

# Kinematics of the eastern Caucasus near Baku, Azerbaijan

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**Abstract** The potential for large, shallow earthquakes and their associated seismic hazard in the eastern Caucasus, an area of dense population and sensitive industrial infrastructure, remains speculative based on historical precedent and current geologic and seismologic observations. Here we present updated and expanded results from a GPS network between the northern edge of the Lesser Caucasus and Greater Caucasus, providing geodetic constraints to the problem. A significant strain rate is observed in a profile over a distance of about 150 km across the Kura Basin. We attribute this to inter-seismic strain accumulation on buried fault structures and present simple elastic dislocation models for their plausible geometry and slip rate based on the known geology, seismicity and the GPS velocities. Due to the close proximity of the strain anomaly to Baku, further observations are needed to determine whether observed contraction is due to inter-seismically locked faults and, if so, implications for the seismic hazard in the region.

**Keywords** GPS velocities · Arabia–Eurasia collision · Caucasus Mountains · Azerbaijan · Caspian Sea · Inter-seismic strain accumulation

## 1 Introduction

The Caucasus Mountains are the northernmost part of the Arabia–Eurasian continental collision zone. Deformation is complex, including lateral transport and rotation of crustal blocks along strike-slip faults (e.g., Reilinger et al. 2006; Copley and Jackson 2006; Hollingsworth et al. 2008). At the longitude of the Caspian Sea, previous studies (e.g., Jackson et al. 2002) have noted that the majority of deformation occurs within three broad but distinct zones of high seismicity: from south to north, the Bitlis-Zagros Fold and Thrust

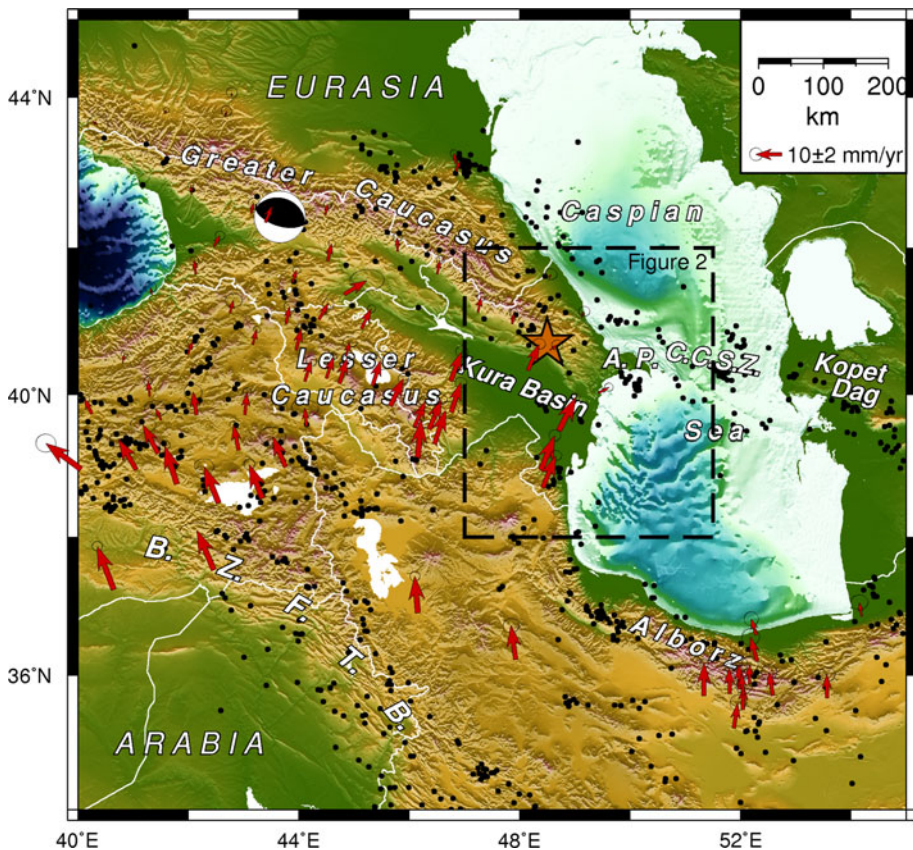
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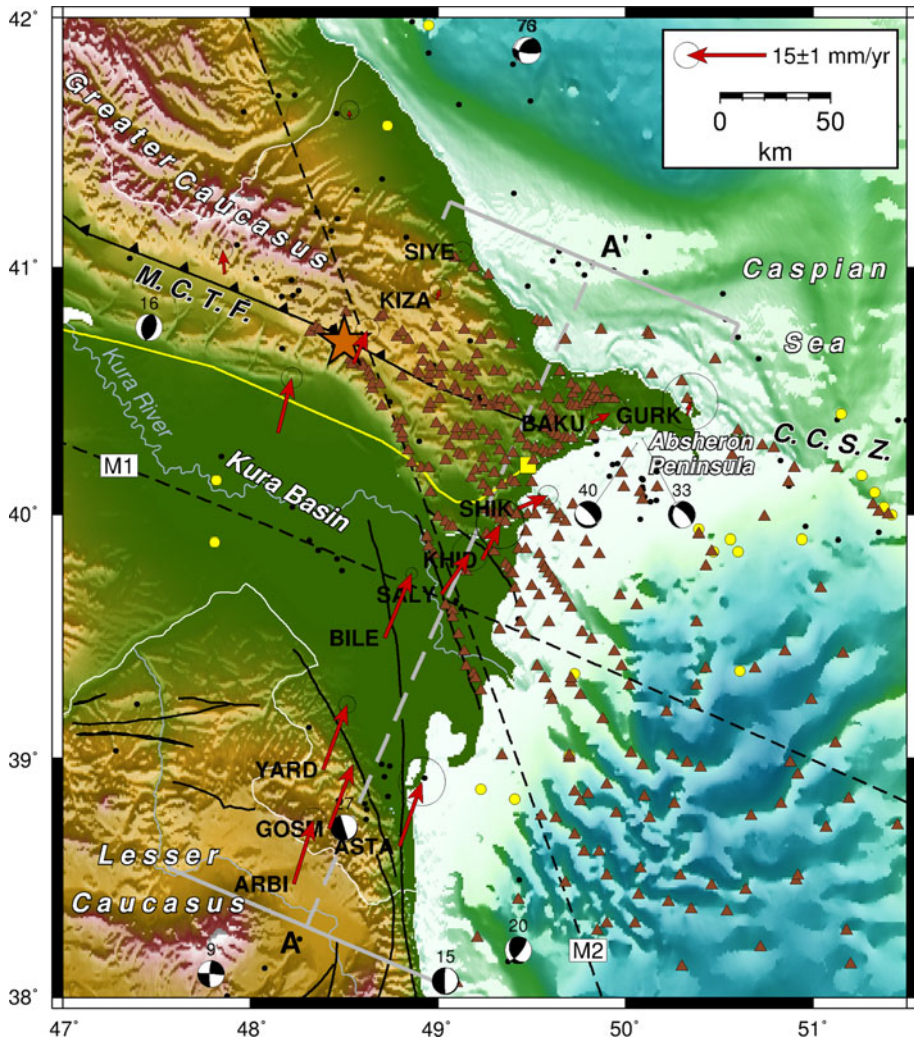
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Belt, the Alborz-Kopet Dag, and the Greater Caucasus Mountains and Central Caspian Seismic Zone (CCSZ); see Fig. 1. Major horizontal shortening west of the Caspian Sea is confined to this northernmost zone where the Main Caucasus Thrust Fault (MCTF) is the dominant structure (see Fig. 2). The MCTF strikes approximately WNW, dips to the north and is the major fault accommodating shortening between the Lesser and Greater Caucasus Mountains from the eastern Black Sea to the Caspian Sea. The CCSZ is thought to be a result of the early stages of subduction of the southern Caspian ocean basin beneath the northern Caspian continental lithosphere (e.g., Jackson et al. 2002).

In the western Greater Caucasus, there is precedent for large, shallow thrust earthquakes in the instrumental record, where the 1991  $M_w$  6.9 Racha, Georgia, earthquake occurred (see Fig. 1). GPS velocities (e.g., Reilinger et al. 2006) show that this earthquake occurred in a region of relatively low strain rate, where the Greater Caucasus accommodate a velocity gradient of approximately 6–8 mm/year of contraction over a distance of about



**Fig. 1** Overview of the tectonics of the Arabia–Eurasia collision zone. *Red vectors* are GPS velocities relative to Eurasia from Reilinger et al. (2006). *Black dots* are high-quality earthquake epicenters from the EHB catalog (Engdahl et al. 1998, and subsequent updates). The focal mechanism solution in the western Greater Caucasus is the 1991  $M_w$  6.9 Racha, Georgia, earthquake (Tan and Taymaz 2006), and the orange star marks the approximate location of the 1902 Shamakhi earthquake. A.P. is the Absheron Peninsula and B.Z.F.T.B. is the Bitlis-Zagros Fold and Thrust Belt. Topography is SRTM30 (Farr et al. 2007) and bathymetry is GEBCO\_08 (The GEBCO\_08 Grid, version 20100927, <http://www.gebco.net/>)



**Fig. 2** Map showing the area of study around the Absheron Peninsula. *Red vectors* are this study’s GPS velocities, updated and expanded from Reilinger et al. (2006). Annotated sites are used in the profile and analysis of deformation in the vicinity of the Absheron Peninsula. The *yellow square* is the Sangachal Terminal, and *yellow line* is the approximate location of the Baku-Ceyhan pipeline; *yellow circles* are oil wells and platforms. *Brown triangles* are mud volcanoes. Focal mechanism solutions are from Jackson et al. (2002) and Tan and Taymaz (2006); depths in km are annotated above the solutions. The Main Caucasus Thrust Fault (M.C.T.F.) is marked with ticks on the hanging wall side and C.C.S.Z. is the Central Caspian Seismic Zone. Model 1, representing the projection of the interface at depth to the surface within the Kura Basin, is shown by the *dashed line “M1”*; Model 2, representing an approximation of a West Caspian Fault, is shown by the *dashed line “M2”*

300 km perpendicular to the strike of the range (~20–25 nanostrain/year). Further east along the range, there is also evidence of destructive historical earthquakes near the city of Shamakhi in 1902 ( $M_w \sim 6.9$ ; orange star in Figs. 1, 2), with a similar event in 1667 and another earthquake ( $M_w \sim 5.9$ ) significantly affecting the city in 1859 (Kondorskaya et al.

1982; Berberian 1994). Baku, on the Absheron Peninsula, lies approximately 100 km further to the east of these earthquakes, and we present here GPS evidence that suggests a much larger strain rate is accommodated between the Lesser Caucasus and Eurasia at this eastern end of the Greater Caucasus.

The Absheron Peninsula lies at the junction between the MCTF and the CCSZ. Although the high topography of the Greater Caucasus Mountains terminates east of the Absheron Peninsula, the seismicity continues across the central Caspian Sea and further east along the Kopet Dag in Turkmenistan, suggesting a continuous structure. The change from shallow thrusting to deeper, extensional focal mechanisms is also consistent with a transition from continental thrusting along the MCTF to the early stages of subduction along the CCSZ. As such, both structures likely accommodate a portion of the ongoing collision between Arabia and Eurasia. Seismic activity and morphological evidence indicate deformation along the west side of the Caspian Sea south of Baku too, but the nature of this deformation remains more speculative due to the lack of direct constraints on the motion of the south Caspian “block” (e.g., Hollingsworth et al. 2008; Kadirov et al. 2008; Djamour et al. 2010).

The juxtaposition of these different tectonic processes near Baku is manifested by broadly distributed seismicity, intense mud volcano activity, and faulting and folding of the thick sediment pile within the south Caspian basin (Figs. 1, 2). The large numbers of mud volcanoes, some hundreds of meters high, in the area are a result of the extrusion of mobile, probably saturated, sediments from depth. The apparent NNW-SSE alignment of the mud volcanoes in the eastern Kura Basin may be indicative of fault control on their locations (Aliyev et al. 2009).

A primary motivation of this study is to establish plausible structures onto which the deformation is accommodated south and west of the Absheron peninsula, which provides some indication of the likely sources of seismic hazard in the region. Here we present a small network of sites in eastern Azerbaijan, near the west Caspian Sea coast, to provide quantitative geodetic control on the deformation between the Lesser and Greater Caucasus.

## 2 GPS data and processing

We initiated GPS measurements in Azerbaijan in 1998, expanding the network and repeating surveys through 2010. The results presented here are updated and expanded from Reilinger et al. (2006), in which four (BILE, GOSM, SHIK, YARD) of the twelve sites in this study were included; others are presented for the first time here. All sites have additional measurements between 2007 and 2010. Raw GPS phase data are processed using the GAMIT/GLOBK software suite (Herring et al. 2010), and velocities, associated uncertainties and a Eurasian reference frame are calculated using standard procedures as described in McClusky et al. (2003). Details of the GPS observations and velocities shown in Fig. 2 are given in Table 1.

The zone of deformation across the Kura Basin and Absheron Peninsula is well illustrated in map view in Fig. 2 by the decreasing GPS velocities for the sequence of GPS sites along the line from southeast Azerbaijan (YARD, GOSM) to Baku (SHIK, BAKU). It is clear that the highest gradient in GPS velocities occurs between sites BILE and BAKU, across the northern part of the Kura Basin and south of the surface trace of the MCTF, an area of intense mud volcano activity. This suggests that any accommodating structures such as folds exist at the surface in this region or, if a fault locked at depth, is likely to project to the surface at this approximate location (see inset of Fig. 4, left). In addition to

**Table 1** GPS velocities relative to Eurasia in eastern Azerbaijan from this study relative to Eurasia

| Site | T1       | T2       | Lon./°E | Lat./°N | $v_e$ | $v_n$ | $\sigma_e$ | $\sigma_n$ | $\rho$ | M1  | M2   |
|------|----------|----------|---------|---------|-------|-------|------------|------------|--------|-----|------|
| ARBI | 1999.790 | 1999.790 | 48.2314 | 38.4768 | 3.7   | 12.0  | 1.0        | 0.9        | 0.002  | 5.1 | 12.0 |
| ASTA | 2007.711 | 2007.711 | 48.7965 | 38.6350 | 4.2   | 12.1  | 1.8        | 1.9        | 0.004  | 5.0 | 11.8 |
| BAKU | 2007.711 | 2010.695 | 49.8144 | 40.3722 | 3.7   | 1.9   | 1.4        | 1.4        | 0.002  | 0.4 | 1.0  |
| BILE | 1998.785 | 2008.821 | 48.7170 | 39.4974 | 5.0   | 12.2  | 0.5        | 0.4        | 0.004  | 4.4 | 10.3 |
| GOSM | 1998.785 | 2008.821 | 48.4194 | 38.7056 | 4.5   | 12.2  | 0.5        | 0.5        | 0.001  | 5.0 | 11.9 |
| GURK | 2007.711 | 2009.837 | 50.3286 | 40.4044 | 0.6   | 2.6   | 2.1        | 2.2        | 0.005  | 0.3 | 0.6  |
| KHID | 2004.818 | 2006.903 | 49.2374 | 39.8177 | 3.5   | 6.6   | 1.9        | 1.9        | 0.000  | 1.5 | 3.7  |
| KIZA | 2002.744 | 2007.711 | 48.9930 | 40.8700 | 0.7   | 2.1   | 0.9        | 0.8        | 0.005  | 0.2 | 0.6  |
| SALY | 2004.818 | 2006.903 | 49.0203 | 39.6757 | 5.4   | 7.8   | 1.4        | 1.4        | 0.005  | 3.3 | 7.8  |
| SHIK | 1998.785 | 2007.711 | 49.4256 | 40.0252 | 5.7   | 2.5   | 0.8        | 0.8        | 0.011  | 1.2 | 2.9  |
| SIYE | 1998.711 | 2007.711 | 49.1205 | 41.0658 | 0.3   | -0.0  | 0.8        | 0.8        | 0.006  | 0.1 | 0.4  |
| YARD | 1998.785 | 2008.821 | 48.3877 | 38.9522 | 4.5   | 12.3  | 0.7        | 0.7        | 0.000  | 4.9 | 11.7 |

T1 and T2 are the first and last epochs of observation, respectively.  $v_e$ ,  $v_n$ ,  $\sigma_e$  and  $\sigma_n$  are east and north components of velocity and associated one-sigma uncertainties, respectively, in mm/year, and  $\rho$  is the correlation coefficient. M1 and M2 are model velocities

NNE-SSE shortening, there is also a rotation of the velocities to a more easterly direction on and immediately south of the Absheron Peninsula, indicating the presence of a shear component to the velocity gradient.

### 3 Discussion

There is little (<1 mm/year and within 95 % confidence) residual velocity relative to Eurasia to the north of Baku, suggesting that nearly all of this velocity gradient is accommodated on some structure or structures on the southern side of the Greater Caucasus near the Absheron Peninsula and Kura Basin. The limited spatial coverage of the current GPS network in the region allows us only to test simple end-member models of plausible structures based on what has previously been suggested from geologic and seismicity studies.

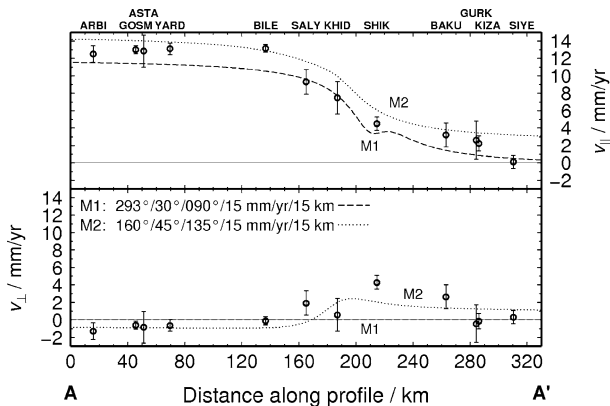
Earthquake locations and focal mechanisms do not aid directly to the determination of the dominant structures in the region. A broad band of seismicity runs along the strike of the Greater Caucasus and continues offshore to delineate the CCSZ. As noted by Jackson et al. (2002), Copley and Jackson (2006), and Tan and Taymaz (2006), earthquake focal depths from teleseismic body waveform modeling are often different from global catalogs, even for reportedly good solutions from the EHB catalog (Engdahl et al. 1998, and subsequent updates). The few well-determined focal mechanisms of interest in our region of study (see Fig. 2) fall into two categories: normal mechanisms just offshore of Baku and within the CCSZ, which are interpreted to be symptomatic of the bending of the lithosphere of the south Caspian Basin as it begins to subduct below the central Caspian; and those beneath the Kura Basin. All mechanisms are deep (35–60 km) and unlikely to be indicative of crustal tectonics.

The continuation of seismicity across the central Caspian Sea, however, and the likely transition from continental thrusting to early subduction that it represents, suggests that a straightforward continuation of a low-angle thrust from the MCTF eastwards beyond the Absheron Peninsula and into the central Caspian Sea (Fig. 2, M1) may be a plausible structure accommodating the observed deformation. The location of the greatest velocity gradient and geometry of the MCTF, as well as subsidiary faults and folds between it and the Kura Basin to the south (e.g., Forte et al. 2010), may support the notion of a deep, gently dipping thrust interface below the Greater Caucasus, Absheron Peninsula and CCSZ, from which the MCTF and other faults splay at a higher angle (see Fig. 4) or indicate that the main deformation front is propagating southwards (e.g., Forte et al. 2010). Alternatively, previous studies (e.g., Allen et al. 2003; Vernant et al. 2004) have suggested the existence of an active West Caspian Fault, striking approximately north–south near the west coast of the south Caspian Basin between the Absheron Peninsula and the Talesh Mountains of the Lesser Caucasus, with an estimated rate of strike-slip motion of 7–8 mm/year. Existing models of the kinematics of this area (e.g., Kadirov et al. 2008; Reilinger et al. 2006) use a similar block geometry, with boundaries tracing the MCTF to the Absheron Peninsula before striking southwards along the west Caspian Sea coast. Jackson et al. (2002) attribute the existence of west-dipping, low-angle thrust mechanisms to the south of our region of study (see Fig. 2) to the relatively simple westward subduction of the south Caspian Basin beneath the Talesh. While these mechanisms clearly support this conclusion, we suggest that a lack of evidence in the instrumental seismic record for more oblique motion along a hypothetical “West Caspian Fault” is not evidence against such a structure existing, especially when the GPS data show that some right-lateral shear across

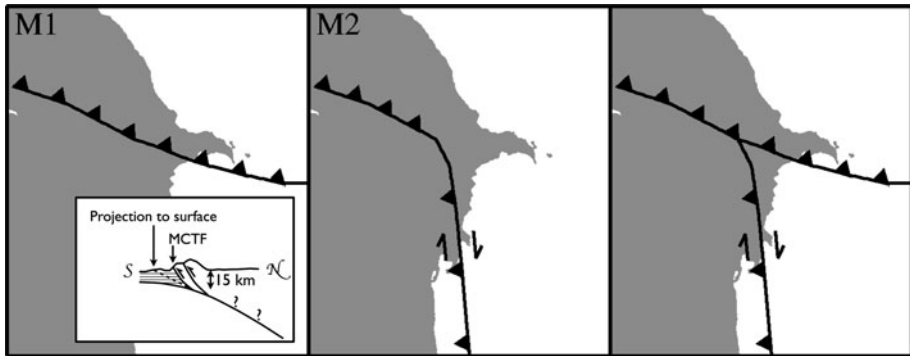
such a north–south structure immediately south of the Absheron Peninsula (Fig. 2, M2) is plausible. This is supported by the strike of folds visible in the bathymetry diverging offshore and lineaments of mud volcanoes following the same pattern. We suggest that there is a bounding structure along the west Caspian shoreline, to the north along the MCTF and CCSZ, or both.

Although we cannot constrain more precisely the geometry of the structures responsible for the observed deformation with the present spatial distribution of GPS, we investigate strain accumulation models that include structures consistent with the regional tectonics. We perform simple forward model calculations for infinitely long elastic dislocations with uniform slip rate below a locking depth (Okada 1985) representing these plausible fault structures. Model 1 (M1) considers a low-angle (30°) thrust fault striking approximately parallel to the MCTF and CCSZ. Model 2 (M2) considers a fault striking parallel to NNW–SSE structures, including bathymetric ridges and troughs, and mud volcanoes, approximating a “West Caspian Fault” dipping (45°) to the west (Fig. 2). We present a moderately dipping structure to accommodate the fact that the data require some contraction (~5 mm/year) across such a structure. Our simple models constitute a plausibility study given that the network can offer only broad constraint on parameters such as dip and rake. For model 1, it is necessary to have the projection to the surface of this fault appear further south than the trace of the MCTF to reproduce the observed pattern of deformation, specifically the location of the velocity gradient. The RMS (WRMS) misfits of models 1 and 2 are 2.4 (1.6) mm/year and 2.1 (1.3) mm/year, respectively, for the horizontal components of velocity.

Figure 3 shows a velocity profile along a line oriented normal to the strike of the MCTF (A–A’ in Fig. 2). The top plot shows the component of velocity parallel to this line (shortening) while the bottom plot shows the component of velocity perpendicular to the profile (shear). The former is consistent with approximately 13 mm/year of contraction normal to the strike of the MCTF and CCSZ. Strain rates between BILE and SHIK are ~13 × 10<sup>-8</sup>/year, which can be compared to strain rates across the MCTF in central Azerbaijan (at approximately 47°E) of ~2 × 10<sup>-8</sup>/year (Reilinger et al. 2006, their Fig. 4, panel C). The component of velocity perpendicular to the profile is considerably smaller



**Fig. 3** Components of velocity parallel (*top*) and perpendicular (*bottom*) to profile A–A’, as shown in Fig. 2. Parameters for models M1 and M2 are given as strike/dip/rake/slip rate/locking depth. Note that the perpendicular component of velocity for model M1 is everywhere zero



**Fig. 4** Schematic representation of the possible tectonics around the Absheron Peninsula. Model 1 (*left*) shows a continuous structure from the MCTF to the CCSZ, where the MCTF is a splay from a deeper structure whose locked portion projects to the surface within the Kura Basin (e.g., Knapp et al. 2004, Fig. 4). Model 2 (*center*) is similar to current kinematic models where deformation on the MCTF is transferred onto an oblique right-lateral and thrust fault running down the west side of the Caspian Sea south of the Absheron Peninsula. It is also possible that the actual scenario is some combination of both (*right*)

and is approximately 4 mm/year confined to the southwest Absheron Peninsula and northeast Kura Basin.

Both models reproduce the first-order characteristics of the deformation, indicating a predominance of shortening perpendicular to the strike of the MCTF and CCSZ. Models including a substantial component of thrusting along a structure subparallel to the MCTF south of the Absheron Peninsula are appropriate to the extent that the western part of the south Caspian Sea is moving northwards relative to Eurasia. These models imply that the strain rate anomaly is located near the junction between continental thrusting along the MCTF and the early stages of subduction along the CCSZ (Jackson et al. 2002), where a complexity in the accommodating structures, such as the existence of an active West Caspian Fault, may exist. Further support for this interpretation is offered by Djamour et al. (2010), who report GPS estimates of surface deformation in Iran and surrounding areas. Based primarily on velocities for GPS sites along the southern edge of the Caspian Sea, they suggest that the south Caspian Sea is rotating clockwise relative to Eurasia around a Euler pole located about 500 km to the east ( $59.1 \pm 0.8^\circ\text{E}$ ,  $40.4 \pm 0.3^\circ\text{N}$ ). This Euler pole predicts  $8.8 \pm 1.1$  mm/year of northward motion of the south Caspian Basin relative to Eurasia to the immediate south of the Absheron Peninsula (at  $39.5^\circ\text{E}$ ,  $49.7^\circ\text{N}$ ). This is nominally slower than the northward motion of the adjacent Kura Basin (for instance, the velocity of BILE with respect to Eurasia is northward at  $13.2 \pm 0.5$  mm/year) and thus consistent with a right-lateral shear along the west coast of the Caspian Sea. However, we are reluctant to place too much significance to this difference because of the absence of constraints on the south Caspian–Eurasia Euler pole in the northwest part of the south Caspian.

It is currently not possible to conclude whether the deformation seen at the surface is a result of inter-seismic elastic strain accumulation or plastic deformation of the thick pile of sediments of the Kura Basin. However, some structure or structures must be accommodating the contraction that we observe and it is sensible, from a seismic hazard analysis perspective, to assume the worst-case scenario and consider the possibility that the observed strain may be released ultimately in a seismic event. Fold structures, for example, may exist at the tip of deeper, blind faults. Forte et al. (2010) indicate that the deformation



front is now likely south of the MCTF and main Greater Caucasus range front, and that this deformation may be propagating to the east where a larger relative velocity is expected (and observed here) near the Caspian Sea and Absheron Peninsula. Furthermore, blind faulting has been the case for some notable continental earthquakes, most recently the 2010  $M_w$  7.1 Darfield and 2011  $M_w$  6.2 Christchurch, New Zealand, earthquakes for which little to no recorded seismicity nor mapped active fault traces existed in the alluvial Canterbury Plains region prior to the 2010 event (e.g., Kaiser et al. 2012). Further geophysical studies, including denser geodetic coverage, historic and paleoseismic studies, and seismic imaging, are necessary to provide improved estimates for seismic hazards in this critical region.

#### 4 Conclusions

GPS measurements in eastern Azerbaijan, traversing the Lesser Caucasus, Kura Basin and Absheron Peninsula, indicate anomalous strain associated with primarily active convergence within the northernmost part of the Arabia–Eurasia collision zone. Although present data distribution and precision are insufficient to determine unambiguously the cause of the observed strain, deformation is nonetheless consistent with simple models of strain accumulation on a north-dipping thrust fault striking approximately parallel to the Main Caucasus Thrust Fault and/or right-lateral shear and convergence across a fault striking approximately NNW–SSE along the west coast of the Caspian Sea south of the Absheron Peninsula at a rate of approximately 15 mm/year. More GPS data are needed along with detailed geologic and seismic surveys to determine the nature of folding and faulting throughout the Kura Basin at depth.

Given the proximity of a large population center (Baku) and petroleum industry installations and pipelines (e.g., the Sangachal Terminal), we conclude that there may be significant seismic hazard in the region, which is thus far not clear from the seismic or geologic record. A focused study of this area, including geodetic densification and other geophysical and geological studies to determine strain patterns, the nature of folding within the Kura Basin, the location of buried faults and implications for earthquake generation, is needed to understand more completely the kinematics of the transition from continental thrusting along the Main Caucasus Thrust Fault to subduction along the Central Caspian Seismic Zone or structures transferring relative motion southwards to the Talesh Mountains of the Lesser Caucasus and Alborz.

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