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An active fault zone in the Western Kopeh Dagh (Iran)

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Abstract

Based on remote sensing studies, field work and microstructural investigations, we present new kinematic data and a structural model for the evolution of the Ashkhaneh/Takal-Kuh Fault (ASHF), an approximately 80 km long E-W trending fault in the S part of the Western KopehDagh (Iran). The ASHF system consists of an oblique thrust with a number of sinistral strike slip faults and tear faults with a marked displacement gradient. The tear faults clearly offset the thrust front, which consists of Cretaceous limestones. The offset and change of modern river courses suggest that the fault movement is still active. Several meters long and decimeter thick NE-oriented, monomineralic calcite vein systems are associated with the faults and suggest a strong fluid interaction during fault slip. Fluid pulses during brittle deformation are furthermore confirmed by microtectonic studies revealing alternating processes of frictional velocity weakening processes and velocity hardening deformation mechanisms by dissolution precipitation creep.

We therefore suggest that part of the Miocene to recent N-S shortening between the Iran and Eurasia has been accommodated by SSW-directed thrusting and sinistral strike-slip deformation along the ASHF.

Basierend auf Fernerkundung, Geländearbeit und mikrostrukturellen Untersuchungen werden neue kinematische Daten und ein strukturgeologisches Model für die Entwicklung der Ashkhaneh/Takal-Kuh Störung (ASHF) präsentiert. Die ASHF bildet eine etwa 80 km lange E-W streichende Störung im südlichen Teil des westlichen Kopeh Dagh (Iran). Das Ashkhaneh/Takal-Kuh Störungssystem besteht aus einer schräg zum Streichen gerichteten Überschiebung („oblique thrust“) und einer Reihe von sinistralen Seitenverschiebungen („tear faults“) mit signifikanten Versetzungs-Gradienten. Die aus kretazischen Kalken aufgebaute Überschiebungsfront wird von diesen „tear faults“ teilweise sehr deutlich versetzt. Abgelenkte Flussläufe entlang dieser Störungen lassen auf eine rezente Aktivität derselben schließen. Zusammen mit den Störungen vorkommende, einige Meter lange und mehrere Dezimeter mächtige Systeme von monomineralischen Kalzit-Extensionsspalten deuten auf starke Fluid-Interaktionen während der Störungsbewegung hin. Das teilweise Auftreten von Fluids während der spröden Deformation wird außerdem durch mikrotektonische Untersuchungen bestätigt, welche abwechselnde Phasen von schwächenden kataklastischen (bruchhaftes Gleiten) und verhärtenden duktilen Deformationsprozessen (Drucklösungskriechen) anzeigen.

Die Interpretation unserer Ergebnisse lässt darauf schließen, dass ein Teil der miozänen bis rezenten Verkürzung zwischen Iran und Eurasien von SSW-gerichteten Überschiebungen und sinistralen strike-slip Deformationen entlang der ASHF aufgenommen wird.

1. Introduction

The collision between the Eurasian and the Afro-Arabian plates and its influence on the geologic and tectonic settings in Iran has been discussed by a large number of geologists from different points of views (e.g. Stöcklin, 1968; Berberian, 1976; Jackson et al., 1995; Allen et al., 2004; Reilinger et al., 2006; Vernant and Cherý, 2006; Kaviani et al., 2009; Karganbafghi et al., 2011). Because of the enormous hydrocarbon potential, mountain ranges and associated sedimentary basins resulting from this collision, such as the Zagros (e.g. Berberian, 1995; McQuarrie, 2004; Mouthereau et al., 2007), the Alborz (e.g. Allen et al., 2003; Zanchi et al., 2006; Guest et al., 2007), or the South Caspian Basin (e.g. Buryakovsky et al., 2001; Allen et al., 2002; Jackson et al., 2002; Guliyev et al., 2003; Ali-Zadeh, 2004; Hollingsworth et al., 2008; Brunet et al. 2009; Richardson et al., 2011) have been the focus of numerous studies. In contrast to these areas, the KopehDagh fold and thrust belt located at the NE margin of the Eurasia-Arabian collision zone has received considerably less attention.

Only recently, the KopehDagh (Dagh = Mountains) and its transition towards the South Caspian Basin and the eastern Alborz started to become the target of more detailed investigations (e.g. Jackson et al., 2002; Hollingsworth et al., 2006; Hollingsworth et al., 2008; Hollingsworth et al., 2009; Shabanian et al., 2009a; Shabanian et al., 2009b; Hollingsworth et al., 2010; Javidfakhr, 2010; Shabanian et al., 2010; Javidfakhr et al., 2011a; Javidfakhr et al., 2011b). Most of these publications investigated the neo-tectonic geodynamics in this region and use tectonic geomorphology as an integral part in order to quantify recent fault activity.

Building on previous studies, the present work concentrates on the Ashkhaneh/Takal-Kuh Fault (ASHF), an approximately 80 km long E-W trending oblique-slip fault in the S part of the Western KopehDagh region (Fig. 1). This major fault cuts the Quaternary deposits creating a linear escarpment, along which there is evidence for both lateral and reverse offset (Javidfakhr et al., 2011a). Based on field work and remote sensing studies, evidences for recent fault activities along the ASHF have been observed. We document the signal of faulting activities in the morphology of river courses and the landscape evolution and determine the kinematics and deformation mechanisms of the fault system.

2. Geology of the KopehDagh

The KopehDagh (Fig.1), which extends along the border area between Iran and Turkmenistan, forms a linear fold-and-thrust belt between the stable Turan Block in the North and Central Iran in the South (Berberian, 1981; Lyberis and Manby, 1999). It is located within the Alpine-Himalayan orogenic belt and is defined as the N limit of the Cenozoic deformation in Iran (Hollingsworth et al., 2006). Recent GPS measurements (McClusky et al., 2003; Vernant et al., 2004a) indicate a northward movement of Arabia, with respect to Eurasia of about 23 mm/a, and therefore the deformation within the mountain belts around Iran is considered to be active. Because deformation in the Zagros accommodates approximately the half of this northward motion (Tatar et al., 2002), deformation in the KopehDagh, the Alborz and in the central Caspian Sea (Vernant et al., 2004a; Vernant et al., 2004b; Masson et al., 2005) must account for the remaining horizontal plate tectonic movement. Detailed quantifications of shortening across NE Iran are missing and estimations vary because currently only three GPS stations are installed. Vernant et al. (2004a) show a GPS based shortening of ~7 mm/a in this region, while Lyberis and Manby (1999) estimate a shortening of ~16 mm/a by the reconstruction of balanced cross sections. Other geodetic data show that the northward motion in the KopehDagh and Allah Dagh-Binalud Mountains (NE Iran) is accommodated at a rate of between 4 and 10 mm/a (Vernant et al., 2004a; Reilinger et al., 2006; Masson et al., 2007).

The KopehDagh Basin, together with the Amu-Darya Basin to the S in Turkmenistan, form a large intracontinental basin filled by a thick post-Triassic sequence of mostly marine sediments that mainly consist of limestones, marls and sandstones (Stöcklin 1968; Berberian, 1976). These sedimentary sequences record an almost complete succession from Lower Jurassic to Pliocene rocks (Lyberis and Manby, 1999). Less is known about the deformation history of the pre-Jurassic successions in the KopehDagh, although it has been interpreted resulting from the closure of the Paleo-Tethys (AfsharHarb, 1979). The successions are partly eroded by and unconformably overlain by Jurassic and younger sediments (AfsharHarb, 1979).

From the early Jurassic onwards, the opening of the KopehDagh-Amu-Darya Basin started. Subsidence was mostly bound to major E-W trending normal faults. This continuous subsidence led to the deposition of the thick post-Triassic sequence of mostly marine sedimentary rocks. Onset of the convergence between the Iran and Turan blocks started in the Paleocene and gave rise to the inversion of the basin. Consequently previous major normal faults were reactivated to become reverse faults. Reactivation of these faults continued into the Oligocene and the Miocene. During that time fault propagation folds and related thrusts developed parallel to the main direction of the mountain range. From Pliocene onwards the N-S shortening has been partly accommodated by large strike-slip fault systems oriented oblique to the mountain front.

Structurally, the KopehDagh can be divided in two subareas, which are characterized by differently oriented structures: (i) the eastern KopehDagh is characterized by fold trains with a

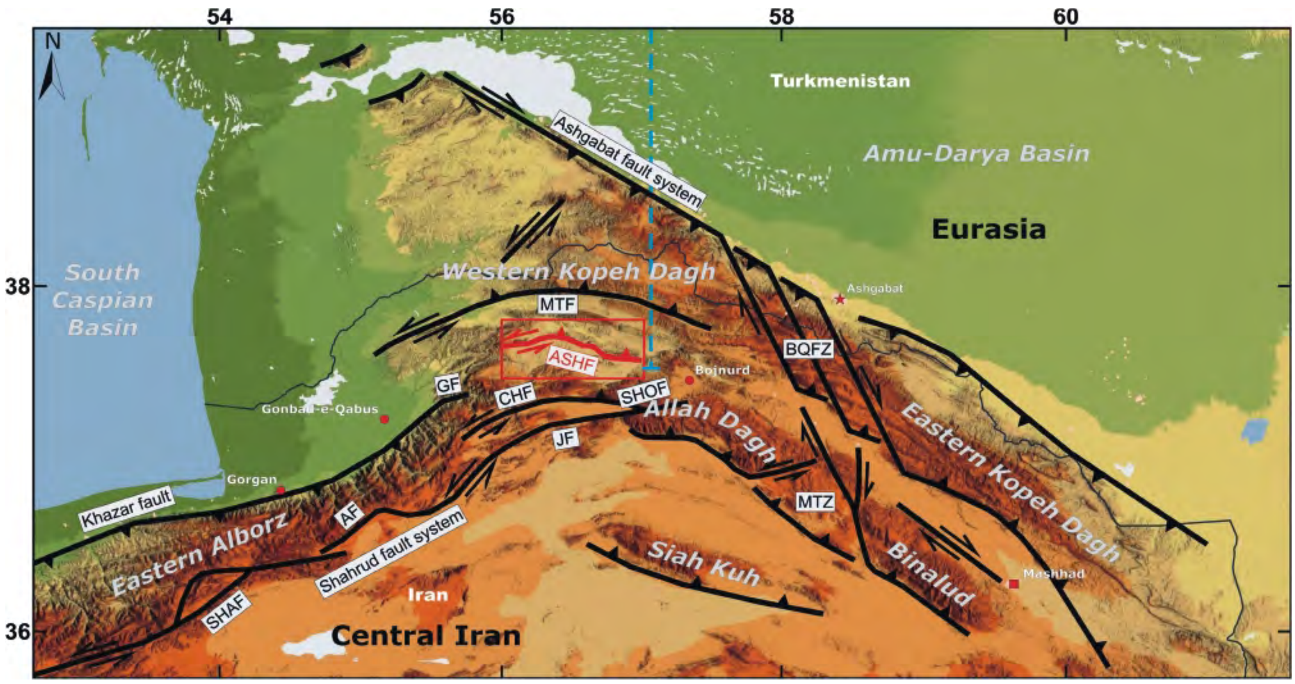

Figure 1: Overview showing the simplified fault map summary of NE Iran; 1:2000000 (source: www.topomapper.com); Abbreviations: Astaneh Fault (AF), Ashkhaneh Fault (ASHF, red rectangle=investigation area), Bakharden-Quchan Fault Zone (BQFZ); Cheshmeh-Nik Fault (CHF); Golestan Fault (GF); Jarjam Fault (JF); MaravehTappeh Fault (MTF), Main Triangle Zone (MTZ), Shahrud Fault Zone (SHAF), Showqan Fault (SHOF); dashed blue line=approximate location of section in Fig.2.

uniform NW-SE trend. (ii) and the Western KopehDagh, where the general trend of structures appears to bend into a W-E direction (Fig. 1). According to Hollingsworth et al. (2006) the transition between these two spatial orientations is located between 57°-59° E along the Bakharden-Quchan Fault zone (BQFZ). Here the range is dominated by a zone of right-lateral strike-slip faults, which cut obliquely across the KopehDagh without continuing towards the S into the Binalud Range (Hollingsworth et al., 2006). These strike-slip faults link with NW-SE striking thrusts dipping towards NE (Hollingsworth et al., 2006). A significant part (up to 80 % according to Javidfakhr et al., 2011a) of the deformation in NE Iran is accommodated by the BQFZ and transferred to the Ashgabat fault system N of it. Shabanian et al. (2009b) estimate shortening rates of 7±2 mm/a in this region. The total N-S motion resolved along the BQFZ is estimated as being in the range of ~60 km in the last 10 Ma (Hollingsworth et al., 2006).

In addition to the different trend of the western and eastern KopehDagh, the kinematics of the faults vary between these regions (Hollingsworth et al., 2006). In the eastern part, shortening is mostly accommodated by thrusting on the N and S edges of the mountain range with almost no evidence for strike-slip faulting. However the exact location and the kinematics of faulting in this region are not fully understood (Hollingsworth et al., 2006). In particular the northern range front is less linear and continuous than NW of Ashgabat. Nevertheless free-air gravity anomalies (Maggi et al., 2000) show clear depression characteristics and bending of the crust in a foreland basin in front of a major thrust of the eastern KopehDagh over the Turan platform (Hollingsworth et al., 2006).

The Western KopehDagh is characterized by W-E trending thrust-fault related folds, which are partly cut by NW-SE and NE-SW striking strike-slip faults with dextral and sinistral kinematics respectively.

The kinematics in the SW parts of the Western KopehDagh as well as the eastern Alborz are dominated by NE-SW trending left-lateral strike slip faults, which are part of the Shahrud fault system. The Shahrud fault system is a 400km long, NE striking zone which is characterized by major left lateral strike-slip fault zones (e.g. Astaneh (AF), Shahrud (SHAF), Abr, Jarjam (JF), Ashkhaneh (ASHF) faults, see Javidfakhr et al., 2011b). This major fault system is considered to form the transition zone between the Alborz and the KopehDagh/AllahDagh mountain ranges. Fault slip analyses, GPS measurements and focal mechanisms of earthquakes suggest sinistral strike-slip and reverse faulting mechanisms of this fault system characteristic for a regional transpressional tectonic regime (Javidfakhr, 2010). In the eastern part of the Shahrud

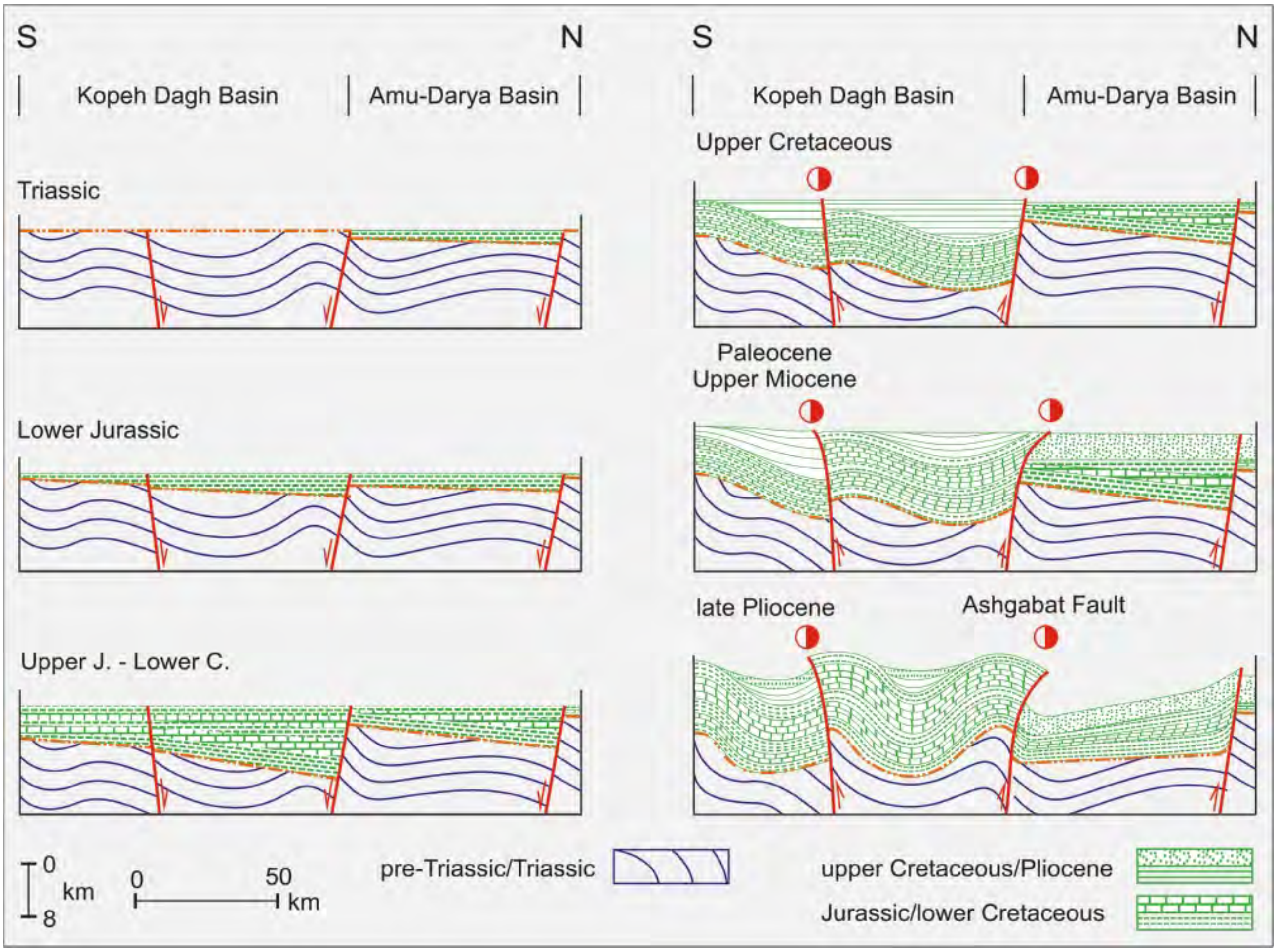

FIGURE 2: Tectonic history of the KopehDagh basin (strongly modified after Lyberis and Manby, 1999).

fault system several fault zones (e.g. Jarjam, Cheshmeh-Nik, Golestan faults) accommodate regional N-S shortening (Javidfahkr et al., 2011b).

The NE border of the KopehDagh towards the NW of Ashgabat is a prominent and sharp linear right-lateral strike-slip fault zone, the Ashgabat fault system. Although there is little direct field evidence for the strike-slip offset along the Ashgabat fault (Hollingsworth et al., 2006). Lyberis and Manby (1999) estimated a total offset of 35 km by kinematically balancing an estimation of 75 km total N–S shortening.

The afore mentioned sinistral and dextral strike slip fault zones result in block rotation and an along-strike elongation of the KopehDagh mountain chain and extrusion of the Western KopehDagh towards the W (Hollingsworth et al., 2006). The location and accommodation processes of this westward movement are still a matter of debate. The westernmost part of the KopehDagh range, near the transition to the Caspian Sea, is buried by more than 4.5 km Pliocene sediments of the S Caspian Sea margin (Lyberis and Manby, 1999). The crystalline basement in the Western KopehDagh has a general westerly plunge and at a depth of 12-14 km (Lyberis and Manby, 1999). Towards the SW of the KopehDagh the Caspian basin is overthrusted towards the S by the Alborz range. Lyberis and Manby (1999) mentioned that there is no surface indication for the presence of major transverse faults that separate the Western KopehDagh from the South Caspian Basin.

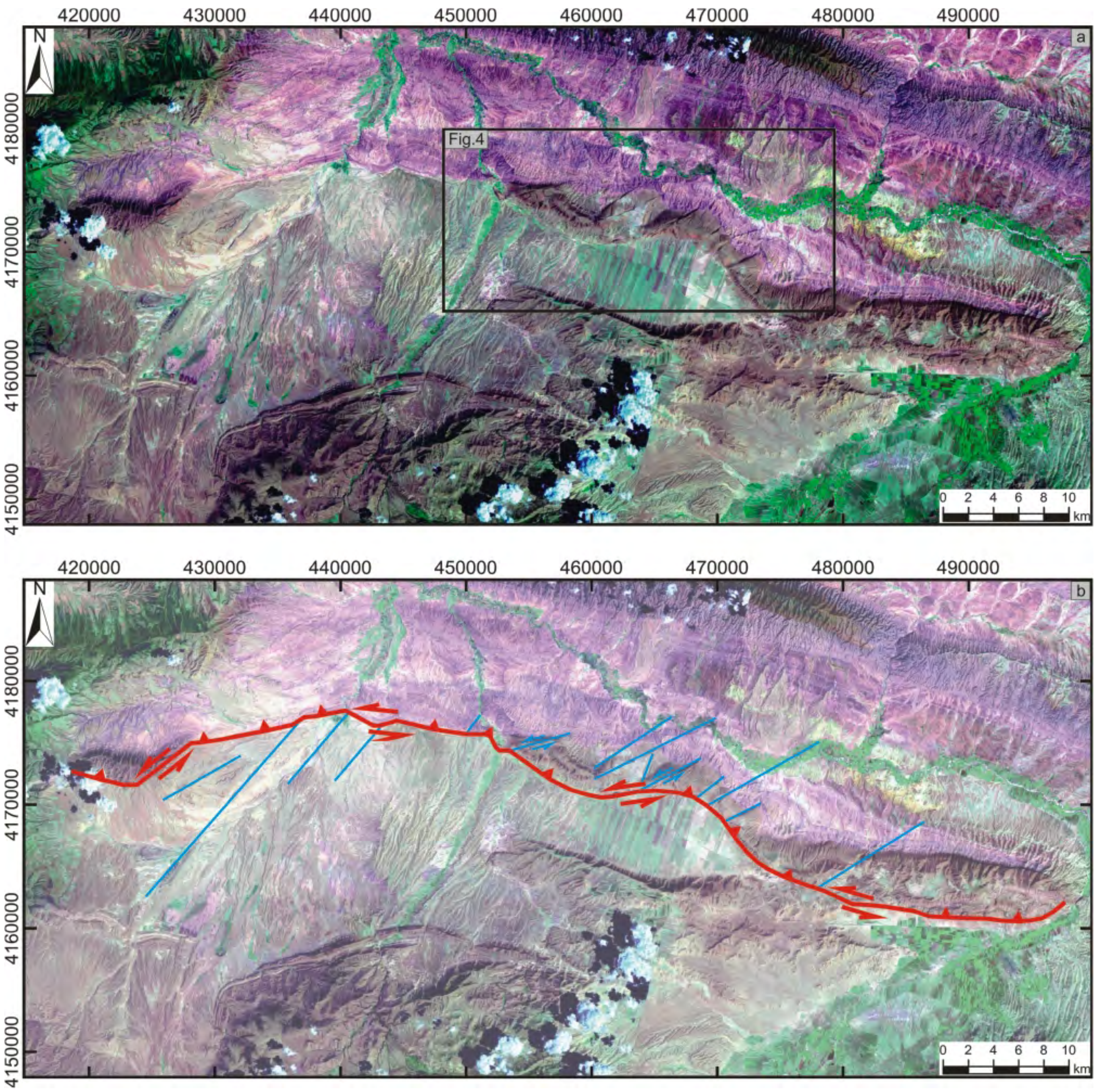

FIGURE 3: a) Aster false color satellite image of the Ashkhaneh Fault (ASHF); the black rectangle is showing the position of Fig.4. b) transparent version of the Aster false color satellite image overlain by the fault trace of Ashkhaneh Fault (ASHF, red) and the accompanied strike-slip faults (blue); shear sense was only added where measured in the field.

Thus they consider the KopehDagh as being part of a wider extension of the South Caspian Basin.

3. The Ashkhaneh (TakalKuh) Fault

3.1 Geomorphology

The transition zone between the Alborz and the Western KopehDagh is characterized by four major fault zones. The Shahrud and the Abr/Jarjam fault zones in the eastern Alborz and the Ashkhaneh and Showqan fault zones in the Western KopehDagh (Javidfakhr et al., 2011a). Few direct field observations about the kinematics of present-day deformation and its relationship to the seismicity in this area exist. This study focuses on the ASHF (location Fig.1) and combines tectonic and geomorphologic investigations along the fault zone.

The ASHF is defined as a WNW-trending 80km long oblique-slip fault extending to the west of Ashkhaneh town (Javidfakhr et al., 2011a). It represents a clear geomorphologic signal by creating a sharp, linear fault escarpment at the contact of Cretaceous limestone and marl sequences, which have been thrusted on Quaternary sediments (Fig.3a). In the investigated area, Upper Cretaceous strata (Sanganeh Formation) conformably overlies shales and limestones of the Lower Cretaceous Sarcheshmeh Formation and shallow water facies of the Tirgan Formation. Offset of geomorphologic markers visible in the satellite images and structural field observations, such as brittle kinematic indicators parallel to slickenlines on fault surfaces, suggest both, reverse and left-lateral offsets along the

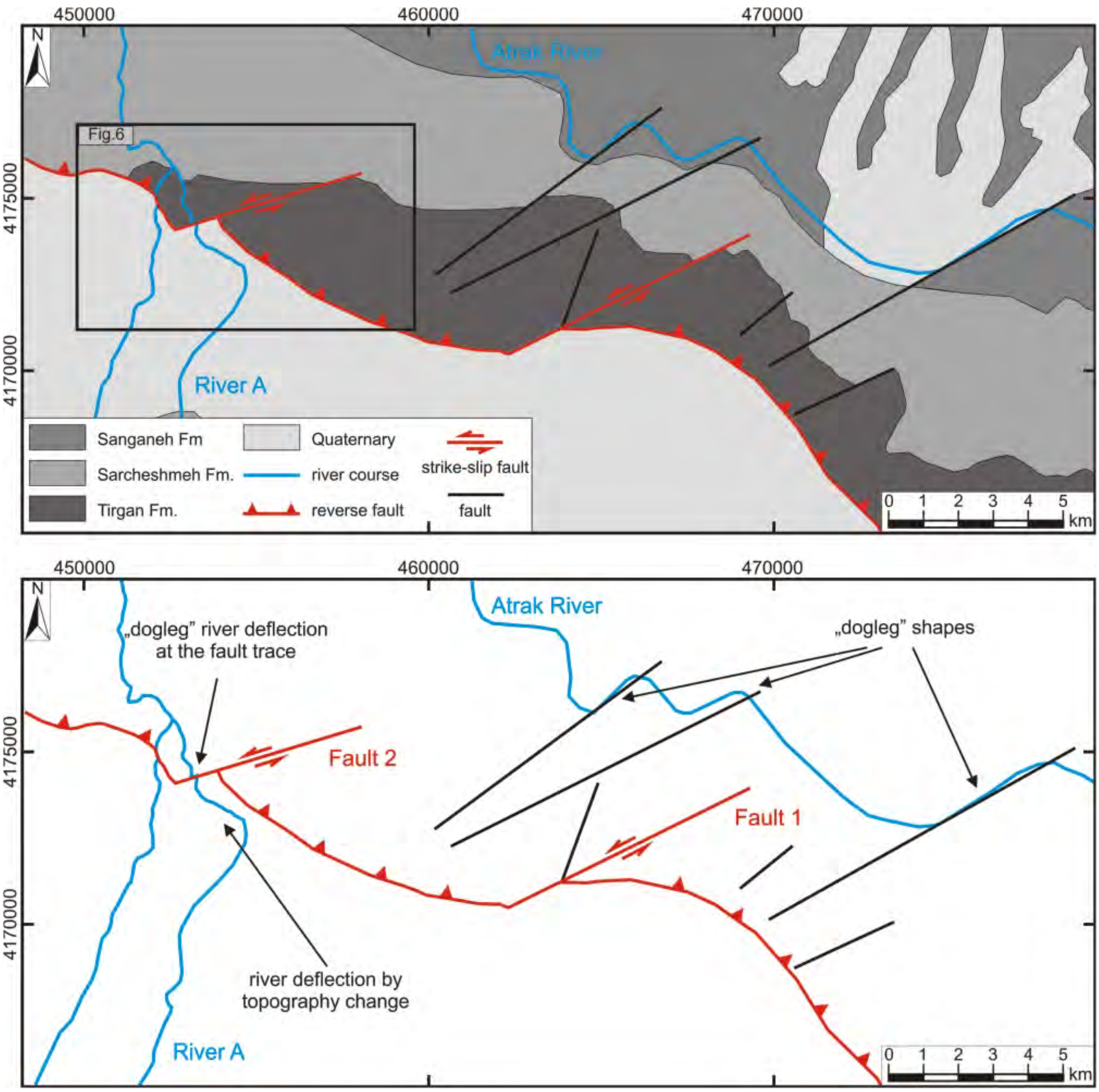

Figure 4: Simplified geological map (modified after 1:250000 map Afshar Harb et al., 1987) of the investigated area (location see Figure 3). Sanganeh Fm. – Upper Cretaceous; Sarcheshmeh Fm. and Tirgan Fm. Lower Cretaceous.

ASHF (Fig.3b).

Towards the N and S of the ASHF, secondary sinistral strike-slip faults with a strong displacement gradient can be observed. Since these faults are located in the hanging wall and the footwall of the ASHF they could be interpreted as cogenetic Riedel shear, which developed synthetically to the sinistral strike-slip component of the main fault (Fig.3b). They occur as approximately 50 to 100 m broad, NE-oriented cataclasite zones, which are accompanied by massive, calcite filled joints paralleling maximum principal stress direction (σ1) of the region. Javidfakhr et al. (2011a) recorded a present day state of stress in this area by a regional mean NE36 ± 20°E horizontal trending σ1, which is consistent with the active stress state

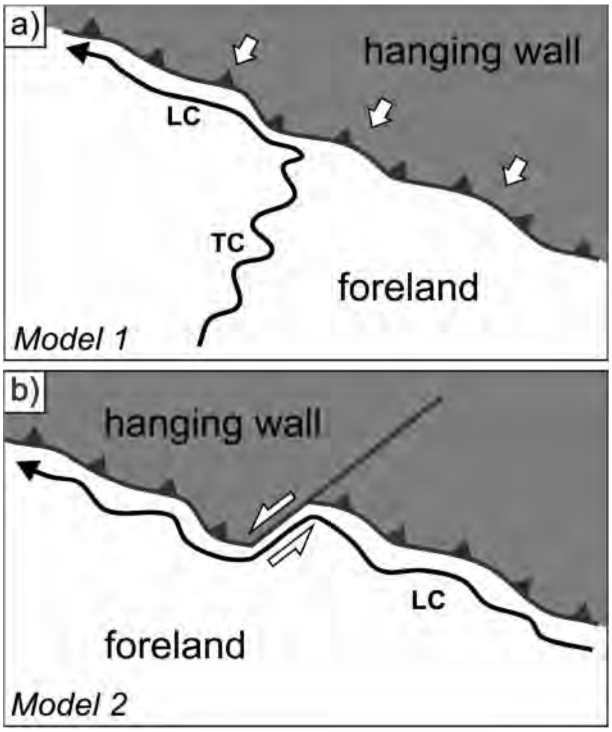

Figure 5: a) Model 1: Foreland originating transverse river (TR) deflected into a longitudinal river (LR) by the rising topography above a thrust fault. b) Model 2: Longitudinal river offset by a strike-slip fault. The shape of the "dogleg" (DL) river course reflects the shear sense of the fault.

(N47°E trending σ1) deduced from the inversion of earthquake focal mechanisms.

The hanging wall of the ASHF gets partly displaced by some of these sinistral shear zones resulting in a prominent segmentation of the main fault (Fig.4). This tear faults strike NE-SW at a high angle to the thrust front and the fold axis (Twiss and Moores, 2007). They have a strong displacement gradient and develop as a result of the propagating ASHF towards SW into the foreland. The active hanging wall segmentation strongly influences the geomorphology and the drainage evolution in the study area.

Most of the recorded strike-slip faults do not show significant lateral offset, although leaving a strong geomorphologic signal at least in the more competent strata. Most of the brittle structures are clearly visible in the competent limestone members (i.e. Tirgan and Mozduran Formations), which represent only a minor part of the outcropping strata in the investigated areas. In the incompetent marl, shale and sandstone layers erosion has obliterated almost any evidence for tectonic activity. However, even the fault zones without significant lateral offset, which are not clearly visible in the incompetent strata, still have an important influence on the drainage pattern of the region. An excellent example of this fault controlled drainage pattern is given in Figure 4: Towards the NE of the ASHF, the Atrak River directly follows the trace of several of these faults with a prominent bending of its course.

Geomorphologic markers like river courses, alluvial fans, shorelines, and glacial valleys may record offset along active faults. River diversions per se are the clearest indicators that the stream is approaching a rising topographic ridge above a thrust or fold. Deflection of river courses are also the most durable and active geomorphologic markers (Gaudemer et al. 1989). Based on remote sensing data combined with our field observations two different types of river deflection can be discriminated (Fig.5, see also Burbank et al. 1996):

(i) In Model 1, the transverse river originating in the foreland is diverted into a longitudinal river (LR) by the uplifted topography above a thrust fault. The LR is following the structural trend and flows roughly parallel to the thrust fault scarp in the footwall basin in front of the structure (Ori and Friend, 1984).

(ii) In Model 2 a longitudinal river flowing parallel to the structural trend is deflected by a tear fault (i.e. a strike-slip fault) forming a bayonet-shaped (i.e. "dogleg") deflection, which generally enables an assessment of the slip-sense on the fault (Lacassin et al., 1998).

Both models can be observed along the ASHF. In Figure 4 the Atrak river course records several dogleg shapes. These locations coincide with the position of left-lateral strike-slip faults. The foreland originating transverse River A (Fig. 4 and 6) meets the uplifted ridge of the DonghozDagh Anticline (Fig. 6c) above the ASHF and is deflected into a longitudinal river flowing towards NW parallel to the structural trend. Towards the NW the DonghozDagh Anticline is offset by a tear fault (Fault 2) with a sinistral shear sense. This tear fault also offsets the longitudinal river A creating a dogleg shape of the river course.

3.2 Structural field data

Since active faulting plays a very important role in the present-day tectonic and geologic setting of the investigated area, the ENE-WSW trending tear fault (Fault 2 in Fig.4) was studied in more detail in the field in order to get more precise information about the regional deformation mechanisms.

The tear fault (Fault 2 in Fig. 4, 6a and 7a) forms an approximately 100 m broad cataclasite zone, which is characterized by multiple generations of fault rocks derived from large amounts of carbonatic fluids. Fracture fillling cements partly show a fibrous growth structure (Fig. 7c). The cataclasites

(Fig. 7b) record several generations of deformation events that refer to different degrees of fracturing and grinding, ranging from protocataclasites to ultracataclasites. It is noted that "earlier" generations of cataclasites may appear as components in "later stage" cataclasites giving evidence for poly-phase fault slip events. All brittle shear sense indicators suggest a left lateral strike slip kinematic. The cataclasites are cut by poly-phase open mode I cracks, which have been filled with monomineralic calcite. The poly-phase deformation cycles are also evidenced by the fact that earlier veins are cataclas-

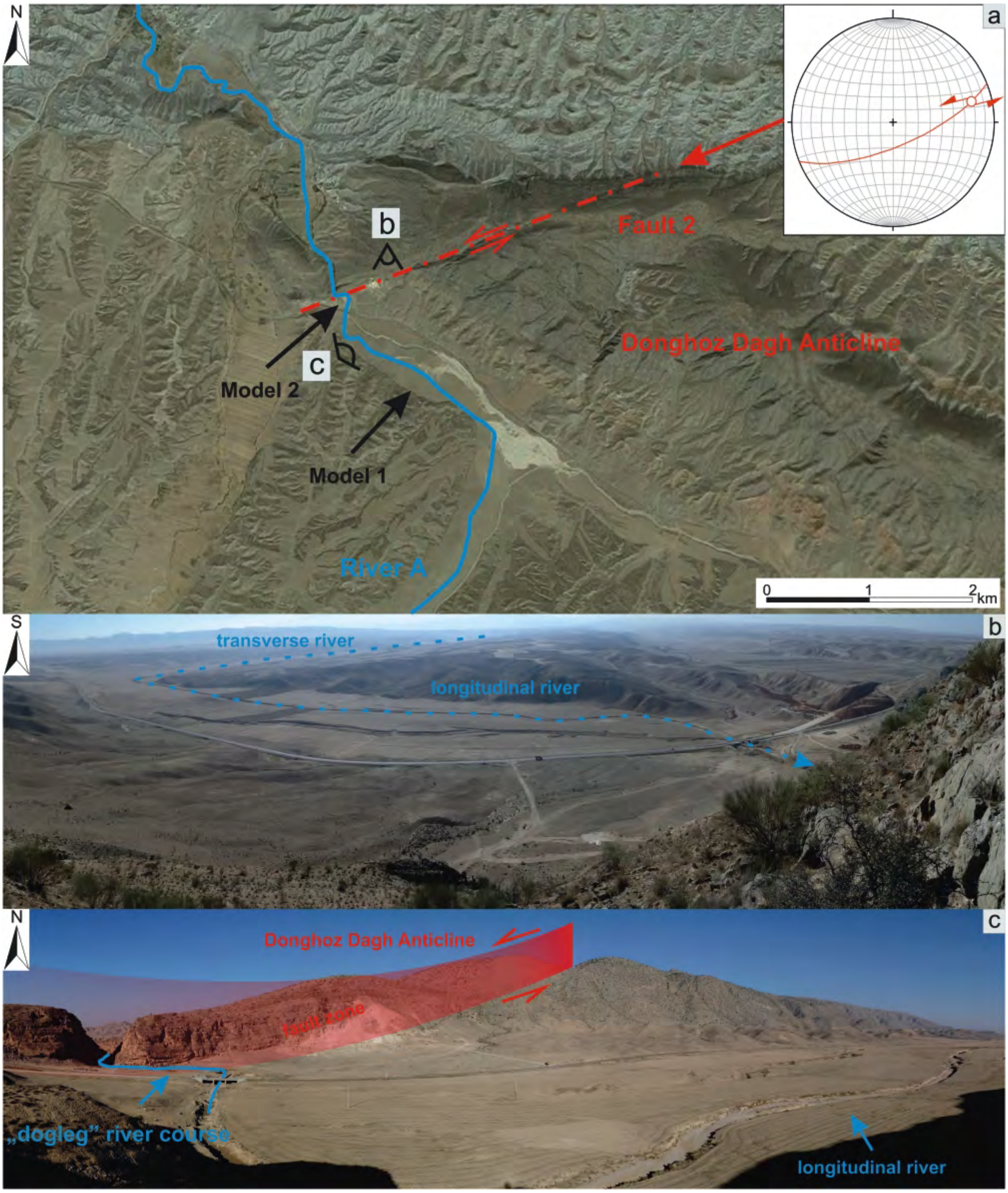

FIGURE 6: a) location see Figure 4; Google Earth satellite image of the western part of the DonghozDagh Anticline showing the deflection of the foreland originating transverse river A into a longitudinal river and the "dogleg" river deflection directly at the trace of *Fault 2*. b) View from the DonghozDagh Anticline towards the S where the transverse river A is deflected into a longitudinal river (location see Fig. 6a) c) View towards the N (location see Figure 6a) showing the lateral offset along Fault 2 and deflection of river A into a dogleg river course.

tically deformed and appear as components in the cataclasite. Another distinctive feature of Fault 2 is the occurrence of zones with massive, calcite filled veins which are parallel to the fault (Fig. 7 d, e). The calcite records fibrous growth with the long axis of the crystals being perpendicular to the crack surface. A change in the color along the fibrous crystals suggest various generations of fluid pulses. Given that the long axis of the fibrous crystals indicate the direction of the minimum principal stress (σ3), the veins indicate a NNW-SSE directed transtensional component for the strike-slip faults. A minimum estimation for the offset along the Fault 2 is given by the "dogleg" deflection of river A along the fault, which suggests a left lateral offset of at least 100m.

3.3 Microstructure

As an example we investigated the several tens of meters thick cohesive cataclasites of Fault 2 in more detail in order to get some indications of the deformation mechanisms during faulting. In accord with the large calcite vein systems associated with the faults (see chapter above), the cataclasites show also evidences for a strong interaction between frictional deformation and fluid flow. Macroscopically the voids between the angular millimeter to centimeter large limestone fragments are filled with white calcite crystals and frequently, also the cohesive cataclasites are cut by veins (Fig. 8a).

In the thin sections, the larger fragments still record the host rocks of the fault, which are fossiliferous, argillaceous lime-

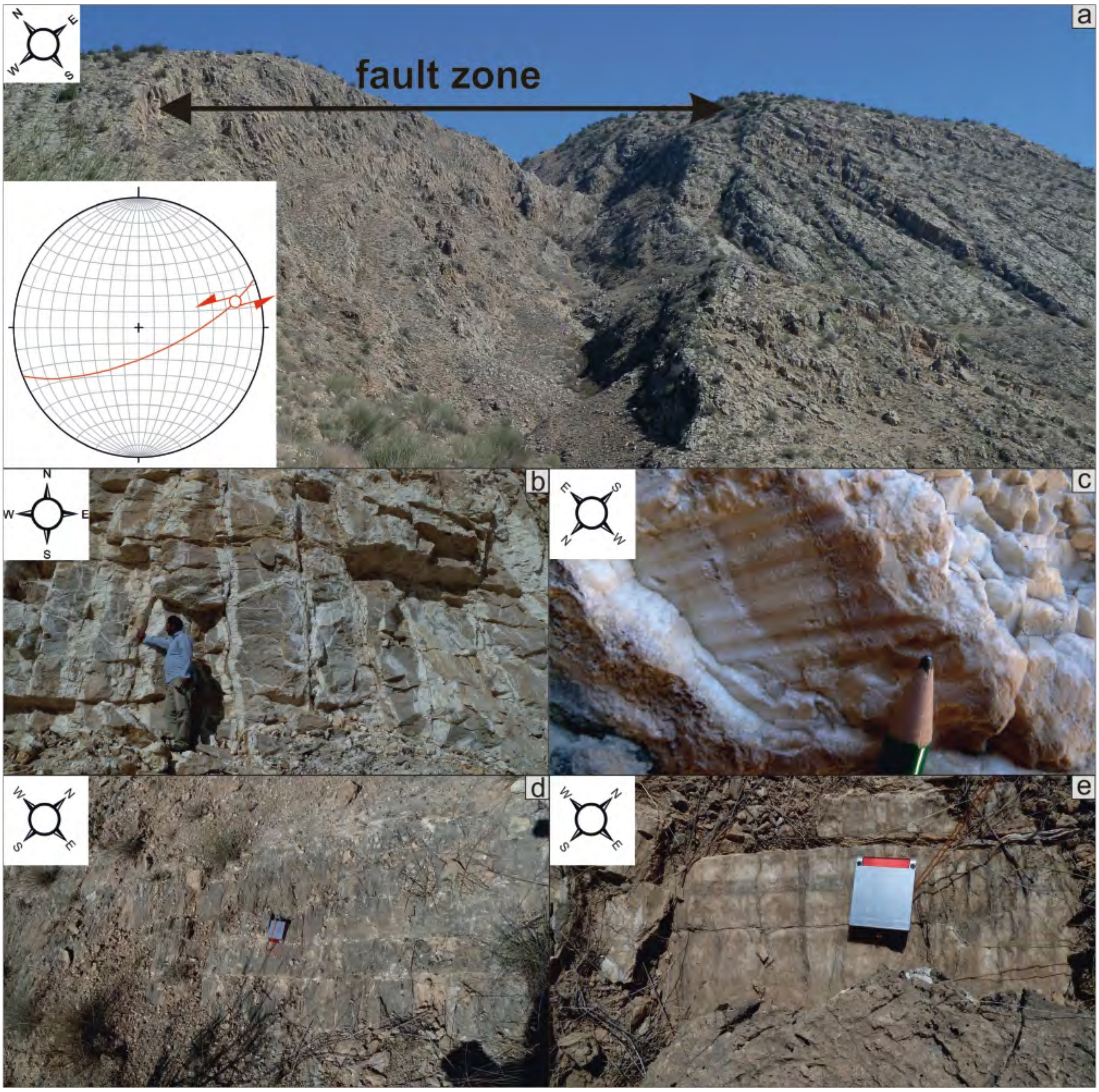

Figure 7: a) Picture of the around 100 m broad cataclasite zone of Fault 2 (view from E56°28'26''; N37°42'59'' towards NE); b) cataclasitic fault rock crosscut by calcite veins (view from E56°28'15''; N37°42'56'' towards N);c) fibroid growth of calcite (view from E56°28'03''; N37°42'52'' towards SE); d/e) massive calcite veins parallel to the fault zone (view from E56°28'26''; N37°42'59'' towards NW).

stones of the Lower Cretaceous Tirgan Formation (Fig. 8b). The smaller fragments consist either of cohesive cataclasites or of crushed calcite vein material. Most of the cataclastic components are highly angular. However, close to the slicken sides, several generations of cataclasites record rounded grains, suggesting high strain fault slip resulting in abrasion of the components. The monomineralic vein calcites crystals are about 1 mm large and record several generations of mechanical e-twinning. The twin morphology ranges from thin twins, thick twins to curved tapered lensoid twins suggesting brittle deformation of the rocks during varying temperature conditions (Ferrill et al., 2004) and polyphase monomineralic calcite fluid injection. Few veins crosscut all structures and have clear strain free calcite, which lack any evidence of deformation (Fig. 8c). Precipitation of the fluids is associated with dissolution of material along stylolites recording solution of a significant amount of material. This observation suggests that not only frictional velocity weakening deformation mechanisms but also velocity hardening dissolution precipitation creep occurred during fault slip (Niemeijer and Spiers, 2006). Because the stylolites cut through fragments of host rocks, cataclasites and calcite vein material, and because stylolites and veins are also affected by frictional processes, velocity hardening and weakening were alternating processes.

4. Discussion

In the following the investigated ASHF is discussed in a larger regional frame focusing on the complicate tectonic setting in NE Iran W of the South Caspian Sea.

In general the deformation in the Western KopehDagh is a result of the partial accommodation of the movement of the Arabian shield versus stable Eurasia and is characterized by several different tectonic features which combined create the present-day geological setting (Fig. 9). GPS velocities from coarsely-spaced stations in NE Iran, where shortening is both slower and more distributed, suggest N–S shortening across the KopehDagh of about 6mm/a (Hollingsworth et al., 2010). Shortening across the KopehDagh is currently accommodated

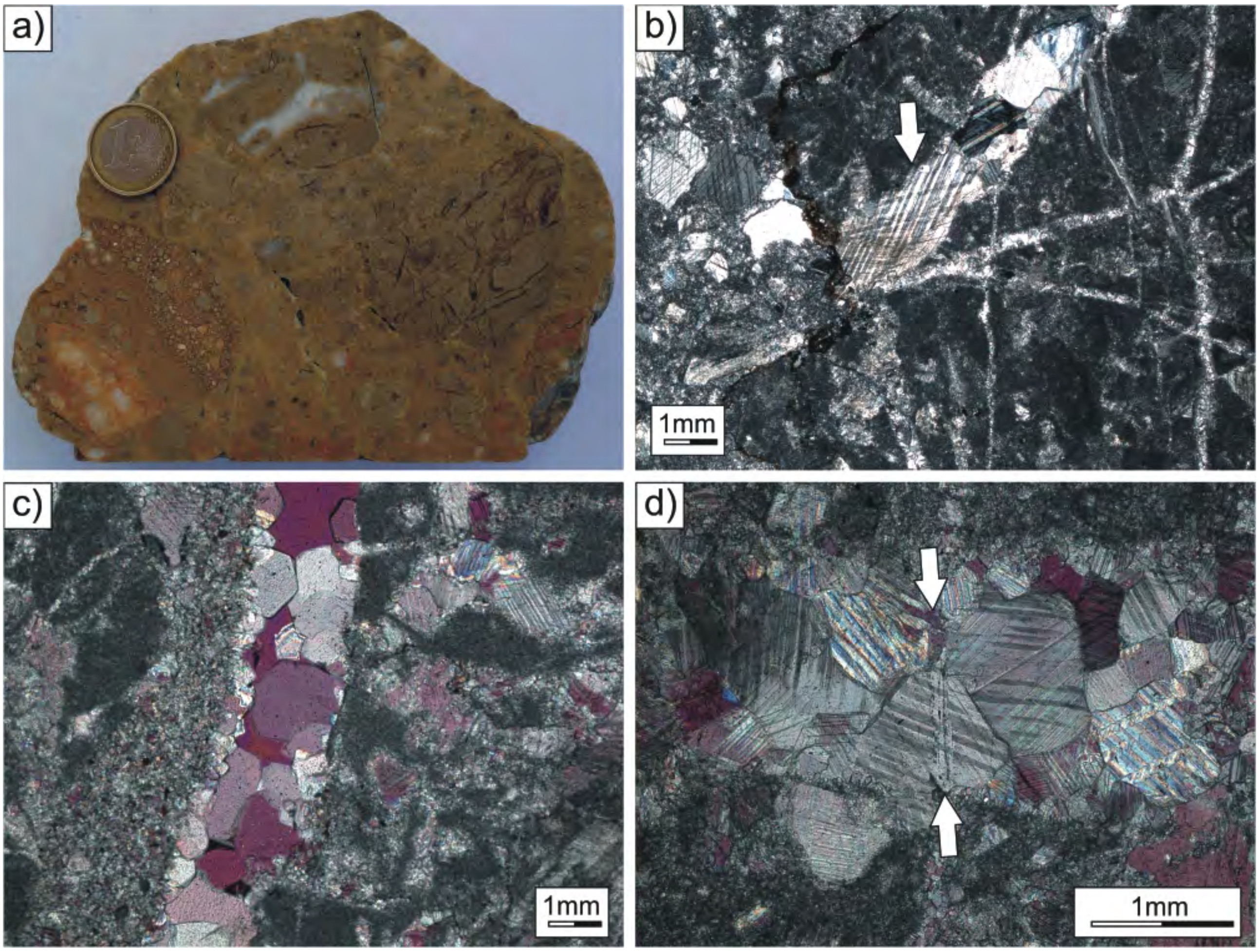

Figure 8: a) Handsample of the cohesive cataclasites from Fault 2. Note the polyphase cataclasite components and intra-clast vein systems. b) Thin section (crossed polarizer) of (a) showing interpenetration of the cataclasite with a large component of the fossiliferous Lower Cretaceous Tirgan Fm along a stylolite. The monomineralic calcite vein (indicated with an arrow) records strong mechanical deformation twin lamellae. c) Vein with two generations of calcite crystals which have grown into an open space. The clear crystals have no mechanical e-twins (crossed polarizer and inserted tint plate.). d) Calcite vein with mechanically twinned and kinked crystals (crossed polarizer and inserted tint plate). In the center of the picture the vein is cut by another vein fracture, which has grown by re-opening of the fracture and progressive deposition of calcite by crack-seal mechanism (indicated by arrows).

on range-bounding thrust faults east of 59°E, anticlockwise rotation of right-lateral strike-slip faults between 57–59°E and westward extrusion of material along thrust and strike-slip faults west of 57°E (Lyberis and Manby 1999; Hollingsworth et al. 2006, 2008; Shabanian et al.2009a).

The investigated ASHF is located in this Western KopehDagh. Folding in this part of the KopehDagh is mostly related to S-vergent thrusting, either initialized by basement faulting or a basal detachment. Typically, folds with steeper southern forelimbs and more gently dipping northern backlimbs are formed above N-dipping thrusts. The wavelength of the folds varies between 5 and 15 kilometers. The vergency of folding changes towards the N border of the orogen. In the Turkmenian part of the Western KopehDagh thrusting and the related folding is N-vergent with steeper northern forelimbs and more gently dipping southern backlimbs (Lyberis & Manby, 1999). The differences of the vergency of folding can be explained by the compression related inversion of the basin and the reactivation of its faults.

Generally the Western KopehDagh is bordered by two major strike-slip fault zones, i.e. by the Ashgabat fault zone towards the N and by the Shahrud fault zone in the S. The Ashgabat fault zone forms a clearly visible, linear geomorphological scarp NW of Ashgabat and is characterized by right lateral displacement. Its counterpart S of the Western KopehDagh is the Shahrud fault zone, which is characterized by left lateral displacement. These two fault zones accommodate most of the shortening and the westward extrusion of the Western KopehDagh resulting from the shortening-related, counterclockwise block rotation in the central KopehDagh. This process leads to an along strike elongation in the entire region (Hollingsworth et al. 2006, 2008).

Tectonic features of interest in the study area, besides the N-dipping thrusts, are sinistral strike slip faults. Some of them are restricted to the hanging wall of the thrusts and are faulting the Cretaceous formations; others occur also in the footwall while offsetting Quarternary sediments. At least some of the strike slip faults in the hanging wall of the ASHF mechanically interact with the thrusts and are clearly tear faults, which offset the thrust faults scarps. The rest of the sinistral faults are most probably related to the W-E extension and accommodate the westward extrusion of the region. Some of the faults may have also formed initially as synthetic Riedel faults to the major shear zone corridors, which accommodate the westwards extrusion of the Western KopehDagh towards the South Caspian Sea (Hollingsworth et al., 2008). All investigated faults record strong evidences for fluid interactions, which at least periodically exceeded the hydrostatic conditions during crustal deformation. Macro- and microstructural investigations suggest that the ultracataclasites were largely impermeable perpendicular to the faults but became highly permeable channel ways for fluid discharge as testified by periods of massif vein formations, which were frequently overprinted by cataclasis. These observations strongly support models, which describe the behavior of faults as fluid-pressure-activated valves wherever they transect a supra-hydrostatic fluid pressure gradient (Hacker, 1997; Sibson, 2000). Such fault-valve behavior, causing abrupt fluctuations in fluid pressure linked to possible earthquake cycles, is particularly likely for faults that remain active while unfavorably oriented for frictional reactivation in prevailing stress fields. The most extreme fault-valve action is likely to be associated with high-angle re-

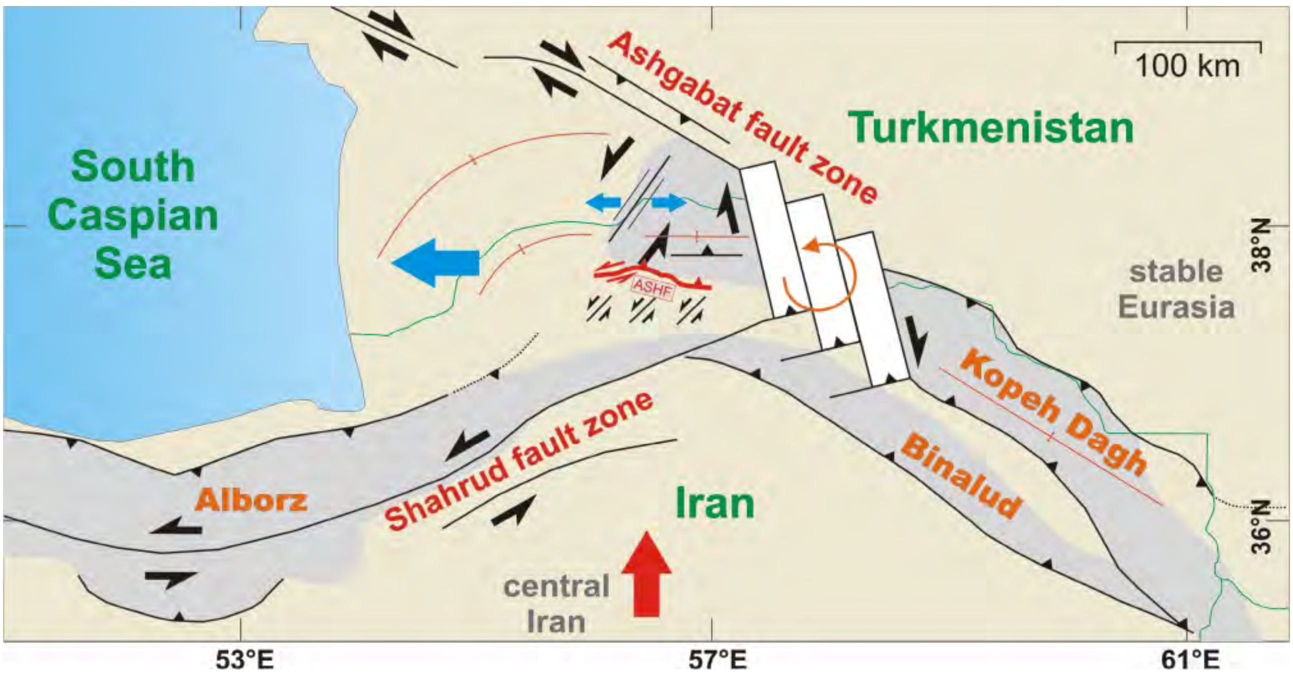

Figure 9: Simplified summary of the tectonic setting of the SE Caspian region and the KopehDagh/Binalud (strongly modified after Hollingsworth et al (2008); faults: black lines; green lines: national borders; red lines: fold axes; grey areas: mountain ranges; orange arrow: anticlockwise rotation of blocks in the central KopehDagh; red arrow: shortening; blue arrow: extension; red fault: investigated Ashkhaneh Fault (ASHF).

verse faults, like the investigated AHSF. Valve activity may be especially prevalent near the base of the seismogenic zone when unstable frictional faulting gives way to aseismic shearing with increasing depth. At such structural levels, cyclic variations in the style of deformation may accompany fluid pressure cycling.

Although direct absolute age dating of the youngest sediments, which are offset by the investigated faults, is out of the scope of this study, there are some good geomorphological evidences of active deformation along the faults. The best indication of the recent activity of these fault systems is indicated by the adaption of the active river course to uplifting areas or lateral displacement of more competent formations. Although thrusting of the Cretaceous rocks on Quaternary sediments can be locally observed, planned absolute age dating of the sediments by means of optical stimulated luminescence and cosmogenic nuclides will pin the age and rate of deformation of the faults in the Western KopehDagh.

5. Conclusions

The ASHF is an active NNE-dipping thrust with mechanically linked ENE-WSW striking left lateral strike slip faults. These faults accommodate the N-S oriented shortening between Iran and Eurasia and the W-E extension of the Western Kopeh-Dagh towards the South Caspian Sea. The ASHF is an active fault system, which offsets Quaternary sediments and which has a major influence on the geomorphology of the region. Two different models of active river course deflection occur: (i) Foreland originated transverse rivers are deflected to longitudinal rivers by the southward propagating topography above N-dipping thrust faults. (ii) Strike slip offset of longitudinal rivers into dogleg shaped river courses facilitating a minimum estimation of the offset along these faults. All faults record a strong involvement of fluid pulses associated with deformation.

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