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The vertical separation of mainshock rupture and microseismicity at Qeshm island in the Zagros fold-and-thrust belt, Iran

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ABSTRACT

We investigate the depth and geometry of faulting within a cluster of buried, reverse faulting earthquakes that struck Qeshm island, in the Zagros fold-and-thrust belt, over a four year period between November 2005 and July 2009. Of particular interest is our observation that there was a vertical separation between the largest two earthquakes (M_w 5.8 and 5.9), which ruptured the lower parts of a ~10-km thick sedimentary cover, and microseismicity recorded by a local network after the first, M_w 5.8 event, which was concentrated within the underlying basement at depths of 10–20 km. Although measured in different ways — the largest three earthquakes using radar interferometry, moderate-sized events with teleseismically-recorded, long-period waveforms, and the microseismicity using data from a local seismic network — we used consistent velocity and elastic parameters in all our modelling, and the observed vertical separation is robust and resolvable. We suggest that it reflects the influence of the Proterozoic Hormuz salt, a weak layer at the base of the sedimentary cover across which rupture failed to propagate. Because the full thickness of the seismogenic layer failed to rupture during the largest earthquakes in the sequence, the lower, unruptured part may constitute a continued seismic hazard to the region. Considering the rarity of earthquakes larger than M_w 6.2 in the Zagros Simply Folded Belt, we suggest that the Hormuz salt forms an important, regional barrier to rupture, not just a local one. Finally, we note that buried faulting involved in the largest earthquakes is almost perpendicular to the trend of an anticline exposed at the surface immediately above them. This suggests that locally, faulting and folding are decoupled, probably along a weak layer of marls or evaporites in the middle part of the sedimentary cover.

1. Introduction

The Zagros mountains in south-western Iran are one of the most rapidly-deforming and seismically-active fold-and-thrust belts in the world, accommodating almost half of the present-day shortening between Arabia and Eurasia (Fig. 1). Because direct observations of earthquake faulting are possible here, and can be made relatively frequently, the Zagros potentially provides a superb present-day analogue for fold-and-thrust belts elsewhere on the continents, including those which are no longer active. However, earthquakes in the Zagros only very rarely rupture the surface and so far, most observations of faulting in moderate-sized earthquakes have been inferred from seismology (e.g. Adams et al., 2009; Talebian and Jackson, 2004). Errors in the best teleseismically-recorded epicenters and waveform-constrained depths — 10–15 km and ~4 km, respectively (Engdahl et al., 2006) — are such that the precise location and geometry of earthquake faulting, and thus its relationship to the geological structure, have proven difficult to ascertain.

One important issue which remains unresolved, and which is the focus of this study, concerns the relative behaviour and seismogenic potential of the crystalline basement and the overlying sedimentary cover. The cover is up to 10–15-km thick and encompasses a mixture of strong units (mainly platform carbonates) and weaker evaporites, marls and shales. Although the occurrence of small and moderate magnitude earthquakes (M_w 4.5–5.5) at these shallow depths is well resolved (Adams et al., 2009; Lohman and Simons, 2005; Roustaei et al., 2010; Talebian and Jackson, 2004), it is not clear whether the cover is strong enough to generate larger events (M_w ~6), or whether these are restricted to the basement. There has also been much debate about the

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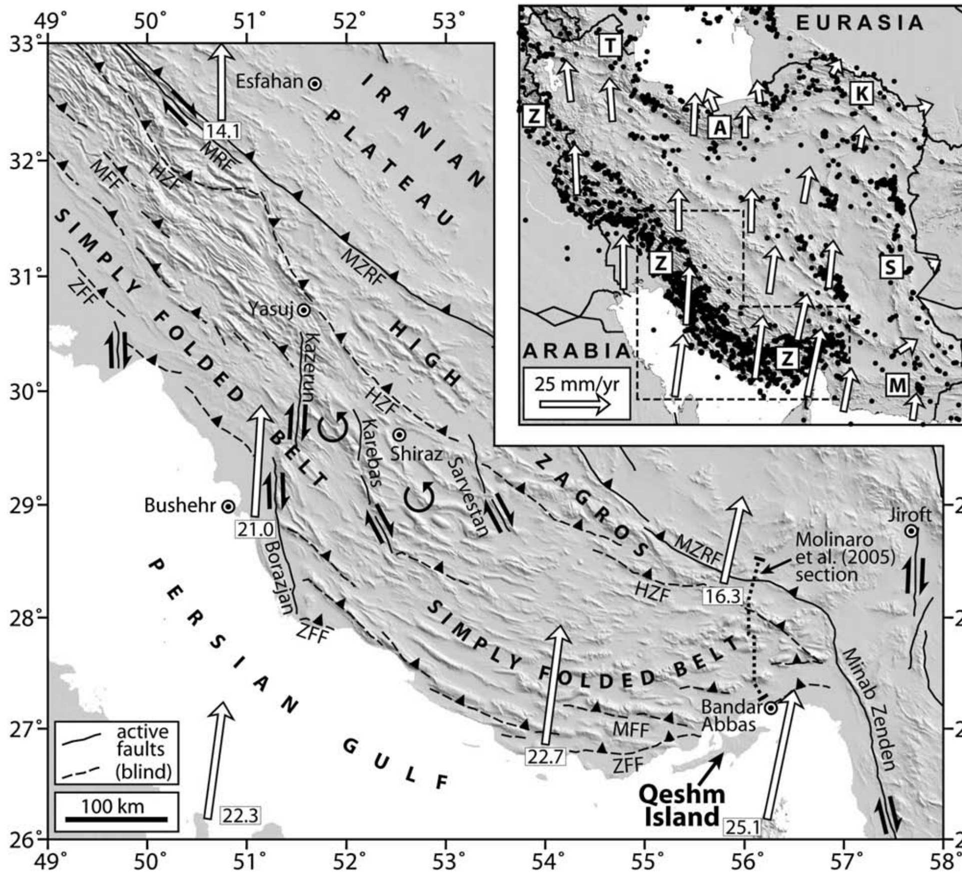

Fig. 1. Inset: topographic map of Iran, illuminated from the NE. Black dots are earthquakes from an updated version of the Engdahl et al. (1998) catalogue, and arrows are GPS velocities relative to stable Eurasia from Vernant et al. (2004). Major earthquake belts are marked Z (Zagros), T (Talesh), A (Alborz), K (Kopeh Dag), S (Sistan) and M (Makran). The location of the main figure is outlined by a dashed black line. Main figure: the south-eastern Zagros, with GPS velocities (as above, with rates in mm year^{-1}) and major faults (black lines, dashed if blind). The suture between rocks of the Arabian margin and those of central Iran follows the MZRF (Main Zagros Reverse Fault) and the right-lateral MRF (Main Recent Fault), and the "master blind thrusts" of Berberian (1995) are marked HZF (High Zagros Fault), MFF (Mountain Front Fault) and ZFF (Zagros Foredeep Fault). The dotted line north of Bandar Abbas marks the cross-section of Molinaro et al. (2005), from which the stratigraphic thicknesses in Fig. 2 were compiled.

extent to which the weaker units, especially the Proterozoic Hormuz salt at the base of the cover, separate deformation in underlying and overlying layers.

A recent cluster of eleven, M_w 5–6 earthquakes at Qeshm island (SE Zagros) provide an opportunity to investigate these problems. In this paper we establish the vertical distribution of faulting that occurred during these earthquakes, using detailed observations from radar interferometry (InSAR), locally-recorded seismic data, and teleseismically-recorded body-waves. By combining these different methodologies we are able to locate the causative faulting more precisely than would be possible using any single method on its own.

2. Geological and tectonic setting

2.1. Overview

The Zagros mountains extend ~1800 km from northern Iraq to the Strait of Hormuz (inset, Fig. 1), and comprise the deformed, north-eastern margin of the Arabian plate following its collision with central Iran in the Miocene, Oligocene or Eocene (Agard et al., 2005; Allen and Armstrong, 2008; McQuarrie et al., 2003). Present-day shortening across the range, measured with GPS, increases from ~4 mm year^{-1} in the NW to ~9 mm year^{-1} in the SE (Vernant et al., 2004; Walpersdorf et al., 2006).

The Zagros can be divided into two distinct zones, based on topography, geomorphology, exposed stratigraphy, and seismicity. The north-eastern zone, bordering the Iranian plateau, is known as the High Zagros (Fig. 1). This area contains Paleozoic and Mesozoic sediments and ophiolites, cut by major thrust and reverse faults which are well-exposed at the surface (Berberian, 1995). However, present-day seismicity in the High Zagros is relatively low, except for the active Main Recent Fault, which accommodates the right-lateral component of Arabia–Iran motion in the NW (e.g. Peyret et al., 2008; Talebian and Jackson, 2002).

The south-western zone, bordering the Persian Gulf, is known as the Simply Folded Belt (SFB) (Fig. 1). This area contains a thick sedimentary cover spanning the entire Phanerozoic, which is folded into parallel trains of 'whaleback' anticlines and synclines (e.g. Colman-Sadd, 1978; Falcon, 1969; O'Brien, 1957; Stöcklin, 1968). It is also the most seismically-active part of the range, with frequent earthquakes of M_w 5–6 and occasional larger events up to M_w 6.7. Observations from stratigraphy, GPS and geomorphology suggest that deformation migrated from the High Zagros to the SFB at an earlier stage in the collision (Hessami et al., 2001b; Oveisi et al., 2009; Walpersdorf et al., 2006).

2.2. Stratigraphy

The sedimentary cover in the Simply Folded Belt plays an important role in its deformation and warrants further description. Fig. 2 shows a simplified stratigraphy for the SE Zagros, close to where our study is based, from Molinaro et al. (2005). At the base of the sequence is the Proterozoic Hormuz Salt formation, which comes to the surface in salt plugs and diapirs across the central and south-eastern SFB (e.g. Kent, 1979). Paleozoic and lower Mesozoic strata comprise conglomerates and massive limestones and dolomites, collectively termed the 'Competent Group.' Upper Cretaceous to middle Miocene rocks