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

F. Masson, M. Anvari, Yahya Djamour, Andrea Walpersdorf, Farokh Tavakoli, M. Daignieres, H. Nankali, S. van Gorp

To cite this version:

HAL Id: insu-00346744
https://hal-insu.archives-ouvertes.fr/insu-00346744
Submitted on 30 Jul 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
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

Frédéric Masson1, Mohammad Anvari2,5, Yahya Djamour2, Andrea Walpersdorf3, Farokh Tavakoli2,3, Marc Daignières4, Hamid Nankali2 and Sébastien Van Gorp4

1 Institut de Physique du Globe de Strasbourg, Université Strasbourg I/CNRS, Strasbourg, France
2 Geodynamic Department, National Cartographic Center, PO Box 13185-1684, Meraj Ave, Tehran, Iran
3 Laboratoire de Géophysique Interne et Tectonophysique, Université Grenoble/CNRS, Grenoble, France
4 Laboratoire geosciences Montpellier, Université Montpellier II/CNRS, Montpellier, France
5 Khorasan Department of NCC, Iran

Accepted 2007 April 25. Received 2007 April 25; in original form 2006 September 19

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...
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$^\circ$ and 40$^\circ$ of longitude east and between 39$^\circ$ and 80$^\circ$ 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 $\sim 21$ mm yr$^{-1}$ at the longitude of Bahrain. East of 58$^\circ$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$^\circ$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
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 Y AZT takes place mainly on the Tabriz fault and is surprisingly associated to NE–SW extension. At the eastern border of Iran, ZABO and Y AZT.

### 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 (\(\sigma_E\) and \(\sigma_N\)) are given in mm yr\(^{-1}\). Corr = correlation coefficient between the east and north uncertainties.

<table>
<thead>
<tr>
<th>Site</th>
<th>Position</th>
<th>Velocity (mm yr(^{-1}))</th>
<th>Uncertainties</th>
<th>Corr.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\lambda)</td>
<td>(\phi)</td>
<td>(E)</td>
<td>(N)</td>
</tr>
<tr>
<td>ALIS</td>
<td>51.082</td>
<td>28.919</td>
<td>1.19</td>
<td>20.65</td>
</tr>
<tr>
<td>ARDA</td>
<td>53.822</td>
<td>32.313</td>
<td>-0.28</td>
<td>13.60</td>
</tr>
<tr>
<td>BAZM</td>
<td>60.180</td>
<td>27.865</td>
<td>6.24</td>
<td>3.20</td>
</tr>
<tr>
<td>BAHR</td>
<td>50.608</td>
<td>26.209</td>
<td>4.21</td>
<td>20.45</td>
</tr>
<tr>
<td>BIJA</td>
<td>47.930</td>
<td>36.232</td>
<td>-1.79</td>
<td>13.09</td>
</tr>
<tr>
<td>CHAB</td>
<td>60.694</td>
<td>25.300</td>
<td>5.05</td>
<td>7.23</td>
</tr>
<tr>
<td>DAMO</td>
<td>47.744</td>
<td>39.513</td>
<td>7.45</td>
<td>15.31</td>
</tr>
<tr>
<td>HARA</td>
<td>54.608</td>
<td>30.079</td>
<td>1.68</td>
<td>13.58</td>
</tr>
<tr>
<td>ILAM</td>
<td>46.427</td>
<td>33.648</td>
<td>-3.14</td>
<td>16.46</td>
</tr>
<tr>
<td>JASK</td>
<td>57.767</td>
<td>25.636</td>
<td>3.52</td>
<td>12.62</td>
</tr>
<tr>
<td>KASH</td>
<td>58.464</td>
<td>35.293</td>
<td>0.74</td>
<td>5.71</td>
</tr>
<tr>
<td>KERM</td>
<td>57.119</td>
<td>30.277</td>
<td>1.42</td>
<td>16.30</td>
</tr>
<tr>
<td>KHAS</td>
<td>56.233</td>
<td>26.208</td>
<td>5.79</td>
<td>25.50</td>
</tr>
<tr>
<td>KROS</td>
<td>48.409</td>
<td>30.246</td>
<td>0.58</td>
<td>19.10</td>
</tr>
<tr>
<td>KORD</td>
<td>54.199</td>
<td>36.860</td>
<td>-2.53</td>
<td>7.48</td>
</tr>
<tr>
<td>KSHA</td>
<td>51.255</td>
<td>34.150</td>
<td>-1.18</td>
<td>12.69</td>
</tr>
<tr>
<td>LAMB</td>
<td>54.004</td>
<td>26.883</td>
<td>2.52</td>
<td>20.96</td>
</tr>
<tr>
<td>MAHM</td>
<td>52.285</td>
<td>35.693</td>
<td>1.30</td>
<td>10.63</td>
</tr>
<tr>
<td>MIAN</td>
<td>46.162</td>
<td>36.908</td>
<td>-1.66</td>
<td>13.70</td>
</tr>
<tr>
<td>MSHN</td>
<td>59.480</td>
<td>36.335</td>
<td>0.29</td>
<td>2.70</td>
</tr>
<tr>
<td>MUSC</td>
<td>58.569</td>
<td>23.564</td>
<td>8.85</td>
<td>25.95</td>
</tr>
<tr>
<td>NSSP</td>
<td>44.503</td>
<td>40.226</td>
<td>2.23</td>
<td>7.17</td>
</tr>
<tr>
<td>RAZD</td>
<td>55.800</td>
<td>28.330</td>
<td>3.76</td>
<td>14.70</td>
</tr>
<tr>
<td>ROBA</td>
<td>56.070</td>
<td>33.369</td>
<td>1.10</td>
<td>10.67</td>
</tr>
<tr>
<td>SEMN</td>
<td>53.564</td>
<td>35.662</td>
<td>0.28</td>
<td>9.04</td>
</tr>
<tr>
<td>SHAH</td>
<td>50.748</td>
<td>32.367</td>
<td>-1.47</td>
<td>12.65</td>
</tr>
<tr>
<td>SHIR</td>
<td>57.308</td>
<td>37.814</td>
<td>1.14</td>
<td>22.46</td>
</tr>
<tr>
<td>TEHN</td>
<td>51.334</td>
<td>35.697</td>
<td>0.19</td>
<td>11.63</td>
</tr>
<tr>
<td>YAZT</td>
<td>61.034</td>
<td>36.601</td>
<td>0.72</td>
<td>9.71</td>
</tr>
</tbody>
</table>

### 3.1 Velocity field of NE Iran

The main refinements obtained from the new velocity field are presented in Figure 2. The present-day shortening rate across the mountain belts of NE Iran can be estimated by the differential velocities of KASH, situated between the Kopet Dag range and the Binalud; 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 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 Kopet Dag range are separated by the NNW–SSE trending Bakhtarden-Qu chan fault zone, called Qu chan 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 Qu chan fault zone, and expelling the west Kopet Dag along the Ashkabad and Sharur fault systems to the west. Examining the individual fault offsets in the Qu chan fault system, the authors propose 60 km of NS shortening across Kopet Dag, and 30 km of along-strike elongation. 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 ± 1 mm yr\(^{-1}\) at about N11\(^\circ\). 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 5 ± 1 mm yr\(^{-1}\) at about N11\(^\circ\).
Large-scale velocity field and strain tensor in Iran inferred from GPS measurements

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 \( L = \text{grad}(v) \) over each triangle. Because the velocity gradient generally incorporates both deformation and rotation, this 2-D tensor is asymmetric. \( L \) can be separated in a symmetric and antisymmetric part as follow:

\[
L = \frac{1}{2}(L + L^T) + \frac{1}{2}(L - L^T).
\]

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 \( \sim 20^\circ \). 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 Quohan 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.

ACKNOWLEDGMENTS

We thank all the participants who helped during the fieldwork. The French Embassy in Tehran contributes to make the experiments successful. The Iran Global GPS project has been sponsored by the French CNRS-INSU, the National Cartographic Center (NCC-Tehran) and the International Institute of Earthquake Engineering and seismology (IIEES-Tehran). We are grateful to James Jackson for his precious help on Kopet Dag tectonics, Barry Parsons and an anonymous reviewer for constructive reviews. We thank Denis Hatzfeld who efficiently organizes the French-Iranian collaboration.

Maps were produced using the public domain Generic Mapping Tools (GMT) software (Wessel and Smith 1995) and with the help of Anne Delplanque.

REFERENCES


Regard, V. et al., 2005. Cumulative right-lateral fault slip rate across the Zagros – Makran transfer zone and role of the Minab-Zendan fault system within the accommodation convergence between Arabia and Eurasia (SE Iran), Geophys. J. Int., 162, 177–203.


