Tectonophysics 691 (2016) 362–374

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Focal mechanisms and stress variations in the Caucasus and Northeast Turkey from constraints of regional waveforms

Tai-Lin Tseng [a,*], Hsin-Chih Hsu [a,b], Pei-Ru Jian [a], Bor-Shouh Huang [c], Jyr-Ching Hu [a], Sun-Lin Chung [a,c]

[a] Department of Geosciences, National Taiwan University, No. 1, Roosevelt Rd., Sec, 4, Taipei 10617, Taiwan
[b] Weather Central Bureau, Taipei 10048, Taiwan
[c] Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 11529, Taiwan

A R T I C L E I N F O

Article history:
Received 19 April 2016
Received in revised form 15 September 2016
Accepted 24 October 2016
Available online 26 October 2016

Keywords:
Caucasus
Focal mechanisms
Racha earthquake
Crustal stress
Continental collision

A B S T R A C T

The continental collision between Arabia and Eurasia created large strike-slip faults in Turkey as well as mountains in the Caucasus and the volcanic plateau between them. In this study, we use regional waveforms of a new seismic array deployed between 2008 and 2012 to constrain the focal mechanisms and depths of small to moderate sized earthquakes occurring in the western part of the Central Caucasus and northeast Turkey. The distribution of aftershocks and the twelve focal mechanisms involved in the sequence of the 2009 earthquake in Racha are clearly a reactivation of a deeper segment of the 1991 M7 Racha rupture zone. The deeper segment is not well connected to the shallower décollement separating the basement and sedimentary basin. The earthquakes we determined in northeastern Turkey and southern Georgia are related to the strike-slip fault system. We further combined all of the reliably determined focal mechanisms over the last 30 years to investigate the current stress status of the crust in three areas: Racha in the western Greater Caucasus, Javakheti near the Lesser Caucasus and in Northeast Turkey. Our results show that the directions of maximum compressional stress consistently fall within −2 to 14°N throughout the entire study region. This appears to be controlled by the continental collision. Nonetheless, the minimum compression switches from vertical (in the Greater Caucasus) to the east-west direction (in northeastern Turkey), due to the westward extrusion of the Anatolia block, which is driven partly by the Hellenic subduction. The transition of the stress field is close to the Javakheti volcanic plateau in the Lesser Caucasus, where the relative magnitude between the principal stresses appears to be strongly variable.

1. Introduction

The major tectonic features and earthquakes in western Asia are strongly associated with the continental collision of Eurasia and Arabia, which began during the Oligocene following the closure of Neotethys ocean (Şengör and Yilmaz, 1981; Agard et al., 2005; Hatzfeld and Molnar, 2010). The continuous north-south compression induced by this collision produced the Caucasus mountain belts as well as the westward extrusion of the wedged Anatolia block, which is offset by the North and East Anatolia Faults (e.g., McKenzie, 1972; Taymaz et al., 1991; Taymaz et al., 2007; Armijo et al., 1999; Legendre et al., 2012; Fichtner et al., 2013). Due to significant shortening and thickening of the crust since the Middle Miocene, the East Anatolia Plateau (part of Turkish-Iranian Plateau) has reached its current elevation of approximatively 2 km (Dewey et al., 1986). The effect of this collision propagated into the Caucasus region in the early Pliocene, as evidenced by its rapid uplift/exhumation (e.g., Philip et al., 1989; Avdeev and Niemi, 2011).

The region of interest in this study is located in the northern central part of the collision zone, including the Greater and Lesser Caucasus, and the area of Northeast Turkey (Fig. 1). Modern GPS measurements show that the current convergence is predominantly in the N-S direction and the velocity relative to fixed Eurasia decreases gradually in a northward direction from ~15 mm/yr near the western Zagros mountain in Iran to ~11 mm/yr in the Lesser Caucasus and to only ~4 mm/yr in the southern Greater Caucasus (McClusky et al., 2003; Reilinger et al., 2006; Djamour et al., 2011; Karakhanyan et al., 2013). Thus, the Greater Caucasus mountain belts can be considered the northern terminus of the Eurasia-Arabia collision. Much of the convergence is accommodated by faults, leaving little shortening in the interior portion of the collision zone (Reilinger et al., 2006).

In the principal region of the collision zone (between the Black Sea and Caspian Sea), most of the earthquakes occur along active structure

* Corresponding author.
E-mail addresses: tailintseng@ntu.edu.tw (T.-L. Tseng), hchsu@scman.cwb.gov.tw (H.-C. Hsu), d01224005@ntu.edu.tw (P.-R. Jian), hwbs@earth.sinica.edu.tw (B.-S. Huang), jchu@ntu.edu.tw (J.-C. Hu), sunlin@ntu.edu.tw (S.-L. Chung).

http://dx.doi.org/10.1016/j.tecto.2016.10.028
0040-1951/

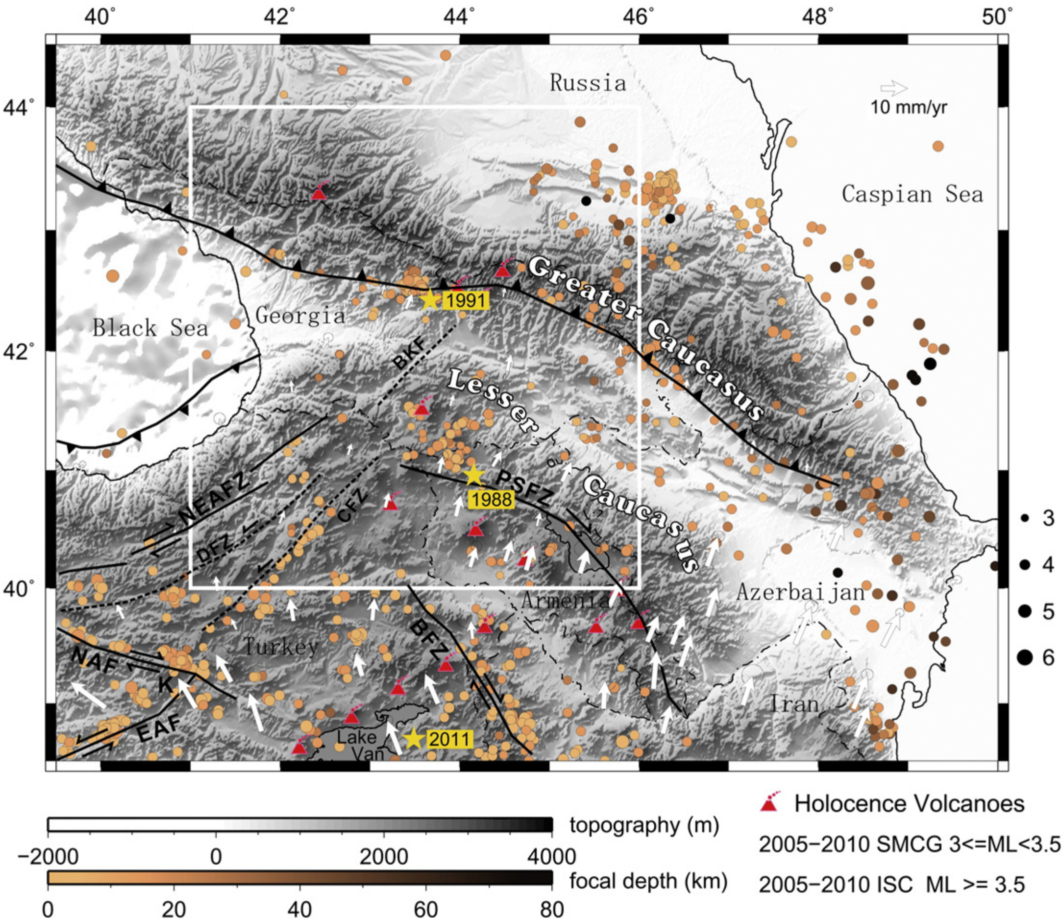

Fig. 1. Tectonic background and earthquakes in the region. White arrows indicate observed GPS rates relative to fixed Eurasia (Reilinger et al., 2006). Locations of Holocene volcanoes were obtained from the Global Volcanism Program (GVP, 2013). Note that two earthquake catalogs were used to plot background seismicity (colored circles) between 2005 and 2010. The yellow starts mark three large earthquakes in the region. The white rectangle delineates the region of study. The solid and dashed structure lines were compiled from Dewey et al. (1986), Gamkrelidze et al. (1998), Dhont and Chorowicz (2006), and Irmak et al. (2012). BKF Borjomi-Kazbegi fault; BFZ Balik-lake fault zone; CFZ Cobandede fault zone; DFZ Dumlu fault zone; EAF East Anatolian fault; K Karliova; NAF North Anatolian fault; NEAFZ North East Anatolian fault zone; PSFZ Pambak-Sevan fault zone.

within the crust at depths shallower than 40 km (Fig. 1). Deep subcrustal earthquakes are found only in the eastern part of the Greater Caucasus to the east of longitude 45°E where the north-dipping seismicity delineates a possible subducting slab (Mellors et al., 2012; Mumladze et al., 2015). This is also implied by the kinematic block model derived from GPS observations (Reilinger et al., 2006). The two largest earthquakes in the Caucasus region in recent decades were the 1988 Spitak earthquake (Ms = 6.8) in northern Armenia and the 1991 Racha earthquake (Ms = 7.0) in northern Georgia (e.g. Triep et al., 1995; Tan and Taymaz, 2006). Both of these events caused considerable damage and loss of lives. The most notable earthquake nearby was the 2011 Lake Van earthquake (Mw = 7.1) in eastern Turkey located just to the south of our study region (Irmak et al., 2012; Fielding et al., 2013). Overall, two clusters of seismicity can be observed in Racha area in the Greater Caucasus and Javakheti highland (north of Spitak) in the Lesser Caucasus. Conversely, seismicity in the plateau area of eastern Turkey shows linear patterns depicting major strike-slip faults intersecting at Karliova (Fig. 1).

In response to N-S shortening, the major active structures are either thrust faults with strikes generally parallel to the mountain belts or conjugate strike-slip faults with strikes in the NE-SW or NW-SE directions (e.g., Philip et al., 1989; Tan and Taymaz, 2006). The neotectonic structure in northeast Turkey near the border between Armenia and Georgia is particularly complicated. As indicated by the simplification in Fig. 1, the NE-SW trend of the North East Anatolian fault zone (NEAFZ) and the nearby faults are probably connected to the Pambak-Sevan fault (related to the 1988 Spitak earthquake) and the Borjomi-Kazbegi fault (possibly transecting the Greater Caucasus) (Philip et al., 1989; Rebai et al., 1993; Dhont and Chorowicz, 2006). This region presents N-S oriented fissures and/or lines of Plio-Queternary volcanoes, indicating the existence of E-W extension (Koçyiğit et al., 2001). These features are similar to the oblique conjugate faults and N-S rifting systems in the interior of the Tibetan plateau, which are the result of the India-Eurasia collision and eastward spreading (e.g., Peltzer and Tapponnier, 1988; Yin and Taylor, 2011). Large normal-faulting earthquakes are abundant in Tibet; however, comparable events are absent in the plateau region associated with the indentation of Arabia.

Based on waveforms at teleseismic distances in the earlier studies, it has been determined that the Caucasus collision zone includes well-constrained focal mechanisms; however, these are applicable only to large earthquakes exceeding magnitude around 5.5 (Jackson and McKenzie, 1984; Tan and Taymaz, 2006; Ekström et al., 2012). Most previous studies focused on the source properties of individual earthquakes (such as Racha and Spitak), and/or the associated rupture zones. The accumulated number of large earthquakes in recent decades has been limited due to slow deformation process (e.g., Reilinger et al., 2006; Karakhanyan et al., 2013). Smaller earthquakes could potentially provide information useful to the elucidation of fault structures and the status of regional stresses. In this study, we employed local-regional waveforms obtained from a new seismic array in Georgia to constrain the focal mechanisms for earthquakes down to a magnitude of approximately 3.5. Using seismic moment tensors, we investigated the