Earth and Planetary Science Letters 496 (2018) 96–107

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Ramp-flat basement structures of the Zagros Mountains inferred from co-seismic slip and afterslip of the 2017 M_W7.3 Darbandikhan, Iran/Iraq earthquake

William D. Barnhart *, Clayton M.J. Brengman, Shaoyang Li, Katherine E. Peterson

Department of Earth and Environmental Sciences, The University of Iowa, Iowa City, IA 52242, United States of America

A R T I C L E I N F O

Article history:
Received 1 February 2018
Received in revised form 8 May 2018
Accepted 20 May 2018
Available online xxxx
Editor: J.-P. Avouac

Keywords:
InSAR geodesy
earthquake
Zagros Mountains

A B S T R A C T

The November 2017 M_w7.3 Darbandikhan earthquake in the northern Zagros Mountains of Iran/Iraq was the largest instrumentally recorded earthquake to date in this mountain belt. Despite extensive research in this region, the nature of active faults in the Arabian basement beneath the Zagros Mountains is largely unresolved. Additionally, there is active debate regarding the interaction of thin- and thick-skin shortening of the Zagros, and whether these processes are accommodated seismogenically. Here, we use interferometric synthetic aperture radar (InSAR) of co- and post-seismic surface displacements to document the source of the Darbandikhan earthquake and the first 120 days of afterslip following the earthquake. We apply a fault inversion approach that finds permissible geometries, locations, and slip depths as a means to image subsurface structure with remote sensing geodesy. We find that the Darbandikhan earthquake ruptured the shallowly dipping (14°–19°) Mountain Front Fault within the Arabian crystalline basement (∼12–22 km deep). We additionally find that afterslip propagated up-dip of the earthquake onto the nearly horizontal (dip = 1°–5°) basal decollement of the Zagros Mountains, indicating that the earthquake and its initial afterslip activated a ramp-flat structure. We also inverted co-seismic InSAR displacements of the January 11, 2018 Mandali earthquake sequence that occurred ∼80 km south of the Darbandikhan earthquake and find that these moderate magnitude events (M_w5.0–5.5) ruptured the lower Phanerozoic cover of the Zagros. Together, the Darbandikhan and Mandali sequences demonstrate that the Zagros Mountains actively shorten via both thin- and thick-skin styles, and that these modes of shortening are accommodated in part by earthquakes. Moreover, the Darbandikhan earthquake and afterslip highlight the presence of seismically active low-angle thrust faults beneath the Zagros that were not previously recognized, highlighting sources for potential future large earthquakes. We compare these results to the 2015 Gorkha, Nepal earthquake to argue that frictional characteristics of decollement govern spatial relationships between seismic and aseismic slip in ramp-flat geometries.

1. Introduction

The Zagros Mountains of Iran and Iraq are one of the most seismically active orogens of the world. The mountain belt is the manifestation of active continental convergence between Arabia and Eurasia and currently accommodates one third to one half of the current convergence rate (e.g., Masson et al., 2005; Vernant et al., 2004). As a relatively young mountain belt, the Zagros have often been likened to an early stage analog of the Himalayan orogeny (e.g., Hatzfeld and Molnar, 2010; Ni and Barazangi, 1986). Accordingly, the Zagros provide a natural laboratory to explore the early interplay of thin- and thick-skin style deformation in a region of continental underthrusting. The Zagros Fold-and-Thrust Belt (ZFTB), a thin-skin thrust belt that defines the western-most tectonostratigraphic region of the Zagros Mountains, is the actively shortening portion of the Zagros Mountains and locus of the majority of seismicity in the mountain range. The ZFTB is commonly subdivided into four domains from southeast to northwest – the Fars Arc, the Dezful Embayment, the Lurestan Arc, and the Kirkuk Embayment (Fig. 1). Geologically, the ZFTB contains an 8–13 km thick Phanerozoic sedimentary cover that is folded into the characteristic whaleback anticlines apparent in the regional topography (e.g., Alavi, 2004; Bahroudi and Talbot, 2003; Casciello et al., 2009; Colman-Sadd, 1978; Falcon, 1969). The Phanerozoic cover is separated from the underlying Arabian crystalline basement by the Hormuz Units that consists of salt in the

* Corresponding author.
E-mail address: william-barnhart-1@uiowa.edu (W.D. Barnhart).

https://doi.org/10.1016/j.epsl.2018.05.036
0012-821X/

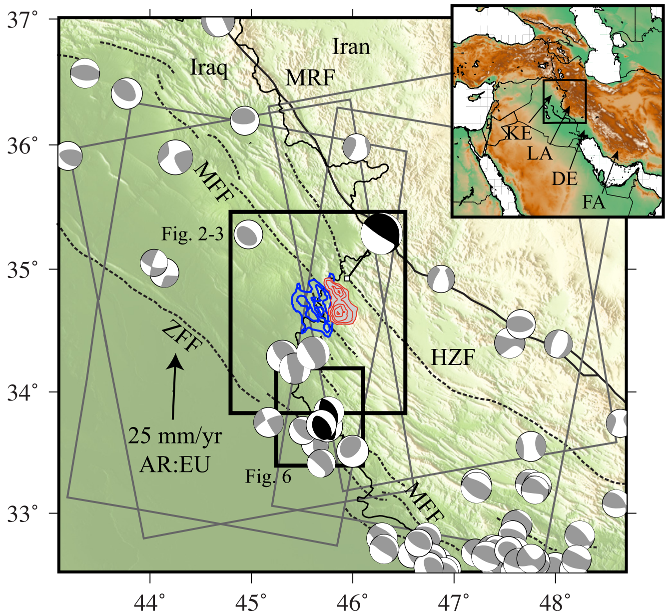

Fig. 1. Regional seismotectonic context of the 2017 Darbandikhan and 2018 Mandali earthquake sequences. Smoothed 1-m contours of co-seismic slip of the Darbandikhan earthquake are shown in red, smoothed 10 cm contours of afterslip are shown in blue. Gray moment tensors are instrumental-era events documented in the Global CMT catalog (through January, 2018). Black moment tensors are the USGS W-Phase solutions for the Darbandikhan earthquake and events of the Mandali Sequence. Black lines indicate the locations of major regionals faults from Berberian (1995); MRF: Main Recent Fault; ZFF: Zagros Foredeep Fault; MFF: Mountain Front Fault; HZF: High Zagros Fault. Dashed fault traces indicate the proposed location of blind basement faults (Berberian, 1995). Gray boxes indicate the spatial extent of Sentinel imagery used in this study. The vector indicates the magnitude and azimuth of Arabia convergence with respect to stable Eurasia (AR:EU, DeMets et al., 2010). Image overlain on the shaded 30 m SRTM DEM (Farr et al., 2007). The image inset shows the locations of the major tectonogeographic divisions of the Zagros Fold-and-Thrust Belt: FA: Fars Arc; DE: Dezful Embayment; LA: Lurestan Arc; KE: Kirkuk Embayment. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Fars Arc and shales in the Lurestan Arc (e.g., McQuarrie, 2004; Sherkati and Letouzey, 2004). Moderate magnitude (~M_w5–6) thrust earthquakes are common in the ZFTB, but surface rupturing earthquakes are rare (Walker et al., 2005), and most reverse faults remain blind. Historical views of seismicity in the ZFTB stipulate that earthquakes modulate thick-skin shortening of the crystalline Arabian basement through the reactivation of normal faults as high angle reverse faults, and that the thin-skin Phanerozoic cover shortens aseismically (e.g., Berberian, 1995, 1981; Engdahl et al., 2006; Jackson et al., 1995; Ni and Barazangi, 1986). Recent thick-skin shortening is additionally supported by gravitational observations (Snyder and Barazangi, 1986) and structural cross sections (e.g., Alavi, 2007; Allen and Talebian, 2011; Blanc et al., 2003; Emami et al., 2010). This view of a seismogenic Arabian basement and aseismic fold belt has been refined in recent years in both the Lurestan and Fars Arcs where geodetic and seismic observations indicate that moderate earthquakes rupture within the Phanerozoic cover and drive a component of thin-skin shortening and fold growth (e.g., Barnhart and Lohman, 2013; Copley et al., 2015; Nissen et al., 2011). Despite these extensive field, seismic, and geodetic studies of earthquakes and structure in the Zagros, the abnormal thickness of the Phanerozoic cover and the relative inaccessibility of the region have left a decisive characterization of the nature of vertical strain-style partitioning unresolved.

The M_w7.3 November 12, 2017 Darbandikhan thrust earthquake along the Iraq/Iran border, its subsequent afterslip, and a sequence of five moderate magnitude (M_w5.0–5.5) earthquakes that occurred on January 11, 2018 (herein termed the "Mandali Sequence") in the Lurestan Arc of the Zagros provide an opportunity to further explore the nature of thin- and thick-skin in the Zagros, and to characterize the interplay of seismic and aseismic slip on ramp-flat structures in the Arabian basement (Fig. 1). The Darbandikhan earthquake is the largest instrumentally recorded earthquake to have occurred in the Zagros to date. The earthquake occurred along the northern edge of the Lurestan Arc adjacent to the Kirkuk Embayment of eastern Iraq (Fig. 1). Moment tensor solutions indicate that the earthquake ruptured a shallowly dipping thrust plane at a depth of 19 km. The shallow dip angle associated with this event is uncommon for documented earthquakes in this region and suggests that the Darbandikhan earthquake may have ruptured an underthrust structure (Fig. 1).

We use interferometric synthetic aperture radar (InSAR) observations of both the co- and post-seismic displacement to image the Darbandikhan and Mandali earthquake sequences (Fig. 2). We implement an iterative fault slip inversion approach designed to elucidate the geometry and location of faults associated with this sequence and their relationship to the mechanical stratigraphy of the Zagros. We find that InSAR observations are best described by co-seismic slip on a shallowly (15–19°) dipping plane that dips eastward beneath the Zagros Mountains at depths of 12–22 km. The earthquake is followed by afterslip up-dip of the co-seismic slip area on a resolvably shallower (1–5°) dipping plane, highlighting the activation of a ramp-flat structure (Fig. 1). Unlike the Darbandikhan earthquake, events of the Mandali sequence have a slip source that is likely within the lowermost Phanerozoic cover of the Lurestan Arc that are similar to the August 2014 Murmuri, Iran earthquake sequence (Copley et al., 2015). These sequences together demonstrate that both thin- and thick-skin shortening are actively accommodated in the northern Zagros, and that shortening is accommodated in part via earthquakes.

2. Observations: InSAR and InSAR time series

2.1. Processing approach

Spatially dense remote sensing geodetic observations of surface displacements caused by fault slip can provide a powerful tool for determining subsurface fault locations and geometries (e.g., Elliott et al., 2016; Johnson and Segall, 2004; Jouanne et al., 2011; Simons et al., 2002). Here, we use C-band synthetic aperture radar (SAR) observations from the European Space Agency's Sentinel-1a and 1b satellites to quantify surface displacements associated with the Dabandikhan earthquake and the Mandali Sequence. We constructed co-seismic interferograms from four different viewing geometries (paths) using the JPL/Caltech *ISCE* software package (version 2.0.0_201708, Rosen et al., 2012). Interferometric pairs for the Darbandikhan earthquake were chosen to minimize the post-seismic time interval in the post-event observations (Table 1). While this approach does not allow for multiple independent interferograms from a single look direction, the availability of multiple independent look directions in part offsets issues that may arise from inverting a single independent interferogram such as biases introduced by atmospheric noise. Interferometric pairs of the Mandali Sequence were chosen so that each entailed approximately the same post-seismic time span (Table 1). Each interferogram was processed at a spatial resolution of 30 m, and we used the 30 m Shuttle Radar Topography Mission digital elevation model to remove topographic phase (Farr et al., 2007). We unwrapped interferograms with the Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (SNAPHU, Chen and Zebker, 2001). We used the Precise Orbit Ephemerides provided by the European Space Agency for all images acquired prior to February 22, 2018, and Restituted Orbit Ephemerides for images acquired after.