High strain rates observed near Baku, Azerbaijan

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GPS measurements along a traverse crossing the eastern Kura Depression adjacent to the Absheron Peninsula and the city of Baku, Azerbaijan, indicate high strain rates that raise concerns about geologic hazards in this densely populated and highly industrialized region. High strain rates appear to be continuous with high strain rates along the Main Caucasus Thrust Fault (MCTF) located along the southern edge of the Greater Caucasus Mountains to the west of the Peninsula. While the MCTF has experienced a number of M > 6.5 historic earthquakes (including the 1991, M=7.1 Racha, Georgia event), present observations are not sufficient to determine whether the high strains observed near Baku are due to permanent deformation (folding), aseismic fault slip, or elastic strain accumulation that will eventually be released by earthquakes. Given the proximity of this area to the city of Baku and the potential environmental and economic impact from

damage to the petroleum infrastructure, we recommend intensified investigations to determine the possible implications of these high strain rates for future earthquake activity.

The Caucasus Mountains are the northernmost part of the Arabia-Eurasia collision zone that includes, from south to north, the Bitlis-Zagros Fold and Thrust Belt, the Eastern Turkey-Iranian High Plateau/Lesser Caucasus Mountains, and the Kura Depression (Figure 1). Deformation within the collision zone is complex, involving lateral transport and rotation of crustal blocks along strike slip faults (e.g., 1, 2, 3). Major horizontal shortening west of the Caspian Sea is confined to the MCTF. The high topography of the Greater Caucasus Mountains terminates west of the Absheron Peninsula, although seismicity along the Caucasus continues across the central Caspian Sea. The continuity of seismicity across the Caspian and east along the Kopeh Dagh in Turkmenistan suggests a continuous structure, while the change from shallow thrusting to deeper extensional focal mechanisms is consistent with a transition from continental underthrusting along the MCTF to the early stages of ocean subduction along the CCSZ (e.g., 4). Seismic activity and morphologic evidence indicate deformation along the west side of the Caspian Sea south of Baku as well, 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., 3, 5, 6).

The juxtaposition of these different tectonic processes near Baku is manifest by broadly distributed seismicity, intense mud volcanic activity, and faulting and folding of the thick sediment pile within the south Caspian Basin (Figures 1 and 2). The apparent NNW-SSE alignment of the mud volcanoes in the eastern Kura Depression may be indicative of fault control.

We initiated GPS-geodynamic measurements in Azerbaijan in 1998, expanding the network and repeating surveys through 2010. Figure 2 shows present-day motions for stations in eastern Azerbaijan with respect to Eurasia. GPS station velocities were determined using the GAMIT/GLOBK software (7), and uncertainties and the Eurasia reference frame were estimated following standard procedures described by (8). Details of the GPS observations, and GPS velocities shown in Figure 2 are given in Supplementary Table 1.

The zone of high strain is well illustrated in map-view in Figure 2 by the decreasing GPS velocities for the sequence of GPS sites along the line from SE Azerbaijan (YARD, GOSM) to Baku (SHIK, BAKU). Observable strain is confined to the NE Kura Depression and SW Absheron Peninsula between GPS sites BILE and SHIK, an area of intense mud volcanic activity. Although we can not constrain the strike of the structures controlling the observed deformation with present GPS observations, the reduced amplitude of velocity vectors NE of station BILE is consistent with either thrusting on structures sub-parallel to the strike of the MCTF and Central Caspian Seismic Zone (CCSZ; ~108° Azimuth) or right-lateral shearing on roughly NE-SW striking structures within the northeastern Kura Depression and SW Absheron Peninsula.

Figures 3A and B show 2 velocity profiles, one (Figure 3A; profile A—A') projected onto a line normal to the strike of the CCSZ (~105° Az), and the other (Figure 3B; profile B—B') onto a line normal to the SSE alignment of mud volcanoes crossing the Kura Depression and westernmost Caspian Sea that may be an extension of the MCT (5) (see Figure 2 for profile locations). The velocity profiles show both the motion parallel and perpendicular to these lines. The component of velocity parallel to A—A' (Figure 3A, top) is consistent with ~12 mm/yr shortening across structures roughly aligned with the MCT and CCSZ. Compressional strain rates between BILE and SHIK are ~13 x 10^{-8} yr^{-1} which can be compared to strain rates across the MCT in central Azerbaijan (~47°E) of ~2 x 10^{-8} yr^{-1} (1, their Figure 4, panel C). The component of velocity perpendicular to line A—A' indicates ~2 mm/yr right-lateral, strike slip between these same benchmarks. The component of velocity perpendicular to B—B' (Figure 3B, bottom) is consistent with ~9 mm/yr right-lateral, strike slip across structures roughly aligned with the possible SSE extension of the MCT. Shear strain rates between BILE and SHIK are ~12 x 10^{-8} yr^{-1} which can be compared to the average shear strain rate along the North Anatolian Fault (e.g., ~17 x 10^{-8}/yr; *9*). The component of velocity parallel to line B—B' (Figure 3B, top) indicates ~3 mm/yr shortening between these same benchmarks.

Profile A—A' is appropriate to the extent that the western part of the South Caspian Basin is moving more or less coherently with the adjacent Kura Depression (6). In this case, the strain rate anomaly is located at the junction between continental thrust faulting along the MCT and the early stages of oceanic subduction along the CCSZ. The small profile-parallel strain rate (~2 mm/yr) suggests a small component of right-lateral strike slip. We caution, however, that while differential motion SW of Baku is unambiguous, the distribution of motion on the responsible structures (faults?) depends on the strike of the structures that remain poorly constrained with the limited spatial coverage of our GPS observations.

Baku has a population of well over 2 million (~25% of the population of the country) and is the political, cultural, business, and industrial heart of the country. The large majority of the petroleum infrastructure, that generates much of the revenue for the country, is located within and SW of the Absheron Peninsula and adjacent Caspian Sea (Figure 2). A significant earthquake in the northeastern Kura Depression/Absheron area of high strain could have calamitous effects on the entire country. Accordingly, we recommend a focused study of this area, including geodetic densification and other geophysical and geological studies to determine detailed strain patterns, the location of possible buried faults, and implications for earthquake generation.

Acknowledgements

Maps were generated using the GMT software (10). We are grateful to Simon McClusky for assistance with processing the CGPS data, and UNAVCO for technical help with the GPS field observations. MIT participation was supported in part by NSF EAR-0838488 and NSF EAR-0609730.

Figure and Table Captions:

Figure 1. Simplified tectonic map showing topography (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info), seismicity (http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php) and earthquake focal mechanisms (http://www.globalcmt.org/CMTsearch.html) for the eastern part of the Arabia-Eurasia plate collision zone. The Main Caucasus Trust Fault (MCTF), Central Caspian Seismic Zone (CCSZ), and the Bitlis-Zagros Fold and Thrust Belt (BZFTB) are shown schematically.

Figure 2. GPS-derived velocities with respect to Eurasia and 95% confidence ellipses for eastern Azerbaijan and adjacent areas. The locations of the velocity profiles shown in Figure 3 are indicated by the dashed blue lines. The Main Caucasus Trust Fault (Figure 1) and other reported lineaments (modified from http://atlas.geo.cornell.edu/report/tablec.html) are shown as dashed black lines. Mud volcanoes (red triangles; 11), major oil producing facilities (yellow circles), and the Sangachal Baku-Ceyhan Pipeline Terminal (yellow square) and Pipeline (yellow dashed line) are also shown (http://en.wikipedia.org/wiki/Sangachal_Terminal). LC=Lesser Caucasus.

Figure 3. A. GPS velocities and 1-sigma uncertainties parallel (top) and perpendicular (bottom) to the 15° azimuth line shown in map view in Figure 2 (A-A').
B. GPS velocities and 1-sigma uncertainties parallel (top) and perpendicular (bottom) to the 70° azimuth line shown in map view in Figure 2 (B-B'). Note the offsets between sites BILE and SHIK are consistent with either thrusting along the MCT and CCSZ (A—

A'), or right-lateral faulting along SSW striking structures along the W side of the Caspian Sea (B—B'). GPS site names are shown above the plots and correspond to those shown in Figure 2.

Supplementary Table 1S. GPS velocities in E Azerbaijan with respect to Eurasia given in terms of east [VE] and north [VN] rate, and 1-sigma uncertainties (±). Abbreviations: Lon=longitude, Lat=latitude, Rho=correlation between VN and VE, T1=time of initial observations, T2=time of last observations.

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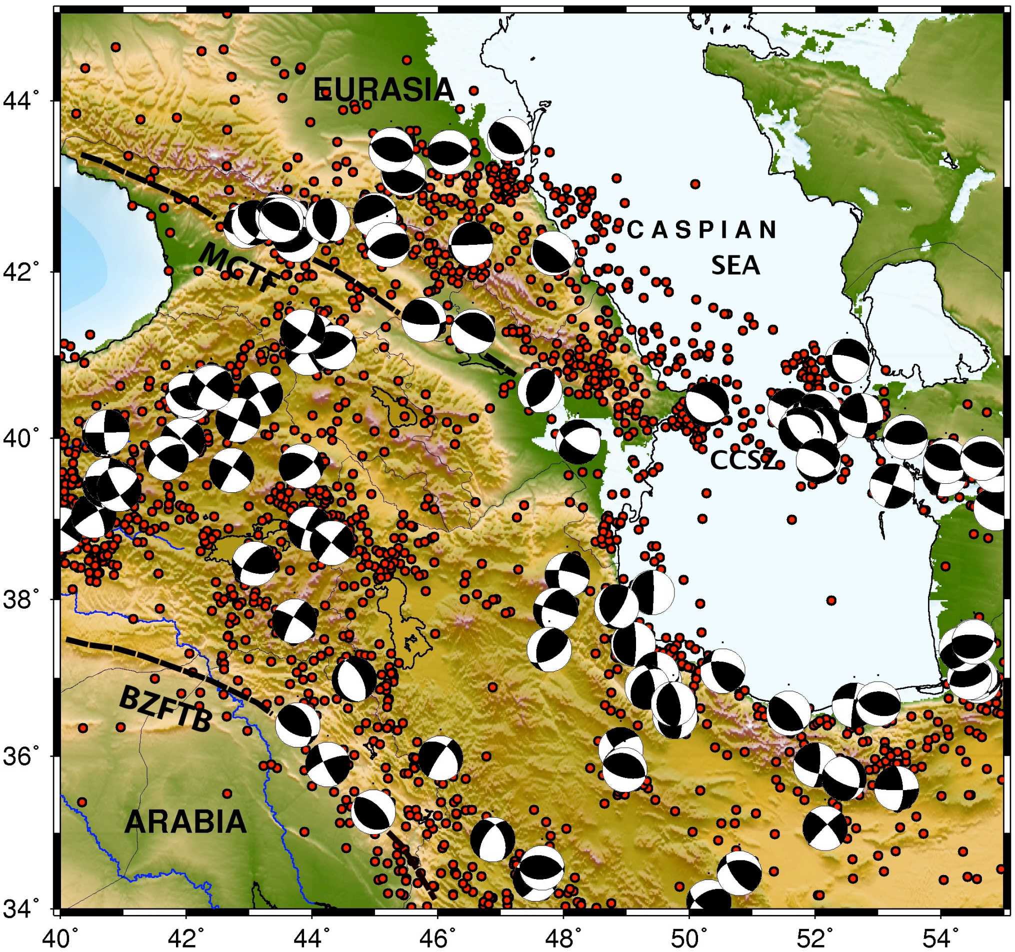
EURASIA
CASPIAN
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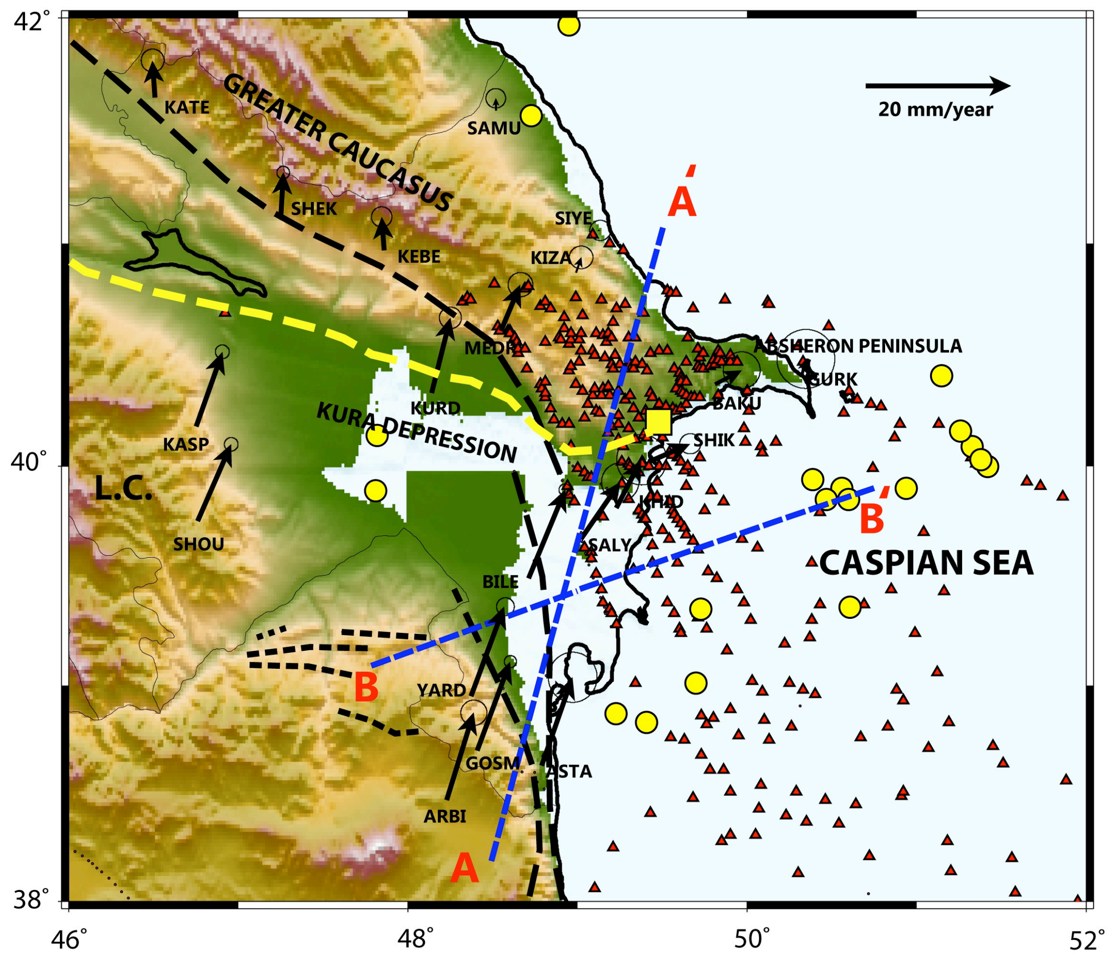
Figure 1.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20 mm/year
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KATE
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SHEK
KEBE
SIYE
KIZA
A'
MEDR
ABSHERON PENINSULA
GURK
BAKU
KURD
KURA DEPRESSION
KASP
SHIK
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Figure 2.

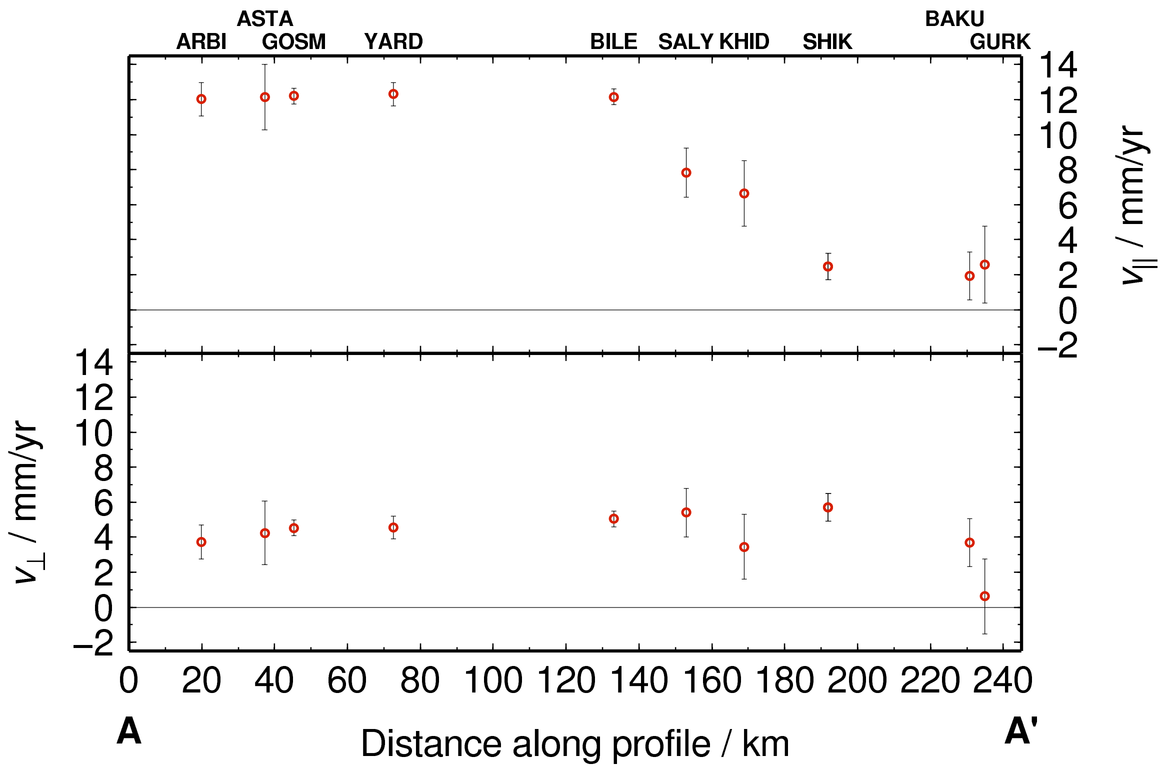

Figure 3A.

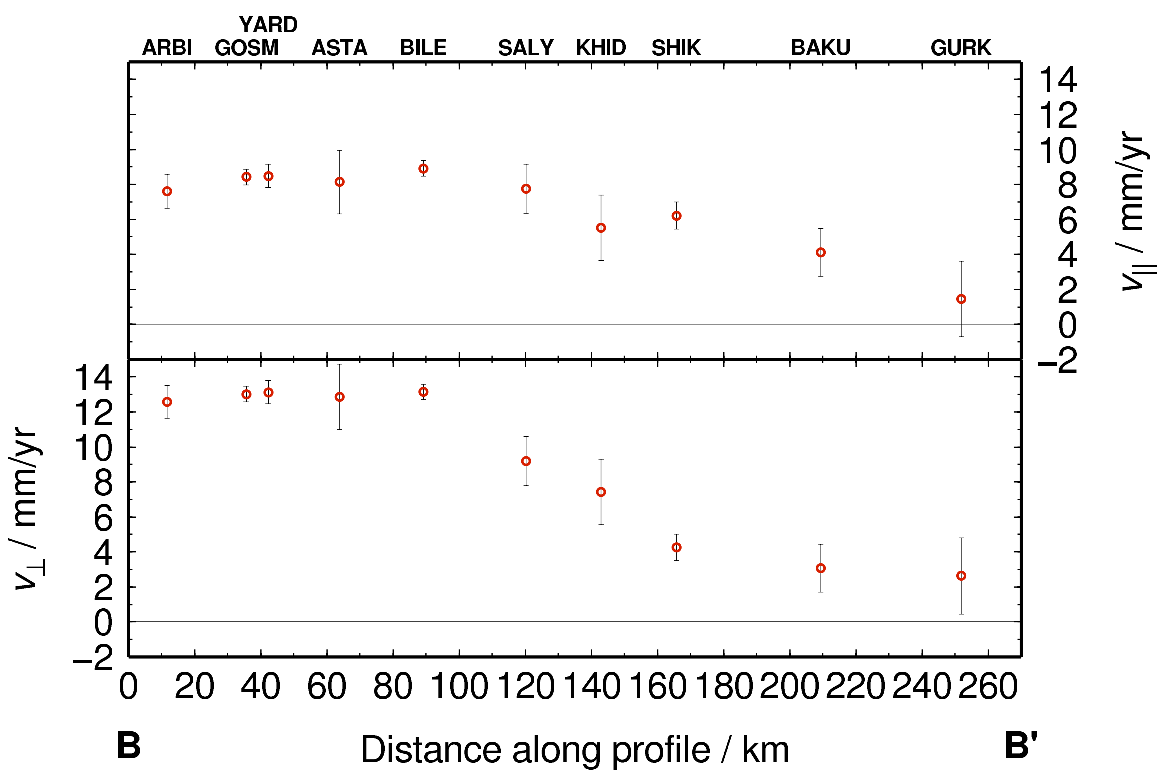

Figure 3B.

Supplementary Table 1S. GPS velocities in E Azerbaijan with respect to Eurasia given in terms of east [VE] and north [VN] rate, and 1-sigma uncertainties (ve±, vn±). Abbreviations: Lon=longitude, Lat=latitude, Rho=correlation between N and E velocity components, T1=time of initial observations, T2=time of last observations.

Site	Lon.	Lat.	VE	VN	ve±	vn±	Rho	T1	T2
GURK	50.32	40.40	0.62	2.57	2.15	2.19	0.005	2007.7	2009.8
BAKU	49.81	40.37	3.69	1.92	1.37	1.37	0.002	2007.7	2010.7
SHIK	49.42	40.02	5.71	2.47	0.78	0.75	0.011	1998.8	2007.7
KHID	49.23	39.81	3.45	6.64	1.86	1.87	0.000	2004.8	2006.9
SIYE	49.12	41.06	0.33	-0.02	0.78	0.75	0.006	1998.7	2007.7
SALY	49.02	39.67	5.41	7.82	1.39	1.41	0.005	2004.8	2008.7
KIZA	48.99	40.87	0.73	2.12	0.88	0.84	0.005	2002.7	2007.7
ASTA	48.79	38.63	4.24	12.14	1.81	1.86	0.004	2007.7	2009.8
BILE	48.71	39.49	5.05	12.16	0.45	0.44	0.004	1998.8	2008.8
MEDR	48.55	40.61	2.65	6.35	0.92	0.90	0.001	1998.7	2008.7
SAMU	48.52	41.59	-0.04	1.73	0.73	0.72	0.001	1998.7	2008.7
GOSM	48.41	38.70	4.53	12.21	0.45	0.45	0.001	1998.8	2008.8
YARD	48.38	38.95	4.55	12.31	0.66	0.66	0.000	1998.8	2008.8
ARBI	48.23	38.47	3.71	12.02	0.97	0.94	0.002	1999.8	2003.7
KURD	48.14	40.33	2.58	10.34	0.82	0.80	-0.001	2000.8	2008.8
KEBE	47.86	40.97	-0.34	4.60	0.76	0.75	0.000	1998.7	2007.7
SHEK	47.25	41.13	0.34	5.76	0.47	0.47	0.006	1998.7	2008.8
SHOU	46.76	39.75	4.62	10.57	0.51	0.50	0.002	1998.8	2007.7
KASP	46.75	40.18	3.63	10.24	0.52	0.51	-0.003	1998.8	2007.7
KATE	46.51	41.65	-0.36	5.05	0.85	0.85	-0.000	1998.7	2008.8