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Active convergence between the Lesser and Greater Caucasus in Georgia: Constraints on the tectonic evolution of the Lesser–Greater Caucasus continental collision

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A B S T R A C T

We present and interpret newly determined site motions derived from GPS observations made from 2008 through 2016 in the Republic of Georgia, which constrain the rate and locus of active shortening in the Lesser–Greater Caucasus continental collision zone. Observation sites are located along two ∼160 km-long profiles crossing the Lesser–Greater Caucasus boundary zone: one crossing the Rioni Basin in western Georgia and the other crossing further east near the longitude of Tbilisi. Convergence across the Rioni Basin Profile occurs along the southern margin of the Greater Caucasus, near the surface trace of the north-dipping Main Caucasus Thrust Fault (MCTF) system, and is consistent with strain accumulation on the fault that generated the 1991 M_W6.9 Racha earthquake. In contrast, convergence along the Tbilisi Profile occurs near Tbilisi and the northern boundary of the Lesser Caucasus (near the south-dipping Lesser Caucasus Thrust Fault), approximately 50–70 km south of the MCTF, which is inactive within the resolution of geodetic observations ($< \pm 0.5$ mm/yr) at the location of the Tbilisi Profile. We suggest that the southward offset of convergence along strike of the range is related to the incipient collision of the Lesser–Greater Caucasus, and closing of the intervening Kura Basin, which is most advanced along this segment of the collision zone. The identification of active shortening near Tbilisi requires a reevaluation of seismic hazards in this area.

1. Introduction

The Caucasus region, including the Lesser and Greater Caucasus Mountains and intervening Kura and Rioni Basins, represents the northernmost edge of the ongoing continental collision of the Arabian and Eurasian plates. The timing of the initial collision of Arabia with the southern edge of Eurasia is complicated by intervening island arcs and continental fragments (e.g., Philip et al., 1989; Forte et al., 2010; McQuarrie and von Hinsbergen, 2013; Cowgill et al., 2016; Rolland et al., 2012). Estimates for the onset of collision range from Late Eocene to Late Miocene (∼35–10 Ma). Since formation of the North Anatolian Fault in the Late Miocene (∼12 Ma; Sengor et al., 2004), collision of Arabia with Eurasia has been accommodated by westward "extrusion" of Anatolia in the west (McKenzie, 1972; Sengor et al., 1985) and by oblique convergence across Iran and the South Caspian Sea in the eastern third (Talebian and Jackson, 2002; Axen et al., 2001; Ballato et al., 2013; Allen et al., 2002). In the central part of the range, plate convergence has led to northeast-directed shortening and associated uplift and exhumation of the Greater Caucasus (Jackson, 1992; Allen et al., 2002; Avdeev and Niemi, 2011) and possible subduction of the Kura Basin in the east (Mellors et al., 2012; Mumladze et al., 2015; Cowgill et al., 2016). These processes continue to the present time (McClusky et al., 2000; Reilinger et al., 2006; Kadirov et al., 2012; Karakhanian et al., 2013; Forte et al., 2013).

Structurally, the Lesser Caucasus is thought to have formed during the Mesozoic as a volcanic island arc resulting from northward subduction of the Neotethys Ocean beneath Eurasia (e.g., Adamia et al., 2011; Gamkrelidze, 1986; Zonenshain and Le Pichon, 1986). Rifting from the southern margin formed the Greater Caucasus back-arc basin. Both the Lesser and Greater Caucasus are characterized by relatively thick crust (∼45–55 km, Gok et al., 2011)

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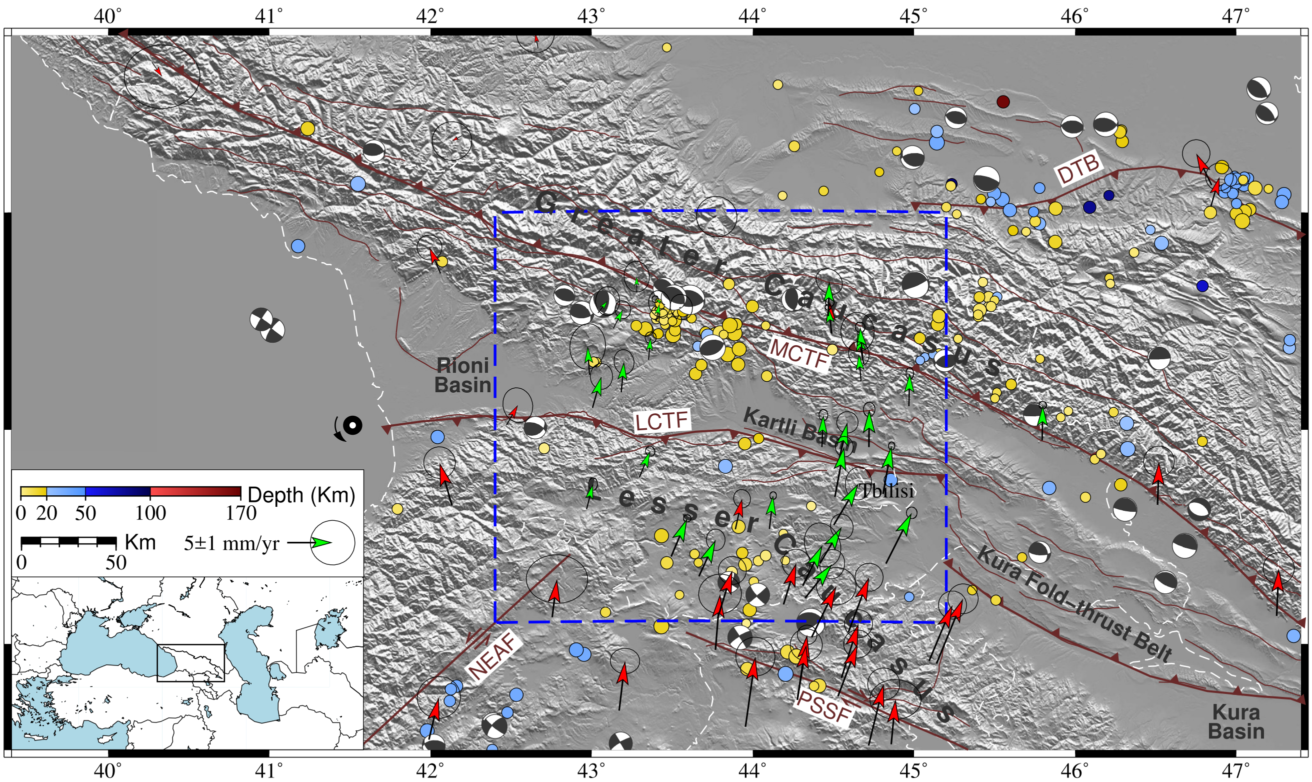

Fig. 1. Map showing GPS velocities relative to Eurasia with 95% confidence ellipses, where red vectors are published (Reilinger et al., 2006; Karakhanian et al., 2013) and green vectors are new velocities presented here. Black circle with white dot and arc with the arrowhead shows the location and rotation direction of the western Lesser Caucasus Euler pole (see text for discussion). Earthquakes greater than M_W5 are plotted with focal mechanisms from the Global CMT project (Dziewonski et al., 1981; Ekström et al., 2012), and as circles (colored by depth) for events between M4–5 from the EHB catalog before 2009 (International Seismological Centre, 2014a) and the ISC catalog since 2009 (International Seismological Centre, 2014b). The cluster of focal mechanisms and shallow (yellow) earthquakes near 42.5°N, 43.5°E includes the Racha $M_W6.9$ event (largest focal mechanism) and aftershocks > M4. Red lines schematically show faults, with heavier line weights for selected faults mentioned in text (Gamkrelidze et al., 1998; Forte et al., 2014); paired arrows indicate relative motion for strike-slip faults; barbed lines indicate thrust faults, with triangles on hanging wall block. Abbreviations are, Main Caucasus Thrust Fault (MCTF), Lesser Caucasus Thrust Fault (LCTF), and North–East Anatolian Fault (NEAF), Dagestan Thrust Belt (DTB), Pambak–Sevan–Sunik Fault (PSSF). Blue dashed box outlines study area shown in detail in Fig. 2. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

with voluminous volcanic rocks in the Lesser Caucasus and western Greater Caucasus (e.g., Adamia et al., 2011). The Kura and Rioni Basins separating the Lesser and Greater Caucasus (Fig. 1) appear to be the last vestiges of the intervening oceanic or island arc crust, with 5–7 km of sedimentary cover, remnants of which exist in the South Caspian and eastern Black Seas (e.g., Zonenshain and Le Pichon, 1986; Rupple and McNutt, 1990; Forte et al., 2010; Cowgill et al., 2016).

Geodetic, geologic and seismic observations indicate that major present-day convergence within the Caucasus system occurs primarily across the intervening Kura and Rioni Basins, where convergence rates increase eastwards along strike, from ∼2 to ∼12 mm/yr (e.g., Jackson, 1992; Berberian, 1997; Reilinger et al., 2006; Forte et al., 2013, 2014; Karakhanian et al., 2013) (Fig. 1). While there is no evidence for convergence along the northern boundary of the western Greater Caucasus west of ∼43.5°E, seismic, geodetic and geologic observations indicate active shortening (2–3 mm/yr) along the northern boundary of the eastern Greater Caucasus (Fig. 1) (Tan and Taymaz, 2006; Kadirov et al., 2012; Forte et al., 2014).

Convergence along the eastern Greater Caucasus (i.e., ∼46–48°E) is accommodated in part along the Kura Fold and Thrust Belt, a series of sub-parallel, north-dipping low-angle blind thrusts that extend well south of the main southern slope of the mountain range (Fig. 1) (e.g., Forte et al., 2010, 2013, 2015). Seismic (e.g., Berberian, 1997; Copley and Jackson, 2006; Tan and Taymaz, 2006) and geodetic (e.g., Kadirov et al., 2015) observations suggest that these low-angle faults root in a north-dipping thrust beneath the southern slope of the Greater Caucasus range (e.g., Forte et al., 2014). However, the principal structures accommodating convergence remain poorly known in both the western part of Kura Basin and the eastern part of the Rioni Basin (Fig. 2; 42.5°–45.5°E), where the Lesser and Greater Caucasus are in incipient collision. Banks et al. (1997) interpret geologic and seismic reflection data to indicate both a north-dipping thrust fault beneath the Greater Caucasus north of the Rioni Basin, and a south-dipping thrust fault along the south side of the basin beneath the Lesser Caucasus (LCTF). It is unclear if the LCTF extends east of Tbilisi. Importantly, the extent to which these oppositely verging thrust faults are active at present remains to be quantified.

In this study we present and interpret new GPS observations made during the period 2008 through 2016 for 21 survey-mode sites and 9 continuous stations. The GPS observations are primarily aligned along two roughly range-perpendicular profiles that cross the Lesser–Greater Caucasus boundary zone (Fig. 2). Our objectives are to determine the rate of active deformation across these two segments of the boundary and use the observed deformation and elastic fault models to constrain the locations and character of active structures in this portion of the Arabia–Eurasia collision zone. Our main finding is that shortening across the Rioni Basin is located along the southern margin of the Greater Caucasus and is best fit by models using a north-dipping fault that roots beneath the range, consistent with the location and focal mechanism of the 1991 $M_W6.9$ Racha, Georgia earthquake (Triep et al., 1995). In con-