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Co-seismic, geomorphic, and geologic fold growth associated with the 1978 Tabas-e-Golshan earthquake fault in eastern Iran

R.T. Walker [a,*], M.M. Khatib [b], A. Bahroudi [c,d], A. Rodés [e], C. Schnabel [e], M. Fattahi [f,g], M. Talebian [c], E. Bergman [h]

[a] Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK
[b] Department of Geology, Birjand University, Birjand, Iran
[c] Geological Survey of Iran, Azadi Square, Meraj Avenue, P.O. Box 11365-4563, Iran
[d] Mining Engineering Faculty of the Engineering University College, University of Tehran, Kargar Shomali, Tehran, Iran
[e] NERC Cosmogenic Isotope Analysis Facility, East Kilbride G75 0QF, UK
[f] Institute of Geophysics, University of Tehran, Kargar Shomali, Tehran, Iran
[g] School of Geography, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
[h] Center for Imaging the Earth's Interior, Department of Physics, University of Colorado at Boulder, 390 UCB, CO 80309, USA

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ABSTRACT

We describe the seismicity and late Cenozoic deformation associated with a blind thrust fault at Tabas-e-Golshan (hereafter referred to as Tabas), eastern Iran, which generated a devastating M_w 7.3 earthquake on the 16th September 1978. Measurements from a structural transect through the Sardar anticline segment indicate fault-propagation folding above a gently ~20° eastward-dipping blind thrust fault. The thrust flattens into a horizontal detachment at a depth of only ~2 km. Tightening of the fold forelimb is accommodated by flexural slip along numerous bedding planes, with many of the slip surfaces showing fresh striations with a large component of right-lateral strike–slip. A steeply dipping fault zone showing almost pure strike–slip is also developed within the forelimb of the fold. Our field observations are consistent with the source parameters of the 1978 Tabas earthquake, and additional events in 1979 and 1980, which all involved slip on a shallowly-dipping thrust with a significant component of right-lateral slip. The surface of an alluvial fan, which is likely to have been abandoned at 8–10 ka, has been folded as it crosses the Sardar anticline. The age constraints, combined with topographic profiles along the deformed fan surface and constraints on the dip of the fault at depth, provide an approximate rate of horizontal shortening of ~1.5 mm/yr. Shortening at Tabas appears to result from transpressional bending at the north end of the Nayband strike–slip fault. A northward continuation of the Nayband Fault, which may be slipping at rates of >2 mm/yr, is identified along the base of the Shotori Mountains ~10–20 km east of the Tabas thrust. The range-front fault did not move in 1978 and constitutes an additional threat to local populations.

1. Introduction

On September 16, 1978, the oasis town of Tabas in eastern Iran was destroyed, and ~20,000 people were killed, by an earthquake of M_w 7.3 (Berberian, 1979; Fig. 1). This earthquake, which occurred on a series of previously unrecognised blind thrust faults, was one of the largest and most destructive to have occurred in Iran in recent decades. Despite having a long history of occupation, there are no records of destructive earthquakes in the area prior to 1978 (e.g. Berberian, 1979; Ambraseys and Melville, 1982). Evidence of long-term active faulting is, however, preserved in the landscape in the form of anticlinal folding in Neogene basin deposits, deformation of late Quaternary alluvial fan deposits, and widespread river incision (Walker et al., 2003). No estimates exist of the rate of slip, and hence the average interval between large earthquakes, on the Tabas Fault system.

The Tabas folds, and presumably the thrust faults that underlie them, are segmented (Fig. 2). For the purposes of this study we focus primarily on the segment located close to the Sardar River in the northern part of the system (Fig. 3). We choose this segment for three reasons. (1) The Sardar fold is the only visible fold segment present at this latitude; farther south, several parallel folds appear to be active simultaneously, thus making shortening estimates much more difficult to determine. (2) Uninterrupted exposures of folded and faulted strata outcrop along the walls of the deeply incised Sardar River allowing a detailed structural cross-section to be produced. (3) The Sardar River is incised into the surface of a large alluvial fan, which is continuous across the fold, and, when combined with estimates of its age, can be used to determine a rate of shortening across the fold.

* Corresponding author.
E-mail address: richard.walker@earth.ox.ac.uk (R.T. Walker).

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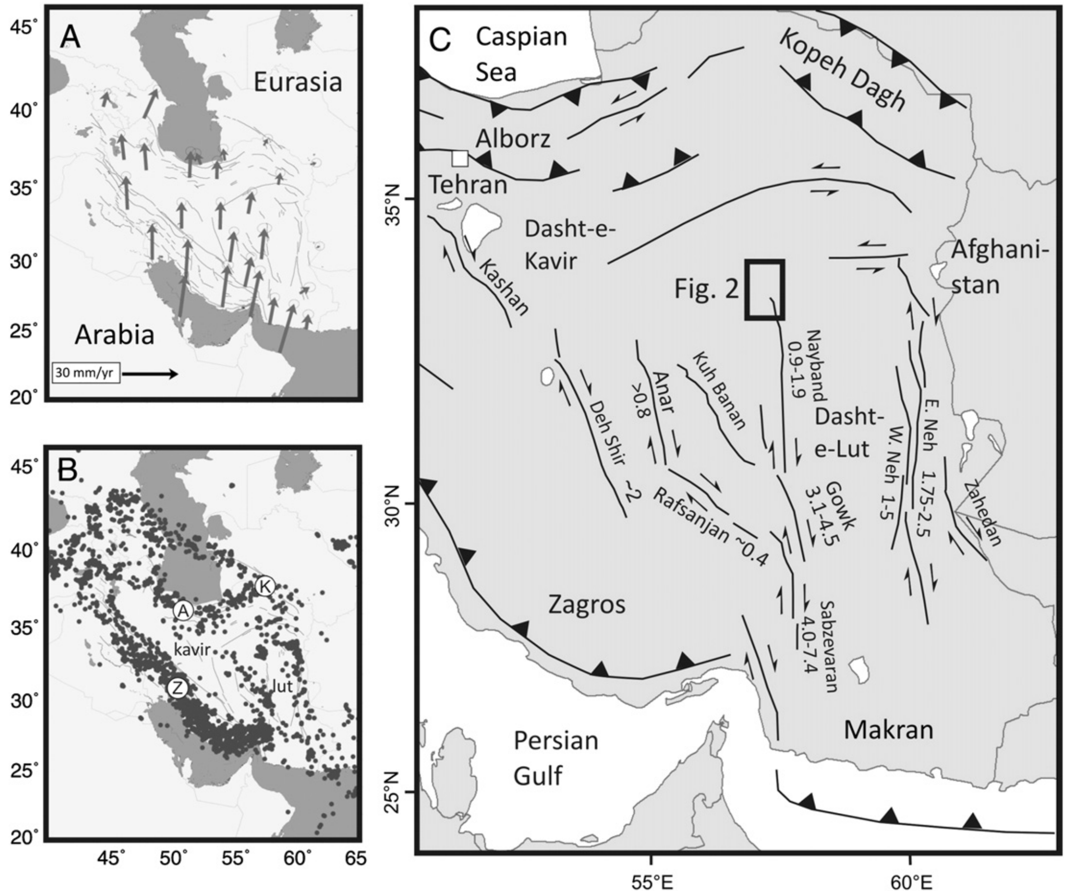

Fig. 1. (A) GPS velocities of points within Iran relative to Eurasia (Vernant et al., 2004). (B) Epicentres of earthquakes (Mw > 5.3) in Iran from the catalogue of Engdahl et al. (1998). Much of the seismicity is located within the Zagros Mountains (Z) in the south, and the Alborz (A) and Kopeh Dagh (K) ranges in the north. The Kavir and Lut deserts have fewer earthquakes within them. (C) Map of Iran showing the locations and estimated slip-rates (in mm/yr) of the major strike–slip faults in eastern Iran (from Regard et al., 2005; Meyer et al., 2006; Meyer and LeDortz, 2007; Le Dortz et al., 2009; Walker et al., 2009, 2010; Le Dortz et al., 2011; Fattahi et al., 2011). The Tabas reverse faults are situated at the northern end of the Nayband Fault (the boxed region is shown in more detail in Fig. 2).

In the following sections, we first describe the tectonic setting of the Tabas earthquake. To aid our description of the earthquake we present improved epicentres of seismicity in the Tabas region obtained from a multiple-event relocation technique. We then use the deformation of an alluvial fan crossing the Sardar fold segment, combined with age constraints from luminescence and cosmogenic ^{36}Cl exposure dating on the abandonment of the fan surface, to estimate a rate of uplift across the underlying fault. With constraints on the dip of the Tabas Fault at depth (obtained from seismology and a structural cross-section) we convert this rate of uplift into rates of horizontal shortening (important for regional tectonic studies) and a rate of slip along the fault (useful for estimating the average interval between earthquakes). Finally, we assess the implications of our study for the source processes of the 1978 earthquake, the tectonics of eastern Iran, and for the evolution of the landscape observed at the present-day near Tabas.

2. Tectonic setting

The active tectonics of Iran are controlled by the northward motion of Arabia, at a velocity of ~25 mm/yr at longitude 60°E, with respect to the interior of Eurasia (Fig. 1A; Vernant et al., 2004). Deformation resulting from this northward motion is broadly confined to within the political borders of Iran, and surrounding parts of Pakistan, Afghanistan and Turkmenistan appear to behave as non-deforming parts of stable Eurasia. Northward motion of central and northern Iran with respect to Afghanistan introduces a north–south right-lateral shear of ~15 mm/yr along the eastern border of Iran (Jackson and McKenzie, 1984; Vernant et al., 2004).

The north–south shear between Iran and Afghanistan is accommodated by several right-lateral strike–slip fault systems bordering the Dasht-e-Lut Desert (Fig. 1; Walker and Jackson, 2004; Meyer and LeDortz, 2007). The East Neh, West Neh and Zahedan faults follow the eastern margin of the Dasht-e-Lut. In the west, right-lateral shear is accommodated on the Sabzevaran–Gowk–Nayband Fault system (Walker and Jackson, 2002; Walker et al., 2010). Regard et al. (2005) estimate, from the ^{10}Be exposure dating of displaced alluvial fans, that the Jiroft–Sabzevaran Fault system in the southwest of the Dasht-e-Lut accommodates ~6 mm/yr of the 15 mm/yr of regional right-lateral shear. However, the slip-rate of faults bordering the western margin of the Dasht-e-Lut desert decreases northwards, with the Holocene slip-rate on the Gowk Fault estimated at 3.8 ± 0.7 mm/yr (Walker et al., 2010), and a slip-rate of 1.4 ± 0.5 mm/yr estimated on the Nayband Fault from ~2 Ma basalts displaced across it (Camp and Griffis, 1982; Walker et al., 2009). The epicentral zone of the 1978 Tabas earthquake is situated at the northern end of the Nayband Fault (Fig. 2).

3. Geology and geomorphology of the Tabas thrust fault system

The Tabas folds are situated between the Tabas playa depression (~600 m above sea level) and the Shotori Mountains, with peak elevations of ~2900 m (Fig. 2). The folds are expressed in the topography as a series of low rounded hills with no more than ~100 m of relief above