DeMets *et al.*, 1994]. The empty dots are earthquakes of magnitude greater than 4.5 located by NEIS. The main geological faults are shown as barbed lines for reverse faults and bold lines for strike-slip faults. The rectangular box marks the location of GPS-benchmarks in the central Zagros area. (D): Dorud; (N): Neyriz. (b) Map of the central Zagros area. The main faults have been reported (barbed lines: reverse faults; bold lines: strike slip faults). MZRF: Main Zagros Reverse Fault; HZF: High Zagros Fault; MFF: Main Front Fault; ZFF: Zagros Foredeep Fault, [after Berberian, 1995]. Neyriz is located near TMN. The Simple Folded belt is located between the HZF and the MFF. The MRF is not present in this part of the Zagros. All the GPS benchmarks are reported.

East, the right lateral Karez Bas fault [Ricou, 1974] offsets the fold axes by 10 km. Further east, NNW-SSE oriented right lateral strike-slip faults (the Sabz-Pushan and Sarvestan faults) are also associated with a probable displacement yielding about 20 km for the Sarvestan Fault [Ricou, 1974].

[6] In December 1997 and February 2000, we measured a geodetic network located in the central Zagros in order to estimate the total shortening accommodated by this mountain belt. This shortening will be compared with the deformation in central Iran and in the Persian Gulf. We will study whether the deformation is homogeneous over the whole mountain belt or localised on individual faults.

2. Data

[7] The purpose of the GPS campaign was to obtain a first-order estimate of the present-day deformation in the Zagros, from stable Arabia to central Iran, across the Main Zagros Reverse Fault. Because of the limited availability of GPS receivers and of logistical problems, we decided to re-occupy a network of GPS benchmarks installed by the Iranian National Cartographic Center (NCC) for mapping purposes (Figure 1b). We measured 14 benchmarks during two surveys two years apart. During the first campaign in December 1997, we deployed 4 dual frequency Ashtech Z12 receivers. One receiver was recording continuously at QIR, the 3 other receivers were installed on different benchmarks for sessions of 4 to 46 hours with an average of 15 hours. A few benchmarks were measured twice. During the second survey in February 2000, we deployed 8 dual frequency Ashtech Z12 receivers. One receiver was again installed permanently at QIR. The other receivers were deployed for sessions that lasted 60 hours on average.

[8] The data processing was performed independently using the BERNSE [Rothacher *et al.*, 1993] and the GAMIT [King and Bock, 1995] software packages. For the GAMIT solution, data from the International GPS Service stations (IGS) were used to locate our network within the International Terrestrial Reference Frame [ITRF; Boucher *et al.*, 1996]. We used 23 and 4 IGS stations (for GAMIT and BERNSE, respectively) and we held IGS final orbits fixed. We accounted for tropospheric variability by estimating new zenith delays every 3 hours and modelled antenna phase center variations using IGS tables. The comparison with the BERNSE independent analysis solution accounts for possible software bias or difference in the reference systems. We found an average difference of 2 mm/yr and a systematic pattern corresponding to a slight rotation of the local network within the reference system due to the different number of IGS stations.

[9] An estimate of the short term precision of the measurements is the repeatability of baseline results calculated from independent measurement sessions. For the 2000 campaign, the mean repeatability of the horizontal components in the local 500 km network is 1 mm in the GAMIT solution. In the 1997 campaign, only a few baselines were measured more than once, indicating repeatabilities of 3 mm on horizontal components in the local network. These short term errors can be used to estimate the accuracy of the relative displacement rates within the local network: the root mean square of the repeatabilities of the 1997 and 2000 campaigns divided by the 2 years time span is 1.5 mm/yr.

[10] These estimates do not take into account long term errors which dominate most of the GPS analyses [e.g. McClusky *et al.*, 2000]. An estimate of the total errors can be obtained by comparing the velocities for stations in presumably non-deforming regions (QIR/ISL on one hand, KHO/BES on the other hand). The one-sigma (68% confidence) error in each horizontal component for the two pairs of stations is less than 1 mm/yr. However, two pairs of stations are few to infer the total error for the entire network.

[11] A reasonable estimate of the total uncertainties is therefore 1–1.5 mm/yr, but it does not take into account systematic errors which are undetectable with only 2 measurement epochs. For instance, we observe an inconsistent motion for BIG which could be due to several reasons (bad data, monument instability, blunder...).

[12] The standard deviation of the horizontal displacement rates (Figure 2a, and Table 1), evaluated formally by a Kalman filter (GLOBK) in a Eurasian reference frame to a mean of 1 mm/yr is therefore a reasonable value.

3. Results

[13] The displacement rates of the GAMIT solution are given in Table 1. We plotted, in Figure 2a, the velocities of the different benchmarks relative to the point BES (considered as fixed) located in central Iran.

[14] We observe that:

1. The velocity of KHO (also located in central Iran) relative to BES is 0.6 ± 0.9 mm/yr, which suggests that the motion of BES and KHO is representative of the motion of the central Iranian block.

2. The velocity of BES and KHO, relative to the IGS stations located in Eurasia, is 15 ± 1 mm/yr and trends $30^\circ \pm 4^\circ$ northwestward.

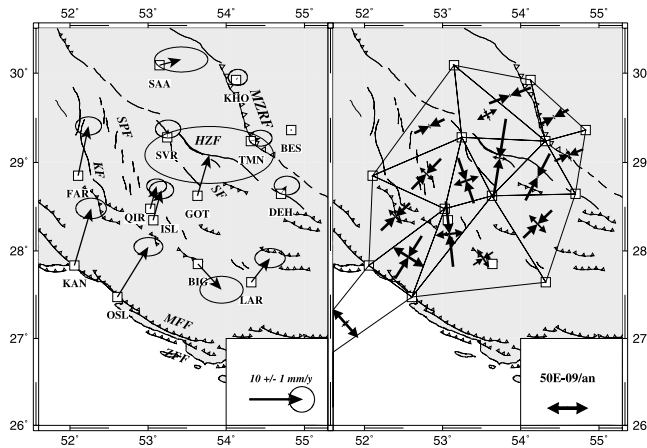


Figure 2. (a) Map of the displacement rates of the benchmarks relative to BES located in central Iran. The ellipses show regions of 95% confidence corresponding to the one-sigma uncertainties given for each component in Table 1. MZR is Main Zagros Reverse Fault, SF is Sarvestan Fault, KF is Kareh Bas Fault. (b) Strain rates computed for triangles defined by 3 benchmarks. Convergent arrows mark shortening, while divergent arrows mark extension. We did not include the station BIG whose motion seems inconsistent. No significant deformation is observed for the Persian Gulf.

3. Benchmarks located near BES, but on the southern side of the MZR (SAA, TMN, DEH) do not move significantly with respect to those located in central Iran, suggesting that this part of the Main Zagros Reverse Fault is not a major active structure.

4. The velocity of the benchmarks located on the coast of the Persian Gulf (KAN and OSL) with respect to BES is about 10 ± 4 mm/yr.

5. The Zagros benchmarks move in a NNE direction relative to central Iran.

6. We observe a decrease in velocity, relative to central Iran, across the Zagros from a maximum at sites on the Arabian plate.

7. The velocity of the IGS station BAHR, located on the Arabian plate, relative to KAN and OSL, is less than 5 mm/yr in a NW direction, suggesting that the Persian Gulf does not experience much shortening.

8. The velocity of BAHR relative to 12 IGS Eurasian stations located in stable areas (CAGL, GRAS, HFKL, JOZE, KOSG, MATE, METS, PENC, SOFI, WSRT, ZECK, ZIMM) is 21 mm/yr NNE.

[15] Indeed, a third measurement campaign is necessary to identify systematic errors and quantify more precisely the accuracy of our velocity field. However, we observe a clear consistency in the velocity pattern for most stations and no significant displacement between stations located in undeformed regions. Therefore, we think that our observations are adequate to support our conclusions.

4. Discussion

[16] The Zagros represents the deforming part of the Arabian platform as attested by the active seismicity and the folded upper layer of sediments. The motion of the benchmarks KAN and OSL on the coast of the Persian Gulf seems to be close to that of the stable Arabian platform. Therefore, the total amount of shortening, measured between the stations KHO and BES on one side, and KAN and OSL on the other, represents an estimate of the shortening that affects the central Zagros as a whole. We measure a present-day shortening rate of about 10 mm/yr for the central Zagros which is consistent with geomorphological observations [Falcon, 1974]. The shortening between Arabia and Eurasia can be estimated from the IGS stations to be approximately 21 mm/yr [consistent with the results of McClusky *et al.*, 2000]. This value and orientation are also supported by the results of another experiment including several benchmarks on Arabia [Vernant *et al.*, 2002]. This means that about 50% of the total convergence between Arabia and Eurasia is accommodated in the Zagros mountain belt.

[17] The MZR is a very important geological discontinuity, related to the geodynamics that prevailed during the Mesozoic. It corresponds to a former subduction zone that accommodated the convergence between Arabia and Eur-

Table 1. Station Velocities Calculated Relative to Eurasia and to BES

Site	Lon E	Lat N	Vel/Eurasia		σ mm/yr		δ	Vel/BES		σ mm/yr	
			E	N	E	N		E	N	E	N
BAHR	50.608	26.209	1.8	20.6	.4	.2	-.20	10.20	8.45	.8	.5
BES	54.832	29.363	-8.0	13.5	.8	.5	-.00	0	0	.0	.0
BIG	53.637	27.852	-3.4	8.0	1.5	.9	-.12	4.54	-4.96	1.7	1.1
DEH	54.700	28.645	-6.9	14.9	.7	.6	-.00	1.14	1.61	1.0	.7
FAR	52.106	28.851	-6.1	22.5	.7	.5	.04	1.99	9.54	1.0	.7
GOT	53.631	28.624	-5.9	21.0	5.0	2.2	.11	2.27	7.84	5.0	2.2
KAN	52.056	27.834	-5.1	23.6	.9	.6	.08	3.23	10.95	1.2	.8
KHO	54.126	29.923	-7.7	14.1	.8	.5	.02	.34	.50	.8	.6
ISL	53.066	28.347	-6.3	18.9	.6	.5	-.02	1.60	5.81	1.0	.7
LAR	54.320	27.644	-4.3	17.7	1.0	.6	.01	3.61	4.62	1.2	.8
OSL	52.607	27.474	-2.3	22.4	.9	.5	.10	5.96	9.66	1.1	.7
QIR	53.029	28.477	-6.9	17.3	.5	.3	-.06	1.21	4.36	.8	.6
SAA	53.146	30.087	-4.4	14.4	1.9	.9	-.20	4.18	1.11	2.1	1.0
SVR	53.244	29.281	-7.9	14.8	.7	.5	-.02	.18	1.61	1.0	.7
TMN	54.316	29.239	-6.2	13.9	.6	.4	.01	1.85	.56	.9	.6

Latitude and Longitude are given in degrees north and east, respectively. Station velocities are given in mm/yr. The Eurasian frame is determined by 12 IGS stations located on stable areas. σ is the 1 sigma uncertainties and δ is the correlation coefficient between north and east uncertainties for the Eurasian frame.

sia. However, the motion of SAA, DEH and TMN, relative to KHO and BES is not significant. Therefore, it seems that this part of the MZRF is inactive in the central Zagros.

[18] To study the geographical repartition of the Zagros internal deformation, we computed the strain-rate for triangular cells formed by sets of 3 neighbouring benchmarks, excluding the anomalous motion at BIG (Figure 2b). Although our network of benchmarks does not allow a detailed analysis, we observe that the shortening accommodated by the Zagros seems to be homogeneously distributed from the coast to central Iran. The shortening rate, and the azimuth trending NNE-SSW, are roughly similar for all triangles. This NNE-SSW shortening is associated to a consistent pattern of stretching trending approximately WNW-ESE, except for the triangles located across the MZRF. This combination of shortening and stretching results from strike slip motion and corresponds probably to the activity of the Karez-Bas and Sabs-Pushan strike-slip fault zones. These faults contribute to transfer part of the present-day shortening, from the high regions of the NW Zagros to the external (lower) parts of the SE Zagros.

5. Conclusion

[19] The geodetic measurements across the central Zagros mountain belt indicate that (at the scale of our network) the shallow part of the Zagros, consisting of a thick layer of sediments, responds to the shortening by distributed deformation. The total present-day shortening is about 10 mm/yr, trends NNE-SSW, and therefore accommodates about 50% of the total 21 mm/yr convergence between Arabia and Eurasia as deduced from the IGS stations. The Persian Gulf does not seem to deform as much as the Zagros mountains, which is consistent with the lack of seismicity. The Main Zagros Reverse Fault, which is the main structural boundary between Arabia and central Iran, seems to be inactive. However, the Karez-Bas and Sabs Pushan strike slip fault zones seem to contribute to the total active deformation which affects the central Zagros.

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References

- Baker, C., J. Jackson, and K. Priestley, Earthquakes on the Kazerun Line in the Zagros Mountains of Iran: Strike-slip faulting within a fold-and-thrust belt, *Geophys. J. Int.*, *115*, 41–61, 1993.
- Berberian, M., Active faulting and tectonics of Iran, in *Zagros-Hindu-Kush-Himalaya Geodynamic evolution*, edited by H. K. Gupta and F. M. Delany, *Am. Geophys. Union, Geodyn. Ser.*, *3*, 33–69, 1981.
- Berberian, M., Master blind thrust faults hidden under the Zagros folds: Active basement tectonics and surface morphotectonics, *Tectonophysics*, *241*, 193–224, 1995.
- Boucher, C., Z. Altimimi, M. Feissel, and P. Sillard, Results and analysis of the ITRF94, *IERS technical note 20*, *Observatoire de Paris*, 1996.
- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, 1994.
- Falcon, N., Southern Iran: Zagros Mountains, in *Mesozoic-Cenozoic Orogenic Belts*, edited by A. M. Spencer, *Sp. Pub. Geol. Soc. London*, *4*, 199–211, 1974.
- Haynes, S. J., and H. McQuillan, Evolution of the Zagros suture zone, southern Iran, *Bull. Geol. Soc. Am.*, *85*, 739–744, 1974.
- Jackson, J., and D. McKenzie, The relationship between plate motions and seismic moment tensors and the rates of active deformation in the Mediterranean and Middle East, *Geophys. J. R. Astr. Soc. London*, *83*, 45–73, 1988.
- King, R. W., and Y. Bock, Documentation for the Gamit analysis software, release 9.4, Mass. Inst. of Tech, Cambridge, 1995.
- McClusky, S., et al., Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. Geophys. Res.*, *105*, 5695–5719, 2000.
- Ricou, L. E., L'évolution géologique de la région de Neyriz (Zagros iraniens) et l'évolution structurale des zagrides, Thèse, Université d'Orsay, France, 1974.
- Ricou, L. E., J. Braud, and J. H. Brunn, Le Zagros, *Mém. h. Sér. Soc. Géol. Fr.*, *8*, 33–52, 1977.
- Rothacher, M., G. Beutler, W. Gurtner, E. Brockmann, and L. Mervart, Bernese GPS software version 3.4 documentation, Astronomical Institute, University of Berne, Switzerland, 1993.
- Stocklin, J., Possible ancient continental margin in Iran, in *Geology of Continental Margins*, edited by C. Burke and C. Drake, Springer-Verlag, New York, pp. 873–877, 1974.
- Stoneley, R., The geology of the Kuh-e Daldeshin area of southern Iran, and its bearing on the evolution of southern Tethys, *J. Geol. Soc. London*, *138*, 509–526, 1981.
- Tchalenko, J. S., and J. Braud, Seismicity and structure of the Zagros (Iran)—the main recent fault between 33 and 35°N, *Phil. Trans. Roy. Soc. London*, *277*, 1–25, 1974.
- Vernant, P., et al., Tectonic implications of GPS measurements in Iran (abstract), *E.G.S. 27th General assembly*, Nice, April 21–26, 2002.

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