The kinematics of the Zagros Mountains (Iran)

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Abstract: We present a synthesis of recently conducted tectonic, global positioning system (GPS), geomorphological and seismic studies to describe the kinematics of the Zagros mountain belt, with a special focus on the transverse right-lateral strike-slip Kazerun Fault System (KFS). Both the seismicity and present-day deformation (as observed from tectonics, geomorphology and GPS) appear to concentrate near the 1000 m elevation contour, suggesting that basement and shallow deformation are related. This observation supports a thick-skinned model of southwestward propagation of deformation, starting from the Main Zagros Reverse Fault. The KFS distributes right-lateral strike-slip motion of the Main Recent Fault onto several segments located in an en echelon system to the east. We observe a marked difference in the kinematics of the Zagros across the Kazerun Fault System. To the NW, in the North Zagros, present-day deformation is partitioned between localized strike-slip motion on the Main Recent Fault and shortening located on the deformation front. To the SE, in the Central Zagros, strike-slip motion is distributed on several branches of the KFS. The decoupling of the Hormuz Salt layer, restricted to the east of the KFS and favouring the spreading of the sedimentary cover, cannot be the only cause of this distributed mechanism because seismicity (and therefore basement deformation) is associated with all active strike-slip faults, including those to the east of the Kazerun Fault System.

Mountain building is the surface expression of crustal thickening caused by plate convergence. Mountains are located on continental lithosphere, which, because of its mechanical properties, generally accommodates plate convergence in a more distributed and diffuse way than oceanic lithosphere. Because thickening stores gravitational potential energy, it reaches a limit imposed by the mechanical strength of the crust and lithosphere, after which further storage of gravitational energy is possible only by increasing the lateral size of the mountain belt rather than its height (e.g. Molnar & Lyon-Caen 1988). Therefore, mountain building is a dynamic process, which, to be quantified, requires a detailed description of both the surface kinematics and its relation with crustal

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deformation. In this paper, we show that shallow deformation, as evidenced by global positioning system (GPS) measurements and geomorphology, correlates well, both spatially and temporally, with basement deformation as evidenced by seismicity and topography, suggesting that they image the same mountain-building process.

The Zagros fold-and-thrust belt is located within Iran at the edge of the Arabian plate (Fig. 1). It is *c*. 1200 km long and trends NW–SE between eastern Turkey, where it connects to the Anatolian mountain belt, and the Strait of Hormuz, where it connects to the Makran subduction zone. Its width varies from *c*. 200 km in the west to *c*. 350 km in the east. The Zagros mountain belt results from convergence between Arabia and Eurasia, which has been continuous since Late Cretaceous times, with a late episode of accentuated shortening during the Pliocene–Quaternary. The Zagros is classically described in terms of longitudinal units separated by lateral discontinuities (Fig. 1). The High Zagros comprises highly deformed metamorphic rocks of Mesozoic age; it is bounded to the NE by the Main Zagros Thrust (MZT), which is the boundary with Central Iran, and to the SW by the High Zagros Fault (HZF). This is the highest part of the Zagros, with maximum elevations reaching more than 4500 m. The High Zagros overthrusts to the south the Zagros Fold Belt, which comprises a 10 km thick Palaeozoic–Cenozoic sequence of sediments. The Zagros Fold Belt is characterized by large anticlines several tens of kilometres long. Longitudinally, the Zagros is divided into two geological domains, the North Zagros (and the Dezful embayment) to the west and the Central Zagros (or Fars) to the east, separated by the north–south-trending strike-slip Kazerun Fault System that cross-cuts the entire belt. Significant differences in mechanical stratigraphy exist between the North and the Central Zagros; the sedimentary cover of the latter has been deposited on top of the infra-Cambrian Hormuz Salt layer, whereas this layer is absent in the North Zagros.

The amount of shortening between Arabia and Iran since Jurassic times, resulting from subduction of the Neotethys, is about 2000 km (McQuarrie *et al.* 2003). Ocean closure and cessation of subduction probably occurred during the Oligocene (Agard *et al.* 2005). This event is recorded by a slight decrease in the convergence velocity from 30 to 20 mm a^{-1} (McQuarrie *et al.* 2003). The total amount of shortening since the onset of continental collision is debated, depending on which marker is used to measure it. Estimates have been based on reconstructions of Late Cretaceous **Q1** (Haynes & McQuillan 1974; Stöcklin 1974) to late **Q2** Miocene (Stoneley 1981) strata. Shortening is accommodated differently in the North and Central Zagros because of the differing boundary conditions and pre-existing tectonics. In the North Zagros, the Main Recent Fault accommodates the lateral component of oblique convergence and may transfer some of the motion to the North Anatolian system, whereas deformation partitioning does not appear to exist in the Central Zagros.

Basement deformation

Morphotectonics and balanced cross-sections

Because the basement is decoupled from the shallow sediments by several ductile layers (e.g. the infra-Cambrian Hormuz and Miocene Gahsaran interfaces), surface deformation may not be representative of the total crustal deformation. Furthermore, deformation mechanisms may differ between the basement and the sedimentary cover because of their different mechanical properties. This view is partially supported by the fact that less than 10% of the total deformation of the Zagros (as measured at the surface) is released by seismic deformation (supposed to be related to the crustal deformation) whereas most of the deformation is seismic in other areas of Iran (Jackson & McKenzie 1988; Masson *et al.* 2005). There is no direct access to basement deformation in the Zagros because there are no basement outcrops at the surface, seismic reflection profiles do not clearly image the basement and earthquake ruptures on the reverse faults generally do not reach the surface.

An approach that implies a model assumption is to indirectly infer basement deformation from surface observations. Berberian (1995) mapped first-order changes in the stratigraphy and identified five morphotectonic units with different characteristics of folding, uplift, erosion and sedimentation. He suggested that these morphotectonic units are separated by major reverse faults affecting the basement and striking parallel to the main structures (Fig. 1). These faults are partially associated with seismicity, consistent mostly with reverse mechanisms, but the accuracy of earthquake locations (*c*. 20 km, Engdahl *et al.* 1998) does not permit mapping of active faults in detail. Moreover, some large earthquakes are not related to any of the inferred faults.

Another approach to indirectly infer crustal deformation is to compute the amount of shortening from balanced cross-sections (Blanc *et al.* 2003; McQuarrie 2004; Molinaro *et al.* 2004; Sherkati & Letouzey 2004). In this method, the different layers that constitute the sedimentary cover are supposed to only fold or fault, without internal deformation. However, the location at depth of the decoupling layers, the amount of decoupling

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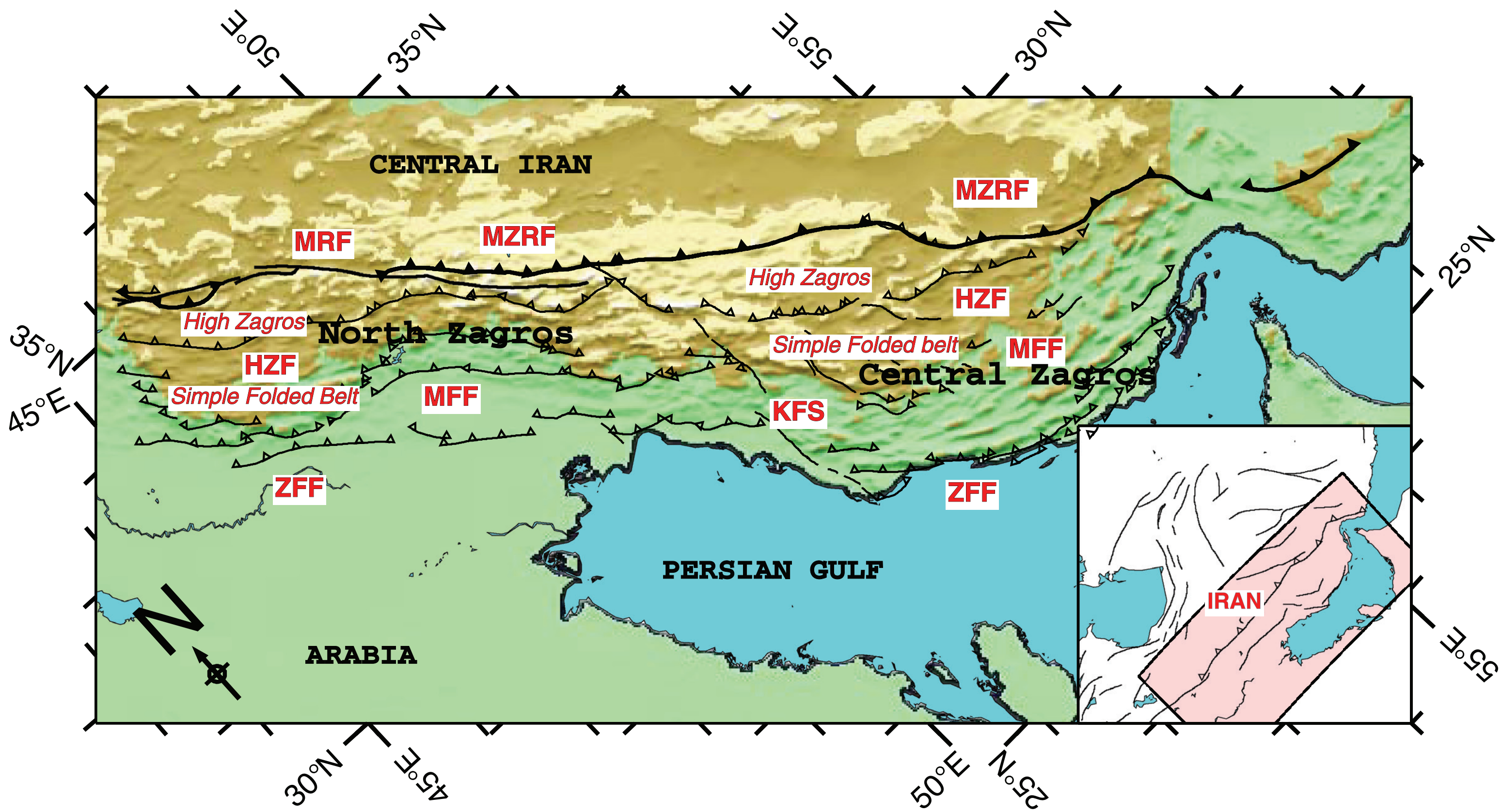

Fig. 1. Location map showing the main geographical and tectonic features of the Zagros (Iran) modified after Berberian (1995), Talebian & Jackson (2004) and Authemayou *et al.* (2006). For the faults, we use the terminology of Berberian (1995). MZRF, Main Zagros Reverse Fault; MRF, Main Recent Fault; HZF, High Zagros Fault; MFF, Main Frontal Fault; ZFF, Zagros Frontal Fault; KFS, Kazerun Fault System, which separates the North Zagros from the Central Zagros. The colours represent topography, with changes at 1000, 2000 and 3000 m levels.

related to these layers, and the relationship between folding and faulting are all complex, and solutions are generally non-unique. Usually, basement faults are assumed where unfolding creates a space problem in the core of folds. The link between surface and basement deformation is strongly debated. Some researches do not require faults in the basement (McQuarrie 2004), whereas others have proposed that deformation started in a thin-skinned mode and continued as thick-skinned deformation (Blanc *et al.* 2003; Molinaro *et al.* 2004; Sherkati *et al.* 2005). Some workers have suggested that faulting post-dates folding (Blanc *et al.* 2003; Molinaro *et al.* 2005), whereas others have proposed that basement faulting predated folding (Mouthereau *et al.* 2006). It is therefore problematic to infer basement faulting, and moreover to estimate the amount of shortening, from balanced cross-sections alone, without complete control of the geometry of the different interfaces.

Seismicity

The other way to access basement deformation is to study seismicity (Fig. 2). Two sets of data provide complementary information: earthquakes located teleseismically and earthquakes located by local networks. Teleseismically located earthquakes have been recorded since the early 1960s; the duration of the available time window is thus comparable with the usual return period of continental earthquakes. However, because of the lack of regional stations, catalogues (ISC, USGS) of teleseismically located earthquakes in Zagros are subject to large mislocations (Ambraseys 1978; Berberian 1979; Jackson 1980; Engdahl *et al.* 1998, 2006). Errors in epicentre location are up to *c*. 20 km and depths are generally unreliable.

Jackson & McKenzie (1984), Ni & Barazangi (1986) and Engdahl *et al.* (2006), amongst others, filtered catalogues or relocated seismicity to improve the accuracy of epicentres and depths. The Zagros seismicity is totally confined between the Persian Gulf coast and the Main Zagros Thrust (MZT), which both limit the active (or deforming) area and exclude seismic accommodation of shortening by the MZT (Fig. 2). Moreover, although seismicity is spread over the entire width of the Zagros, the larger magnitude ($M_b > 5$) earthquakes appear to concentrate in the Zagros Fold Belt, which is an area of low ($z < 1500$–2000 m) topography (Jackson & McKenzie 1984; Ni & Barazangi 1986; Talebian & Jackson 2004). This larger seismic energy release at low elevations has been explained by differential stress owing to the gradient in topography (Jackson & McKenzie 1984; Talebian & Jackson 2004). Epicentres are not obviously correlated with geological structures or surface tectonics (Fig. 2). Moreover, no instrumental earthquake has a magnitude M_w greater than 6.7 and, as a consequence, no co-seismic ruptures have been observed, except for one earthquake in 1990 ($M_w \approx 6.4$) located at the eastern termination of the HZF (Walker *et al.* 2005). **Q3**

The only reliable depths for teleseismically located earthquakes are those computed by body-wave modelling with uncertainties in depth of ± 4 km (Talebian & Jackson 2004). In the Zagros these depth of large earthquakes is 5–19 km with a mean *c*. 11 km, suggesting that earthquakes occur in the basement below the sedimentary cover.

Most focal mechanisms computed from first-motion polarities (McKenzie 1978; Jackson & McKenzie 1984) or by body-wave modelling (Talebian & Jackson 2004) are reverse faulting with NW–SE strikes, parallel to the folding (Fig. 3). Some of these mechanisms are associated with the major faults proposed by Berberian (1995) but others are not. Most of the mechanisms are high-angle reverse faulting probably occurring in the basement at depths between *c*. 5 and 15 km; they are thus unrelated to a low-angle detachment at the base of the sedimentary layer (Fig. 3). Jackson (1980) proposed that they reactivate **Q4** normal faults inherited from a stretching episode affecting the Arabian platform during opening of the Tethys Ocean in the Early Mesozoic.

Strike-slip mechanisms are related to two fault systems: the north–south-trending Kazerun Fault System (KFS; comprising the Kazerun, Kareh-Bas, Sabz-Pushan and Sarvestan faults), which crosses the Zagros between 51.5°E and 54.0°E, and the Main Recent Fault (MRF), which runs parallel to the MZT and connects at its SE termination to the Kazerun Fault System. The MRF helps to accommodate the oblique shortening experienced by the North Zagros by partitioning the slip motion into pure reverse faulting and strike-slip faulting.

Early studies based on unfiltered earthquake catalogues (Nowroozi 1971; Haynes & McQuillan **Q5** 1974; Bird *et al.* 1975; Snyder & Barazangi 1986) **Q6** postulated that some intermediate seismicity could be related to continental subduction located NE of the MZT. However, no reliably located earthquake is located NE of the MZT (Engdahl *et al.* 1998) and no earthquakes have been located at a depth greater than 20 km in this area (Jackson & Fitch 1981; Jackson & McKenzie 1984; Maggi *et al.* 2000; Engdahl *et al.* 2006), implying that continental subduction is either aseismic or active.

Microearthquake studies complement the teleseismic information because they locate epicentres with an accuracy of a few kilometres; an order of magnitude better than teleseismic locations. On the other hand, they span a relatively short time window, which may not record the tectonic

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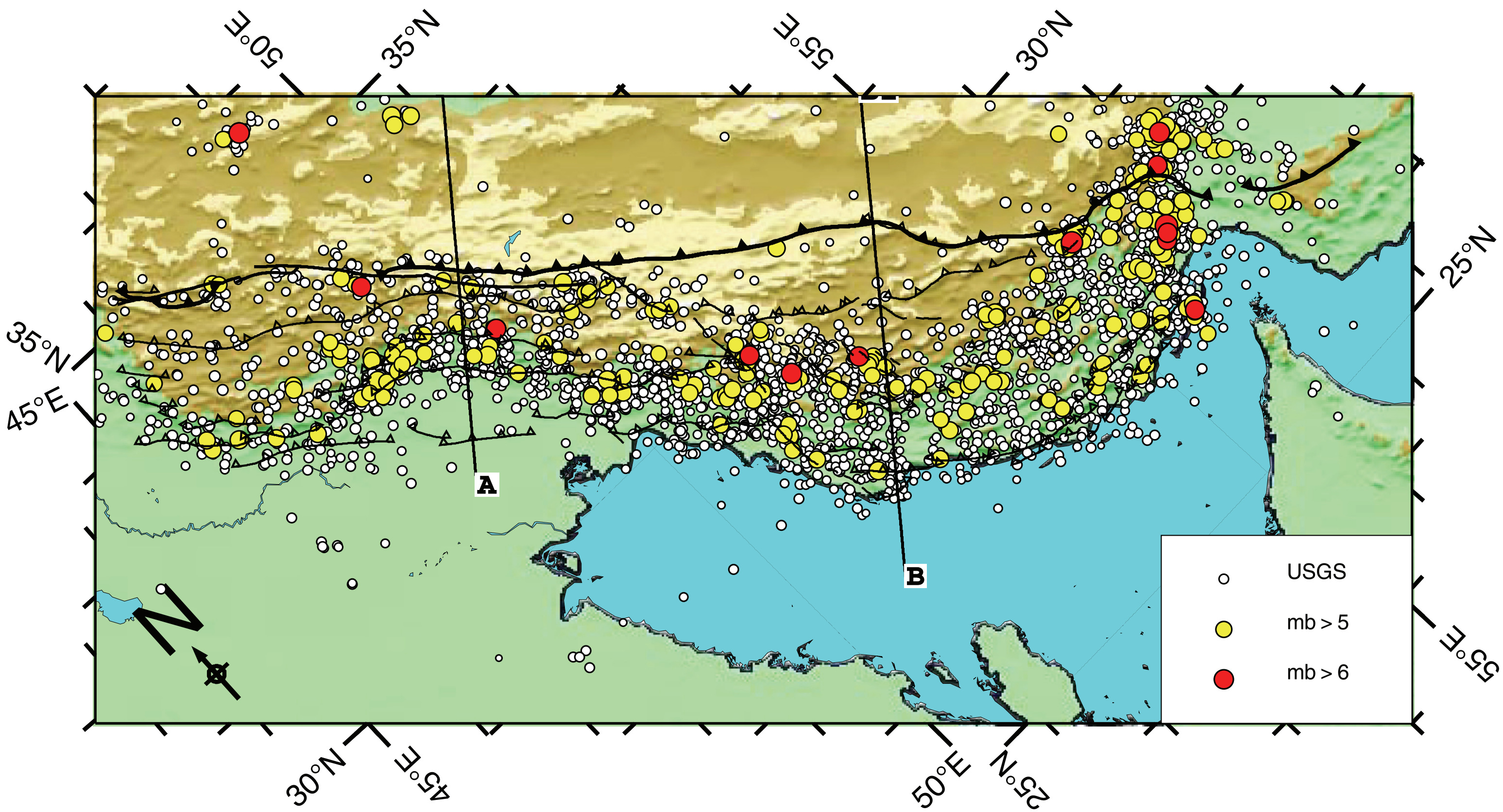

Fig. 2. Seismicity map of the Zagros based on the US Geological Survey catalogue, confirming the observation of Talebian & Jackson (2004) that seismicity (and especially large magnitude earthquakes) is restricted to the SW of the Zagros topography. Cross-sections for lines A and B are shown in Figure 11.

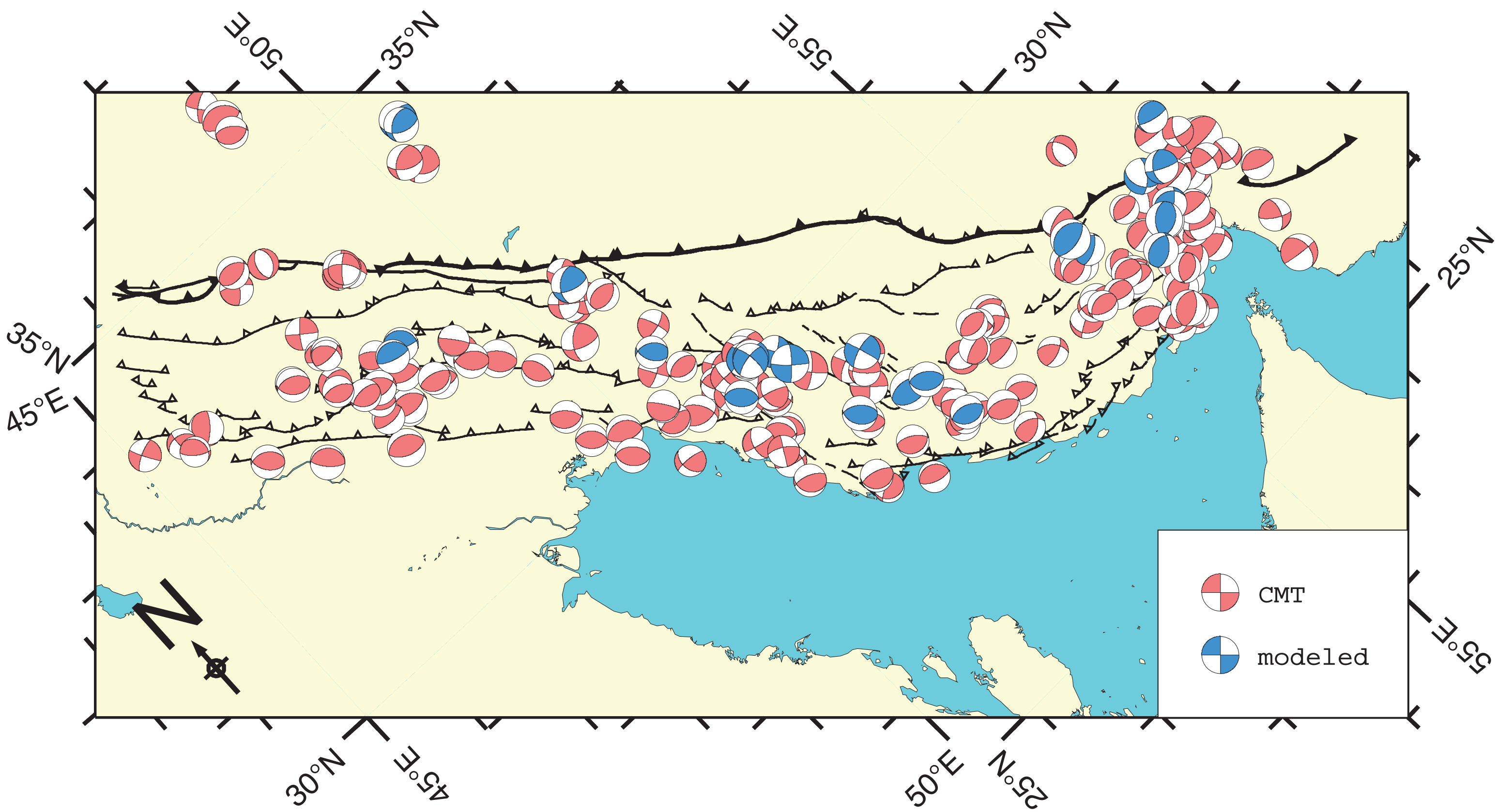

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Fig. 3. Fault-plane solutions in the Zagros. Blue focal spheres are body-wave solutions modelled by Talebian & Jackson (2004) and red focal spheres are CMT solutions (http://www.seismology.harvard.edu/CMTsearch.hml). As pointed out by Talebian & Jackson (2004), most of the Zagros experiences reverse faulting, except near the MZRF and the KFS.

processes in a representative manner. Several temporary networks have been installed in the Zagros, at Qir (Savage *et al.* 1977; Tatar *et al.* 2003), Kermansha (Niazi *et al.* 1978), Bandar-Abbas (Niazi 1980; Yamini-Fard *et al.* 2007) and near the Kazerun Fault System (Yamini-Fard *et al.* 2006). Whereas earlier studies are of limited use because the small number of stations does not allow sufficient accuracy in earthquake location, more recent studies have helped to determine some aspects of the crustal structure by inverting travel-time delays of local earthquakes recorded at stations located directly above the seismicity. Tatar *et al.* (2003) confirmed that seismicity in the Central Zagros is confined between *c.* 10 and *c.* 15 km depth, beneath the sedimentary cover and in the upper part of the basement (Fig. 4). As for the teleseismic events, no microearthquake is located north of the MZT and no earthquake is deeper than 20 km. The seismicity is not confined to the main faults, as observed at the surface, but is spread over a wider area. More interestingly, the microseismicity defines elongated NW–SE-trending lineaments parallel to the fold axes but with a different spacing,

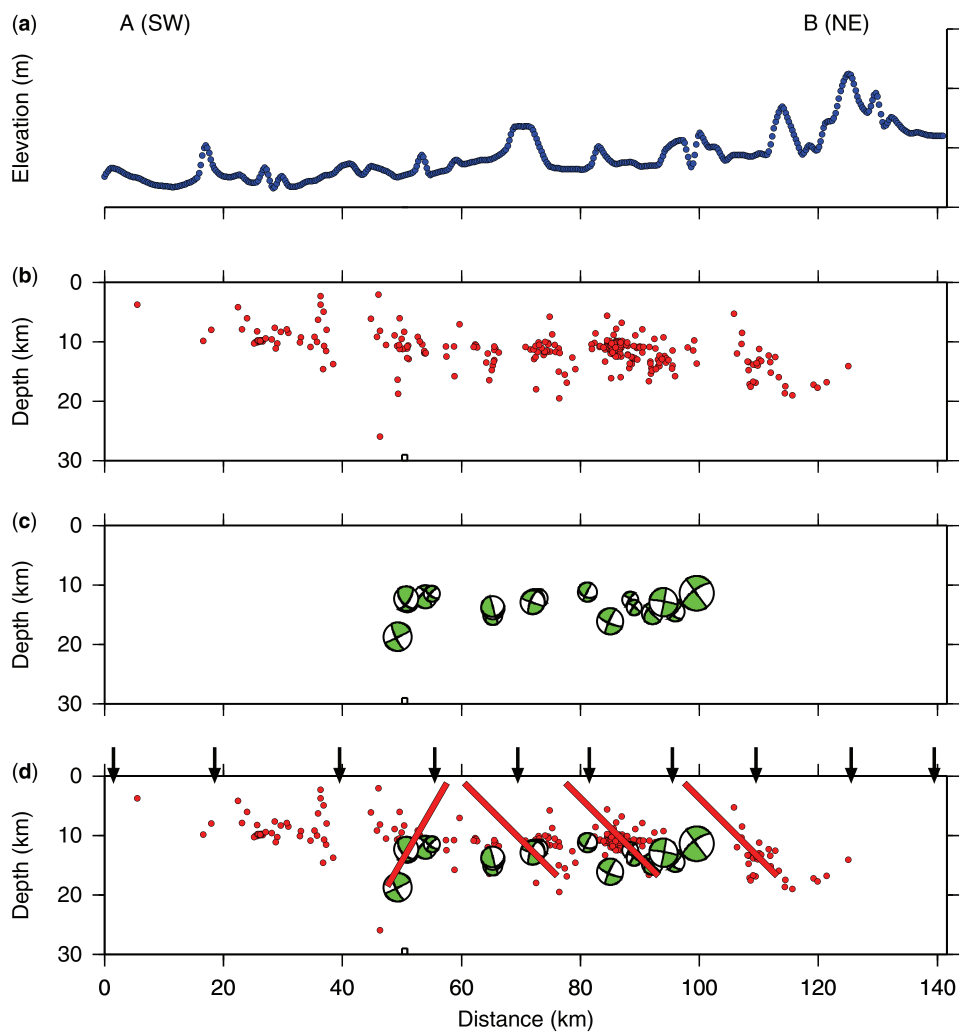

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Fig. 4. SW–NE cross-section across the Central Zagros (after Tatar *et al.* 2003). (**a**) Topography. (**b**) Well-located (better than 2 km) microseismicity recorded during a 7 week period. Microseismicity is restricted to the upper basement beneath the sedimentary layer and dips slightly NE. (**c**) Fault-plane solutions (in cross-section), showing mostly reverse mechanisms. (**d**) Our interpretation of clustering possibly associated with active faults (red lines). Black arrows at the surface represent fold axes, the spacing of which is unrelated to any clustering in seismicity.

suggesting that folds and faults are not directly related. The seismicity clusters appear to dip NE (Fig. 4), supporting the model of normal-fault reactivation (Jackson 1980). Focal mechanisms are consistent with NW–SE-striking reverse faults connected by NNW–SSE right-lateral strike-slip faults. The main direction of the P-axes fits well the direction of GPS shortening, suggesting that microearthquakes are the response of the crust to north–south shortening.

Two other surveys, at the intersection between the Kazerun Fault and the MRF in Borujen (Yamini-Fard *et al.* 2006) and at the transition between the Zagros collision zone and the Makran subduction zone near Bandar-Abbas (Yamini-Fard *et al.* 2007), show an interesting result. Reverse-slip focal mechanisms are confined to depths greater than 12 km along NE-dipping décollements striking perpendicular to the motion, whereas dextral strike-slip focal mechanisms are recorded at shallower depths under the trace of the MRF. This difference in mechanism with depth suggests that the upper brittle crust deforms mostly by slip (either strike-slip or reverse, depending on the orientation) on weak pre-existing faults, but that the lower crust is more pervasively weakened and accommodates the shortening by reverse faulting perpendicular to regional motion.

Surface deformation

GPS deformation

GPS measurements provide instantaneous velocities between benchmarks. Depending on the surveying procedure and on the duration of the measurements for each survey, the accuracy of the position can reach *c*. 2 mm. If the time span between two measurements is several years, and moreover if three or more measurements are available allowing some redundancy, we estimate the velocity uncertainties to be less than 2 mm a^{-1}.

Several campaigns have been conducted in the Zagros. One was part of a regional-scale survey conducted throughout Iran, with a spacing between stations larger than *c*. 150 km (Nilforoushan *et al.* 2003; Vernant *et al.* 2004; Masson *et al.* 2007), which does not provide sufficient resolution to study the deformation in great detail. However, a dozen benchmarks from this network record 6–7.5 mm a^{-1} of NNE–SSW shortening for the Zagros, which corresponds to *c*. 30% of the total convergence between Arabia and Eurasia at this longitude. The transition between the Makran subduction and the Zagros collision is clearly evidenced by the contrast in the velocities relative to Central Iran across the area.

Hessami *et al.* (2006) installed a network of 35 benchmarks covering the entire Zagros. These stations were measured during three campaigns over 3 years in 1998, 1999 and 2001. Each station was measured several times and sessions lasted 8 h. The observations of 4–6 IGS stations were included for reference. Hessami *et al.* claimed their accuracy to be 3 mm a^{-1}. The main results are that west of the Kazerun Fault shortening is accommodated by the Mountain Front Fault, whereas east of it, it seems to be accommodated 100 km north of the Mountain Front Fault and by the Main Zagros reverse Fault.

Since 1997, we installed several regional GPS networks in the Zagros (Fig. 5). These networks covered the Central Zagros (15 benchmarks), the Kazerun Fault System (11 benchmarks) and the Northern Zagros (18 benchmarks), and were measured simultaneously with several stations of the Iran Global network as well as with Iranian permanent stations. Each site was continuously observed for at least 48 h per campaign. All networks were measured a minimum of three times over a time period lasting usually 2–5 years. The data have been analysed with the GAMIT/GLOBK 10.1 software (King & Bock 2002). As many as 32 IGS stations (depending on the survey) have been included to establish the terrestrial reference frame. Final IGS orbits and corresponding Earth orientation parameters have been used. In the combination of daily solutions with the Kalman filter GLOBK, the continuous time series of daily SOPAC global solution files (IGS3 network) has been included, covering all of the measurement epoch presented here. Mean repeatability is estimated to be less than 2 mm, which yields a precision better than 2 mm a^{-1}. Details of processing procedures can be found in previous papers (Tatar *et al.* 2002; Walpersdorf *et al.* 2006; Tavakoli *et al.* 2008).

The main results (Fig. 5) show some differences from those of Hessami *et al.* (2006). As observed by those workers, the shortening component increases from NW to SE, consistent with a Arabia–Central Iran pole of rotation located at 29.8°N, 35.1°E, inferred by Vernant *et al.* (2004). However, the deformation on each side of the Kazerun Fault System is different from that proposed by Hessami *et al.* (2006). West of the Kazerun Fault System, most of the deformation is located north of the MFF, far from the Zagros Frontal Fault (ZFF). It is clearly partitioned between 4–6 mm a^{-1} of dextral strike-slip motion concentrated in the north, with probably 2–4 mm a^{-1} on the MRF alone, and 3–6 mm a^{-1} of shortening probably on the MFF. East of the Kazerun Fault, the deformation is pure shortening of 8 mm a^{-1} located along the Persian Gulf shore and associated with the

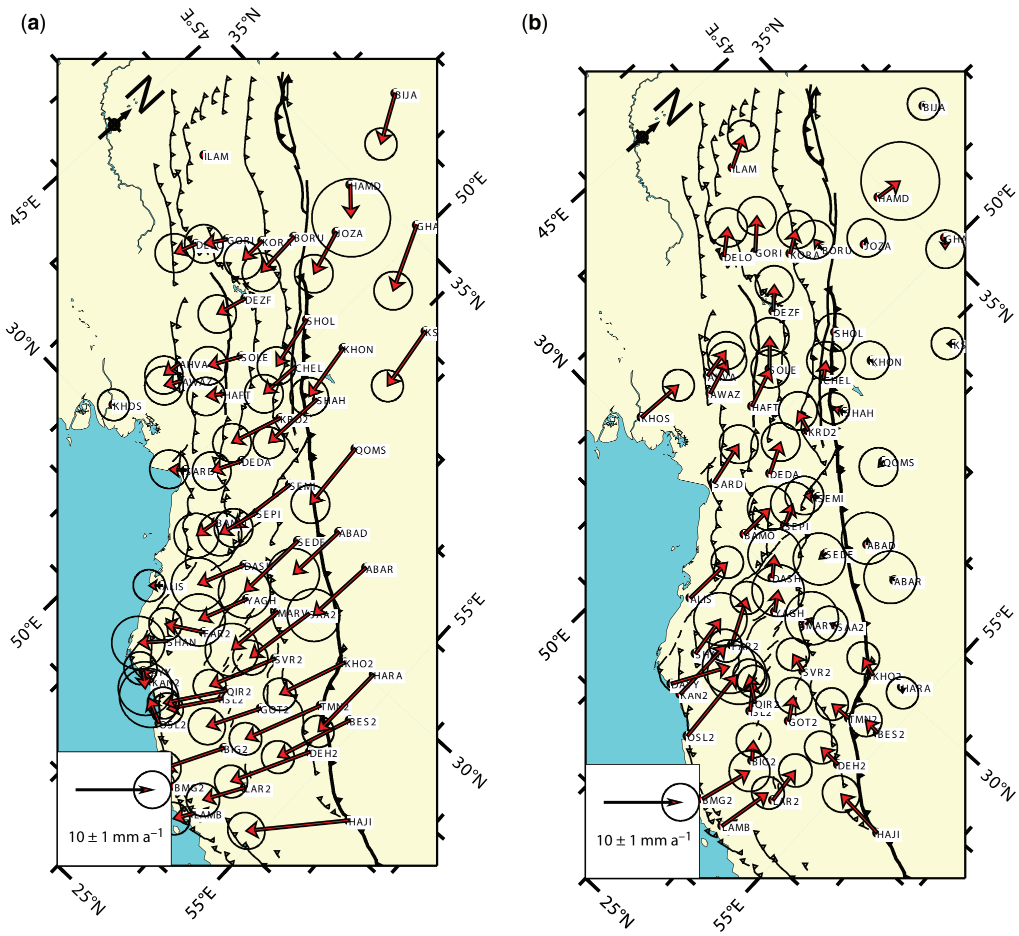

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Fig. 5. GPS-detected motion of the Zagros (Tatar *et al.* 2002; Walpersdorf *et al.* 2006; Tavakoli *et al.* 2007) with 95% confidence ellipses. (**a**) Motion relative to Arabia; (**b**) motion relative to Central Iran. Deformation appears localized near the MFF. We do not observe a fan-shaped pattern in the Central Zagros, as expected from spreading of the motion as a result of the Hormuz salt layer. Q19

ZFF. In contrast to Hessami *et al.* (2006), we do not observe significant along-strike extension (i.e. larger than 2 mm a^{-1}) between the two extremities of the Zagros. The KFS strike-slip system induces some extension oblique to the faults, but we do not observe significant along-strike extension of the Zagros associated with perpendicular shortening or thickening of the belt. This view is also evidenced by the strain rate between the benchmarks.

We computed the strain rate and rigid rotation in all triangles defined by three adjacent benchmarks, and report here the amount and direction of shortening, as well as the rotation experienced by each triangle assumed to be a rigid block (Fig. 6). GPS measurements show that most of the shortening is neither uniformly located across the belt nor located on one of the major basement faults (i.e. MFF, ZFF) proposed by Berberian (1995). In contrast, shortening appears to be associated again with the topography and more specifically between the 1000 m elevation contour and sea level (Fig. 6a). The correlation between the gradient in topography, basement seismicity (Talebian & Jackson 2004) and instantaneous shortening rate supports the hypothesis that basement and surface deformation are related and that both propagate southwestward. Therefore, a total decoupling by the Hormuz Salt of the shallow sediments from the basement is not needed.

Finally, we observe a consistent pattern of clockwise rotation throughout the Zagros (Fig. 6b). As expected, the largest rotations are associated with the largest strain rates and follow the 1000 m elevation contour. This general rotation is probably

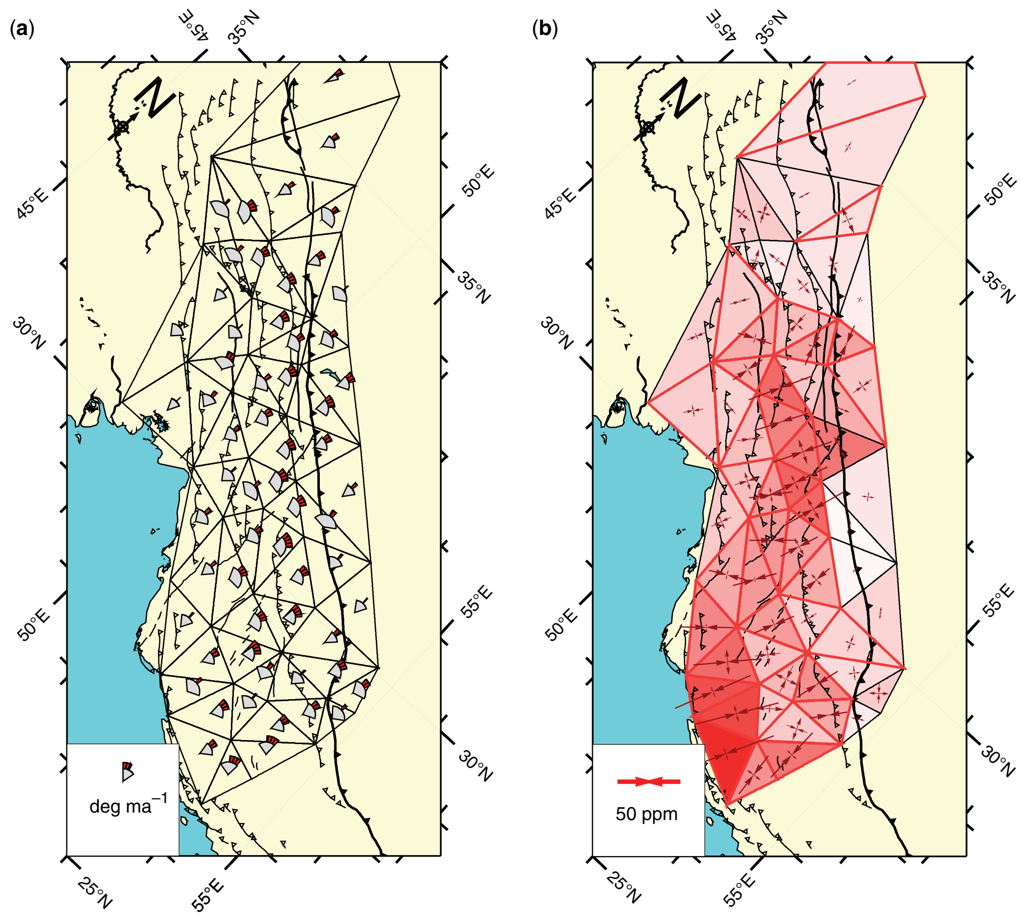

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Fig. 6. (**a**) Strain rate deduced from GPS observations. Triangles are coloured as a function of the intensity of the deformation. The arrows indicate the principal strain rates. The triangles with significant deformation (exceeding the uncertainties) are surrounded by a bold line. The direction of shortening consistently trends NNE–SSW with a slight north–south rotation near the Kazerun Fault System. East of the KFS, the deformation is localized at the MFF near the Persian Gulf. West of the KFS, the deformation is localized further north, also at the MFF. In both cases it can be associated with the 1000 m topography elevation. (**b**) Rotations of triangles defined by three benchmarks. Although uncertainties are large, we observe a consistent clockwise rotation. Only two triangles located at the easternmost location show significant anticlockwise rotation. Triangles with rotations larger than 1° Ma^{-1} are associated with large strain and located along the MFF as is the strain. **Q20**, **Q21**

induced by the general right-lateral transcurrent motion between Central Iran and Arabia. We do not observe larger rotation associated with the strike-slip Kazerun Fault System, nor any anti-clockwise rotation as proposed by Talebian & Jackson (2004).

Tectonics

The Zagros deformation is characterized by constant-wavelength folding, thrusting and strike-slip faulting. Models suggest that detachment folding is the main folding style (Mouthereau *et al.* 2006; Sherkati *et al.* 2006). Fold geometries vary **Q8** significantly with the presence of intermediate décollements (Sherkati *et al.* 2006). Some thrusts branched on décollement levels are formed by progressive fault propagation within the core of the folds. Other thrusts, associated with topographic steps, appear to be linked to basement faults. These reverse faults are generally blind. The difference in elevation of some stratigraphic marker horizons on both sides of the thrusts indicates 5–6 km finite vertical offset on both the MFF and the HZF (Berberian 1995; Sherkati & Letouzey 2004). The southwestward migration of sedimentary depocentres from Late Cretaceous time to Miocene collision, as well as the existence of several stages of folding, suggests that the shortening rates have varied through time (Sherkati & Letouzey 2004; Mouthereau *et al.* 2006).

In contrast to the blind reverse faults, the active traces of strike-slip faults are observable. Finite displacements on strike-slip faults are constrained by piercing points, major river offsets and fold offsets. Talebian & Jackson (2002) suggested 50 km of strike-slip offset on the MRF, which, assuming an onset 3–5 Ma ago (by analogy with the North Anatolian Fault), would require a slip rate of 10–17 mm a^{-1}; much larger than the GPS velocity estimate. Lateral offsets of geomorphological markers and *in situ* cosmogenic dating yield an estimated slip rate of 4.9–7.6 mm a^{-1} on the MRF (Authemayou *et al.* 2009). The other strike-slip fault is the Kazerun Fault System, which we will discuss separately.

Geomorphological record of deformation

Numerous geomorphological markers such as fluvial and marine terraces occur throughout the Central Zagros and can be used to constrain fold kinematics at time scales of 10^4–10^5 years, intermediate between the instantaneous deformation recorded by GPS and seismic studies and the long-term deformation inferred from section balancing. Such markers record incremental deformation and may therefore aid in discriminating between fold models. If they can be dated sufficiently precisely they also constrain deformation rates, which can be transformed into shortening rates using an appropriate fold model.

Q9 Oveisi *et al.* (2007, 2009) studied surface deformation as recorded by marine terraces along the coastal Mand anticline, located south of the Borazjan Fault, as well as by fluvial terraces along the Dalaki and Mand rivers, which cross the northwestern Fars east of the Kazerun Fault System. Their results indicate that shortening on Late Pleistocene time scales is concentrated in the frontal part of the belt, consistent with the GPS results discussed above (Fig. 7). Three or four frontal structures appear to absorb practically all of the shortening across the Central Zagros on intermediate time scales. Immediately east of the Kazerun Fault System, the coastal Mand anticline accommodates 3–4 mm a^{-1} shortening in a NE–SW direction. The Gisakan fold, located at the intersection of the Borazjan Fault and the MFF, also accommodates 2–4 mm a^{-1} of shortening in the same direction. These two structures together thus account for at least 70% and possibly all of the shortening between the stable Arabian and Iranian platforms. Further to the SE, the situation is slightly more complex, with thin-skinned deformation concentrated on the Halikan fold located inboard of the MFF and only *c.* 10% ($\leq$1 mm a^{-1}) of the shortening taken up on the most frontal structures, such as the coastal Madar anticline.

For the active coastal anticlines, structural data as well as seismic sections preclude significant basement involvement. Instead, these anticlines evolve as open detachment or fault-propagation folds above basal (Hormuz Salt) or intermediate (Gachsaran evaporites) décollement levels. Crustal-scale shortening is fed into these structures either from the MFF or from the most internal parts of the Zagros. Active folds associated with the MFF, in contrast, do suggest basement involvement and occasional fault rupture extending to the surface, as observed at the Gisakan fold. Inboard of the MFF, minor (<1 mm a^{-1} along small-scale structures east of the Kazerun Fault) to significant (up to 5 mm a^{-1} for the Halikan anticline) amounts of shortening are absorbed by thin-skinned structures, whereas the surface expressions of major basement faults (e.g. the Surmeh Fault) provide no geomorphological evidence for recent activity.

The total amount of shortening on 10^4–10^5 years time scales, as recorded by geomorphological markers of deformation, is consistent, within error, with the GPS-derived present-day deformation rates of 8–10 mm a^{-1} across the Zagros. The geomorphological data also show that deformation has been concentrated in the outboard regions of the belt, associated with the MFF and other frontal structures, during Late Quaternary times, and that both thick- and thin-skinned structures are active simultaneously.

The Kazerun Fault System

The Kazerun Fault System (KFS) separates the North Zagros from the Central Zagros (Fig. 1). It comprises several roughly north–south-trending right-lateral strike-slip faults. The Kazerun Fault itself is composed of three north–south-trending segments (Fig. 8): the Dena, Kazerun and Borazjan segments, which all terminate to the south with a north-dipping reverse fault (Authemayou *et al.* 2005, 2006). The Kazerun Fault is associated with exhumation of Hormuz Salt (Talbot & Alavi 1996) **Q10** and modifies the trend of folds adjacent to it. The KFS, as well as the other north–south-trending faults, is probably inherited from a Cambrian tectonic event that affected the Arabian platform because it controls the distribution of Hormuz Salt, which is present to the east of the fault system but not to the west (Talbot & Alavi 1996; Sepehr & Cosgrove 2005). It was reactivated as **Q11** early as in the Middle Cretaceous (Koop & Stoneley

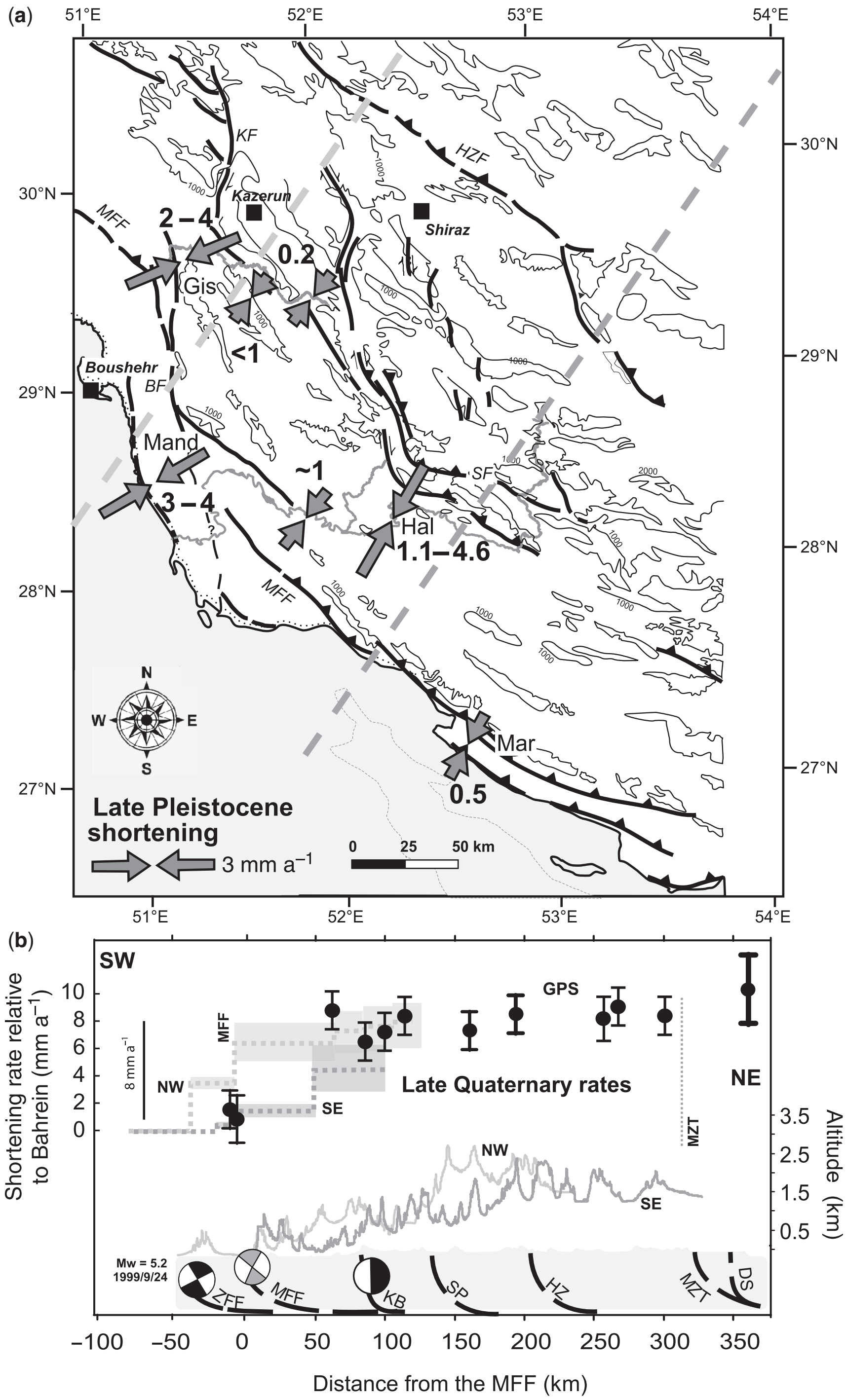

Fig. 7. Summary of the geomorphological observations of Oveisi *et al.* (2007, 2009) (**a**) Map of the Central Zagros showing the inferred shortening rates across various structures (Gis, Gisakan fold; Hal, Halikhan fold; Mand, Mand fold; Mar, Madar fold) as deduced from Late Pleistocene terrace uplift rates (wide shaded arrows, annotated with inferred rate in mm a^{-1}). This pattern should be compared with the pattern of present-day strain rates in Figure 6.

1982). The total offset along the Kazerun Fault is a Q12 matter of debate, varying from 5 km (Pattinson & Takin 1971) or 8.2 km (Authemayou *et al.* 2006) to 140 km (Berberian 1995), depending on the markers used to quantify strike-slip motion. This large difference in displacement results in inferred slip rates of 1–15 mm a^{-1}. Careful mapping of the active faults and of the lateral offsets along the various segments of the fault (Fig. 9) together with precise dating of fans yields a slip rate of *c*. 3.1–4.7 mm a^{-1} on the Dena Fault and 1.5–3.2 mm a^{-1} on the Kazerun Fault (Authemayou *et al.* 2009). The southernmost segment, the Borazjan Fault, seems to have a dominant dip-slip motion (e.g. Oveisi *et al.* 2009). East of the Kazerun Fault, the Kareh-Bas Fault is very active and accommodates *c*. 5.5 mm a^{-1} of right-lateral strike slip; the Sabz-Pushan Fault in contrast looks inactive, and the Sarvestan Fault accommodates only little motion.

The onset of strike-slip motion on the Main Recent Fault is probably of Late Miocene age and therefore synchronous with the increase in shortening rate within the Zagros and the general tectonic readjustment observed throughout Iran (Allen *et al.* 2004). The onset of motion on both the Dena and Kazerun segments is more recent, probably *c*. 3 Ma, and it is much younger (*c*. 0.8–2.8 Ma) for the Kareh-Bas Fault (Authemayou 2006; Authemayou *et al.* 2009).

GPS measurements of 11 benchmarks across the Kazerun Fault System (Fig. 10) allow us to infer slip rates on the various faults with uncertainties of *c*. 2 mm a^{-1} (Tavakoli *et al.* 2008). The Dena and Kazerun faults accommodate *c*. 3.5 mm a^{-1} of right-lateral strike-slip motion. The Borazjan Fault is almost inactive, but the Kareh-bas Fault also accommodates *c*. 3.5 mm a^{-1} of right-lateral strike-slip motion. A cumulative motion of *c*. 1.5 mm a^{-1} (within the uncertainties) affects the High Zagros Fault and the Sabz-Pushan Fault. It seems, therefore, that the motion distributes from the Main Recent Fault to the Dena and Kazerun faults, jumps to the Kareh–Bas Fault and distributes slightly on the High Zagros and Sabz–Pushan faults.

The Kazerun Fault System is seismically active (Berberian 1995; Baker *et al.* 1993; Talebian & Jackson 2004). Clearly, most of the seismicity and especially the largest magnitude earthquakes are located on the central segment of the Kazerun Fault (Fig. 8). The three largest ($M_s > 6$) instrumental earthquakes were located on the Kazerun segment and the Kareh-Bas and Sabz-Pushan faults. Very little activity is observed on both the Dena and Borazjan faults, and no activity is associated with either the High Zagros Fault or the Sarvestan Fault. The depth of the reliably located earthquakes associated with the KFS is 9 ± 4 km, which probably associates them with the basement. Most mechanisms are strike-slip on the Kazerun, Kareh-Bas and Sabz-Pushan faults. Reverse mechanisms are associated with the Mountain Front Fault, on both sides of the Kazerun Fault System. A few reverse mechanisms are also associated with the Borazjan segment, which suggests that it is not an active strike-slip fault but more probably a transpressive lateral ramp (e.g. Oveisi *et al.* 2009).

Discussion

The separation of the Zagros mountain belt into three longitudinal structural domains (sedimentary, ophiolitic and metamorphic; Ricou *et al.* 1977) is valid only as a first-order approximation. In a second approximation the Zagros can be divided into two main units along strike, the North Zagros and the Central Zagros (the Fars), separated by the Kazerun Fault System (Berberian 1995; Talebian & Jackson 2004). These two domains show differences in width, in the activity of bounding faults, and in the direction of folding. To further investigate the present-day kinematics of the Zagros, we need to know the relative roles of the basement (and ultimately of the lithosphere) and the surface cover. The present-day kinematics is certainly influenced by both the structure and the tectonic evolution of the fold belt, and therefore should be studied in this perspective. We thus concentrate in this discussion on the comparison of shallow and crustal deformation patterns, both spatially and in time.

Surface deformation

The coupling between surface and basement varies across the Kazerun Fault System. This variation in coupling may induce variations in the response of the surface layer to the deformation. To estimate the shortening of the North Zagros, we use the balanced cross-sections of Blanc *et al.* (2003) and McQuarrie (2004), because those of Sherkati &

Fig. 7. (*Continued*) BF, Borazjan Fault; HZF, High Zagros Fault; KF, Kazerun Fault; MFF, Main Frontal Fault; SF, Surmeh Fault. Light and dark grey dashed lines indicate locations of transects shown in (**b**). (b) Synthetic profiles of convergence rates (relative to stable Arabia) across the Central Zagros according to GPS and geomorphological data, compared with topographic profiles along a northwestern (light shading) and southeastern (dark shading) transect. Modified from Oveisi *et al.* (2009). KB, Karesh Bas; SP, Sabz Pushan; HZ, High Zagros Fault; DS, . . . Q22

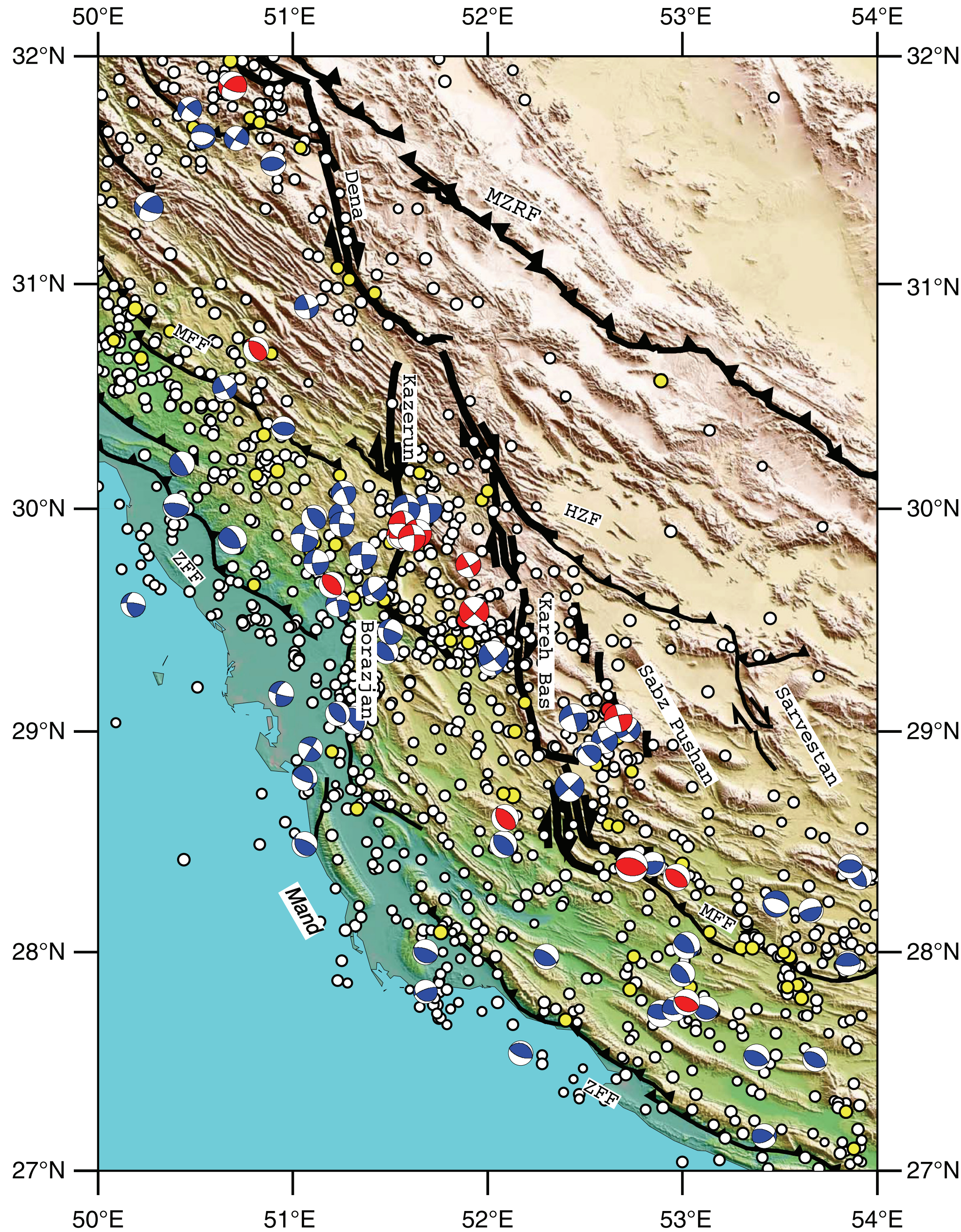

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Fig. 8. Detailed seismotectonic map of the Kazerun Fault System. Bold lines indicate the active faults (Authemayou *et al.* 2006) with significant present-day motion (Tavakoli *et al.* 2007). Symbols for seismicity and focal mechanisms are as in Figures 2 and 3. The MZRF appears to be totally inactive. Most seismicity is restricted to the SW of the MFF. Seismicity is associated with the Dena, Kazerun, Kareh-Bas and Sabz-Pushan strike-slip faults.

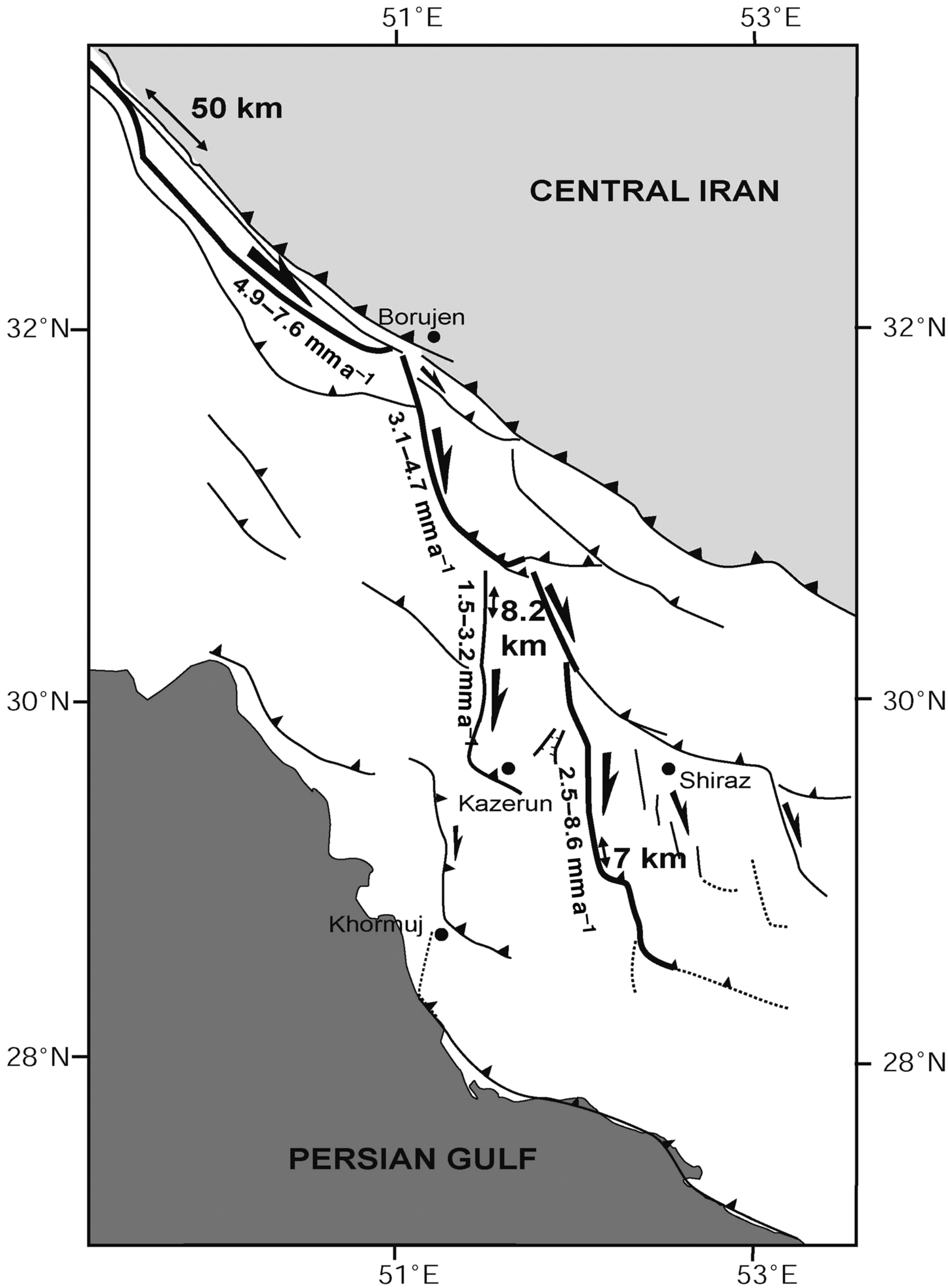

Fig. 9. Quaternary slip rate and finite horizontal displacement, showing the motion distribution from the Main Recent Fault to the Kazerun Fault System (after Authemayou *et al.* 2006).

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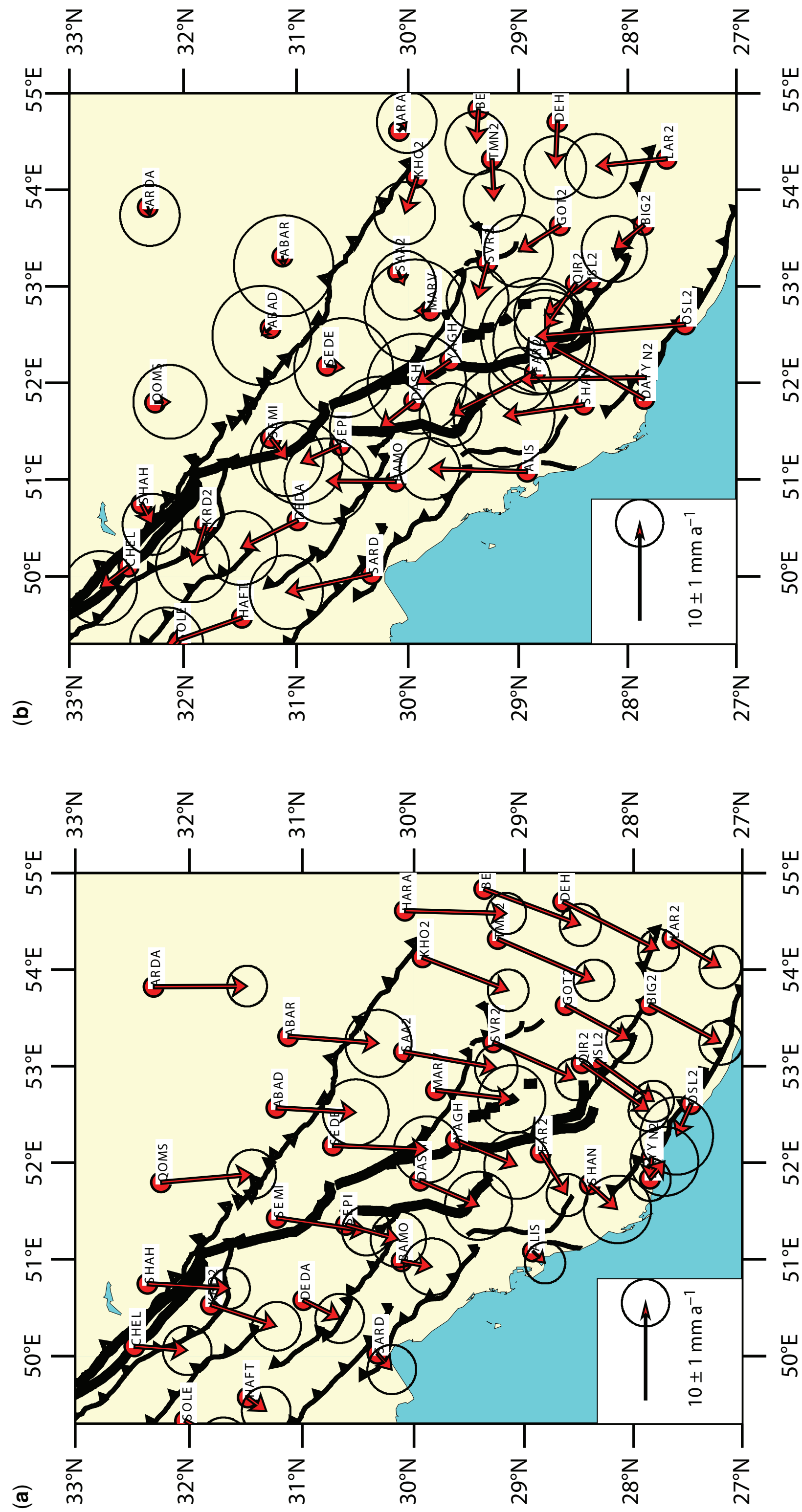

Fig. 10. GPS velocity for benchmarks located near the Kazerun Fault System (after Tavakoli *et al.* 2007). (**a**) Motion relative to Arabia; (**b**) motion relative to Central Iran.

Letouzey (2004) cross the Kazerun Fault and may not be representative of the shortening of the whole Zagros. For the Fars region, we use the cross-section of McQuarrie (2004), which is the only section that really crosses Fars, the section of Molinaro *et al.* (2004) being located at the Zagros–Makran transition. Paradoxically, the total amount of shortening is larger in the North Zagros than in Fars, both for the whole Zagros (from 57 to 85 km) and for the Zagros Fold Belt (from 35 to 50 km), even though the Fars is located further from the long-term Arabia–Central Iran pole of rotation located at 29.8°N, 35.1°E. This variation in finite shortening could be explained by an underestimate of the displacement along the suture zone in the Central Zagros by McQuarrie (2004), or by an earlier onset of deformation in the North Zagros compared with the Central Zagros as a result of the progressive southeastward closure of the Neotethys associated with the anti-clockwise rotation of the Arabian plate.

The GPS measurements also show a difference in present-day deformation across the Kazerun Fault System (Walpersdorf *et al.* 2006). In contrast to the total shortening, the present-day shortening rates increase slightly from the North Zagros (4–6 mm a^{-1}) to the Fars (8 mm a^{-1}), consistent with the increasing distance to the pole of rotation. The strike-slip component is mostly localized on the Main Recent Fault in the North Zagros but seems to be smaller and distributed in Fars. Both in the North Zagros and in the Fars, shortening seems to be concentrated between the 1000 m elevation topography and sea level.

Geomorphological observations suggest that the folds located at the shore of the Persian Gulf are the most active structures of the Zagros. This is consistent with the GPS measurements showing that most of the present-day shortening in Fars is also accommodated at the shore. This present-day activity located at the edge of the Zagros fold belt, along the Persian Gulf shore, is consistent with the southwestward propagation of the front of the Simply Folded Belt from the Eocene (and therefore earlier than the onset of collision) to the present time (Shearman 1977; Hessami *et al.* 2001).

Basement deformation

The debate concerning thick-skinned and thin-skinned models for Zagros fold belt deformation may never find a satisfactory answer because of the lack of seismic profiles reaching the basement. The only reliably (on the base of balanced cross-sections) inferred basement reverse faults are the HZF and the MFF (Blanc *et al.* 2003; Sherkati & Letouzey 2004; Bosold *et al.* 2005) because they clearly offset the sedimentary sequence and are controlled by seismic reflection profiles. The Zagros Frontal Fault itself generally does not propagate to the surface through the sedimentary cover, although a few surface breaks have been described (Bachmanov *et al.* 2004; Oveisi *et al.* 2009).

The seismicity associated with shortening and reverse mechanisms is mostly located in the Zagros Fold Belt (Fig. 11). Therefore neither the MZT nor the HZF is active or both are lubricated and slip aseismically. This seems true both for the North Zagros, where the only large earthquakes located north of the HZF belong to the strike-slip MRF, and for the Fars, where the seismic inactivity of these two faults is consistent with the absence of surface motion from GPS measurements across them. More precisely, the seismicity associated with reverse mechanisms is restricted to topography less than 1000 m, as pointed out by Talebian & Jackson (2004). This could be due to the gradient in topography (Talebian & Jackson 2004) but we suspect it is related to the propagation of the deformation front to the SW, as evidenced from structural studies (Sherkati & Letouzey 2004), geomorphology and GPS. The two could be linked, however, if we consider a critical-wedge model for the evolution of the Zagros Fold Belt (e.g. Mouthereau *et al.* 2006). This propagation of deformation, and therefore of the construction of topography, explains why seismicity is bounded by the Persian Gulf shore (Fig. 12), even though this shoreline has no tectonic significance and the water depth in the Persian Gulf is less than 70 m.

The relation between seismicity and surface faults differs between the North Zagros and the Fars arc (Fig. 11). In the North Zagros, seismicity is restricted to a narrow band limited by the 1000 m elevation contour, which is also the trace of the MFF. Because the topography is relatively steep, the relation between the 1000 m contour and the MFF is clear. The seismicity does not fit totally with the distribution of GPS shortening, which also affects the low topography north of the Persian Gulf. However, because GPS deformation there is controlled only by the station KHOS (Fig. 5a) and no folding or topography generation is observed in the lowland, this frontal shortening remains to be confirmed.

In Fars, seismicity is spread throughout the area between 1000 m elevation and the shore (which might be related to the MFF and the ZFF, respectively); the zone of seismicity is wider than in the North Zagros but does not encompass the entire width of the fold belt. The gradient in topography is also smoother in Fars than in the North Zagros. GPS shortening is restricted to the shore and unrelated to the high elevation.

Thus, both the seismicity and the gradient in topography (which record basement deformation)

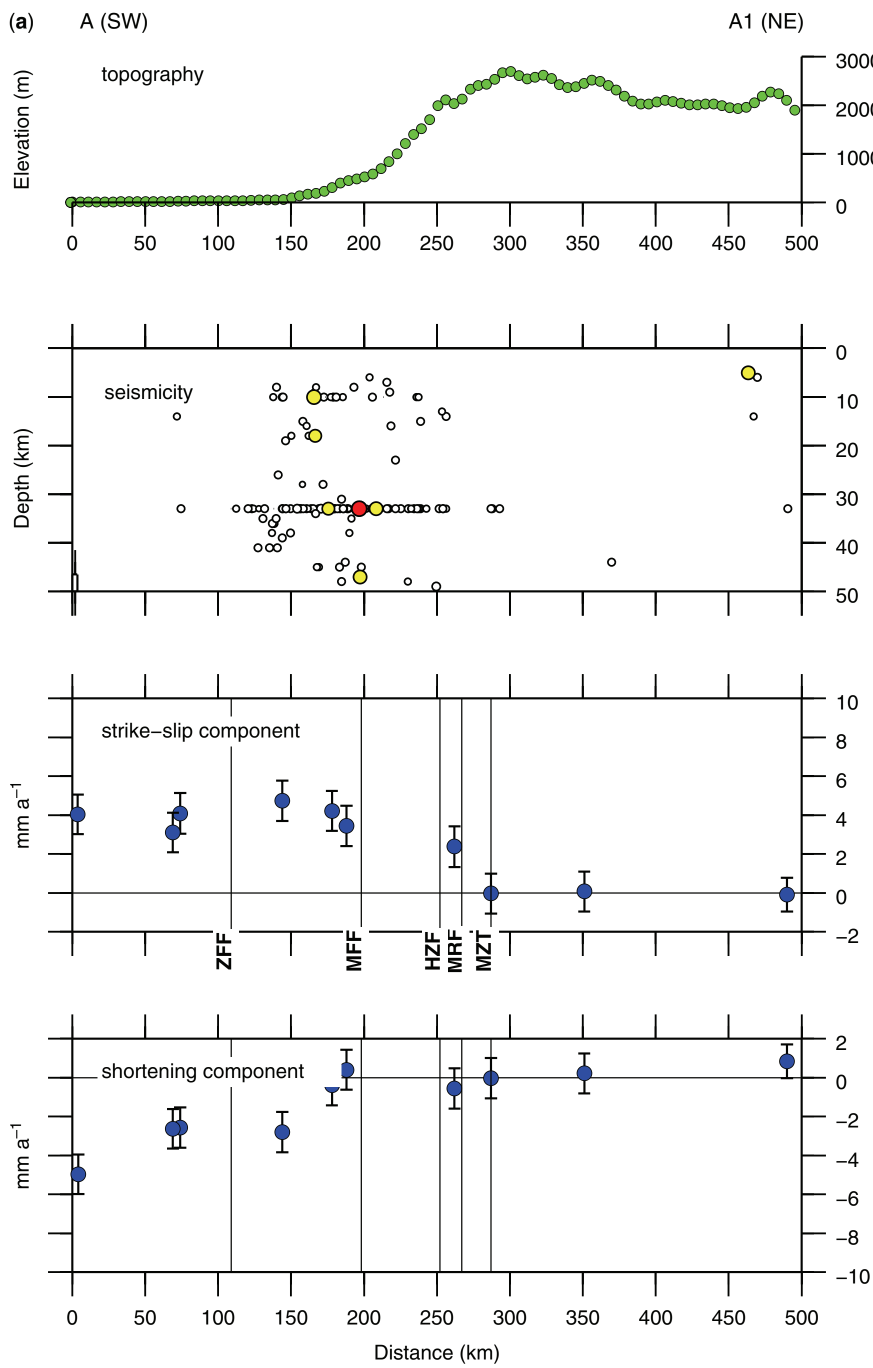

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Fig. 11. (**a**, **b**) Cross-sections through the North and Central Zagros (see location in Fig. 2) displaying for each the topography, seismicity, present-day GPS-detected motion parallel to the mountain belt, and present-day shortening perpendicular to the mountain belt. Symbols for seismicity are as in Figure 2. The present-day motion is from GPS-determined velocities relative to Central Iran. We plot the location of the main faults (Berberian 1995). There is a strong correlation between the gradient in topography, the seismicity (relative to the basement deformation) and the shallow deformation. In the North Zagros, the strike-slip motion is concentrated near the MRF, whereas it is more distributed in the Central Zagros.

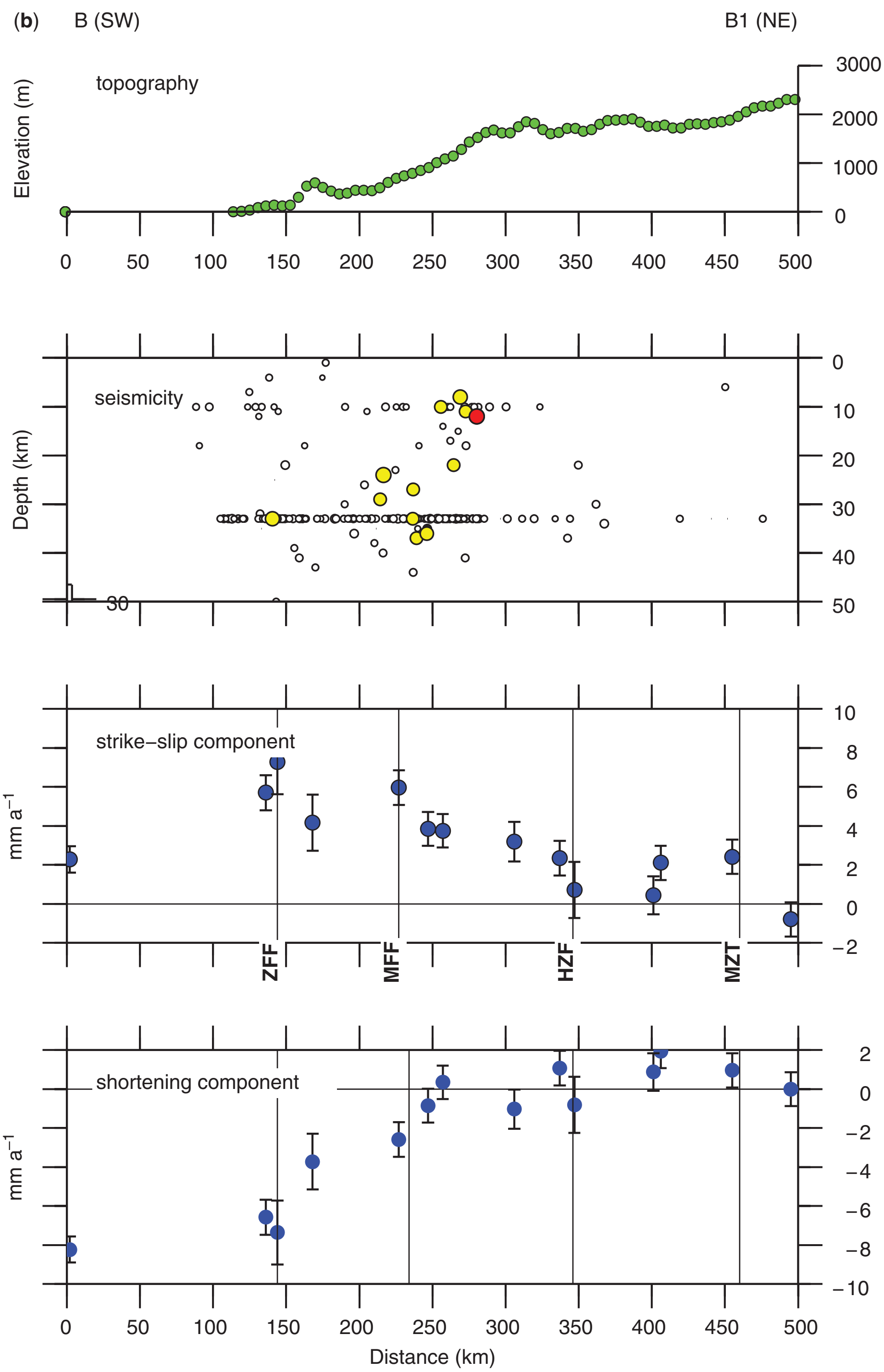

Fig. 11. *Continued.*

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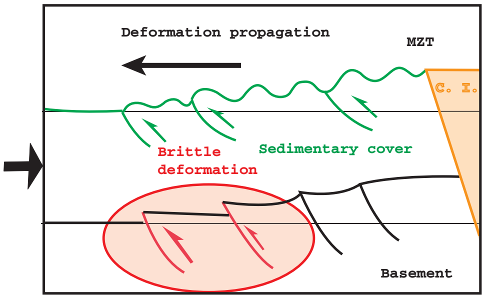

Fig. 12. Sketch summarizing our results and interpretation. C.I., Central Iran; MZT, Main Zagros Thrust. Both the shallow deformation of the sedimentary cover and the brittle deformation of the basement are associated with the gradient in topography, suggesting that they are related. Faulting in the basement is unrelated to faulting and folding in the sedimentary cover. Because we know the shallow deformation propagated southwestward with time, we suspect the basement deformation to do the same.

are correlated with the pattern of cumulative (on a million years scale) deformation. On the other hand, GPS shortening and geomorphology (which record shallow deformation) are concentrated at the front of the deformation.

Less than 10% of the total deformation is released by earthquakes. However, there is a remarkable good fit in the directions of the tensor of deformation computed from both the GPS measurements and the seismological catalogues (Masson *et al.* 2005). This deficit could mean that some faults slip aseismically. An alternative and complementary explanation is that seismicity is restricted between 10 and 15 km depth because of the thick sedimentary cover, which limits the thickness of the brittle part of the crust to 5 km only (rather than 15–18 km as usual). The stress accumulated from boundary conditions is released by seismic energy for the brittle part but also by ductile deformation both for the sedimentary cover (by folding) and by lower crustal flow. If the brittle part of the crust is 30% of the usual thickness, we expect only 30% of seismic energy release.

Significance of the Kazerun Fault System

The tectonics of the Kazerun Fault System is more complex than it looks first. The KFS is generally interpreted as an inherited fracture of an old tectonic event affecting the Arabian platform. Such inherited fractures are observed in several places in both the Zagros and the Arabian platform across the Persian Gulf, whereas we observe motion and seismicity only on part of the fractures located within the Zagros and only around the Kazerun zone. This focusing of seismicity could be due either to a non-homogeneous state of stress within the Zagros or to the Zagros part of the Arabian platform being more brittle (it is thinner) than the remaining part.

These inherited fractures were activated during Permian and Mesozoic sedimentation, resulting in a change of the mechanical behaviour of the lithostratigraphic horizons. During collision, because the Kazerun Fault System marks the boundary of the Hormuz Salt layer in the Central Zagros, the fault plays the role of a lateral ramp for the Fars arc. A lateral ramp generally implies transpressional motion as observed along the Borazjan segment, which can be interpreted as the active part of the Kazerun Fault lateral ramp. The southward propagation of this segment can be detected by a structural study of the Mand anticline. The bending of this large coastal anticline suggests the presence of a hidden segment of the Kazerun Fault System bounding the Mand fold to the west. As the Mand anticline is a Plio-Quaternary fold, the propagation of the Kazerun Fault lateral ramp must be very recent.

If the Kazerun Fault is a lateral ramp of the Fars arc, the fault motion must be restricted to the cover. However, the seismic activity localized along the Kazerun segment implies basement faulting because earthquakes are probably located in the basement, and thus an important role for the Kazerun Fault System in the Zagros deformation.

We observe an important contrast in the style of deformation west and east of the KFS. To the west, the belt is narrow and the deformation is partitioned between the strike-slip MRF and the shortening. To the east, the belt is wider, the deformation is more localized than in the west, and the MRF spreads into several strike-slip faults that look like a large distributed en echelon system (Dena, Kazerun–HZF, HZF–Kareh-Bas–Sabz-Pushan). In fact, the Kazerun Fault System is connected to the MRF (Authemayou *et al.* 2005). Consequently, since the Pliocene, the right-lateral strike-slip motion from the MRF has been distributed onto several north–south- to NNE–SSW-trending strike-slip faults that are part of the Kazerun Fault System. The Dena Fault connects to both the Kazerun and the High Zagros faults, the High Zagros Fault connects to both the Sabz-Pushan and the Sarvestan faults, and the Kazerun Fault connects to both the Kareh-Bas and Borazjan faults. The connection between the MRF and the KFS has been attributed to the existence of inherited fractures (which were ultimately reactivated as the KFS) disturbing and stopping eastward propagation of slip on the MRF. The presence of Hormuz Salt limited to the east of the Kazerun Fault may facilitate the diffusion of deformation above a ductile layer and thus the slip motion. However, the existence of the Hormuz Salt cannot explain on its own the distribution of motion, because some of these faults (Kareh-Bas, Sabz-Pushan) are also seismically very active. Furthermore, our GPS results do not support a 'spreading' pattern of deformation for the Kazerun Fault System similar to gravity spreading as claimed by Nilforoushan & Koyi (2007) on the basis of analogue experiments. They predicted a divergent motion of the GPS vectors relative to Arabia, as reported by Hessami *et al.* (2006), but that does not correspond to our observations. We think that the distribution of deformation from the MRF to the Kazerun Fault System affects both the shallow sediments and the basement beneath the ductile layer.

Partitioning

Partitioning is one of the mechanisms that accommodate oblique motion (e.g. Fitch 1972). Usually, strike-slip and reverse motion occur on two parallel faults that are a few tens of kilometres apart. In continental areas, it is likely that pre-existing faults localize the deformation because they are weak (e.g. Zoback *et al.* 1987). It has also been proposed that a ductile layer decouples the oblique motion (Richard & Cobbold 1989) and helps partitioning. However, we observe partitioning of oblique convergence between shortening perpendicular to the belt and strike-slip motion on the MRF to the west of the Kazerun Fault System only, where the coupling between sediments and basement is strongest. Therefore, a ductile layer is probably not responsible for deformation partitioning in the North Zagros. We suspect instead that the MRF introduces a weak discontinuity that localizes strike-slip motion and, as a consequence, favours partitioning.

Vernant & Chéry (2006) designed a numerical mechanical model to explain the oblique convergence in the Zagros. They suggested low partitioning along the MRF (1–2 mm a^{-1}) associated with transpressionnal deformation throughout the belt. In contrast to their model predictions, GPS strike-slip motion is slightly higher (2–4 mm a^{-1}) and geomorphological slip rate estimates on the MRF appear to match nearly completely the strike-slip component of convergence between Arabia and Central Iran. Fault kinematic measurements along the HZF, south of the MRF, indicate a transpressional regime on this fault (Malekzadeh 2007). If partitioning exists, the shortening that complements the minimum Quaternary slip rate on the MRF of 4.9–7.6 mm a^{-1} (Authemayou *et al.* 2009) must be accommodated somewhere else. However, the fast slip rate along the MRF probably suggests a very weak MRF with a lower friction coefficient than adopted by Vernant & Chéry (2006), or possibly strong decoupling of the surface from the basement, rendering a model without mechanical layering somewhat irrelevant.

Conclusion

Our first conclusion is that we find, on both sides of the KFS, a good correlation between present-day surface deformation, as measured by GPS and geomorphology on one hand, and seismicity (affecting only the upper basement) and topography on the other hand (Fig. 11), suggesting that both the sedimentary cover and the basement deform together (i.e. a thick-skinned system). Because we know that deformation of the sedimentary cover propagates southwestward, we suspect basement deformation, which is required to explain the average topography, to do the same (Fig. 12). In contrast to Hessami *et al.* (2006), we do not observe any active shortening across the southern segment of the MZT. Thus, the reason for such propagation is probably the recent locking of the continental collision, propagating the stress away from the MZT onto inherited normal faults of the Arabian platform (Jackson 1980). Because the strike of the belt is perpendicular to the motion of Arabia relative to Central Iran, no partitioning is required in the Central Zagros (Talebian & Jackson 2004).

The second conclusion is that the Kazerun Fault System separates the North Zagros (experiencing slip partitioning), from the Central Zagros (experiencing distributed deformation), as proposed previously. There is a good agreement between present-day deformation observed by GPS and tectonic observations, suggesting that this deformation has been stable for some time. The Kazerun Fault System distributes the strike-slip motion from the MRF onto different branches in an en echelon arrangement, from the Dena segment to the Sabz-Pushan and High Zagros faults. The presence of the decoupling Hormuz Salt layer cannot be the only reason for such distribution, because seismicity is associated with the active faults, indicating that the basement deforms in the same way. Consequently, the Kazerun Fault System affects both the sedimentary cover and the basement, playing the role of a lateral ramp of the deformation front for its southern Borazjan segment and of a 'horse-tail' termination of the MRF for its northern and central segments.

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