Offset on the Main Recent Fault of NW Iran and implications for the late Cenozoic tectonics of the Arabia–Eurasia collision zone

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SUMMARY

We use drainage patterns, geological markers and geomorphological features to determine a right-lateral offset of $\sim 50$ km, and possibly as much as $\sim 70$ km, on the Main Recent Fault in NW Iran. This fault trends NW–SE and forms the NE border of the Zagros mountains. It accommodates the strike-slip component of the N–S convergence between Arabia and Eurasia, with the NE–SW shortening component being accommodated in the Zagros Fold Belt. Its $\sim 50$ km strike-slip offset implies a shortening of $\sim 50$ km in the fold belt and $\sim 70$ km total N–S convergence accommodated in the NW Zagros. This is a substantial fraction of the 85–140 km overall Arabia–Eurasia convergence expected over the last 3–5 Ma. If the Main Recent Fault initiated at that time, as seems likely from geological arguments, it has a horizontal slip rate of at least 10–17 mm yr$^{-1}$ and should be the source of frequent earthquakes of $M_f$ 6–7, as has been seen in the 20th century and the earlier historical record. The similarity of the offsets and probable ages of the North Anatolian and Main Recent Faults suggests that they have been active as an almost continuous zone of right-lateral shear on the north edge of the Arabian and Anatolian plates since the early Pliocene.

Key words: active faulting, earthquakes, Iran, Middle East, seismotectonics.

1 INTRODUCTION

The purpose of this paper is to estimate the right-lateral offset on the Main Recent Fault, a major strike-slip fault system in NW Iran and one of the key structural elements in the active tectonics of the Middle East. The Main Recent Fault strikes NW–SE and can be traced as a narrow, linear series of fault segments from near the Turkey–Iran border at 37°N for over 800 km to the SE (Fig. 1). Right-lateral strike-slip faulting also continues NW in a broader zone through eastern Turkey to eventually join the North Anatolian Fault, thus forming a band of right-lateral shear linking Iran and Turkey. While a lot is now known concerning the slip rate and offsets on the North Anatolian Fault in Turkey (Şengör et al. 1985; Barka 1992; Armijo et al. 1999; McClusky et al. 2000), much less is known about the Main Recent Fault in Iran.

We will first use drainage patterns to estimate offsets on the Main Recent Fault, and compare these offsets with displaced geological markers. We do this in a region of NW Iran near Kermanshah (Fig. 2), where a series of earthquakes in the last century help guide us to the precise location and nature of the faulting. It is much more difficult to estimate the ages of the offsets and hence the slip rate on the fault, though various inferences can be made from the geological history. We will show that the offset on the Main Recent Fault is similar to that on the North Anatolian Fault and if, as we suspect, the two faults initiated at roughly the same time, this allows us to estimate a plausible slip rate on the Main Recent Fault and to assess its significance in the Eurasia–Arabia collision. There are two motivations for this work. One is the need to have some idea of the slip rates on major faults to assess the seismic hazard they represent. The other is more subtle. Eventually we will have reliable short-term estimates of slip rates on most major faults through GPS measurements, though these are not yet available in Iran. At that point we will want to see how far back in time we can extrapolate those slip rates before we account for, or run into conflict with, the observed geological structure or fault offsets. That question moves beyond asking what is the present-day configuration and rate of deformation (the goal of much seismotectonic research for the last 30 years), to asking whether today’s patterns and rates of faulting can also account for the finite, cumulative deformation. Not only is this question essential for understanding how the Arabia–Eurasia convergence has been accommodated in the mountains that now separate them, but it is also a central issue in continental mechanics (e.g. McKenzie & Jackson 1983; Molnar & Gipson 1994; Jackson 1999). To address it, we need to know the total offsets on the major faults.

2 TECTONIC AND GEOLOGICAL BACKGROUND

2.1 Regional tectonics

Whereas the North Anatolian and Main Recent Faults are relatively continuous linear features, the strike-slip faulting in eastern Turkey
is discontinuous and fragmented, with shorter fault segments distributed over a zone perhaps 200 km wide (Fig. 1). This contrast probably arises because the Arabia–Eurasia convergence, which is roughly N–S at ~25–30 mm yr⁻¹ at this longitude, is oblique to the NW–SE trend of the orogenic belt (Jackson 1992; De Mets et al. 1994; Chu & Gordon 1998). The strike-parallel and strike-normal components of this oblique shortening appear to be spatially separated on to different subparallel faults with orthogonal slip vectors, which can be seen in both the earthquake focal mechanisms (Jackson 1992; Jackson & Ambraseys 1997) and the GPS velocity field (McClusky et al. 2000). However, the shortening component is taken up south of the North Anatolian Fault (in SE Turkey) and predominantly south of the Main Recent Fault (in the Zagros), whereas it occurs north of the strike-slip faulting between the two (in the Caucasus). This arrangement is unstable, in that the strike-slip faulting in eastern Turkey and NW Iran must be moving north relative to Eurasia because of the shortening in the Caucasus, whereas the North Anatolian and Main Recent Faults need not do so (Jackson 1992). The configuration of the separated or ‘partitioned’ components of oblique shortening therefore precludes a continuous right-lateral strike-slip fault along the line of the North Anatolian and Main Recent Faults. Thus the North Anatolian and Main Recent Faults perform rather similar functions in the present-day tectonics of the Arabia–Eurasia collision zone.

2.2 Geology

The Main Recent Fault was first identified from offset drainage features by Wellman (1966), and was then later described in more detail and named by Tchalenko & Braud (1974). It borders the NE edge
of the Zagros mountains, approximately following an important geological boundary called the ‘Zagros suture’, the ‘Zagros Thrust Line’ or the ‘Main Zagros Reverse Fault’ by various authors (e.g. Stöcklin 1974; Falcon 1974; Berberian 1995), which approximately separates the rocks of the Arabian continental margin to the SW from metamorphic and volcanic rocks of central Iran to the NE (e.g. Berberian & King 1981). This geological boundary is also an important seismotectonic feature today, marking an abrupt cut-off between the intense seismicity of the Zagros and the almost aseismic central Iran plateau (Fig. 1, inset). The Main Recent Fault roughly follows the NE border of the NW–SE trending High Zagros Thrust Belt (Falcon 1974; Berberian 1995), which has the highest topography and rainfall in the region. Peaks reach heights of 4000 m and gorges reveal deeper exposures into the cores of thrusted anticlines (reaching lower Paleozoic levels) than elsewhere in the Zagros. This part of the Zagros has been uplifted by steep NE-dipping reverse faults to the SW, and is deeply dissected by the drainage. Some shortening occurred in the High Zagros in the Late Cretaceous, at which time ophiolitic rocks and deep sea sediments were emplaced on to the Arabian margin, particularly in the Kermanshah region, which is the focus of this report (Stoneley 1976). These exotic rocks are potentially useful markers for measuring offsets on the Main Recent Fault, which otherwise is subparallel to most of the geological structure.

However, ophiolite emplacement preceded the final suturing of Arabia with central Iran, which probably began in the Miocene (Stoneley 1981). Moreover, the main shortening of the Arabian margin in the Zagros, including all of the Simple Folded Belt SW of the High Zagros, began even later in the Pliocene, probably only 3–5 Ma (Falcon 1974). This is also close to the time at which there
is a major reorganization of the sedimentation and deformation in the South Caspian Basin (Devlin et al. 1999; Jackson et al. 2002). We suspect that this time represents the final closure of the minor oceanic and marginal basins that make up central Iran (Berberian & King 1981; McCall 1996) and the onset of true intracontinental shortening. We also expect that the present-day configuration of the active faulting in Iran dates from roughly that time. A similar geological history is seen further west. Although there is some
evidence for early Tertiary collision in eastern Turkey (Hempton 1987), much of the broader collision zone did not start to deform until the mid-Miocene or later (Dewey et al. 1986). It is also probable that most of the offset on the North Anatolian Fault was achieved over the last 5 Ma (see the later discussion).

2.3 Earthquakes

Several significant earthquakes occurred on or near the Main Recent Fault over the last 100 yr (Fig. 2, Table 1). The largest of these was in 1909 ($M_s = 7.4$) and produced at least 45 km of surface ruptures, downthrown to the NE and following the SW side of the Borujerd–Dorud depression (Ambraseys & Moinfar 1973; Tchalenko & Braud 1974). The vertical component of the 1909 scarp is reflected in the geomorphology, with gorges, river terraces and abandoned stream channels all demonstrating longer-term relative uplift on the SW side of the fault (Figs 3c and d). It is unclear whether the 1957 ($M_s = 6.7$) earthquake produced surface ruptures other than local fissuring (Ambraseys et al. 1973; Tchalenko & Braud 1974). McKenzie (1972) shows a poorly constrained first-motion fault plane solution for the 1957 earthquake (Fig. 2), which suggests a substantial thrust component. Shirakova (1967) reports a similar mechanism, but shows no polarity data. The 1958 ($M_s = 6.6$) earthquake produced up to 20 km of discontinuous surface rupture along the SW side of the Nahavand–Firuzabad depression (see the detailed map in Fig. 9), again with the NE side downthrown (Ambraseys & Moinfar 1974a;
Tchalenko & Braud 1974) and again reflecting the geomorphology, which shows clear evidence of longer-term uplift on the SW side. Shirakova (1967) reports a fault plane solution for the 1958 earthquake indicating NW–SE right-lateral strike-slip, but again without showing polarity data (Fig. 2). A smaller earthquake of $M_s = 5.8$ in 1963 also has a poorly constrained first-motion solution that is consistent with right-lateral strike-slip, perhaps with a normal component (Fig. 2; Jackson & McKenzie 1984). It produced no reported surface faulting (Ambraseys & Moinfar 1974b; Tchalenko & Braud 1974). The best-constrained focal mechanisms are for three smaller earthquakes, all of $M \sim 5$, in 1970, 1987 and 1998 (Fig. 2, Table 1), none of which can be definitely associated with a particular surface fault.

These earthquakes and their surface ruptures are important for two reasons. First, they confirm the right-lateral character of the fault system. Secondly, they indicate an important vertical component in places. Three of the focal mechanisms in Fig. 2 have normal components and two of the surface ruptures (in 1909 and 1958) follow basin-margin scarps that have a classical normal-fault morphology (Figs 3a, b and e). These indicate that at least some of the linear depressions, such as at Nahavand and Dorud, are structurally controlled, which is a feature we will exploit later. Those depressions are clearest where the fault system strikes $\sim 315^\circ$ between Nahavand and Dorud, and are absent where the fault strikes $\sim 300^\circ$ between Kamyaran and Sahneh. This is probably an indication that the regional slip vector, at least in the Kamyaran–Dorud
area, is about 300°–310°. Other earthquakes are also known from this region prior to 1900 (Ambraseys & Melville 1982; Berberian & Yeats 2001).

3 METHODOLOGY AND APPROACH

The drainage provides the key that reveals the cumulative offset on the Main Recent Fault, as it does on other major strike-slip faults in Iran (e.g. Walker & Jackson 2002) and elsewhere (e.g. Replumaz et al. 2001). The High Zagros is crossed by rivers flowing SW to the Persian Gulf that originate from a drainage divide typically 50 km to the NE of the Main Recent Fault. Beyond that divide, rivers drain into the internal desert basins of central Iran or to the Caspian Sea. The rivers crossing the High Zagros occupy deep gorges on the SW side of Main Recent Fault (Fig. 4). These gorges form a small number of restricted exits to the drainage coming from the NE. As the offset on the Main Recent Fault increases, so the drainage on the NE side must either keep contact with its gorge or abandon it for another outlet. The gorge itself may receive different catchments from the NE over time, or it may become abandoned altogether, to

Table 1. Earthquakes near the Main Recent Fault 32°–37° N.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Lat.</th>
<th>Long.</th>
<th>$M_s$</th>
<th>$M_w$</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>sv</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>1909.01.23</td>
<td>0248</td>
<td>33.41</td>
<td>49.13</td>
<td>7.4</td>
<td></td>
<td>136</td>
<td>50</td>
<td>50</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1957.12.13</td>
<td>0145</td>
<td>34.58</td>
<td>48.82</td>
<td>6.7</td>
<td></td>
<td>325</td>
<td>70</td>
<td>170</td>
<td>325</td>
<td>S</td>
</tr>
<tr>
<td>1958.08.16</td>
<td>1913</td>
<td>34.30</td>
<td>48.17</td>
<td>6.6</td>
<td></td>
<td>314</td>
<td>52</td>
<td>−165</td>
<td>304</td>
<td>J</td>
</tr>
<tr>
<td>1963.03.24</td>
<td>1244</td>
<td>34.50</td>
<td>48.02</td>
<td>5.8</td>
<td></td>
<td>319</td>
<td>50</td>
<td>−155</td>
<td>302</td>
<td>J</td>
</tr>
<tr>
<td>1970.10.25</td>
<td>1122</td>
<td>36.77</td>
<td>45.13</td>
<td>4.8</td>
<td></td>
<td>128</td>
<td>88</td>
<td>170</td>
<td>308</td>
<td>H</td>
</tr>
<tr>
<td>1987.05.29</td>
<td>0627</td>
<td>34.05</td>
<td>48.21</td>
<td>4.9</td>
<td>025</td>
<td>39</td>
<td>−84</td>
<td></td>
<td></td>
<td>H</td>
</tr>
<tr>
<td>1998.08.21</td>
<td>0513</td>
<td>34.23</td>
<td>48.16</td>
<td>4.9</td>
<td></td>
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</tr>
</tbody>
</table>

Locations of earthquakes before 1970 are based on their macroseismic areas (Ambraseys & Melville 1982), as instrumental epicentres are seriously in error (Ambraseys 1978; Berberian 1979). The slip vector on the right-lateral plane of the strike-slip solutions is sv. The letter in the last column is the reference for each earthquake: A is Ambraseys & Melville (1982); M is McKenzie (1972); S is Shirakova (1967); J is Jackson & McKenzie (1984); and H is the Harvard CMT solution.

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Main Recent Fault

Figure 7. Present-day (a) and restored (b) drainage maps of the Main Recent Fault. The restoration involves an offset of ∼50 km (see the text for details). Dry valleys that are now abandoned, but which were once major water courses, are dotted and marked with V symbols. The incised valley at Sahneh (see Fig. 4a) is marked G. The dotted line in the NE is the main drainage divide separating rivers that flow to the Persian Gulf (Zagros basin) from those that flow NE to central Iran or the Caspian Sea. The approximate line of the Main Recent Fault, used for the reconstruction, is marked by a dashed line. ZR is the Zayandeh Rud river. The grey shaded area is below 1600 m elevation.

4 RECONSTRUCTIONS OF THE MAIN RECENT FAULT

4.1 Evidence from drainage

In making our reconstructions, we have to ensure that both sides of the Main Recent Fault remain in contact. The strike of the fault varies along its length, being about 330° near Marivan in the NW, 300° in the central part near Sahneh, and 315° in the SE near Dorud (Fig. 2). The central part of the fault zone is notable for being relatively narrow, linear and free from elongated fault-parallel basins on its NE side and from abandoned dry valleys on its SW side (Fig. 7a). In contrast, both the NW and SE sections contain low topography on the NE side (the Baneh–Marivan region, the Nahavand and Borujerd–Dorud basins) and abandoned dry valleys on the SW side (Fig. 7a). As mentioned above, we suspect that this reflects a regional slip vector that has a small extensional component in the NW and SE, with an azimuth close to that of the central section (∼300°–310°). In addition, the Dorud basin is associated with a small right-step in the faulting and is in a pull-apart location. Our interest here is in the strike-slip component of the offset, so we restored the three sections separately, allowing an overlap on the fault in the reconstruction of the northern Marivan section to compensate for what we expect is an extensional component in that region (Fig. 8a). In order for the three blocks south of the fault not to overlap (Fig. 8a), the restoration requires slightly different strike-slip offsets in each section because of their different azimuths, but this is a minor effect of no great significance.

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1958 earthquake faulting and the geomorphology indicate a significant outlet to the SW. However, it also brings those streams opposite to Borujerd (G and H in Fig. 9b) were abandoned. Another abandoned gorge forms a dry valley at I (Fig. 9), suggesting that it was used before the modern Dorud gorge became the dominant exit. At the time of the reconstruction in Fig. 9(b), we imagine that the broad, flat Borujerd–Dorud valley did not exist. It is formed by an extensional component on the Main Recent Fault arising from either a pull-apart location at a right-step in the faulting or from a slightly oblique slip vector. The length of the valley (50–55 km) is very close to the restored offset on the fault in Fig. 9(b) (55 km).

In the central section near Sahneh, the restoration of the Sonqore stream to Kamyaran (A in Fig. 9), which was the original basis for the reconstruction in Fig. 7, also aligns all the other major streams B–E with appropriate outlets on the SW side. In particular, the river north of Nahavand (E) becomes aligned with a deep gorge at Sahneh (Fig. 11) which, although not completely dry today, was clearly made by a catchment much larger than the small stream that now flows through it.

At the NW end of Fig. 7(b), the ~50 km restoration brings the Sanandaj river, which today flows through a gorge NE of Paveh (Fig. 12a), into alignment with a gorge NW of Paveh (Fig. 12b). It also brings a beheaded stream at B in Fig. 12(a) into alignment with a dry valley at A (Fig. 13). The drainage in the Marivan region can be plausibly aligned with outlets on the SW side (Fig. 12), but in this region the fault system consists of several anastomosing strands that cross the Marivan–Baneh depression and is hard to reconstruct in detail. As at Dorud, we expect that this depression arises from an extensional component on the fault system, and that it did not exist as a topographic low at the time of the reconstruction.

Finally, at the SE end of Fig. 7 the reconstruction explains an apparent anomaly in the present-day drainage pattern. For most of Fig. 7 the divide separating the drainage of central Iran from that of the Zagros–Persian Gulf is about 50 km NE of the Main Recent Fault. However, at 32.5° N it makes a salient, with the headwaters of the Zayandeh Rud, which flows NE to Isfahan, projecting SW and crossing the Main Recent Fault (Fig. 7b). In this region the Main Recent Fault system may consist of more than one strand, but if we restore all the motion on the main strand, the Zayandeh Rud is brought into alignment with a prominent dry valley at Sepistan (K in Figs 14a–c). It seems probable that the Zayandeh Rud once flowed SW across the Zagros (Fig. 14d), but reversed its drainage when uplift on the SW side of the Main Recent Fault caused the Sepistan gorge to be abandoned. This reconstruction would remove the anomaly in the drainage divide (Figs 7b and 14b).

Thus our restoration of ~50 km, which arose from moving the Sonqore river from the gorge at Dinevar to the next gorge at Kamyaran, also restores the other major stream systems to exits that are either current gorges or abandoned dry valleys. In addition, it accounts for the length of the Dorud–Borujerd pull-apart basin, for the low topography in the Marivan–Baneh area, and for the apparent reversal of drainage in the Zayandeh Rud. Its most obvious weakness is that it leaves the gorge at Borujerd itself unoccupied (Fig. 7b), in spite of this being a major exit for the drainage today (Fig. 4c). This can be rectified with a small additional offset, making a total of ~70 km (Fig. 15). This new offset causes the Dorud gorge to be used and most of the other streams to the NE have appropriate outlets to the SW as well. Some uncertainty exists around the Dorud–Azna region itself because it is not possible to predict in detail where streams crossed what is now the Borujerd–Dorud depression. The only substantial stream with no apparent outlet at the 70 km offset is that through Sonqore.

In summary, the drainage reconstructions provide evidence for a right-lateral offset of approximately 50 km, and possibly as much

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Figure 8. (a) The Main Recent Fault changes its trend between its NW section near Marivan (330°), its middle section near Sahneh (300°) and its SE section near Dorud (315°). Any single slip vector for the whole fault system will lead to components of extension or shortening in some places, as in (b), where the slip vector is parallel to the central section, or in (c), where it is closer to the trend of the NW and SE sections. We have assumed a slip vector that produces an extensional component in the NW section (see text), so that an overlap is created when that section is restored, as in (a), and have allowed the blocks A, B and C south of the fault to be restored separately.

In the Nahavand–Dorud region, Fig. 9(b) shows that the 50 km reconstruction apparently isolates the rivers through Azna and Borujerd (streams G and H) on the NE side of the fault from any possible outlet to the SW. However, it also brings those streams opposite two dry valleys at G (South Nahavand) and H (South Borujerd). The South Nahavand dry valley is shown in Figs 5 and 6 and its pass is now ~600 m above the Nahavand plain, in a region where the 1958 earthquake faulting and the geomorphology indicate a significant vertical component of slip on the fault, down to the NE. The South Borujerd dry valley forms another pass, this time 500 m above the Dorud plain (Fig. 10). The pass itself is now a broad flat area containing young, almost horizontal, conglomerates at its highest point, probably dating from the time at which it was an active stream (Fig. 10c). Just beyond the pass to the SW is a high village called Khoshk Roud, literally ‘dry river’. The Dorud gorge itself (Fig. 4c) is not used in the reconstruction in Fig. 8(b). Today it takes the drainage from both stream systems G and H (Dorud means ‘two rivers’) after the two air gaps at South Nahavand and South

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Figure 9. Detail of the present-day (a) and ∼50 km reconstruction (b) of the drainage between Kamyaran and Dorud. Streams A–H on the NE side of the fault in (a) have been matched to gorges or dry valleys A–I on the SW side in (b). Dry valleys are marked by thick dashed lines, while the thin dotted line in the NE is the main drainage divide separating the Zagros Basin (ZB) from the Central Iran Basin (CIB). The thick lines in (a) are the major traces of the Main Recent Fault, while the dashed line in (b) is the approximate line of the fault used in the reconstruction. Shaded areas are lower than 1600 m elevation.

as 70 km. The restored stream patterns are shorter, simpler and flow directly across the line of the Main Recent Fault (Figs 7b and 15), with less of the drainage being trapped along the fault, as it is today between Nahavand and Sahneh and between Borujerd and Dorud (Fig. 7a).

4.2 Geological evidence

Potential offset marker beds occur in two places. The central section between Kamyaran and Sahneh contains distinctive ophiolitic rocks of probable Cretaceous age (Stöcklin 1974; Haynes & McQuillan 1974; Stoneley 1976) that are cut by the Main Recent Fault (Fig. 16). An apparent offset between the two sides of 47 km (between the arrows in Fig. 16) is close to that used to reconstruct the drainage in Figs 7(b) and 9(b) (50 km), though this is not a unique reconstruction of the geology. In the Dorud region a distinctive structural and stratigraphic package consisting of folded Upper Cretaceous radiolarites bounded by a thrust fault is truncated by the Main Recent Fault south of Borujerd and can be identified again on the other side of the fault SE of Dorud (Fig. 17; Gidon et al. 1974). Once again, because the structures are at a low angle to the Main Recent Fault, it is difficult to make a definitive reconstruction. Gidon et al. (1974) estimated an offset of ∼60 km in this region, similar to that used to reconstruct the drainage in Figs 7(b) and 9(b) (55 km), and also approximately the same as the length of the Borujerd–Dorud pull-apart basin (50–55 km). The offset between the arrows in Fig. 17, on the apparent ‘piercing point’ where the northern limb of the anticline is truncated by the fault, is ∼75 km, which is rather larger than the estimate of Gidon et al. (1974), but similar to that of the ∼70 km reconstruction in Fig. 15(b) (74 km).

We emphasize that none of the geological estimates of the offsets are precise or unambiguous, as the fault intersects the geological structure at a small angle. Nonetheless, we conclude that the preserved offsets in the geology are not grossly in conflict with our proposed offsets of ∼50 km (and possibly ∼70 km) based on the drainage reconstructions.
Figure 10. The dry valley south of Borujerd, marked H in Fig. 9. (a) LANDSAT image with the pass itself circled. The trace of the Main Recent Fault is the dashed line in the east. (b) Detailed topographic map of the region in (a). The stream now draining east from the pass is the Sardeh River, whose terraces are cut by the Main Recent Fault where it enters the Dorud basin (Figs 3c and d). (c) View looking north in the pass itself (circled region in Fig. 10a) at 33°46.3′N 48°31.8′E. The person is standing on cemented conglomerates on the now dry watershed.

5 DISCUSSION

Our reconstructions of the drainage patterns and the geology are consistent with a right-lateral strike-slip offset of ∼50 km on the Main Recent Fault. The offset could be extended to ∼70 km without severely affecting the quality of the reconstruction, but the evidence for the extra 20 km is not compelling. The ∼50 km reconstruction restores the drainage pattern to a simple network of short streams that flow straight across the line of the Main Recent Fault, accounts for the length of the Borujerd–Dorud pull-apart basin, and provides an adequate restoration of the few distinctive offset geological units. As offset on the fault increased, the streams crossing it switched or abandoned outlets to give the more complicated drainage pattern seen today, in which some stream systems flow subparallel to the...
Main Recent Fault

Figure 11. LANDSAT image of the gorge at Sahneh (black arrows), marked E in Fig. 9 and which was deeply incised by a substantial stream flowing SW, but which is now cut-off from any substantial catchment.

fault for tens of kilometres before finding an exit to the SW. Thus the drainage pattern seems to be a result of the fault itself, and not of the rather complicated capture mechanisms that arise further SW in the Simply Folded Belt of the Zagros, which are dominated by effects related to the alternating hard and soft units in the stratigraphy (Oberlander 1965; Oberlander 1968).

The transverse dry valleys that occur on the SW side of the fault are particularly interesting because their presence is necessary to confirm our reconstructions. They occur in sections of the fault that strike 315°–330° (Fig. 18) and are nearly all 500–600 m above their currently adjacent, or previously adjacent, valley floors or rivers. The ~50 km strike-slip offset is associated with ~500 m relative vertical motion, showing that the ratio of horizontal to vertical slip on the Main Recent Fault in those sections is about 100.

None of these offsets can, yet, be dated directly. The only constraints on timing are those based on regional geological arguments summarized in Section 2.2. We suspect that the present configuration of faulting in Iran dates from about 3–5 Ma, when there was a substantial reorganization of the tectonics in the South Caspian Basin and the Simply Folded Belt of the Zagros. If the Main Recent Fault also dates from that time then its long-term horizontal slip rate is about 10–17 mm yr⁻¹, with a vertical component of ~0.1–0.2 mm yr⁻¹ in the Dorud region. In this part of the Zagros, where the overall N–S motion is partitioned into NW–SE strike-slip and NE–SW shortening, these rates would imply 14–23 mm yr⁻¹ N–S shortening across the NW Zagros, leaving the rest (6–15 mm yr⁻¹) of the Arabia–Eurasia shortening to be taken up elsewhere in NW Iran. At these rates, the Main Recent Fault should be a source of relatively frequent earthquakes of M, 6–7, as is seen in the historical record (Ambraseys & Melville 1982; Berberian & Yeats 2001).

Some support for these dates, and hence rates, comes from a different argument. Further west in Turkey, the modern slip rate on the North Anatolian Fault is now well-constrained by GPS measurements to be about 24 ± 3 mm yr⁻¹ (McClusky et al. 2000). The offset on the North Anatolian Fault is also known to be about 80–85 km at both its eastern and western ends (Westaway 1994; Armijo et al. 1999). At its western end its age can be constrained by a Pliocene marine transgression that follows the Mediterranean Messinian crisis, dating the onset of faulting to ~5 Ma or younger (Armijo et al. 1999). This gives a long-term slip rate of ~16 mm yr⁻¹ if it started at 5 Ma or 28 mm yr⁻¹ if it started at 3 Ma, which brackets the GPS estimates. At the eastern end, it is sometimes claimed that the North Anatolian fault is older, and started about 10 Ma (Şengör et al. 1985; Barka 1992). However, this conclusion is based on an assumed connection between Neogene basins and the faulting and on the age of continental sediments that are difficult to date precisely (see e.g. Bellier et al. 1997). If the North Anatolian Fault is really younger in the west than in the east (e.g. Armijo et al. 1999), it raises the difficult question of how the offset can be the same all along it. Clearly, one possibility is that it is essentially the same age all along its length, and that it has been moving for the last 3–5 Myr at an average rate similar to that seen in the GPS measurements.

If these arguments are correct, the horizontal offset on the Main Recent Fault is not only similar in size (50–70 km versus ~85 km) but also similar in age to that on the North Anatolian Fault. In this light, it looks increasingly as though the two faults have marked
Figure 12. Detail of the present-day (a) and restored (b) drainage pattern in the NW section of the Main Recent Fault, near Marivan. The major trace of the Main Recent Fault system is marked by a thick line in (a), with other faults, which may be inactive, dashed. The approximate course of the fault used in the reconstruction is marked by a dashed line in (b). The reconstruction restores the stream B in (a), which now flows NE, to the dry valley marked A near Paveh. The reconstruction near Marivan itself is conjectural, as this is the area where the low elevation NE of the Main Recent Fault, and the different strike of the fault zone itself, suggest an extensional component of motion, causing the Marivan basin to be destroyed by overlap when the fault offset is restored.

an almost continuous zone of right-lateral shear extending from Istanbul to Isfahan that has been active for the last 3–5 Myr. Its continuity in space is broken only in eastern Turkey and NW Iran, where the shortening component of the Arabia–Eurasia convergence happens to be on the north side of the system, in the Caucasus, rather than on the south (Fig. 1). The offset on the Main Recent Fault can also throw light on the geographical distribution of the Arabia–Eurasia shortening in western Iran. The pattern of active faulting and earthquake slip vectors today leaves little doubt that the N–S Arabia–Eurasia convergence is partitioned into its strike-slip and thrusting components in the NW Zagros. A strike-slip offset of ~50 km therefore implies an accompanying shortening component that is also ~50 km. This estimate is compatible with geological estimates of shortening in the Simply Folded Belt of the Zagros since
the early Pliocene (Falcon 1969, 1974). It also implies an overall N–S convergence of \(\sim 70\) km. Reassessments of current motions in the Red Sea and Gulf of Aden (Jestin et al. 1994; Chu & Gordon 1998) allow better definition of the Arabia–Africa motion than older global models of plate motion (De Mets et al. 1994). Such older models consequently also poorly define the Arabia–Eurasia motion. By combining the Africa–Arabia motion of Chu & Gordon (1998) with the Africa–Eurasia motion of De Mets et al. (1994), we obtained a pole for the Arabia–Eurasia motion at 30.48° N 13.04° E with an angular rotation rate of 0.518° Myr\(^{-1}\). With this motion, the total Arabia–Eurasia convergence over the last \(3–5\) Myr is expected to be 85–140 km in a roughly N–S direction at longitude 48° E. We therefore estimate that over this time, the NW Zagros region has accommodated a substantial fraction of that total convergence, leaving only 15–70 km to be taken up further NE in the western Alborz and southern Caspian. The tectonics of those regions is discussed elsewhere (Jackson et al. 2002).

6 CONCLUSIONS

We have demonstrated that a right-lateral strike-slip offset of \(\sim 50\) km on the Main Recent Fault is compatible with a restoration of the drainage, geological markers and the length of the Borujerd–Dorud pull-apart basin. There is some evidence that the offset may be as much as \(\sim 70\) km. The configuration of the active faulting and earthquake slip vectors today shows that this offset is geometrically linked to a shortening of \(\sim 50\) km across the NW Zagros and to a total N–S convergence of \(\sim 70\) km, which is a substantial fraction of the 85–140 km total Arabia–Eurasia convergence over the last
Figure 14. (a) The present-day configuration and (b) the restored drainage system near the head waters of the Zayandeh Rud river, SE of Dorud. The LANDSAT image of the dry valleys marked K on the SW side of the fault in (a) is shown in (c). The Main Recent Fault is marked by the continuous thick line. Other faults, most of which are thrusts of the High Zagros, are dashed. (d) Cartoon of the restored drainage system, showing how the Zayandeh Rud was probably once a stream draining SW to the Persian Gulf, but has reversed its flow as it failed to maintain its course through the SW side of the Main Recent Fault. This would account for the apparent anomaly in the otherwise linear drainage divide between the Zagros basin and central Iran.

3–5 Myr. If the initiation of the Main Recent Fault dates from that time, as seems likely from geological arguments, then its offset and age are similar to those on the North Anatolian Fault in Turkey. The two faults then represent an almost continuous zone of right-lateral shear on the northern margin of the Arabia and Turkish plates that has been active since the Pliocene. The horizontal slip rate on the Main Recent Fault would then be in the range 10–17 mm yr$^{-1}$, with a vertical component of $\sim$0.1–0.2 mm yr$^{-1}$ in the Dorud region.

In the future we may have better estimates of the age of the Main Recent Fault and its current slip rate will be better determined through GPS measurements. However, measurement of its offset has already demonstrated that the Main Recent Fault is a major structural element in the late Neogene Arabia–Eurasia collision, and that better knowledge of its history and characteristics has important implications for understanding seismic hazard and the active tectonics of Iran.

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Figure 16. Summary geological map of the Kamyaran–Sahneh region, showing the possible offset of distinctive ophiolitic rocks. Simplified from various 1:250 000 and 1:100 000 maps of the Geological Survey of Iran.

Figure 17. Summary geological map of the Borujerd–Dorud area, showing the possible offset of distinctive geological units (see also Gidon et al. 1974). Simplified from various 1:250 000 and 1:100 000 maps of the Geological Survey of Iran.

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In both places the vertical
counters to the geomagnetic reversal timescale on estimates of current
plating on the main Recent Fault system is enhanced, probably by an extensional or normal component. Most of the dry valleys are about 500 m above
their originally adjacent basins, but the Zayande Rud is close to the elevation of the Sepestan dry valley, suggesting little vertical component in that part of the
fault zone.

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Figure 18. Summary of the elevations of gorges and dry valleys along the Main Recent Fault. Entrances to gorges are shown as black lines. Dry valleys are
grey lines, linked by dotted lines to the elevations of their adjacent valleys on the NE side of the fault in the restored drainage configuration (Fig. 7b). Note
how most of the dry valleys occur in the SE, associated with the Borujerd–Dorud basin or in the NW near the Marivan depression. In both places the vertical
component on the Main Recent Fault system is enhanced, probably by an extensional or normal component. Most of the dry valleys are about 500 m above
their originally adjacent basins, but the Zayande Rud is close to the elevation of the Sepestan dry valley, suggesting little vertical component in that part of the
fault zone.

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