Journal of Asian Earth Sciences 156 (2018) 226–245

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

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

Structural development and stress evolution of an arcuate fold-and-thrust system, southwestern Greater Caucasus, Republic of Georgia

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ARTICLE INFO

Keywords:
Greater Caucasus
Faults
Paleostress
Folds

ABSTRACT

The southern front of the Greater Caucasus is quite rectilinear in plan view, with the exception of part of the Rioni Basin, where marine and continental deposits of Cretaceous-Neogene age were locally folded and uplifted; this resulted in the formation of an arcuate fold-and-thrust system that extends 45 km into the foreland. Although previous studies suggested that this system has developed only since Miocene times, our new detailed and systematic field measurements of brittle and ductile structures show a very complex history, consisting in four main phases of brittle deformation and folding, dated from Eocene to Quaternary times. We collected microtectonic data at 248 faults, and calculated the related paleostress tensors. The first two phases which we document here, predated folding and were characterised by dominant transcurrent faulting and subordinate reverse motions; the greatest principal stress σ_1 was perpendicular and later parallel to the mountain belt. Afterwards, NW-SE, E-W and NE-SW trending, south-vergent asymmetrical folds started to form. In the western sector of the study area, folds are sinuous in plan view, whereas to the east they show a left-stepping, en-échelon geometry. Another two, brittle deformation phases took place after the folding, due to the activity of a set of right-lateral, strike-slip faults that strike NW-SE and NE-SW, respectively, as well as by left-lateral strike-slip faults, mostly striking NW-SE, NE-SW and NNE-SSW. These two additional phases were produced by a NE-SW to N-S trending σ_1. The arcuate belt is marked by along-strike variations in the tectonic regime and deformation geometry, plus belt-parallel stretching. Based on our field data, integrated with published analogue models, we suggest a possible explanation for the Rioni structure, in terms of the oblique, asymmetric indentation of an upper crustal blocks moving to the SSW.

1. Introduction

The Greater Caucasus is an orogenic system that formed in Cenozoic times following the Arabian-Eurasian plate collision. The orogeny developed owing to the formation of mainly WNW-ESE trending, folds and faults, which resulted in a rather rectilinear mountain front in plan view, especially along its southern side (Fig. 1). The Transcaucasian intermontane valley, which separates the Greater Caucasus to the north from the Lesser Caucasus to the south, is made up of: (i) the Rioni foreland fold-and-thrust belt and the Rioni foreland basin to the west (Adamia et al., 2011b; Forte et al., 2014), (ii) the Dzirula massif in the centre (Khain, 1975), and (iii) the Kura Basin to the east. The Kura and Rioni basins developed in Oligocene-early Miocene times, and they were then partially involved into the orogenic fold-and-thrust belts (Adamia et al., 1977, 2010; Banks et al., 1997; Mosar et al., 2010; Sosson et al., 2010a,b, 2013; Forte et al., 2010; Alania et al., 2016). The Rioni fold-and-thrust belt is made up of a complex pattern of structures that result in an arcuate zone of deformation extending 45 km to the SSW from the Greater Caucasus foothills (Fig. 1). Some of these structures are still active, as documented by seismological data (Tsereteli et al., 2016) and paleoseismological research (Tibaldi et al., 2017a, 2017b).

In spite of the complex geometry of this sector of the Greater Caucasus frontal system, as well as the occurrence of active deformation that may be associated with potential seismic hazard, this area has received very little attention so far. In the international literature, a preliminary paper describing the general structure of the area was published by Philip et al. (1989), who documented the distribution of the main folds and presented paleostress data gathered at seven sites. Later on, Tibaldi et al. (2017a) performed new measurements along striated faults, and related paleostress inversion, at nine new sites. In regard to geophysical data, Banks et al. (1997) presented a geological-structural cross-section based on seismic exploration data, running across the Rioni Basin; on the other hand, Tibaldi et al. (2017b)

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https://doi.org/10.1016/j.jseaes.2018.01.025
Received 9 August 2017; Received in revised form 19 January 2018; Accepted 24 January 2018
Available online 06 February 2018
1367-9120/

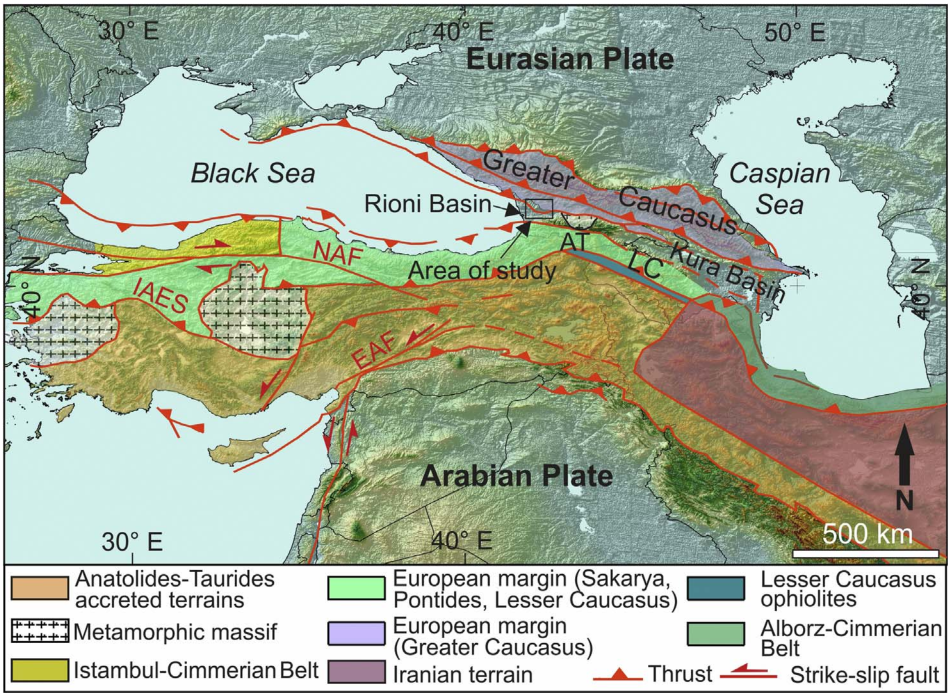

Fig. 1. Tectonic map of the Arabia-Eurasia collision zone (modified after Sosson et al., 2010a, 2016). Abbreviations: AT Achara-Trialeti; LC Lesser Caucasus; EAF Eastern Anatolian Fault; NAF North Anatolian Fault; IAES Izmir-Ankara-Erzincan Suture.

provided a number of seismic reflection sections across a main anticline known as Tsaishi fold, and Tsereteli et al. (2016) analysed earthquake distribution and focal mechanism solutions.

The development of arcuate fold-and-thrust belts has been a major focus of study since the early 90s (Suess, 1909; Hobbs, 1914); this kind of characteristic pattern was referred to as "salient" by Miser (1932), because the structures are convex in plan view and extend farther towards the foreland. Many studies performed at salients suggest that materials are transported in three dimensions (Sussman et al., 2004), so that accurate analyses need to be carried out around and across the arcuate belts, in order to correctly reconstruct their overall architecture and strain pattern. Recent papers have contributed to elucidating the development of salients by way of kinematic field data (e.g. Platt et al., 1989), paleomagnetic data (e.g. Sussman et al., 2004), and analogue modelling (e.g. Lickorish et al., 2002; Calignano et al., 2017, and references therein). In some cases, kinematic data from fault-slip analysis show a quite simple and consistent picture of the development of arcuate belts, such as is the case of the Pannonian Belt. Here, the stress and strain directions of the arcuate fold-and-thrust systems allow to document an overall NW–SE compression, with fanning of the subhorizontal contraction axes from E–W to NNW–SSE (Zweigel et al., 1998). On the other hand, at the Rioni Basin, preliminary fault-slip data indicate a much more complex setting (Tibaldi et al., 2017a), with a major rotation of the horizontal compression axis and the widespread presence of strike-slip faults.

All the above indicates that the Rioni Basin, at the foothill of the Greater Caucasus, represents an outstanding example of a recent salient, marked by a complex deformation history in spite of its short (Miocene-Quaternary) history. In view of the above, we carried out a detailed field survey of the whole Rioni area affected by compression tectonics, in order to unravel the various phases of deformation that affected it. Regional observations were integrated with systematic collection of microtectonic data, aimed at reconstructing the geometry of the folds and the evolution of stress orientations. In doing so, we wish to contribute to addressing a number of challenging scientific questions, including the following: (i) can the regional data confirm the complex evolution of the local stress field, characterised by a NW-SE and NE-SW trending greatest principal stress during the older phases and by a N-S to NNE-SSW trending greatest principal stress during the younger phase, as suggested by Tibaldi et al. (2017a), (ii) is compression parallel to the orogen reflected in the folding processes, (iii) how can the rotation of the stress axes be explained, (iv) how did the curvature of the fold-and-thrust system develop, (v) can field-based, microtectonic data confirm the active stress state as derived by earthquake focal mechanisms and thus contribute to seismic hazard assessment?

The hereby provided data may serve to enhance understanding of how arcuate mountain belts develop, to gain a better knowledge of one of the main orogenic system of Earth, which is still poorly studied, and to improve the database useful for seismic hazard evaluation in a broad area that hosts several towns as well as the Enguri Hydroelectrical Scheme, the main energy production facility in the Republic of Georgia.

2. Geological background

2.1. Regional geology

During the Neotethys subduction, several domains formed in back-arc locations within the Eurasian Plate, among which the Greater Caucasus basin that developed in Early–Middle Jurassic times (Khain, 1975; Dercourt et al., 1986; Adamia et al., 1981, 2011a; Sosson et al., 2016), followed by the opening of the western and eastern Black Sea basins during the Cretaceous and Cenozoic (Adamia et al., 1981; Letouzey et al., 1977; Finetti et al., 1988; Zonenshain and Le Pichon, 1986; Okay et al., 1994, 2013; Robinson et al., 1996; Spadini et al., 1996; Cloetingh et al., 2003; Vincent et al., 2005; Yegorova and Gobarenko, 2010; Khriachtchevskaia et al., 2010; Stephenson and Schellart, 2010; Sheremet et al., 2016). Exhumation processes in the Greater Caucasus started in the Oligocene and reached their climax in the Miocene-Pliocene, as documented by apatite fission-track data (Vincent et al., 2007, 2011; Avdeev and Niemi, 2011). Plate reorganization has then taken place within the Arabia-Eurasia collision zone and the main plate movements have remained relatively constant over the last 5 Ma (Westaway, 1994; McQuarrie et al. 2003; Allen et al., 2004). The Rioni Basin, located between the western Greater Caucasus