The Transfer of Strike-Slip Partitioned Motion of Oblique Convergence Across the Zagros Fold-and-Thrust Belt

C. Authemayou¹, O. Bellier¹, D. Chardon¹, Z. Malekzade², M. Abassi², and E. Shabanian²

1. Centre Européen de Recherche et d’Enseignement de Géosciences de l’Environnement (UMR CNRS 6635), Université Aix-Marseille 3, BP 80, 13545 Aix-en-Provence Cedex 4, France  
email: authemayou@cerege.fr  
2. International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, I.R. Iran

ABSTRACT: Oblique plate convergence in collision zones may lead to complex regional strain partitioning because inherited crustal faults have various orientations with respect to the orogenic belt and the convergence vector. Combined field structural and geomorphic investigations and SPOT image analysis document the kinematic framework enhancing transfer of strike-slip partitioned right-lateral motion from along the backstop to the interior of the Zagros fold-and-thrust belt in a context of active, high-angle right-oblique plate convergence. Transfer occurs by slip on the N-trending right-lateral Kazerun fault system that connects to the termination of the Main Recent Fault, a major NW-trending dextral fault partitioning oblique convergence at the rear of the belt. The Kazerun Fault system consists in three N-trending fault zones ended by bent, orogen-parallel splay thrust faults allowing slip from along the Main Recent Fault to become distributed by transfer to longitudinal thrust faults and folds.

Keywords: Zagros; Strike-slip fault; Kazerun fault system; Segmentation; Fault kinematics

1. Introduction

In oblique plate convergence, deformation may be partitioned between orogen-parallel strike-slip faults and thrusts [1]. This mechanism has been mainly documented along subduction zones e.g., [2, 3], and more rarely in collisional settings e.g., [4] although oblique convergence must be common in active and fossil collision zones. The Zagros fold-and-thrust belt of Southern Iran is a young active collisional orogen that provides a particularly relevant case-study for examining the relations between far-field boundary conditions and internal strain partitioning within a mountain belt. In this paper, we present an integrated study of part of the Zagros fold-and-thrust belt combining field structural and geomorphic investigation and SPOT satellite image analysis. The aim of this work is to assess the recent active geometry and kinematics of the Kazerun Fault System (KFS), one of the longest NNE-trending active strike-slip faults in the Zagros that crosscuts the entire belt at a high angle [5-7]. This allows addressing its relations to active thrusting and orogen-parallel strike-slip partitioned motion at the backstop of the fold-and-thrust belt in the frame of high-angle right-oblique convergence.

2. Geodynamic Setting

The NW-trending Zagros fold-and-thrust belt results from the Neogene collision between the Arabian and Eurasian plates e.g. [8-9]. The belt stretches from eastern Turkey to the Oman Gulf, see Figure (1). The northeastern boundary of the belt coincides with the Main Zagros Reverse Fault (MZRF) that
represents the backstop of the fold-and-thrust belt [8, 10], see Figure (1).

According to GPS measurements, the Arabian and Eurasian plates converge at 21 mm/yr c.a. 50°E [11-13], see Figure (1). At this longitude, the Zagros records a NNE-trending shortening rate of about 10 mm/yr that is oblique with respect to the main fold-and-thrust belt strike [14], see Figure (1). Earthquake focal mechanisms [5, 15, 16] indicate that a significant part of the convergence obliquity is turned into slip on the NW-trending Main Recent Fault (MRF), that runs south of, and parallel to the MZRF at least as far as 51°E to the east [17]. This fault accommodates the orogen-parallel, dextral strike-slip component of the oblique plate convergence at the rear of the Zagros fold-and-thrust belt at a rate of 10-17 mm/yr (estimate by Talebian and Jackson, [18]).

A set of N-trending faults recognized as inherited basement structures, disrupts the NW-trending longitudinal Zagros folds [19-22]. Geomorphic evidence and focal mechanisms indicate that these right-lateral strike-slip faults are active and affect both the cover and basement of the belt [6, 7, 23], see Figure (2a). The most prominent of these faults is the KFS that stretches from the eastern termination of the MRF, in the north, to the Persian Gulf, in the south. The fault marks the boundary between two drastically different structural domains. The width of the belt west of the KFS is narrow (200 km), salt extrusions are lacking suggesting the absence of the Hormuz Salt at depth [21] and earthquakes are localised on major thrust faults e.g., [5]. By contrast, to the east of the fault, earthquakes are distributed throughout the 300 km-width of the Zagros fold-and-thrust belt [5, 16, 24]. According to seismicity data, the KFS is active with a high level of seismicity along its central part, where historical earthquakes of intensity reaching VIII have been reported [6, 25, 26], see Figure (2a).

3. Kazerun Fault Segmentation

Our work, combining SPOT images analysis, compilation of existing geological maps and new field observations and data, allows a reassessment of the fault trace proposed by previous workers [5, 7, 21, 28, 27] by producing the first detailed map of its active segmentation.

The KFS is made of three north-trending fault zones of equivalent length (~100 km-long). They have similar trace shapes with a general N170-180°E-trend and a southern termination bent towards SE strikes, see Figure (2b). Their terminations split as bend splays and are generally connected eastward to the NW-trending thrust and ramp anticlines whose forelimbs are systematically overturned close to the KFS, implying an increase in south verging reverse-slip along the ramps towards the KFS.

The northern fault zone comprises five ~40 km-long segments. The northernmost one reaches the eastern tip of the MRF through a narrow discontinuity arranged in a relay fault bend, see Figure (2b). 30 km further south, the High Zagros Fault (HZF) [25] merges with the northern segment close to the only releasing stepover of the fault zone, see Figure (2b). The central fault zone comprises seven segments with an average trend of N02°E, a majority of discontinuities between the segments being restraining stepovers, see Figure (2b). Contrary to the northern fault zones, several segments of the southern fault zone are arranged in an en echelon pattern and the northernmost one is bent towards NW strikes into a thrust, see Figure (2b). This thrust fault makes up the Zagros front west of the KFS [5] that is shifted 100 km southward, east of the KFS.

Bending of a large coastal anticline seen SW of Khormuj suggests the presence of a hidden, N-trending prolongation of the southern segment of the KFS at least up to the coast, see Figure (2b). It is interesting to note that, although fault zone lengths are comparable, large-scale segmentation displays a
northward increase in the segment length implying an increasing segmentation complexity southward.

4. Southeastern Main Recent Fault Segmentation

In order to evaluate the respective role between the NW-trending MRF and the N-trending KFS, a detailed mapping of the surface fault trace on the southeastern MRF region was conducted. The southeastern MRF is characterized by a single segment in the Dorud region cutting across thrust sheets shown in Figure (3a). These thrust sheets consist on metamorphic rocks coming from Central Iran. They ceased to be active during the early Pliocene [48]. These relationships indicate that MRF strike-slip movement has been initiated during early Pliocene. Southeastward, the MRF splits into two 180km-long major fault zones 15km apart, as shown in Figure (3a). Near the KFS, the southern MRF fault zone is bent northeastward, joining the northern MRF zones that connect with the KFS northern tip, as shown in Figure (3b). The longest segment is located on the southern fault zone measuring 130km-long. Preliminary analysis of Quaternary geomorphic feature offsets (streams and associated alluvial fans) along the two MRF fault zones suggest a significant horizontal slip along the southern MRF fault zone. In Figure (3) two sites located on each fault zone, where stream offsets are clearly representative of the geomorphic feature offset all along the fault zone, are illustrated. On the site of the northern fault zone, as shown in Figure (3b), stream offsets affecting alluvial fans are of the order of 75m, see Figure (4a). On the site of the southern
Table 1. Location of fault measurement sites, results of stress-tensor inversions from slip-data, and age of the faulted formations at each site. Inversion results include the orientation (azimuth and plunge) of the principal stress axes and R, a stress ellipsoid shape parameter. Principal stress axes, $\sigma_1$, $\sigma_2$ and $\sigma_3$, correspond to the compressional, intermediate and extensional deviatoric stress axes, respectively, and $R$ is defined as $R = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$. 

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>N</th>
<th>$\sigma_1$ Az-Pl</th>
<th>$\sigma_2$ Az-Pl</th>
<th>$\sigma_3$ Az-Pl</th>
<th>R</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32°01'871</td>
<td>50°37'819</td>
<td>22</td>
<td>182-7</td>
<td>356-83</td>
<td>92-1</td>
<td>0,4</td>
<td>Quaternary Conglomerate</td>
</tr>
<tr>
<td>2</td>
<td>32°11'223</td>
<td>50°43'308</td>
<td>11</td>
<td>359-17</td>
<td>266-10</td>
<td>146-70</td>
<td>0,921</td>
<td>Cretaceous Marl-Limestone</td>
</tr>
<tr>
<td>3</td>
<td>31°54'941</td>
<td>51°00'007</td>
<td>15</td>
<td>198-5</td>
<td>288-1</td>
<td>24-85</td>
<td>0,229</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>4</td>
<td>31°51'648</td>
<td>51°09'873</td>
<td>6</td>
<td>209-0</td>
<td>119-0</td>
<td>311-90</td>
<td>0,276</td>
<td>Cretaceous Marl-Limestone + Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>5</td>
<td>31°41'996</td>
<td>51°23'443</td>
<td>5</td>
<td>179-0</td>
<td>81-90</td>
<td>269-0</td>
<td>0,871</td>
<td>Cretaceous Marl-Limestone</td>
</tr>
<tr>
<td>6</td>
<td>31°45'523</td>
<td>51°05'747</td>
<td>12</td>
<td>193-0</td>
<td>51-90</td>
<td>283-0</td>
<td>0,323</td>
<td>Cretaceous Marl-Limestone</td>
</tr>
<tr>
<td>7</td>
<td>31°31'746</td>
<td>51°21'913</td>
<td>24</td>
<td>148-9</td>
<td>49-45</td>
<td>247-43</td>
<td>0,991</td>
<td>Miocene Conglomerate Sandstone, Marl</td>
</tr>
<tr>
<td>8</td>
<td>31°24'108</td>
<td>51°39'320</td>
<td>21</td>
<td>148-0</td>
<td>58-57</td>
<td>239-33</td>
<td>0,625</td>
<td>Miocene Conglomerate Sandstone, Marl</td>
</tr>
<tr>
<td>9</td>
<td>31°07'457</td>
<td>51°00'007</td>
<td>22</td>
<td>216-11</td>
<td>100-66</td>
<td>311-21</td>
<td>0,48</td>
<td>Jurassic Dolomite</td>
</tr>
<tr>
<td>10</td>
<td>31°06'913</td>
<td>51°12'137</td>
<td>11</td>
<td>215-18</td>
<td>118-23</td>
<td>339-60</td>
<td>0,782</td>
<td>Miocene Red Marl</td>
</tr>
<tr>
<td>11</td>
<td>30°53'676</td>
<td>51°23'014</td>
<td>17</td>
<td>210-8</td>
<td>83-76</td>
<td>302-11</td>
<td>0,365</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>12</td>
<td>30°42'571</td>
<td>51°36'119</td>
<td>16</td>
<td>201-11</td>
<td>292-7</td>
<td>52-77</td>
<td>0,941</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>13</td>
<td>30°42'082</td>
<td>51°33'123</td>
<td>6</td>
<td>74-0</td>
<td>164-0</td>
<td>343-90</td>
<td>0,943</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>14</td>
<td>30°40'621</td>
<td>51°31'594</td>
<td>6</td>
<td>46-0</td>
<td>136-89</td>
<td>316-1</td>
<td>0,956</td>
<td>Oligo-Miocene Dolomite + Quaternary Conglomerate</td>
</tr>
<tr>
<td>15, 16</td>
<td>30°27'425</td>
<td>51°30'931</td>
<td>20</td>
<td>227-12</td>
<td>330-47</td>
<td>126-41</td>
<td>0,148</td>
<td>Oligo-Miocene Dolomite</td>
</tr>
<tr>
<td>17</td>
<td>30°30'103</td>
<td>51°52'236</td>
<td>18</td>
<td>17-39</td>
<td>220-49</td>
<td>116-12</td>
<td>0,192</td>
<td>Upper Cretaceous Dolomite</td>
</tr>
<tr>
<td>18</td>
<td>30°22'818</td>
<td>51°28'998</td>
<td>11</td>
<td>31-10</td>
<td>300-4</td>
<td>189-80</td>
<td>0,959</td>
<td>Upper Cretaceous Limestone</td>
</tr>
<tr>
<td>19</td>
<td>30°18'719</td>
<td>51°30'147</td>
<td>13</td>
<td>27-10</td>
<td>290-36</td>
<td>130-53</td>
<td>0,741</td>
<td>Upper Cretaceous Limestone</td>
</tr>
<tr>
<td>20</td>
<td>30°07'622</td>
<td>51°29'576</td>
<td>4</td>
<td>219-0</td>
<td>129-0</td>
<td>311-90</td>
<td>0,705</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>21</td>
<td>30°02'378</td>
<td>51°32'879</td>
<td>12</td>
<td>242-3</td>
<td>332-2</td>
<td>97-87</td>
<td>0,972</td>
<td>Upper Cretaceous Limestone</td>
</tr>
<tr>
<td>22</td>
<td>29°55'927</td>
<td>51°35'440</td>
<td>6</td>
<td>40-18</td>
<td>250-70</td>
<td>133-10</td>
<td>0,466</td>
<td>Upper Cretaceous Limestone</td>
</tr>
<tr>
<td>23</td>
<td>29°49'261</td>
<td>51°32'738</td>
<td>14</td>
<td>221-0</td>
<td>131-89</td>
<td>311-1</td>
<td>0,98</td>
<td>Oligo-Miocene Dolomite + Quaternary Conglomerate</td>
</tr>
<tr>
<td>24</td>
<td>29°46'882</td>
<td>51°31'551</td>
<td>12</td>
<td>224-6</td>
<td>105-78</td>
<td>315-10</td>
<td>0,107</td>
<td>Oligo-Miocene Dolomite</td>
</tr>
<tr>
<td>25</td>
<td>29°45'862</td>
<td>51°31'477</td>
<td>16</td>
<td>224-18</td>
<td>98-61</td>
<td>321-22</td>
<td>0,801</td>
<td>Oligo-Miocene Dolomite</td>
</tr>
<tr>
<td>26</td>
<td>29°41'007</td>
<td>51°38'723</td>
<td>10</td>
<td>30-10</td>
<td>246-78</td>
<td>121-7</td>
<td>0,833</td>
<td>Quaternary Conglomerate</td>
</tr>
<tr>
<td>27</td>
<td>29°28'227</td>
<td>51°16'587</td>
<td>6</td>
<td>28-7</td>
<td>119-8</td>
<td>255-79</td>
<td>0,253</td>
<td>Plio-Quaternary Conglomerate</td>
</tr>
<tr>
<td>28</td>
<td>29°16'403</td>
<td>51°16'747</td>
<td>8</td>
<td>205-7</td>
<td>53-82</td>
<td>295-4</td>
<td>0,513</td>
<td>Oligo-Miocene Dolomite + Quaternary Conglomerate</td>
</tr>
</tbody>
</table>

Figure 3. (a) Active segmentation of the western part of southeastern termination of the MRF. (b) Active segmentation of the eastern part of southeastern termination of the MRF. Frame of Figures (3a) and (3b) are located on Figure (1).
The Transfer of Strike-Slip Partitioned Motion of Oblique Convergence Across the Zagros Fold-and-Thrust Belt

fault zone, two orders of right-lateral stream offsets were identified: 650\textit{m} and 1300\textit{m}, as shown in Figure (4b). The longer stream offset (1300\textit{m}-long) is associated with the largest drainage basin surface suggesting an onset of this offset older than the one of the stream offset of 650\textit{m}.

5. Fault Kinematics and Stress Regime

The \textit{N}-trending northern and central fault zones of the \textit{KFS} exhibit evidence for active right-lateral slip (offset of Quaternary streams and alluvial fans, occurrence of pressure ridges; shown in Figure (5a)) whereas in the \textit{NW}-trending splay fault zone terminations, uplifted and tilted benches or Quaternary alluvial terraces are documented, see Figure (5b). This indicates a dominant active strike-slip component on the \textit{N}-trending segments and a reverse dip- to oblique-slip component on the fault zone terminations.

In order to further constrain the tectonic regime of the fault and the associated stress states, a fault kinematic study at 28 sites distributed along the fault system was performed. An inversion of each fault slip data has been performed using the method originally proposed by Carey [29], see Figure (6a). Fault slip-vector inversions, presented in Figure (2c), indicate a consistent right-lateral strike-slip regime all along the \textit{KFS} with a thrust-faulting regime around the bent splay fault zone terminations. Regionally significant stress states were calculated using two methods. The first one results from a statistical analysis of the stress states previously obtained at each site. The second one was computed by inversion of major fault planes slip measurements. Both methods led to consistent results that are also in agreement with a strike-slip stress regime characterised by a $35-40^\circ\text{E}$-trending $\sigma_1$, see Figure (6b). On the two southern fault zones, the strike-slip striations compatible with this stress regime are observed, see Figure (5b).

Figure 4. (a) SPOT satellite image of the northeastern fault zone of the MRF with the drainage offsets of the order of 75\textit{m} and the alluvial fans. (b) SPOT satellite image of the southeastern fault zone of the MRF with the two orders of stream offsets and the alluvial fans. Frame of Figures (4a) and (4b) are located on Figure (3b).

Figure 5. (a) View of the KFS scarp showing stream offset and dextral pressure ridge on the northern fault zone (located on Figure (2c)). (b) View of the Dinar thrust fault (northern KFS fault zone) showing tilted and folded late Quaternary Terrace (station 11, Figure (2c)).
regime were measured on fault planes affecting Jurassic to Plio-Quaternary formations as well as recent alluvial and colluvial deposits. There appears to be no significant temporal changes in the stress state along the two southern fault zones despite the long and complex history of the fault system [30]. While these inversion results are also consistent with earthquake focal mechanisms, as shown in Figure (2a), they are interpreted to reflect the present-day stress regime.

6. Structural Relations at the Rear of the Fold-and-Thrust Belt

In order to address the relations between the KFS, the MRF, and the MZRF, a detailed structural map covering their interaction zone, see Figure (7), based on SPOT images analysis, field observations and available geological maps was compiled [31-37]. The rectilinear MZRF marks the northern limit of the interference zone. At its southeastern tip, the MRF gives way to the NNW-trending northernmost segment of the KFS and to the dextral, oblique-reverse Semirom fault that trends at a low angle with respect to the eastern termination of the MRF, see Figure (7). The GPS measurements and seismologic data provide evidence for no significant activity along the MZRF [13, 26, 38]. This appears to be confirmed by our own geomorphological observations in the Borujen area. Consequently, this structural arrangement, as shown in Figure (7), implies that the cumulated slip of the two strands of the MRF is transmitted to both the KFS and Semirom faults. These faults, together with the main segment of the northern KFS fault zone, define a wedge-shape domain, see Figure (7). In the inner part of that wedge, the southwestern termination of the northernmost segment of the KFS merges into a SE-verging thrust. Within the wedge, finite
shortening trajectories are perturbed, suggesting an interference pattern around the bounding strike-slip and internal thrust fault. This results from superimposed deformation patterns involving potential anticlockwise rotations, dextral-oblique reverse (i.e., transpressional) slip along the Semirom fault, dextral slip along the KFS, as well as differential displacements between these two faults.

7. Discussion-Conclusion

The finite pattern described above has been produced in two stages, see Figure (8): an early phase of westward reverse dip-slip along the northern Kazerun fault zone and a younger phase of strike-slip documented in the present study in relation with the MRF/KFS connection. Evidence for the first phase regime is based 1) on the occurrence of exhumed Jurassic formations on the hanging wall whilst they are deeply buried (at c.a. minimum 5km-depth, [39]) west of the fault [36]; 2) the 5- to 9km-offset of the top of the basement across the fault [40]. These movements started as early as the Late Cretaceous, at the time the northern KFS was the tectonic front of the High Zagros belt [9, 26, 41, 42].

The second deformation phase that initiated strike-slip along the northern KFS is related to the onset of slip along the MRF. Anticlockwise rotation of Arabia allowed the MRF to propagate southeastward from the main Arabian indenter to reach and activate dextral strike-slip along the inherited KFS. This event is classically interpreted to have taken place around 5Ma ago [18], as a result of a regional re-organisation of the Arabia-Eurasia collision [43-47]. Indeed, field relationships from the central part of the MRF indicate that strike-slip initiated during the early Pliocene (i.e., during the deposition of the lower Bakhtiari formation) [48].

At that same time, the Semirom fault was activated and started transmitting part of the slip from the MRF, while the northern KFS absorbed the remaining part of horizontal strike-slip from along the MRF. Subsequent southeastward motion of the eastern KFS compartment south of the stationary MZRF produced southeastward thrusting within the wedge and NW-trending shortening across the Semirom fault as attested to by the fault kinematic analysis, see Figure (2c). Orogen-parallel dextral slip from along the MRF is therefore transmitted to the fold-and-thrust belt along NW-trending dextral transpressional faults and related folds (slightly oblique to the Main Zagros trend) and along the N-trending dextral, northern fault zone of the KFS and its southern thrust termination.

The structural and kinematic patterns shown in Figure (8) may be extrapolated to the scale of the Zagros fold-and-thrust belt, see Figure (9). Indeed, the structural wedge described in the Borujen area widens to the SE into a regional fan-shape fault pattern bounded to the west by the KFS, see Figure (8) [5, 28, 49]. We interpret this pattern to reflect distribution of slip from along the MRF to the

Figure 8. Block diagrams showing the two-stage evolution model of the northern KFS.
to plate convergence. Overall normal convergence is being recorded across the belt east of the fan-shape fault pattern whilst high-angle right oblique convergence would be active to the west of the KFS. The third zone would correspond to the fan shape fault pattern itself. Induced anticlockwise rotations and along-strike stretching of the belt east of the KFS [6, 16, 49] are achieved through this fan-shape fault pattern that displays distributed seismicity [16, 24].

The strike-slip partitioned motion of oblique plate convergence that is achieved by slip along the MRF within the western zone is transmitted and distributed to the central and eastern zones by slip along the KFS and associated faults. This fault system may therefore be seen as an orogen-scale, horse-tail like, strike-slip fault termination. In that sense, the KFS contributes to the fault system allowing partitioning of oblique convergence across the Middle-East Alpine collision belt and Arabia plate rotation associated with the westward extrusion of Anatolia [18] by transferring and distributing orogen-parallel dextral slip into the thrusts and folds of its frontal fold-and-thrust belt.

Acknowledgments

This work was funded by the Intérieur de la Terre and Dyeti programs (INSU-CNRS, France) and the International Institute of Earthquake Engineering and Seismology (IIEES, Tehran, Iran). We thank D. Hatzfeld and M. Ghafory-Ashtiany for supervising the program and M. Mokhtari for support and administrative assistance as well as K. Hessami for fruitful discussions, comments and logistical help. SPOT images (© CNES) were provided, thanks to the ISIS program.

References


