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FAST TRACK PAPER

Large-scale velocity field and strain tensor in Iran inferred from GPS measurements: new insight for the present-day deformation pattern within NE Iran

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SUMMARY

A network of 26 GPS sites was implemented in Iran and Northern Oman to measure displacements in this part of the Arabia–Eurasia collision zone. We present the GPS velocity field obtained from three surveys performed in 1999 September, 2001 October and 2005 September and the deduced strain tensor. This study refines previous studies inferred from only the two first surveys. Improvements are significant in NE Iran. The present-day shortening rate across the mountain belts of NE Iran is estimated to 5 ± 1 mm yr^{-1} at about N11°, 2 ± 1 mm yr^{-1} of NS shortening across the eastern Kopet Dag and 3 ± 1 mm yr^{-1} of NS shortening across Binalud and Kuh-e-Sorkh. Our GPS measurements emphasize the varying character of the Kopet Dag deformation between its southeastern part with prevailing thrusting at low rates and its northwestern part with dominant strike-slip activity at increasing rates. The principal axes of the horizontal strain tensor appears very homogeneous from the Zagros to the Alborz and the Kopet-Dag (N20°) and in eastern Iran (Makran and Lut block: N30°). Only NW Iran suffers a variable strain pattern which seems to wrap the Caspian basin. The strain tensor map underlines the existence of large homogeneous tectonic provinces in terms of style and amplitude of the deformation.

Key words: continental collision, GPS, Iran.

1 INTRODUCTION

The present tectonics in Iran results from the north–south convergence between the plates of Arabia to the southwest and Eurasia to the northeast (Jackson & McKenzie 1984) at a rate of about 22 mm yr^{-1} (Sella *et al.* 2002). It involves a juvenile continental collision (Falcon 1974; Berberian & King 1981) except along the Makran, its southeastern margin, where a remnant part of the Tethys oceanic lithosphere subducts northward beneath southeast Iran (Byrne *et al.* 1992) (Fig. 1a). Within Iran, most of the deformation is accommodated in the major belts (Zagros, Alborz and Kopet-Dag) and along large strike-slip faults which surround blocks (Central Iran, Lut and the southern Caspian sea) with moderate relief and seismicity (Jackson & McKenzie 1984; Berberian & Yeats 1999). We present the results of three campaigns of GPS measurements (1999 September, 2001 October and 2005 September) of a network of 26 benchmarks in Iran and Oman. This data set provides an up-to-date direct measurement of the current displacement rates inside the Arabia–Eurasia plate boundary zone. It allows the determination of an accurate strain rate tensor. It complements and improves the precision of previous studies (Nilforoushan *et al.* 2003; Vernant *et al.* 2004a; Masson *et al.* 2005) based on only the two first campaigns.

2 GPS MEASUREMENTS AND DATA PROCESSING

A GPS network of 26 points has been installed and surveyed within the framework of French Iranian cooperation (Nilforoushan *et al.* 2003). The sites are homogeneously distributed in Iran and Oman. Most of the GPS benchmarks are setup on geodetically designed

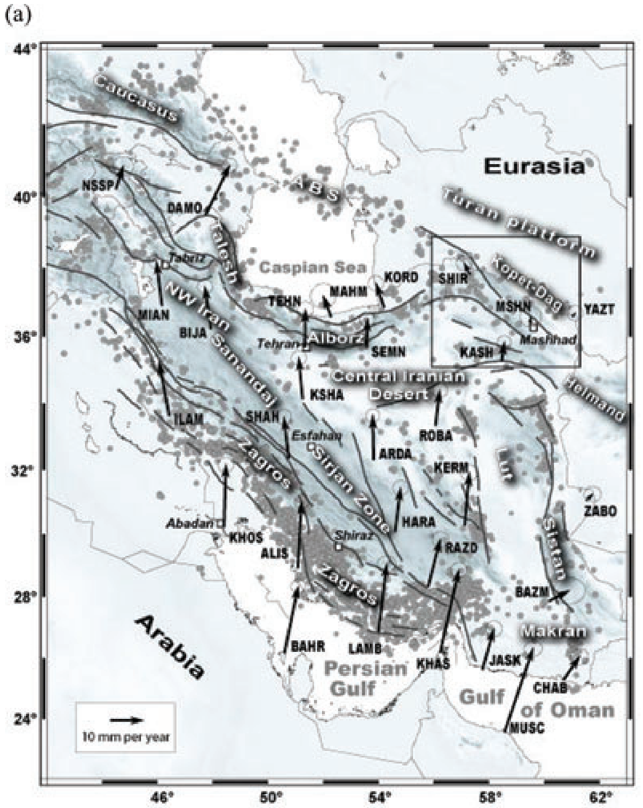

Figure 1. (a) GPS horizontal velocities in a Eurasia-fixed reference frame and their 95 per cent confidence ellipses superimposed on the topographic map of the studied area. GPS stations are indicated by capital letters, and major geological structures are labelled. Earthquake distribution in Iran from instrumental seismicity catalogue (1964–1999, Engdahl *et al.* 1998). ABS : Apsheron–Balkhan Sill. Black square refers to Fig. 2. (b) Principal horizontal axes of the geodetic strain rate tensor obtained using the GPS velocity field of Fig. 1(a) and several velocities from McClusky *et al.* (2000).

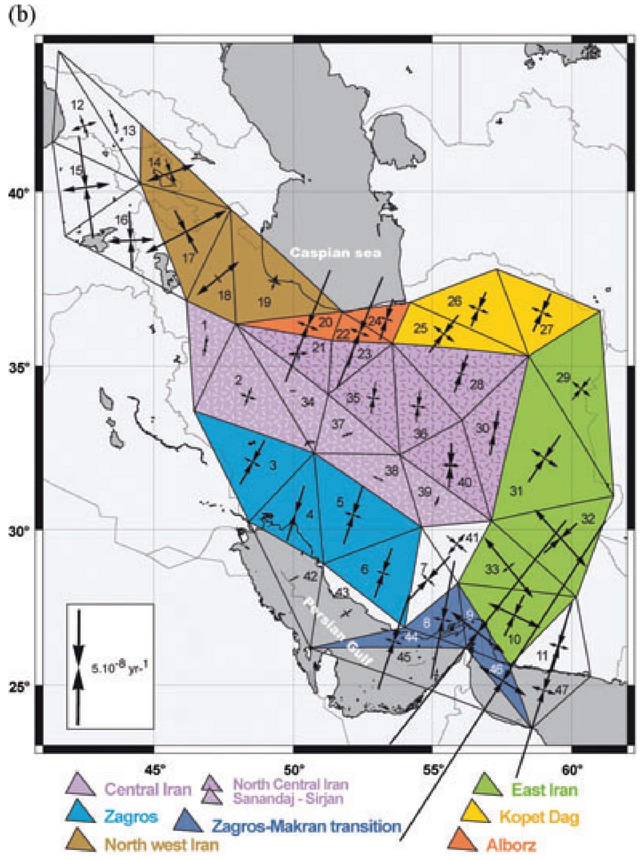

Figure 1. (*Continued.*)

pillars deeply rooted in stabilized ground. All sites but two (BAZM and RAZD) have been surveyed at least three times in 1999 September, 2001 October and 2005 during at least 72 hr. Some sites have been measured four, five or six times since 1999 thanks to some regional GPS network measurements. In order to constrain the motion of our local network relative to the surrounding plate motions, data from 16 GPS stations belonging to Eurasian and Arabian plates have been added to our local data. We also add the data of two Iranian permanent GPS stations (TEHN and MSHN). Data analysis was done using GAMIT, version 10.05 (King & Bock 2002) and GLOBK, version 10.0 (Herring 2002). Details about the processing of the data are given by Vernant *et al.* (2004a). We infer a long-term error of about 1 mm yr^{-1} for the velocities of the sites measured from 1999 to 2005. In order to interpret our results in the framework of Arabia–Eurasia collision, we express the velocities with respect to stable Eurasia. According to McClusky *et al.* (2000), we minimize the site velocity of 14 Eurasian sites spanning between 0° and 40° of longitude east and between 39° and 80° of latitude north. Velocities in Iran with respect to Eurasia are shown on Fig. 1(a). Velocities are given in Table 1.

3 VELOCITY FIELD

The velocity field does not differ significantly from Nilforoushan *et al.* (2003) and Vernant *et al.* (2004a), the average difference yielding 0.44 mm yr^{-1} in the EW direction and 0.26 mm yr^{-1} in the NS direction. The large decrease in the uncertainties (average standard deviation of 1.7 mm yr^{-1} in 2001 and 1.0 mm yr^{-1} in 2005) due to the increase of the time interval between the first and the last measurements allows a more confident description of Iranian tectonics. Interestingly, the new velocity vectors lie within the former error bounds, indicating that the strategy defined to determine the error is reasonable. Significant variations are observed for the site KSHA due to a measurement error in 2001 as confirmed by several intermediate measurements in 2001 and 2003 in the framework of the North Zagros network (Walpersdorf *et al.* 2006). The site TEHN has been substituted for the site TEHR and gives a value close to the one proposed by Nilforoushan *et al.* (2003).

The new velocities confirm the main results of Vernant *et al.* (2004a) with increased precision: GPS sites in Oman show northward motion of the Arabian plate relative to Eurasia of ∼21 mm yr^{-1} at the longitude of Bahrain. East of 58°E, most of the shortening is accommodated by the Makran subduction zone (19.5 mm yr^{-1}) and less by NE Iran (6 mm yr^{-1}). West of 58°E, the deformation is distributed in separate fold and thrust belts. At the longitude of Tehran, the Zagros and the Alborz mountain ranges accommodate 7.5 and 6 mm yr^{-1}, respectively. These results confirm recent results obtained from regional GPS networks in the Zagros (Walpersdorf *et al.* 2006) and the Alborz (Vernant *et al.* 2004b). No GPS evidence of relative displacement is shown in the Sanandaj–Sirjan zone from MIAN to KERM. This does not allow to confirm the average slip rate close to 2 mm yr^{-1} proposed by Meyer *et al.* (2006) along the Deshir fault west of HARA and ARDA. They evaluate this slip rate using cumulative morphologic offsets observed along the southern part of the fault. Large WNW–ESE right lateral displacements take

Table 1. Latitude (Lat) and Longitude (Lon) are given in degrees north and east, respectively. East and north velocity components with respect to Eurasia and their uncertainties (σ_e and σ_n) are given in mm yr^{-1}. Corr = correlation coefficient between the east and north uncertainties.

	Position		Velocity (mm yr^{-1})		Uncertainties		Corr.
Site	λ	ϕ	E	N	σ_e	σ_n	
ALIS	51.082	28.919	1.19	20.65	0.89	0.86	0.024
ARDA	53.822	32.313	−0.28	13.60	0.86	0.84	0.023
BAZM	60.180	27.865	6.24	3.20	2.02	1.65	0.018
BAHR	50.608	26.209	4.21	20.45	0.89	0.87	0.026
BIJA	47.930	36.232	−1.79	13.09	0.95	0.92	0.014
CHAB	60.694	25.300	5.05	7.23	1.11	1.02	0.024
DAMO	47.744	39.513	7.45	15.31	0.94	0.91	0.013
HARA	54.608	30.079	1.68	13.58	0.98	0.96	0.023
ILAM	46.427	33.648	−3.14	16.46	0.97	0.93	0.016
JASK	57.767	25.636	3.52	12.62	1.04	1.00	0.026
KASH	58.464	35.293	0.74	5.71	0.87	0.84	0.019
KERM	57.119	30.277	1.42	16.30	1.07	0.99	0.024
KHAS	56.233	26.208	5.79	25.50	1.01	0.98	0.025
KHOS	48.409	30.246	0.58	19.10	0.98	0.95	0.018
KORD	54.199	36.860	−2.53	7.48	0.98	0.94	0.017
KSHA	51.255	34.150	−1.18	12.69	0.95	0.93	0.017
LAMB	54.004	26.883	2.52	20.96	1.18	1.00	0.019
MAHM	52.285	36.588	−2.43	6.45	1.60	1.56	0.013
MIAN	46.162	36.908	−1.66	13.70	0.95	0.91	0.013
MSHN	59.480	36.335	0.29	2.70	1.36	1.28	0.016
MUSC	58.569	23.564	8.85	25.95	1.11	1.02	0.022
NSSP	44.503	40.226	2.23	7.17	1.29	1.21	0.007
RAZD	55.800	28.330	3.76	14.70	1.04	1.00	0.022
ROBA	56.070	33.369	1.30	10.67	0.97	0.95	0.020
SEMN	53.564	35.662	0.28	9.04	0.96	0.93	0.018
SHAH	50.748	32.367	−1.47	12.65	0.96	0.93	0.018
SHIR	57.308	37.814	−1.80	3.54	0.96	0.95	0.018
TEHN	51.334	35.697	0.19	11.63	1.01	1.00	0.015
YAZT	61.034	36.601	0.72	0.97	0.96	0.95	0.018
ZABO	61.517	31.049	1.97	2.01	1.08	0.98	0.022

place in NW Iran (up to 8 mm yr^{-1} between DAMO and BIJA). Masson *et al.* (2006) have shown that this right lateral movement takes place mainly on the Tabriz fault and is surprisingly associated to NE–SW extension. At the eastern border of Iran, ZABO and YAZT show very low displacements indicating that the Helmand block belongs to Eurasia. The kinematic contrast between western Iran and the Helmand block is accommodated by strike-slip motions along the Lut block. This is underlined by many earthquakes on the borders of the Lut block (see for example, the 1994 M_w 6.0 Sefidabeh earthquake on its eastern border (Parsons *et al.* 2006), the 2003 M_w 6.6 Bam (Jackson *et al.* 2006) and 2005 M_w 6.4 Dayuiyeh (Talebian *et al.* 2006) earthquakes on its western border or the seismicity of the Dasht-e-Bayaz region on its northern border (Walker *et al.* 2004). To the south, our result is consistent with a recent regional GPS study (Bayer *et al.* 2006) which shows that the transition zone between the Zagros continental collision and the Makran subduction is under transpression with right lateral displacements 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 along the Zendan-Minab-Palami and Jiroft-Sabzevaran fault systems (Regard *et al.* 2004, 2005).

3.1 Velocity field of NE Iran

The main refinements obtained from the new velocity field are observed in NE Iran (Fig. 2), which suffers small displacements which needed a longer observation period to be quantified. This region is a mountain belt which extends from the Caspian Sea to the Afghanistan border and separates the Turan region (considered as belonging to Eurasia) from central Iran. It corresponds to the northeast limit of the Arabia–Eurasia collision zone. The belt is 700 km long, and much broader in the west than in the east. Altitudes reach 3000 m in the southeast decreasing towards the northwest. The mountain belt is constituted of several NW–SE trending ranges, the Kopet Dag range being the northernmost one, followed by the Binalud south of Mashhad and the Kuh-e-Sorkh north of Kashmar. The western part of the Kopet Dag range is limited to the Turan shield in the north by the NW–SE trending right-lateral Ashkabad fault (Trifonov 1978). In the eastern part of the Kopet Dag range, thrusts form the northern and southern edges (Lyberis & Manby 1999; Berberian *et al.* 2000). The western and eastern parts of the range are separated by the NNW–SSE trending Bakharden-Quchan fault zone, called Quchan fault zone hereafter (Hollingsworth *et al.* 2006). This fault zone does not continue to the south into the Binalud range, but is limited by the Atrak river valley which forms the southern margin of the Kopet Dag range. Hollingsworth *et al.* (2006) propose a simplified view of NE Iran's tectonics accommodating NS shortening with thrusting in the eastern part of Kopet Dag, NS shortening and EW extension by rotating a series of blocks anticlockwise in the Quchan fault zone, and expelling the west Kopet Dag along the Ashkabad and Sharud fault systems to the west. Examining the individual fault offsets in the Quchan fault system, the authors propose 60 km of NS shortening across Kopet Dag, and 30 km of along-strike elongation.

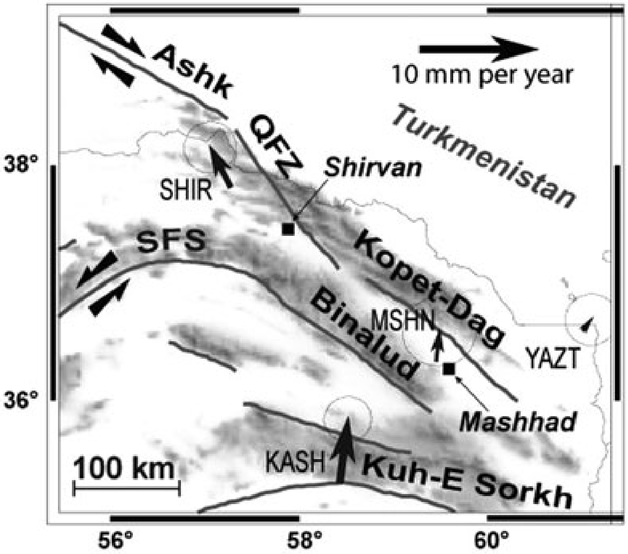

Figure 2. GPS horizontal velocities in a Eurasia-fixed reference frame and their 95 per cent confidence ellipses superimposed on the topographic map of NW Iran. Ashk : Ashkabad fault, QFZ : Quchan fault zone and SFS = Shahrud fault system.

The present-day shortening rate across the mountain belts of NE Iran can be estimated by the differential velocities of KASH, situated south of Kuh-e-Sorkh, and YAZT, situated on the Turan shield, to 5 ± 1 mm yr^{-1} at about N11°. Thanks to the first determination of the velocity of the permanent GPS station of Mashhad (MSHN), situated between the Kopet Dag range and the Binalud, a separate shortening rate can be given for the Kopet Dag. The differential velocities of MSHN and YAZT evaluate 2 ± 1 mm yr^{-1} of NS shortening across the eastern Kopet Dag. The shortening is oblique to the mountain range and can be split up roughly into 1 mm yr^{-1} of range-perpendicular shortening and 1 mm yr^{-1} of range-parallel strike-slip. The KASH and MSHN differential velocities estimate the cumulated NS shortening across Binalud and Kuh-e-Sorkh to 3 ± 1 mm yr^{-1}. At constant shortening rates, it takes 30 Myr to produce the 60 km shortening across Kopet Dag proposed by Hollingsworth *et al.* (2006). This is the upper limit of the onset of formation of the Kopet Dag given by Berberian and King (1981) with loose geological constraints. Allen *et al.* (2003) proposed 30 km of shortening across Alborz-Binalud, which, in contrast, could be achieved in 10 Myr at constant displacement rates (if the 3 mm yr^{-1} shortening takes place on Binalud only).

The comparison of the site velocities of YAZT on the Turan shield and SHIR in the Kopet Dag west of the Quchan fault zone gives an estimate of the along-strike elongation of the mountain range, and of the westward expulsion of the South Caspian Basin with respect to Eurasia. We obtain 3 ± 1 mm yr^{-1} along-strike elogation, which is also an estimate of the rate of along-strike motion on the Ashkabad fault at the limit between this part of the Kopet Dag and the Turan shield. This is consistent with Lyberis and Manby (1999) who proposed 3–8 mm yr^{-1} of right lateral displacements on the Ashkabad fault. The 30 km of cumulative along-strike motion according to Hollingsworth's model could be achieved in 10 Myr.

To give an estimate of the present day displacement rate across the NNW–SSE trending Quchan fault system, we need to compare the SHIR velocity west of the fault zone with the velocity of a site situated east of the fault zone between the thrust zones bounding east Kopet Dag to the south and the north. We cannot directly compare the SHIR velocity to MSHN, because the Quchan fault zone is limited to the Atrak valley north of Mashhad. If we assume an intermediate velocity between the two stations MSHN and YAZT, the strike-slip rate of the Quchan system can be estimated to 2 ± 1 mm yr^{-1}. Hollingsworth *et al.* (2006) indicate a cumulative offset across three faults of this system of 40 km. This would yield an onset of deformation 20 Myr ago with constant displacement rates.

Our GPS measurements emphasize the varying character of the Kopet Dag deformation between its southeastern part with prevailing thrusting at low rates and its northwestern part with dominant strike-slip activity at increasing rates. This contrast is also shown by the lack of large instrumental and historical seismicity east of 57°, and by the higher topography in the eastern part of the range where shortening with crustal thickening seems to be prevailing. The GPS velocities and total fault offsets provided by different authors indicate variable onsets of deformation along the Kopet Dag, with up to 30 Myr in the southeast part of the range, 20 Myr for the Quchan system in the centre of the range and 10 Myr in the northwest. This is clearly older than deformation in other Iranian mountain belts (Zagros, Alborz with 3–7 Myr), but still consistent with geological constraints (Berberian & King 1981).

The western part of Kopet Dag and the Quchan fault system in particular are underlined by a dense historical and instrumental seismicity. Several devastating earthquakes occurred close to Quchan in the last 150 yr, the most recent one in 1997 close to Bojnurd ($M = 6.4$). While the Quchan fault system seems to be disconnected from the faults surrounding Binalud, the seismic loading in the area of Binalud close to the large city of Mashhad is at least as high (3 mm yr^{-1} of shortening across Binalud and Kuh-e-Sarkh). Therefore, a new large earthquake may occur in the Kopet Dag belt damaging Mashhad or the now very densely populated region of Quchan in the next century.

4 STRAIN FIELD

Under the hypothesis that the velocity field v varies linearly inside each triangular subnetwork spanning the GPS network, we calculate the average horizontal velocity gradient $\boldsymbol{L} = \mathrm{grad}(v)$ over each triangle. Because the velocity gradient generally incorporates both deformation and rotation, this 2-D tensor is asymmetric. $\boldsymbol{L}$ can be separated in a symmetric and antisymmetric part as follow:

$$L = {}^{1}\!/_{2}(L + L^{T}) + {}^{1}\!/_{2}(L - L^{T}).$$

Its symmetric part is the strain rate tensor while its antisymmetric part gives a local measure of the rate of rigid rotation (Malvern 1969). The strain rate calculated from the horizontal velocity field is shown in terms of their principal axes in Fig. 1(b). Masson *et al.* (2005) have presented a comparable figure based on the velocity field deduced from the two first measurements of 1999 and 2001. As shown by Masson *et al.* (2005), small variations of the velocities can induce large variations in the amplitude and the direction of the strain tensor. Therefore, although the first order results of our study are comparable to the previous study of Masson *et al.* (2005), there are significant differences that need pointing out.

The main result is the homogeneity of the orientation of the main axis of the strain tensor from south to north in Iran. In the south (Zagros, triangles 3–6; Makran, triangles 10–11) and the north (Alborz, triangles 20, 22, 24; NE Iran, triangles 26–27) the orientation of the shortening axis is ∼20°. Negligible variations are observed indicating that the tectonics of these regions is mainly driven by a similar process which is the Arabia–Eurasia collision. Large deviations from this direction are observed in the Zagros–Makran transition zone and in NW Iran. In both cases, contrasted lithospheric structures are involved in the collision. In the Zagros–Makran collision zone, the strain is related to the lateral variation from a continental collision (Zagros) to an oceanic subduction (Makran) (Regard *et al.* 2004). In the second case, the continental crust of NW Iran is wrapped around the oceanic-like crust of the South Caspian Basin. In this region, the simple sketch of the Arabian indenter is probably too simple to explain all the tectonic observations. A dominant extensional strain is found, confirmed by local GPS studies (Masson *et al.* 2006). Based on finite element modelling, Vernant and Chéry (2006) have suggested that the velocity field in the Lesser Caucasus and the Kura basin cannot be modelled with the Arabian push, and that a slab pull under the Caucasus and the Apsheron–Balkhan Sill is likely to occur.

Homogeneous high strain rates indicating mainly shortening are observed in the Zagros (triangles 3–6). The same pattern is observed in the Alborz (triangles 26 and 27) but with approximately double the rates. The direction of shortening observed in the Alborz is consistent with the direction proposed by Ritz *et al.* (2006) on the basis of field observations. The triangles 1, 2, 34, 37, 38 and 39 belong to the Central Iran Block defined by Vernant *et al.* (2004a) as a stable area corresponding to the Sanandaj–Sirjan zone. They show very small strain. North of the Sanandaj–Sirjan zone, the region corresponding to the triangles 21, 23, 35, 36 and 40 suffers little but significant strain indicating that the northern part of Central Iran (mainly the central Iranian desert) is not a stable area. This is underlined by a small and diffuse seismicity. Eastward, triangles 29, 31 and 32 correspond to the Lut block and indicate both strike-slip and compression. In these large triangles deformation is localized on tectonic structures: compression is located north of the Lut block while strike-slip takes place along the large right lateral north–south faults which mark the bounds of the Lut block.

5 CONCLUSION

The third GPS survey in 2005 increases the precision of the Iranian large-scale velocity field to 1 mm yr^{-1}. This allowed a first evaluation of significant relative displacements in low deformation areas such as NE Iran. One major result is the west–east decrease of slip rate along the Kopet Dag range from 3 mm yr^{-1} on the Ashkabad fault to 1 mm yr^{-1} in the southeastern part of Kopet Dag. 2 mm yr^{-1} of slip rate were measured on the Quchan fault system, and 3 mm yr^{-1} of shortening across Binalud and Kuh-e-Sarkh close to the city of Mashhad. The increased velocity precisions also constrain a significant large-scale strain field covering Iran. The main result is the partition of Iran in large zones of similar strain (Zagros, Makran and Alborz with shortening axes oriented ∼20°N), some of them being rigid (as the Sanandaj–Sirjan block in Central Iran).

However, in complex zones such as NW Iran some triangles are too big to represent a single tectonic mechanism. National Cartographic Center (NCC) of Iran is now establishing a permanent mesh of 150 benchmarks throughout the country. In the next decade, this permanent network should give a more detailed insight of the crustal deformation (i.e. with almost the same resolution as tectonic studies) completing this study in zones of most complex tectonics.

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