Earth and Planetary Science Letters 482 (2018) 454–469

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Quantifying Arabia–Eurasia convergence accommodated in the Greater Caucasus by paleomagnetic reconstruction

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ARTICLE INFO

Article history:
Received 23 June 2017
Received in revised form 20 September 2017
Accepted 9 November 2017
Available online xxxx
Editor: A. Yin

Keywords:
tectonic rotations
paleomagnetism
orocline
Eocene volcanics
Iran
Greater Caucasus

ABSTRACT

Since the late Eocene, convergence and subsequent collision between Arabia and Eurasia was accommodated both in the overriding Eurasian plate forming the Greater Caucasus orogen and the Iranian plateau, and by subduction and accretion of the Neotethys and Arabian margin forming the East Anatolian plateau and the Zagros. To quantify how much Arabia–Eurasia convergence was accommodated in the Greater Caucasus region, we here provide new paleomagnetic results from 97 volcanic sites (∼500 samples) in the Talysh Mountains of NW Iran, that show ∼15° net clockwise rotation relative to Eurasia since the Eocene. We apply a first-order kinematic restoration of the northward convex orocline that formed to the south of the Greater Caucasus, integrating our new data with previously published constraints on rotations of the Eastern Pontides and Lesser Caucasus. This suggests that north of the Talysh ∼120 km of convergence must have been accommodated. North of the Eastern Pontides and Lesser Caucasus this is significantly more: 200–280 km. Our reconstruction independently confirms previous Caucasus convergence estimates. Moreover, we show for the first time a sharp contrast of convergence between the Lesser Caucasus and the Talysh. This implies that the ancient Paleozoic–Mesozoic transform plate boundary, preserved between the Iranian and East-Anatolian plateaus, was likely reactivated as a right-lateral transform fault since late Eocene time.

1. Introduction

Quantification of how convergence is accommodated in continental lithosphere in response to plate collisions – in this case the Arabia–Eurasia collision – is crucial for understanding the orogenic processes and related paleogeographic evolution such as the closure of marine gateways. However, there is often a deficit between estimates of crustal shortening and reconstructions of the amount of convergence from the plate circuit, as e.g. argued for in the India–Asia (Van Hinsbergen et al., 2012), or Iberia–Europe collision (Vissers et al., 2016). Such a mismatch between shortening and convergence has recently also been postulated for the Greater Caucasus on basis of seismological and sediment provenance data (Cowgill et al., 2016). Demonstrating such a mismatch, however, requires firm constraints on convergence, which is often controversial.

The Greater Caucasus mountain range, between the Black Sea and the Caspian Sea, is the world's second largest active orogen in a continental collision setting (Mumladze et al., 2015). Its relatively short length (∼1100 km) and location within the overriding Eurasian part of the plate boundary zone, >350 km north of the suture with Arabia, make it an uncommon orogen. It is thought to have formed since the late Eocene (∼35 Ma) through inversion of a Mesozoic back-arc basin during Arabia–Eurasia convergence and collision (e.g., Adamia et al., 2011a). The formation of the Greater Caucasus fold-thrust belt demonstrates that some of the 800–900 km of ∼N–S Arabia–Eurasia convergence that occurred since 35 Ma along the strike of the Caucasus (McQuarrie and van Hinsbergen, 2013), was accommodated within the Eurasian part of the plate boundary zone. There is considerable debate on the timing of shortening and uplift of the Greater Caucasus Mountains, with estimates ranging from Eocene–Oligocene (Vincent et al., 2016) to Miocene (Forte et al., 2014). Forte et al. (2014) recognized that the Greater Caucasus is made up of several distinct structural zones which may reflect lateral differ-

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https://doi.org/10.1016/j.epsl.2017.11.025

ences in amount of accommodated shortening and convergence along the mountain range. In any case, the geological and seismological estimate of Greater Caucasus shortening and subduction may have been 130 to as much as 400 km (Cowgill et al., 2016; Ershov et al., 2003). The remainder of Arabia–Eurasia convergence then has to be accommodated by subduction within or below the East Anatolian and Iranian plateaus.

Constraining how this convergence was partitioned is particularly complex due to the general absence of detailed structural geologic constraints on Caucasus shortening. Moreover, geologically recorded shortening may underestimate the total amount of convergence if wholesale lithospheric subduction occurred without accretion. Paleomagnetic inclinations may be used to determine paleolatitudinal convergence if convergence is larger than paleomagnetic error bars of typically some 5° (∼500 km), which is unlikely in the Caucasus case. Cowgill et al. (2016) recently suggested that higher convergence in the Greater Caucasus than in the neighboring Black Sea and Caspian Sea regions led to the formation of the Pontide–Lesser Caucasus–Talysh orocline, which extends from the eastern Pontides (NE Turkey), through the Lesser Caucasus (e.g. Bazhenov and Burtman, 2002 and Meijers et al., 2015 and references therein). Here, we therefore explore a novel quantitative geometrical constraint on the amount of Arabia–Eurasia convergence that was accommodated in the Greater Caucasus region since the late Eocene by paleomagnetically restoring the vertical axis rotations accommodated during the formation of this orocline, which we extend towards the Talysh Mountains of Iran (Fig. 1). We use paleomagnetic estimates of net post-Eocene rotation from the limbs of this orocline to restore the convergence accommodated in the Greater Caucasus. Large datasets are available from the western limb in Turkey (Hisarlı, 2011), as well as from the central, Lesser Caucasus segment (Meijers et al., 2015). In the western part of the Alborz mountains, data were collected by Cifelli et al. (2015). We here provide new paleomagnetic constraints on the amount of rotation of the eastern limb of the orocline, in the Talysh Mountains of Iran. Then, we develop a first-order kinematic restoration of the orocline to constrain the minimum amount of northward motion of the Lesser Caucasus relative to the Black Sea and Caspian Sea regions since the Eocene. We use this reconstruction to quantify how convergence was partitioned over the Caucasus orogen and plateaus to the south.

2. Geological setting

2.1. Regional geology

The Caucasus orogen is located along the southern fringes of the Scythian platform of Eurasia. To the south are a series of accreted Gondwana-derived continental blocks that collided with Eurasia upon closure of the Paleotethys and Neotethys oceans in Paleozoic to Cenozoic times (e.g. Barrier et al., 2008). In Iran, Gondwana-derived 'Cimmerian' blocks collided with Eurasia in the Late Triassic, closing the Paleotethys ocean after which they were shortened in the Neogene during Arabia–Eurasia collision by up to ∼175 km (McQuarrie and van Hinsbergen, 2013; Mouthereau et al., 2012). NW Iran consists of at least two Cimmerian blocks, the Sanandaj-Sirjan block and the Alborz block. Neotethys subduction below the Iranian Cimmerian blocks occurred from the Jurassic until the final collision of Arabia with Eurasia (Agard et al., 2011). Present shortening estimates of the Iranian plateau and the Zagros mountains suggest that collision must have been underway by 20 Ma, and may have started around 27–28 Ma (McQuarrie and van Hinsbergen, 2013 and references therein). In Turkey, the tectonic history is different. In the west, at least two Gondwana-derived continental fragments collided with Eurasia (Pontides and Anatolide-Taurides), while in eastern Turkey a long-lived, oceanic crust-derived accretionary prism formed that underlies most of the east Anatolian plateau. The Turkish and Iranian systems were separated by a plate boundary since the Permian (Stampfli and Borel, 2002), probably in the form of a major transform fault system. Eastern Mediterranean paleogeographic reconstructions suggest that this transform may have been reactivated since the early Eocene (visualized in Barrier et al., 2008). The Arax valley fault, on the border between Armenia, Iran and Azerbaijan (Jackson and Mckenzie, 1983) may be a remnant of this ancient plate boundary (Fig. 1).

The Lesser Caucasus region is located to the south of the Greater Caucasus, and is formed by volcanic arc material of Jurassic to Eocene age, which connects to the Pontides in the west and the Talysh in the east during Eocene volcanism (e.g. Adamia et al., 2011b). This region is bordered from the Gondwana-derived South Armenian block to the south by the ophiolitic Sevan-Akera suture (e.g. Rolland et al., 2012; Sosson et al., 2010).

As there are no tectonic maps of the entire studied region, we compiled a new tectonic map (Fig. 1) from the maps of Adamia et al. (2011b); Şengör et al. (2003); Zanchetta et al. (2009), and we added faults from Dilek and Altunkaynak (2010) and Solaymani Azad et al. (2011). All maps were georeferenced, overlain on top of each other and subsequently checked using a digital elevation model in discerning tectonic regions.

2.2. Geology of the Talysh

The geology of the Talysh and Alborz consists of Precambrian up to Quaternary rocks, with abundant Eocene volcanic rocks. The Precambrian and Cambrian make up around 3.5 km and consist mostly of sandstone and dolomite. Silurian and Ordovician units consist of limestone and some basic volcanic rocks. The Devonian is characterized by deposition of limestone, with an unconformity separating it from the underlying Silurian. Post-Silurian basic volcanic rocks are covered by Permo-Carboniferous limestone and lower Carboniferous andesite. The Talysh contains remnants of an Upper Paleozoic ophiolite belt, which is related to closure of a Hercynian ocean. The Triassic–Jurassic consists of shales, sandstones and conglomerates, and is around 4 km thick. During the Upper Jurassic and Cretaceous, shallow marine limestones were deposited in the Talysh and Alborz, which make up around 600 meters (Berberian and King, 1981; Zanchi et al., 2006). Some Cretaceous volcanic rocks with a within-plate signature are also present in the Central Alborz (Doroozi et al., 2016). The Paleogene in the Alborz consists of the Fajan formation, comprising up to 200 meters of continental conglomerates. This formation is covered by Paleocene–middle Eocene nummulitic limestones of the Ziarat formation (100–300 m thick). The top of this formation is of Lutetian age (middle Eocene) in the Alborz, while further east, in the Kopeh Dagh, it extends into the Priabonian (late Eocene) (Gravand and Golgir, 2014). After the Lutetian, a flare-up of volcanism led to deposition of the Karaj formation, which is up to 9 km thick (Verdel et al., 2011), and has a continental arc geochemical signature (van der Boon et al., 2015). During the Oligocene, compression in the region led to uplift and erosion, causing deposition of coarse-grained clastic sedimentary rocks (Morley et al., 2009; Vincent et al., 2005).

There are many large faults present in the region, although these are relatively unstudied. Both thrust faults and strike-slip faults are present in the region, with strike-slip faults showing left lateral motion (e.g. Jackson et al., 2002). The faults in the Alborz and the Talysh are different from each other, with faults in the Talysh having nearly flat fault planes on which thrusting occurs. The motion along faults is disputed. For example, Jackson et al. (2002) interpret the Astara fault as a thrust (Fig. 2), while on 1:100.000 series geologic maps (Geologic Survey of Iran), it is