Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 252 (2006) 180 – 188
EPSL
www.elsevier.com/locate/epsl

Extension in NW Iran driven by the motion of the South Caspian Basin

F. Masson [a,*], Y. Djamour [b], S. Van Gorp [a], J. Chéry [a], M. Tatar [c], F. Tavakoli [b], H. Nankali [b], P. Vernant [d]

[a] *Laboratoire Dynamique de la Lithosphère, Université Montpellier II - CNRS, Pl. E. Bataillon, 34095 Montpellier Cedex 05, France*
[b] *Geodynamic Department, National Cartographic Center, Po. BOX 13185- 1684, Meraj Ave, Tehran, Iran*
[c] *International Institute of Earthquake Engineering and Seismology, Farmanieh, Dibaji, Arghavan St., N° 27, 19531 Tehran, Iran*
[d] *Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Received 11 January 2006; received in revised form 21 September 2006; accepted 21 September 2006
Available online 30 October 2006
Editor: C.P. Jaupart

Abstract

Contrasted tectonic styles occur in northern Iran. West of Kopet Dagh, the south Caspian basin is an aseismic and possibly rigid block involved in the collision zone between Eurasia and Arabia. To the NW, large scale velocity field of Iran given by recent repeated GPS surveys suggests ~8 mm/yr of right-lateral displacement for the WNW–ESE faults in the Tabriz region. More surprisingly, geodetic motion also suggests a prominent N 30° extension north to the Tabriz fault where compression would be expected.

In order to quantify more precisely the right-lateral movement of the Tabriz region, the extension of NW Iran and the motion of the south Caspian basin, we deployed a dense GPS network in NW Iran, from Central Iran to the Turkish, Armenian and Azerbaijan borders. Three repeated surveys from 2002 to 2004 assess that the Tabriz fault concentrates entirely the ~8 mm/yr of right-lateral movement observed in NW Iran. This rate is in good agreement with a recurrence interval time of 250–300 yr proposed from historical seismicity studies. We found also two zones of extension, one just north of the Tabriz fault in the south of the Talesh plateau and another close from the Azerbaijan border north of the Talesh plateau. We suggest that the existence of a northward subduction of the south Caspian Basin could explain such an extension in the core of the Arabia–Eurasia collision. Increasing evidences of quaternary extensional tectonics in the region from Armenia to Alborz may lead to significantly alter our understanding of the northern Iran tectonics and challenge the traditional Arabian indenter plate tectonics.

Keywords: tectonic; GPS; continental collision; Iran

1. Introduction and tectonic setting

Early analysis of plate motion and of the distribution of the seismicity [1] combined with recent geodetic measurement [2,3] reveals the main features of the Arabia–Eurasia collision zone. First, a quasi-rigid behavior of the Sanandaj–Sirjan zone (hereafter called Central Iranian Block) occurs. Second, the strain is distributed in the mountain belts, the Zagros to the south and the Alborz and the Kopet Dagh to the north. Therefore, the north component of the GPS velocity field expressed in a Eurasian reference frame decreases from

* Corresponding author. IPGS – ULP/CNRS, 5 rue René Descartes, 67084 Strasbourg Cedex, France. Tel.: +33 3 90 24 50 29.
E-mail address: Frederic.masson@eost.u-strasbg.fr (F. Masson).

0012-821X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2006.09.038

the Persian Gulf in the south to the Caspian basin in the north. In NW Iran, this simple sketch fails: velocity increases north of Central Iranian Block up to the Kura basin in Azerbaijan (point DAMO in Fig. 1). This intriguing feature may either indicate that the tectonic of this region is not simply driven by the Arabian indenter or that a transient motion is occurring.

Analyzed together with the sites MIAN and BIJA on the Central Iranian Block, the GPS site of northern Talesh (DAMO) suggests ~8 mm/yr of right-lateral displacement in NW Iran [3]. WNW–ESE faults in the Tabriz region, well-known for their large historical seismicity [4,5], appear as good candidates to accommodate this right-lateral deformation. Also, the DAMO motion suggests 8 mm/yr at N 30° extension with respect to the Central Iranian Block (Fig. 1). East of NW Iran, the south Caspian basin is one of the thickest sedimentary basins around the world [6]. This aseismic block is expected to be relatively rigid [7]. Unfortunately no GPS measurements of the south Caspian basin are available, but its motion is suggested to be NW with respect to Eurasia on the base of earthquake analysis and geometrical reconstruction [8]. Moreover, the large GPS velocities difference between the Talesh (DAMO and BIJA) and the Alborz (MAHM and KORD) may suggest a NS strike–slip motion west of the Caspian Sea. Yet, the present day quantification of the south Caspian basin motion and the link with observed geodetic motions on land remains to be done.

In order to quantify the tectonic activity of the Tabriz fault, to better localize the NNE–SSW extension within the Talesh plateau and to constrain the relative movement of the south Caspian basin with respect to Iran, we have installed and measured a dense GPS network in NW Iran, from Central Iran to the Turkish, Armenian and Azerbaijan borders.

2. Data and processing

A GPS network of 19 points has been installed and surveyed in the framework of French Iranian cooperation. Sites span NW Iran, between the Iranian border to the north and west, the south Caspian basin to the east and Central Iran to the south (Fig. 2). The sites are homogeneously distributed in the studied area. The easternmost site ATTA links this network to a GPS network installed in Central Alborz [9]. Southern sites BIJA and MIAN are common sites of the Iran Global GPS network [2,3] located in Central Iran. DAMO is the northernmost site. Most of the GPS benchmarks are

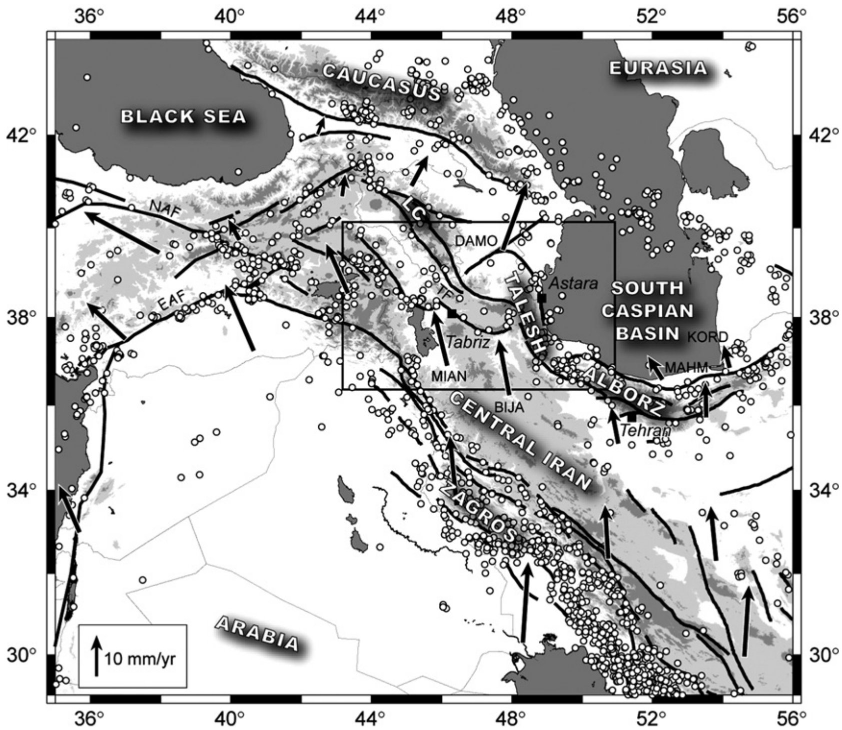

Fig. 1. Map of the central part of the Arabia–Eurasia collision zone. The studied zone is underlined by the rectangle. Black arrows indicate GPS velocities calculated in a Eurasia-fixed reference frame by Vernant et al. [3] and McClusky et al. [37]. Earthquakes are from instrumental seismicity catalogue (1964–1999 [38]). NAF = North Anatolian Fault, EAF = East Anatolian Fault, TF = Tabriz Fault, LC = Lesser Caucasus.

anchored in the bedrock. Others are setup on geodetically designed pillars deeply rooted in stabilized ground. All sites but one (ATTA) have been surveyed at least three times in September 2002, 2003 and 2004 during 48 h. Some sites have been measured four, five or six times since 1999 thanks to the Iran Global and Khazar

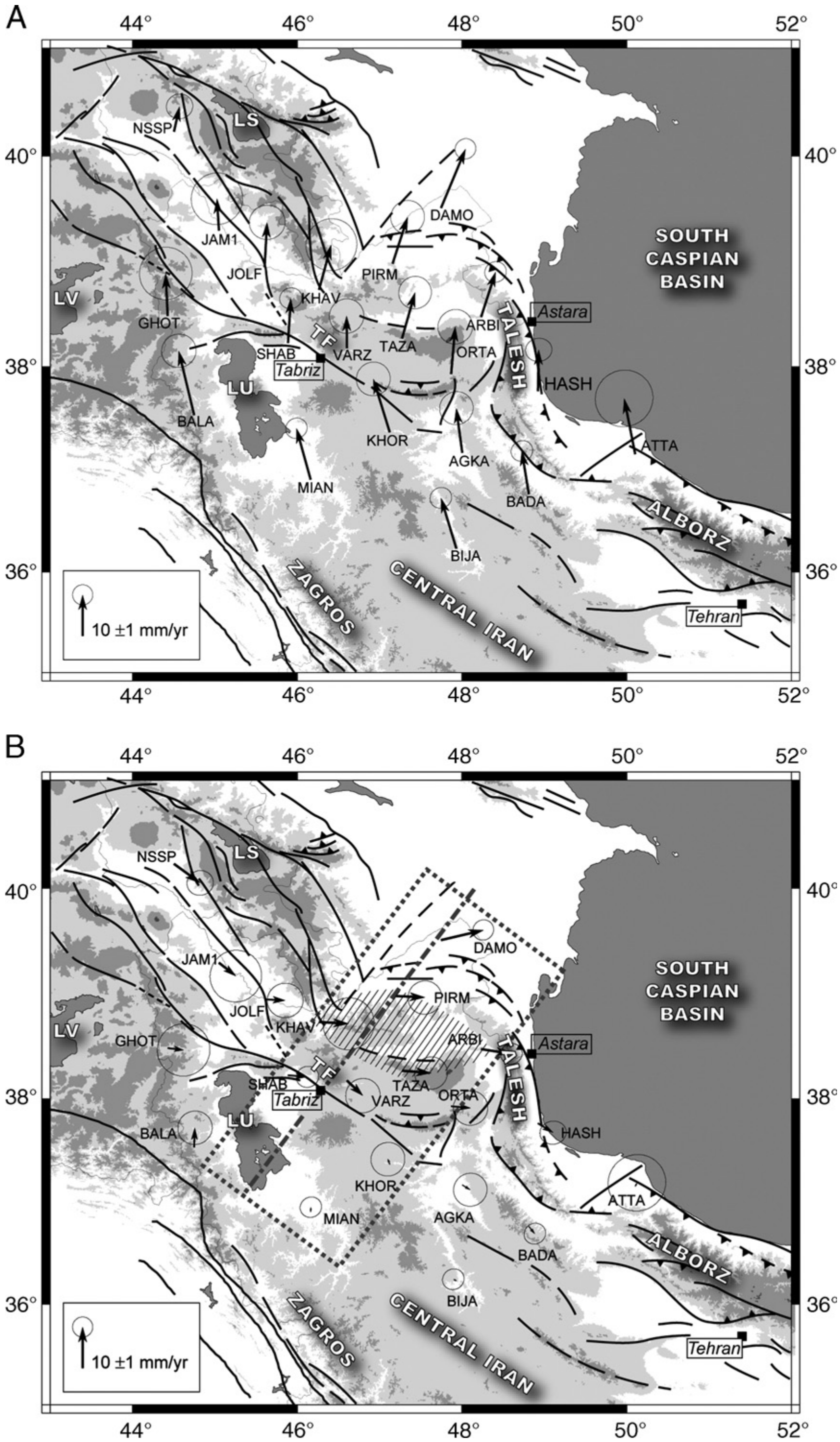

Fig. 2. A — Velocity field of NW Iran with respect to Eurasia. B — Velocity field of NW Iran with respect to Central Iran. LU = Lake Urumieh, LV = Lake Van, LS = Lake Sevan, TF = Tabriz Fault. Shaded area indicates the Talesh block. Faults are drawn from Karakhanian et al. [17] west of Tabriz, Jackson et al. [8] in the Talesh and Ritz [18] in the Alborz.

projects measurements. In order to constrain the motion of our local network relative to the surrounding plate motions, data of 16 GPS stations belonging to Eurasian and Arabian plates have been added to our local data. Data analysis was done using GAMIT, version 10.05 [10] and GLOBK, version 10.0 [11]. The short term accuracy of our measurements can be expressed by the baseline repeatability which displays values of about 1 mm/yr. These values cannot be directly used to estimate the error on the long term velocity. Indeed, assuming that long time correlation (often called colored noise) [12] alters our data leads to define a long term error of about 2 mm/yr for the velocities of the sites measured 3 times. This error decreases when the number of measurements and the time interval between the first and the last measurements increase, as shown by the variable size of the error ellipses.

In order to interpret our results in the framework of Arabia–Eurasia collision, we express the velocities with respect to a stable Eurasia. To do so, 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 NW Iran with respect to Eurasia are shown on Fig. 2A while they are displayed with respect to Central Iranian Block on Fig. 2B. To do this, we use a new Central Iran rotation pole defined in the same way than Vernant et al. [3] and calculated with updated velocities. Velocities are given in Table 1.

3. Discussion

On the base of our GPS results in NW Iran, we address three aspects of the Iranian tectonics: first, the right-lateral movement along the Tabriz fault and its consequence in term of seismic hazard, second the extension within the Talesh and third the movement of the south Caspian basin with respect to Iran. To address the two first points, we analyze the data by considering the direction parallel and normal to the Tabriz fault which is roughly N 120° E. The projection of each point position and its parallel and normal velocities are given on Fig. 3A and B. On both figures, no strain is observed south of the Tabriz fault. This indicates that the Central Iranian Block defined by Vernant et al. [3] extends up to the Tabriz fault.

3.1. Right-lateral movement along the Tabriz fault

Fig. 3A indicates that south of the Tabriz fault, no variation of the longitudinal velocity is observed between MIAN and BIJA on the Central Iranian Block and KHOR, close to the Tabriz fault. North of the Tabriz fault, no right-lateral movement is observed from VARZ to DAMO. Therefore, the overall right-lateral movement of ∼8 mm/yr observed between the Central Iranian Block and DAMO by Vernant et al. [3] seems to occur entirely on the Tabriz fault. This finding is not unexpected as the right-lateral Tabriz fault is known as

Table 1
Latitude (Lat) and Longitude (Lon) are given in degrees north and east, respectively

Site	Lon.	Lat.	V_E eura	V_N eura	V_E CI	V_N CI	E	N	Corr	N 120°	N 30°
AGKA	48.005	37.169	−1.5	10.8	1.9	−1.2	1.7	1.6	0.02	2.2	0.3
ARBI	48.231	38.477	3.5	11.0	7.4	−1.1	1.1	1.0	0.05	6.4	3.9
ATTA	50.102	37.156	−2.7	13.5	0.4	0.8	2.9	2.8	0.03	−0.2	0.9
BADA	48.814	36.764	−1.7	10.5	1.4	−1.8	1.1	1.0	0.06	2.2	−0.5
BALA	44.750	37.534	−3.8	15.6	0.2	4.7	1.7	1.7	0.02	−2.9	3.7
BIJA	47.930	36.232	−3.7	12.3	−0.7	0.3	1.1	1.0	0.06	−0.7	−0.2
DAMO	47.744	39.513	6.0	14.3	10.3	2.4	1.0	1.0	0.05	6.3	8.5
GHOT	44.428	38.489	−0.5	10.3	3.8	−0.5	2.6	2.6	0.01	3.2	2.1
HASH	48.922	37.764	0.2	10.1	3.7	−2.2	1.3	1.2	0.04	4.3	0.7
JAM1	45.049	39.297	−0.5	7.8	4.1	−3.2	2.6	2.6	0.01	5.2	0.2
JOLF	45.605	38.952	0.6	10.9	5.0	−0.3	1.8	1.7	0.02	4.0	3.0
KHAV	46.265	38.736	3.0	11.0	7.2	−0.4	2.5	2.6	0.02	5.8	4.3
KHOR	47.123	37.368	−4.0	13.0	−0.4	1.3	1.7	1.7	0.02	−1.1	0.7
MIAN	46.162	36.908	−3.5	12.5	0.1	1.1	1.1	1.0	0.06	−0.6	0.9
ORTA	47.869	37.929	1.0	11.5	4.7	−0.4	1.7	1.7	0.02	3.9	2.7
PIRM	47.157	38.984	3.7	11.3	7.8	−0.4	1.7	1.7	0.02	6.3	4.7
SHAB	45.887	38.228	0.7	10.9	4.8	−0.4	1.1	1.0	0.05	3.9	2.7
TAZA	47.271	38.270	3.2	11.2	7.1	−0.6	1.6	1.6	0.02	5.8	4.1
VARZ	46.603	38.178	−0.1	7.8	3.9	−3.7	1.7	1.7	0.02	5.3	−0.3

East (V_E eura, V_E CI) and North (V_N eura, V_N CI) velocities components with respect to Eurasia and to Central Iran and their uncertainties (Se and Sn) are given in mm/yr. Corr = correlation coefficient between the east and north uncertainties. N 120° = Longitudinal component of the velocity field along a profile perpendicular to the Tabriz fault. N 30° = Transversal component of the velocity field along a profile perpendicular to the Tabriz fault.

one of the major active faults of the NW Iran–Lesser Caucasus region. It separates the rigid Central Iranian Block from the deformed Talesh. It has an average strike of WNW–ESE over a length of ~150 km. Right-lateral movement documented by Berberian and Arshadi [13] from study of aerial photographs can also be seen clearly in the field [14]. The Tabriz fault did not generate large earthquakes during the last two centuries. Conversely, many historical earthquakes have occurred earlier in the Tabriz region (e.g., the 858, 1042, 1273, 1304, 1550, 1641, 1717, 1721, 1780 and 1786 earthquakes) [5]. The city of Tabriz has been damaged several times by the 1042 (Ms ~ 7.3), 1721 (Ms ~ 7.3), 1780 (Ms ~ 7.4) and 1786 (Ms ~ 6.3) large earthquakes. Historical seismicity of the Tabriz fault suggests that the recurrence time interval is between 250 yr taking into account the whole set of earthquakes and 700 yr taking into account the strongest earthquakes [5]. Hessami et al. [15] proposes a recurrence interval of 821 ± 176 yr based on paleoseismological studies. From trenches, they found evidence for at least four events during the past 3600 yr. If we assume that ~8 mm/yr of right-lateral displacement occurs along the Tabriz fault with a recurrence time interval of 250 yr, the average displacement is ~2.00 m for each event. Using empirical relationship among moment magnitude and maximum displacement, the magnitude is ~7.3 [16]. Assuming a recurrence time interval of 800 yr, the displacement is ~6.40 m for each event and the associated magnitude is ~7.8. To be in agreement with the magnitudes proposed by Berberian and Yeats [5] which are around 7.3, the GPS measurements conduct to propose a recurrence interval time of 250–300 yr. Therefore, a new large earthquake may occur on the Tabriz fault during this century.

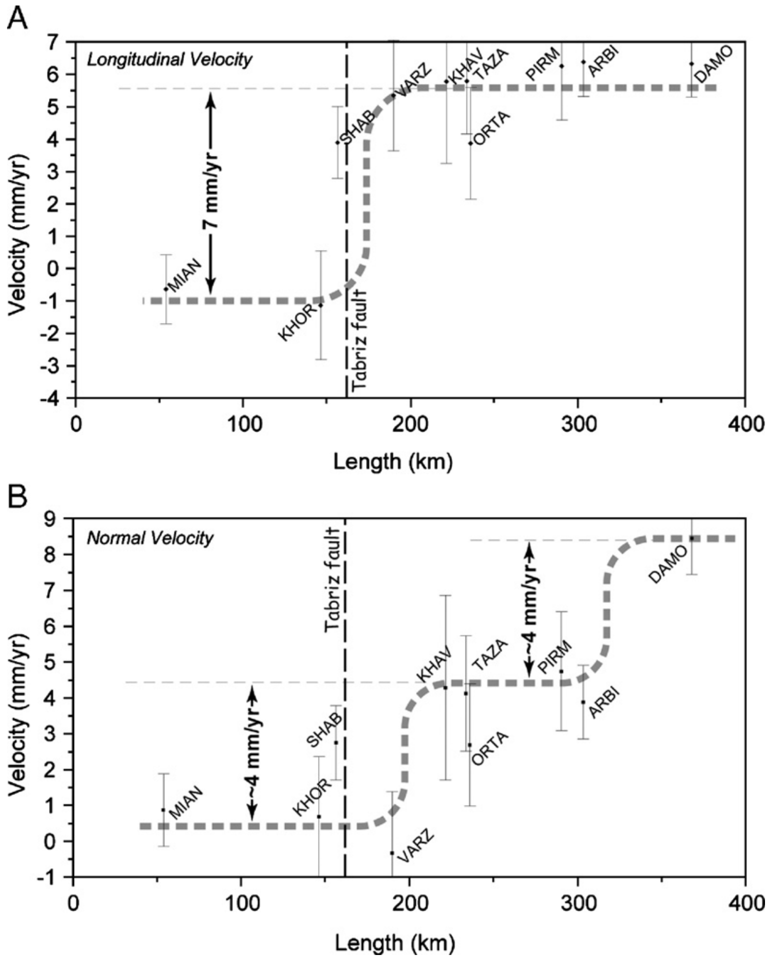

Fig. 3. A — Longitudinal component of the velocity field along a profile perpendicular to the Tabriz fault. The profile is drawn on Fig. 2B. Data taken into account are located into the trapezoidal area drawn on Fig. 2B. B — Transversal component of the velocity field along the profile.

3.2. The Talesh extension

Fig. 3B shows the velocity normal to the Tabriz fault. In a pure strike–slip regime, the normal component should be zero. However, a clear offset of normal velocity is observed north of the Tabriz fault indicating ~4 mm/yr of extension between the Tabriz fault and the sites KHAV, TAZA, PIRM and ARBI (hereafter called the Talesh block). This group of sites moves like a rigid block: computing a rotation pole, we find a RMS of 0.24 mm/yr, well below the velocity error assumed to be 2 mm/yr. North of the Talesh block, ~4 mm/yr of extension is observed up to DAMO. A total of ~8 mm/yr of extension is therefore observed from the Tabriz fault to DAMO. Due to the redundancy of the GPS data, the observed extension between the Tabriz fault and the Talesh block seems to be indubitable. Only based on the DAMO velocity, the northern part of the extension from the Talesh block to DAMO is more questionable. Nevertheless, the velocity of DAMO results from 6 measurements since 1999 and the time series of station position of DAMO show that the successive measurements are well lined up.

To date, no seismological data or morphological observations have suggested extensional faulting north to the Tabriz Fault. Nevertheless, west of NW Iran extension has been documented by Karakhanian et al. [17] along the southernmost segment of the Pambak Sevan Sunik fault system in Armenia (Fig. 2). N–S grabens with E–W extension are also observed west of the Sevan Lake. East of NW Iran extension has also been documented in the Alborz by Ritz et al. [18] even if GPS measurements in Central Alborz indicate ~5 mm of NS shortening [9].

At a larger scale, no significant extension had been documented up to now by GPS measurements in the Arabia–Eurasia collision zone. However, recent GPS results show that the main boundary between Anatolia and Arabia (East Anatolian fault) is presently characterized by pure left-lateral strike slip with no fault-normal convergence and possibly small extension [19]. Therefore, NW Iran is the first part of the Arabia–Eurasia collision zone where significant extension is observed. It takes place in a compressive domain extended from the Central Iranian Block to Eurasia where ~14 mm/yr of shortening is observed, inducing the formation of the Great Caucasus. Therefore, how can we explain this extension? Local extension parallel to the compressive structures in regional compressive domain can be explained by the existence of a subduction zone and back-arc or fore-arc extension. This is the case in the Aegean region where large extension is observed due to the northward Aegean subduction in the global context of the Africa–Eurasia collision. In the case of the Talesh, it is tempting to relate the extension to a possible sinking of the south Caspian lithosphere and the Kura basin. The south Caspian basin is an unusual thick 'oceanic-like' crust (15–18 km) overlaid by a thick sedimentary sequence (15–20 km) [6]. Several origins have been proposed for this remnant piece of oceanic floor: a part of a Late Mesozoic or Early Tertiary marginal basin [20–22], a remnant part of the Tethys ocean [23,24] or a pull-apart basin [25]. The northern boundary of the south Caspian basin is the Apsheron–Balkhan sill, a prominent bathymetric feature separating the deep south Caspian basin from the shallower middle Caspian province. The Apsheron–Balkhan sill connects the Great Caucasus and Kopet–Dag orogens. A stripe of earthquakes containing some substantial events (Mw>6) crosses the central Caspian along the line of the sill. Depths and mechanisms of these earthquakes support the northward subduction of the south Caspian basin beneath Eurasia. Along the Apsheron–Balkhan sill, some earthquakes are deeper than 30 km, and extend at least as deep as 75 km. Most of the focal mechanisms indicate normal faulting parallel to the sill at depth of 30–50 km. Thrust events also parallel to the sill, are observed deeper and further to the north [8]. Deep seismic reflection data across the Apsheron–Balkhan sill [26] show a gentle deepening of the south Caspian basin basement/cover contact towards the north to 26–28 km [6]. It is interpreted to image the subduction of the south Caspian basin below the Apsheron–Balkhan sill.

Tomographic models at ~100 km depth [27–29] show high Vp and Vs velocities and low Sn attenuation north of the Talesh, beneath the Kura and south Caspian basins and low Vp and Vs velocities and high Sn attenuation west of the Kura basin in Armenia, south of the Talesh and in the Alborz (Fig. 4). The boundary zone between the low and high velocities is roughly parallel to the extensional zones observed from Armenia to the Alborz. Based on finite element modeling, Vernant and Chéry [30] have suggested that the velocity field in the Lesser Caucasus and the Kura basin cannot be modeled with the Arabian push, and that a slab pull under the Caucasus is likely to occur. Therefore it is tempting to relate the observed extension to the northward subduction of the south Caspian and Kura basin basement beneath the Apsheron–Balkhan sill and the Great Caucasus respectively.

3.3. From the Talesh to the Alborz

At a first glance, Talesh and Alborz seem to wrap continuously the south Caspian basin along the southwest

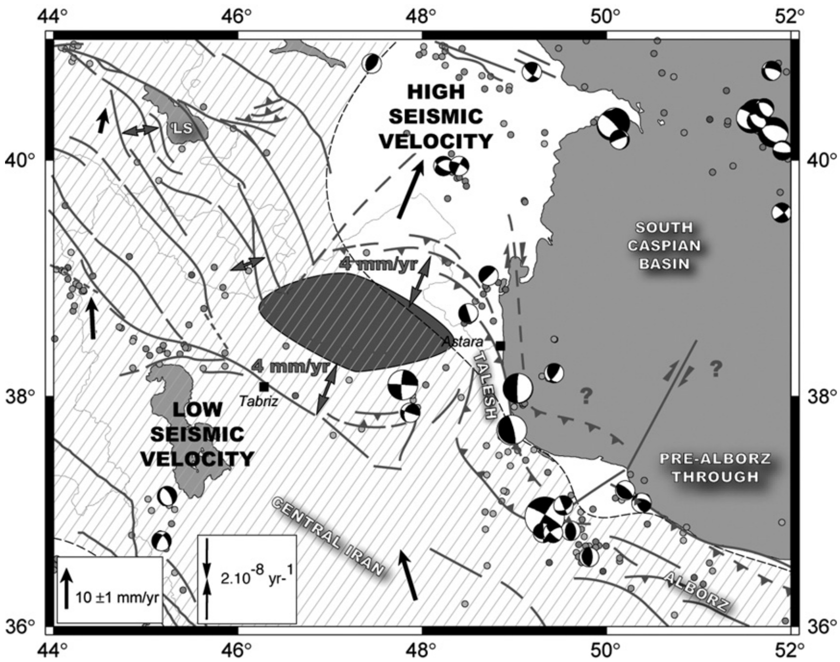

Fig. 4. Synthetic sketch summarizing the main results of this study: right-lateral movement along the Tabriz fault, extension north of the Tabriz fault, subduction of the south Caspian and Kura basins, uncoupling of the Talesh and the Alborz. Shaded area indicates the Talesh block. Focal mechanism solutions are from Jackson et al. [1]. Earthquake distribution are from instrumental seismicity catalogue (1964–1999, [38]). High and low seismic velocity zones are drawn from Bijwaard et al. [27].

and south shorelines of the Caspian Sea. They look like a continuous compressive transition zone crushed between two rigid blocks, the central Iranian Block and the south Caspian block. Based on earthquake mechanisms beneath the Talesh and along the south-west Caspian shore which have shallow thrust mechanisms, Priestley et al. [7] proposed that the continental crust of NW Iran is overthrusting the oceanic crust of the south Caspian basin. Karakhanian et al. [31] and Nadirov et al. [24] propose to accommodate the NS right-lateral movement observed from the Talesh to the Alborz along the west Caspian fault. They extend this NS strike–slip fault from the east of the Kura basin up to the SW corner of the south Caspian basin. Other authors [8,32] suggest that NS right lateral strike slips exist only in the Talesh and not offshore.

Following these sketches, all the GPS sites located along the shoreline of the Caspian Sea should show significant movements with respect to the Central Iranian Block. Surprisingly, the velocity of ATTA, a site located north of the Alborz close to the Caspian Sea, is ~0 mm/yr with respect to the Central Iran Block. Keeping in mind that this site motion has to be interpreted with care as it has been measured only two times, this suggests that western Alborz is a northern extension of Central Iran up to the Caspian shoreline. Even though this region suffers high seismicity as shown by the M7.3, 1990 Rudbar earthquake [33], western Alborz deforms at a significantly lower rate than Central Alborz, for which a NS shortening of at least 5 mm/yr is documentated [9]. The velocity of ATTA documents a progressive evolution from compression in Central Alborz to extension in NW Iran, already pointed out by Masson et al. [34] studying the seismological and geodetic strain rates at the scale of Iran.

The velocity of ATTA also indicates that the NS right-lateral movement observed between the western shoreline of the Caspian Sea and the central Alborz must be accommodated along the west Caspian fault in the south-western corner of the Caspian Sea and transferred inland within the Alborz east of ATTA. This raises the question of the role of the elbow observed along the southern shoreline of the Caspian Sea. It coincides to the southern end of a fault drawn by Brunet et al. [6] which cut into two parts the south Caspian basin: an eastern part with a thick sedimentary coverage and a pronounced Bouguer anomaly (the Pre-Alborz trough) and a western part with a thinner sedimentary coverage [6]. This fault is extended southwestward across the Alborz. A part of the NS strike–slip movement observed from the Talesh to the Alborz may be accommodated.

4. Conclusion

Deformation in NW Iran is characterized by ~8 mm/yr of right-lateral movement on the Tabriz fault, in agreement with a recurrence interval time of 250–300 yr, and ~8 mm/yr of extension within the Talesh. Extension is observed from Armenia to the Alborz and probably results from the northward subduction of the south Caspian and Kura basins beneath the Apsheron–Balkhan sill and Greater Caucasus respectively. One GPS site on the Caspian shoreline documents the northward extension of the Central Iranian Block up to the Caspian Sea.

Surprisingly the tectonics of the NW Iran is not only driven by the Arabian push but seems to be due to the subduction of an old remnant oceanic crust under the Greater Caucasus and the Apsheron–Balkhan sills north of the South Caspian Basin. This questions the Arabian indenter tectonics. If the deformation due to the indenter was prevailing at the onset of the collision, it seems that this is not longer the case. This change from indenter tectonics to slab driven tectonics in the NW Iran/Kura/Caucassus region could be related to a recent reorganization of the deforming zone.

Previous studies [8,35] proposed that the south Caspian basin is moving NW with respect to Eurasia. This movement would have started between 3 and 7 My ago. It could explain the seismic activity along the Apsheron–Balkhan sill, the eastward overthrusting of the Talesh and the left-lateral movement along the WNW–ESE Rudbar fault. Nevertheless it does not explain the transtension observed by Ritz et al. [18] in the Alborz. Ritz et al. [18] propose that there has a transition of the internal domain of the central Alborz from transpression to active transtension in very recent time. Therefore the change from indenter tectonics to slab driven tectonics could be divided in two steps, one around 7–5 My. and one around 1 My.

Acknowledgements

We would like to thank all the participants of the GPS measurements who helped during the fieldwork to make these experiments successful, J.F. Ritz, H. Philip and S. Dominguez for fruitful discussions. This project was sponsored by the French CNRS-INSU 'Intérieur de la Terre' and 'Dyeti' programs, the National Cartographic Center (NCC—Tehran), the International Institute of Earthquake Engineering and Seismology (IIEES—Tehran) and the French embassy in Iran. The CNRS-INSU and NCC provided the GPS receivers. The maps in this paper were produced using the public domain Generic Mapping Tools (GMT) software [36].

References

[1] J. Jackson, J. Haines, W. Holt, The accomodation of the Arabia–Eurasia plate convergence in Iran, J. Geophys. Res. 100 (1995) 15205–15219.

[2] F. Nilforoushan, F. Masson, P. Vernant, C. Vigny, J. Martinod, M. Abbassi, H. Nankali, D. Hatzfeld, R. Bayer, F. Tavakoli, A. Ashtiani, E. Doerflinger, M. Daignières, P. Collard, J. Chéry, GPS network monitors the Arabia–Eurasia collision deformation in Iran, J. Geod. 77 (2003) 411–422.

[3] P. Vernant, F. Nilforoushan, D. Hatzfeld, M. Abbassi, C. Vigny, F. Masson, H. Nankali, J. Martinod, A. Ashtiani, R. Bayer, F. Tavakoli, J. Chery, Contemporary crustal deformation and plate kinematics in middle east constrained by GPS measurement in Iran and northern Oman, Geophys. J. Int. 157 (2004) 381–398.

[4] N.N. Ambraseys, C.P. Melville, A History of Persian Earthquakes, Cambridge University Press, London, 1982, 219 pp.

[5] M. Berberian, R.S. Yeats, Patterns of historical earthquake rupture in the Iranian Plateau, Bull. Seismol. Soc. Am. 89 (1999) 120–139.

[6] M.-F. Brunet, M.V. Korotaev, A.V. Ershov, A.M. Nikishin, The south Caspian basin: a review of its evolution from subsidence modeling, Sediment. Geol. 156 (2003) 119–148.

[7] K. Priestley, C. Baker, C.J. Jackson, Implications of earthquake focal mechanism data for the active tectonics of the South Caspian Basin and surrounding regions, Geophys. J. Int. 118 (1994) 111–141.

[8] J. Jackson, K. Priestley, M. Allen, M. Berberian, Active tectonics of the South Caspian Basin, Geophys. J. Int. 148 (2002) 214–245.

[9] P. Vernant, F. Nilforoushan, J. Chery, R. Bayer, Y. Djamour, F. Masson, H. Nankali, J.-F. Ritz, M. Sedighi, F. Tavakoli, Deciphering oblique shortening of central Alborz in Iran using geodetic data, EPSL 223 (2004) 177–185.

[10] R.W. King, Y. Bock, Documentation for the GAMIT Analysis Software, Release 10.0, Mass. Inst. of Technol., Cambridge, 2002.

[11] T.A. Herring, GLOBK: Global Kalman Filter VLBI and GPS Analysis Program, Version 10.0, Mass. Inst. of Technol., Cambridge, 2002.

[12] A. Mao, C. Harrison, T. Dixon, Noise in GPS coordinate time series, J. Geophys. Res. 104 (1999) 2797–2816.

[13] M. Berberian, S. Arshadi, On the evidence of the youngest activity of the North Tabriz Fault and the seismicity of Tabriz city, Geol. Surv. Iran Rep. 39 (1976) 397–418.

[14] A. Karakhanian, R. Djrbashian, V. Trifonov, H. Philip, S. Arakelian, A. Avagian, Holocene-historical volcanism and active faults as natural risk factors for Armenia and adjacent countries, J. Volcanol. Geotherm. Res. 113 (2002) 319–344.

[15] K. Hessami, D. Pantosi, H. Tabassi, E. Shabanian, M. Abbassi, K. Feghhi, S. Sholaymani, Paleoearthquakes and slip rates of the North Tabriz Fault, NW Iran : preliminary results, Ann. Geophys. 46 (2003) 903–915.

[16] D.L. Wells, K.J. Coppersmith, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seismol. Soc. Am. 84 (4) (1994) 974–1002.

[17] A. Karakhanian, R. Jrbashyan, V. Trifonov, H. Philip, A. Avagyan, K. Hessami, F. Jamali, M. Bayraktutan, H. Bagdassarian, S. Arakelian, V. Davtyan, A. Adilkhanyan, Active faulting and natural hazards in Armenia, eastern Turkey and Northern Iran, Tectonophysics 380 (2004) 189–219.

[18] J.-F. Ritz, H. Nazari, H.A., R. Salamati, A. Shafeii, S. Solaymani, Active transtension inside Central Alborz: a new insight into the Northern Iran–Southern Caspian geodynamics, Geology 34 (2006) 477–480.

[19] R. Reilinger, S. McClusky, P. Vernant, S. Lawrence, S. Ergintav, GPS constraints on continental deformation in the Africa–Arabia–Eurasia continental collision zone and implications for the dynamics of plate interactions, J. Geophys. Res. 111 (2006) doi:10.1029/2005JB004051.

[20] M. Berberian, The southern Caspian: a compressional depression floored by a trapped, modified oceanic crust, Can. J. Earth Sci. 20 (1983) 163–183.

[21] L.P. Zonenshain, X. Le Pichon, Deep basins of the Black sea as remnants of Mesozoic back-arc basins, Tectonophysics 123 (1986) 181–211.

[22] H. Philip, A. Cisternas, A. Gvishiani, A. Gorshkov, The Caucasus: an actual example of the initial stages of continental collision, Tectonophysics 161 (1989) 1–21.

[23] J. Dercourt, L.P. Zonenshain, L.E. Ricou, V.G. Kazmin, X. Le Pichon, A.L. Knipper, C. Grandjacquet, I.M. Sbortshikov, J. Geyssant, C. Lepvrier, D.H. Pechersky, J. Boulin, J.-C. Sibuet, L.A. Savostin, O. Sorokhtin, M. Westphal, M.L. Bazhenov, J.P. Lauer, B. Biju-Duval, Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias, Tectonophysics 123 (1986) 241–315.

[24] R.S. Nadirov, E. Bagirov, M. Tagiyev, I. Lerche, Flexural plate subsidence, sedimentation rates, and structural development of the super-deep South Caspian Basin, Mar. Pet. Geol. 14 (1997) 383–400.

[25] A.M.C. Sengör, A new model for the late Paleozoic–Mesozoic tectonic evolution of Iran and implications for Oman, in The Geology and Tectonics of the Oman region, Geol. Soc. Spec. Publ. London (1990) 797–831.

[26] J.H. Knapp, C.C. Diaconescu, J.A. Connor, J.H. McBride, M.D. Simmons, Deep seismic exploration of the South Caspian Basin: lithospheric-scale imaging of the world's deepest basin, Istanbul, AAPG's Inaugural Regional International Conference, July 9–12, 2000, Istanbul, Turkey, 2000, pp. 35–37, abstract volume.

[27] H. Bijwaard, W. Spakman, E.R. Engdahl, Closing the gap between regional and global travel time tomography, J. Geophys. Res. 103 (1998) 30055–30078.

[28] A. Maggi, J.A. Jackson, K. Priestley, C. Baker, A re-assessment of focal depth distributions in southern Iran, the Tien Shan and northern India; do earthquake really occur in the continental mantle? Geophys. J. Int. 143 (2000) 629–661.

[29] A. Maggi, K. Priestley, Surface waveform tomography of the Turkish–Iranian plateau, Geophys. J. Int. 160 (2005) 1068–1080.

[30] P. Vernant, J. Chery, Low fault friction in Iran implies localized deformation for the Arabia–Eurasia collision zone, EPSL 246 (2006) 197–206.

[31] A.S. Karakhanian, R.T. Djrbashian, V.G. Trifonov, H. Philip, J.F. Ritz, Active faults and strong earthquakes of the Armenian upland, in: D. Giardini, S. Balassanian (Eds.), Historical and Prehistorical Earthquakes in the Caucasus, Kluwer Academic Publishers, Dordrecht, 1997, pp. 181–187.

[32] M.B. Allen, S.J. Vincent, I. Alsop, A. Ismail-zadeh, R. Flecker, Late Cenozoic deformation in the South Caspian region: effects of a rigid basement block within a collision zone, Tectonophysics 366 (2003) 223–239.

[33] M. Berberian, M. Qorashi, J. Jackson, K. Priestley, T. Wallace, The Rudbar–Tarom earthquake of 20 June 1990 in NSW Persia — preliminary field and seismological observations and its tectonic significance, Bull. Seismol. Soc. Am. 82 (1992) 1726–1755.

[34] F. Masson, J. Chéry, J. Martinod, D. Hatzfeld, P. Vernant, F. Tavakoli, A. Ashtiani, Seismic versus aseismic deformation in Iran inferred from GPS and seismicity dat, GJI 160 (2005), doi:10.1111/j.1365-246X.2004.02465.x.

[35] M.B. Allen, J. Jackson, R. Walker, Late Cenozoic reorganization of the Arabia–Eurasia collision and the comparison of short-term and long-term deformation rates, Tectonics 23 (2004), doi:10.1029/2003TC001530.

[36] P. Wessel, W.H.F. Smith, New version of the generic mapping tools released, EOS, Trans. AGU 76 (1995) 329.

[37] S. McClusky, S. Balassanian, A. Barka, C. Demir, S. Ergintav, I. Georgiev, O. Gurkan, M. Hamburger, K. Hurst, H. Kahle, K. Kastens, G. Kekelidze, R. King, V. Kotzev, O. Lenk, S. Mahmoud, A. Mishin, M. Nadariya, A. Ouzounis, D. Paradissis, Y. Peter, M. Prilepin, R. Reilinger, I. Sanli, H. Seeger, A. Tealeb, M. Toksoz, G. Veis, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, J. Geophys. Res. 105 (2000) 5695–5719.

[38] E.R. Engdahl, R.D. Van der Hilst, R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, Bull. Seismol. Soc. Am. 88 (1998) 722–743.