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Inversion tectonics in central Alborz, Iran

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Abstract

Structural analyses carried out in the southern-central Alborz (Iran) have shown that the evolution of this belt has been strongly conditioned by the inversion of pre-existent extensional faults. Inversion tectonics has been identified especially in the southern part of the belt, and it is related to the reactivation of grabens formed in the foreland of the Late Triassic Eo-Cimmerian orogen, resulting from the accretion of the Iranian block to Eurasia. Three main associations of structures—active during the late Cenozoic—have been distinguished: (1) E–W thrust faults and folds followed by the activation of (2) E–W right-lateral strike-slip faults associated to large ENE–WSW trending en échelon folds, and finally (3) ESE–WNW to SE–NW thrust faults and left-lateral strike-slip faults inverting in some cases previous E–W right-lateral faults. Central Alborz is strongly controlled by the geometry of pre-existing tectonic discontinuities, which are responsible for strain partitioning between strike-slip and reverse faults during convergence. These results provide new insights on the style and evolution of this complex intracontinental belt, which can be considered a significant example of transpressive tectonics.

Keywords: Tectonic inversion; Fault analysis; Paleostress; Central Alborz; Cimmerian orogeny; Iran

1. Introduction

Inversion tectonics plays a fundamental role in the evolution of mountain belts (Trumpy, 1980; Lemoine et al., 1986; Gillcrist et al., 1987; Butler, 1989; Coward, 1994; Tavarnelli, 1999; Turner and Williams, 2004), especially in the external part of the orogens and in intracontinental belts (Laville et al., 1977; Letouzey, 1990; Sawaf et al., 1993; Searle, 1994; Song, 1997).

The Alborz mountain chain extends for several hundreds of kilometres between the Caspian Sea and the Iranian Plateau (Fig. 1) and represents a key-area to test the role of inversion tectonics. The belt is the result of different tectonic events: from the Late Triassic Cimmerian orogeny, resulting from the collision of the Iranian block with Eurasia, to the present day stage of intracontinental deformation related to the convergence between the Arabian and Eurasian plates. Important large-scale features of the belt consist in the lack of an axial metamorphic zone and in the absence of deep crustal roots (crustal thickness is 35 km, according to Tatar et al., 2002), which is apparently in contrast with the present day elevation of the belt (several summits over 4000 m) which was achieved since Late Miocene (Axen et al., 2001).

As observed by Gansser and Huber (1962), the main faults of the belt still show a normal separation which suggests the occurrence of ''anomalous'' tectonic contacts possibly related to partial inversion or weak reactivation of pre-existing normal faults. In addition, the recent Cenozoic evolution has been explained as the result of strain partitioning between left-lateral strike-slip and thrust faults, parallel to the belt (Jackson et al., 2002; Allen et al., 2003a,b), possibly related to the reactivation of previous faults.

Our field observations support the occurrence of inversion phenomena, which can strongly condition the tectonic style

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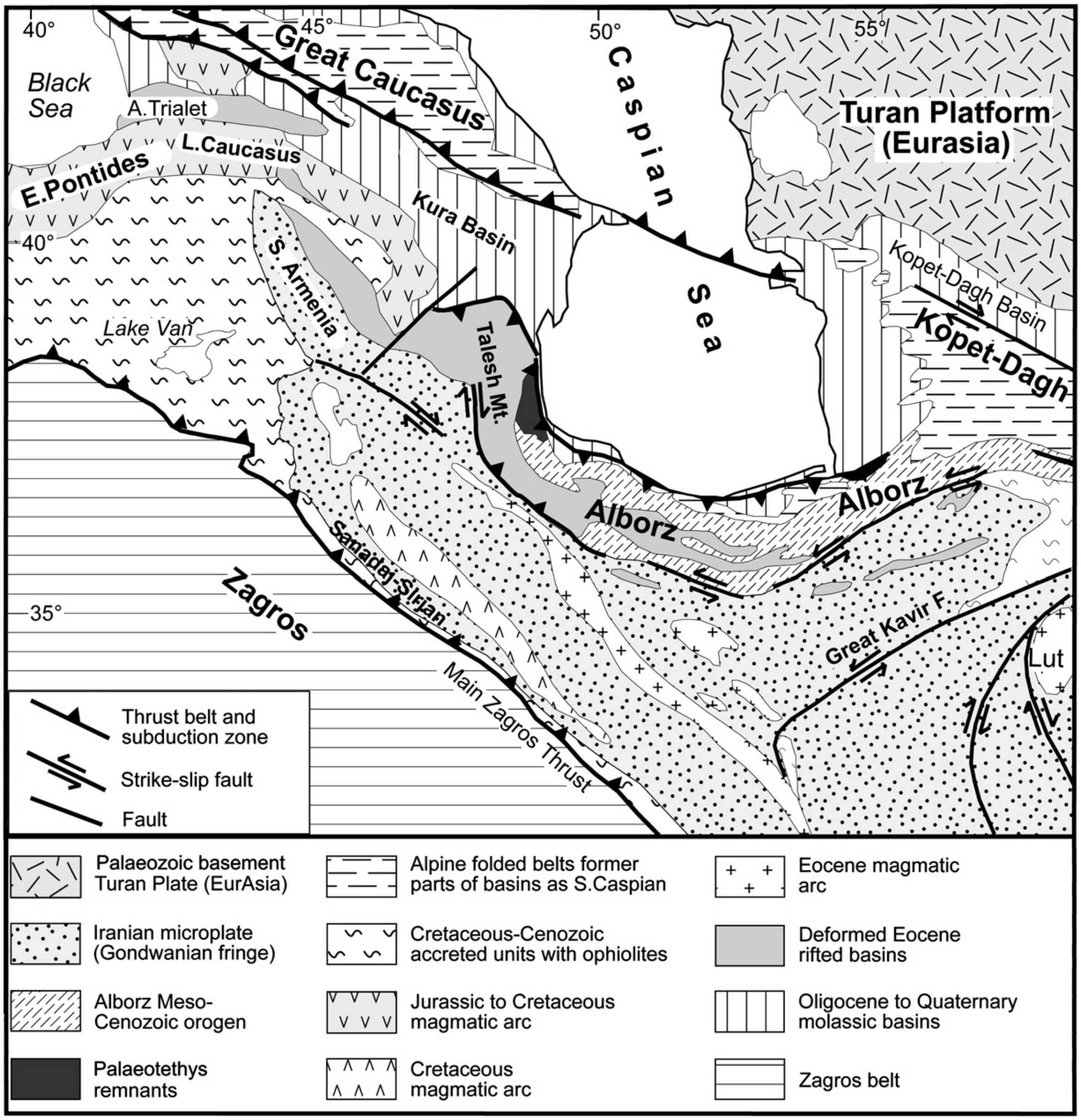

Fig. 1. General tectonic map of North Iran and of the South Caspian region. Modified from Brunet et al. (2003).

of this mountain chain. The aim of this paper is to describe in detail the structural setting and evolution of the Shahrestanak region located in the southern part of the central Alborz in the light of inversion tectonics and to test its possible occurrence along a N–S transect from Teheran to Chalus. Our work seeks to understand how the complex present-day pattern of deformation is conditioned by the structural framework inherited from the ancient history of the belt.

2. The Cimmerian orogeny

The oldest compressional event recorded in the area is the Cimmerian orogeny, which affected the Eurasian margin from Turkey to Thailand. It was chiefly caused by the early Mesozoic collision of several microplates detached from Gondwana. According to palaeogeographic reconstructions (Stocklin, 1974; Davoudzadeh and Schmidt, 1984; Sengor, 1984; Stampfli et al., 1991; Saidi et al., 1997; Besse et al., 1998; Gaetani et al., 2000; Stampfli and Borel, 2002), the Iranian microplate was the first block to collide with Eurasia during Middle-Late Triassic forming the Eo-Cimmerian orogen. This event is recorded by a low-angle regional angular unconformity (Stocklin, 1974; Jenny and Stampfli, 1978) along the northern margin of the Iranian plate, sealed by the Upper Triassic-Jurassic Shemshak Formation (Assereto, 1966a; Seyed-Emami, 2003). A Permo-Triassic accretionary-subduction complex marking the Paleotethys suture between the Turan and the Iranian plate has been recognized in the Mashad and Torbatjam regions to the east (Alavi, 1991; Ruttner, 1993). Alavi (1996) tentatively traces the Paleotethys suture westward across the Gorgan region to the Talesh mountains (western Alborz), where metamorphic nappes (Clark et al., 1975; Geological Survey of

Iran, 1998) are unconformably covered by the Shemshak Formation. The record of the Eo-Cimmerian orogeny is less evident in the central part of the Alborz. The Upper Triassic succession is almost continuous (Ghasemi-Nejad et al., 2004) and is marked by a sudden change in sedimentation, from shallow sea carbonates to silicilastic sandstones, suggesting that central Alborz was located south of the main suture zone and then behaved as a stable foreland region during the collision.

3. Geological setting of the central Alborz

3.1. Stratigraphic framework

The stratigraphic succession of the central Alborz (Assereto, 1966b; Alavi, 1991) spans the whole Phanerozoic and it is about 11 to 13 km thick. The Precambrian and Cambrian succession (3000–3500 m thick) is represented by coastal sandstones and dolostones, with continental deposits (eolian?) in the Early Cambrian. Ordovician and Silurian are poorly represented, whereas the Devonian–Middle Triassic succession is well developed (1300–1500 m) and consists of predominantly shallow marine carbonates intercalated with basaltic lava flows, evolving to a widespread carbonate platform sedimentation in the Triassic (Elika Formation). The latest Precambrian to Middle Triassic succession is unconformably covered by the Shemshak Formation, up to 4000 m thick, deposited after docking of the Iran microplate to the Eurasian margin. The age of the base of the Shemshak Formation is diachronous, being Late Triassic in the central Alborz and Early to Middle Jurassic to the north toward the Caspian Sea (Clark et al., 1975; Geological Survey of Iran, 1992; Seyed-Emami, 2003; Ghasemi-Nejad et al., 2004; Fursich et al., 2005). The formation consists of continental sandstones, shale and coal passing upward to shallow marine deposits blanketing the Eo-Cimmerian orogen and its foreland. The Eo-Cimmerian unconformity is particularly evident in the Shemshak area, where the basal beds of the formation lie directly on the Permo-Carboniferous units.

The shallow water Upper Jurassic–Cretaceous carbonate succession (400–600 m), which is irregularly preserved and locally folded (Guest et al., 2006), is unconformably covered by the Palaeocene Fajan continental conglomerates, up to 300 m thick. They are succeeded by the Eocene volcanic and volcaniclastic complex of the Karaj Formation, more than 3000 m thick. The Karaj Formation records the activation, in an extensional regime, of an intracontinental volcanic arc related to northward subduction along the Zagros suture (Alavi, 1996).

The Miocene succession (up to 200 m thick) consists of coastal fine-grained terrigenous units with evaporites and limestones. Continental Plio-Quaternary uplifted and deformed conglomerates are widespread, especially along the frontal parts of the belt.

3.2. Tectonic setting

The present-day tectonic framework of central Alborz is characterized by WNW–ESE and E–W trending high-angle faults parallel to the belt (Fig. 2), showing both right- and left-lateral strike-slip motions as well as oblique to dip-slip

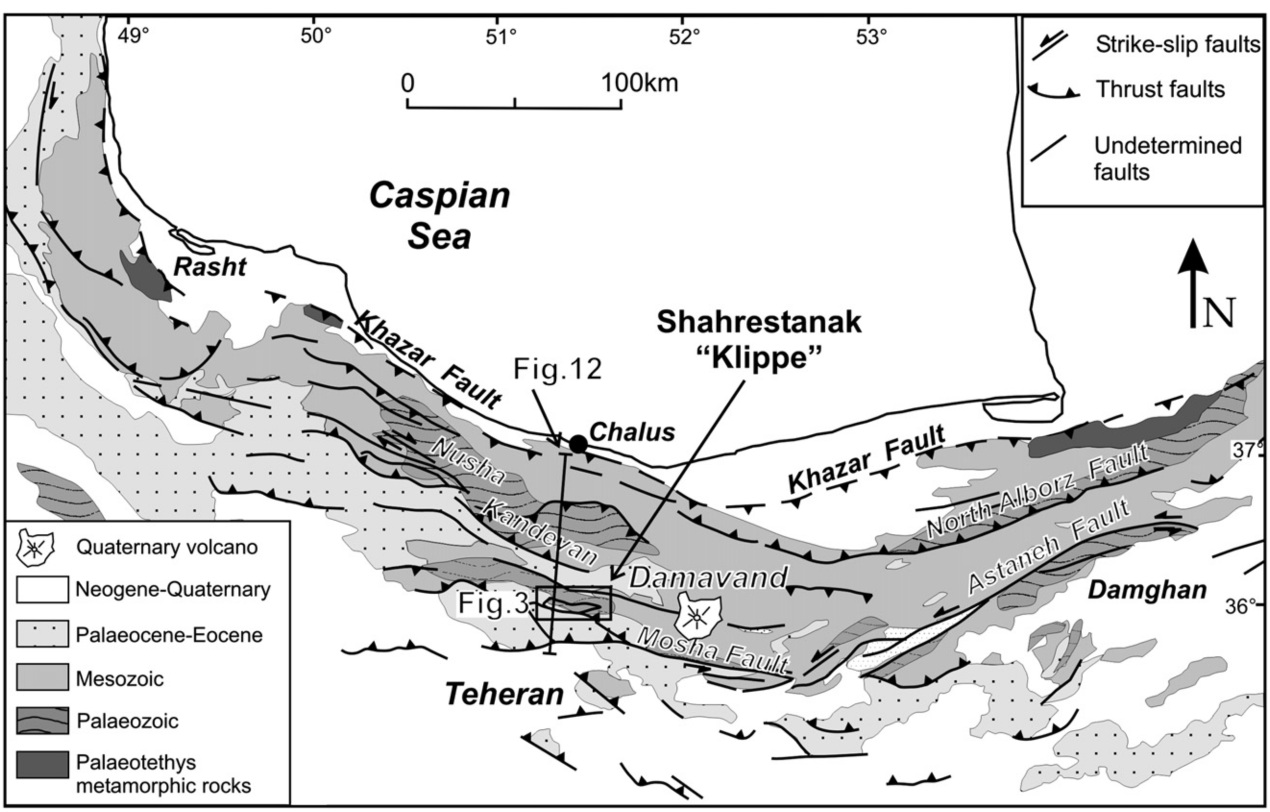

Fig. 2. Tectonic map of the Central Alborz, modified from Allen et al. (2003a). The box refers to the main study area.

movements (Allen et al., 2003a,b), often with a normal component of separation (Gansser and Huber, 1962). The main faults generally dip symmetrically inward from the southern and northern parts of the range. Spacing between the faults ranges from 10 to 20 km. Compressive deformation has been active since Oligocene (Allen et al., 2003a) and active faults occur along the southern part of the belt (Bachmanov et al., 2004), as well as along the Caspian coast. An older compression is testified by folded Cretaceous limestones sealed by flat-lying Eocene volcanics (Guest et al., 2006).

The oldest Precambrian and Cambrian units are exposed in the axial part of the belt between the Kojour fault to the north and the Kandevan thrust to the south and are slightly deformed, showing gentle folds. Most of these faults are high-angle reverse or right-lateral strike-slip faults and are now seismically inactive (Jackson et al., 2002). The Kandevan thrust, a 200 km long fault parallel to the belt, stacks the Shemshak Formation on the Eocene volcanics. North of the Kojour fault, Jurassic to Cretaceous successions are displaced by minor reverse faults and extend up to the active N-verging Khazar thrust which runs parallel to the Caspian coast. South of the Kandevan thrust, previous authors describe one of the most important piece of evidence of crustal shortening in central Alborz, the Shahrestanak klippe (Fig. 3), as an allochthonous tectonic unit possibly related to the Kandevan thrust (Assereto, 1966b; Alavi, 1996; Allen et al., 2003a). The Precambrian and Palaeozoic units are here uplifted again southward between the Taleghan and the Shahrestanak-Maygoon faults and are stacked southward on the Tertiary successions (Guest et al., 2006).

Right-lateral strike-slip motions along ESE–WNW faults have been related to a N–S compression active during the Miocene (Allen et al., 2003a). A dextral transpression is also suggested by the en-échelon arrangement of the main folds of the area, consisting of large ENE–WSW trending open anticlines oblique to the main faults, such as the ones located east of Karur and north of Zaigun (Fig. 3) which expose the Cambrian and Precambrian successions. Axen et al. (2001) also recognized important dextral faults displacing Early Tertiary plutons. These faults, including also the Kandevan Thrust, are intruded by the 7 Ma old Alam Kuh granite and are thus older.

An inversion in the sense of motion along longitudinal faults from right-lateral to left-lateral has been related to a major reorganization in plates configuration (Allen et al., 2002). One of the major active structure absorbing oblique convergence is the Astaneh-Firuzkuh-Mosha fault system. A left-lateral offset of about 30 km has been estimated along the Mosha Fault (Allen et al., 2003a), forming a transpressional wedge between Teheran and Karaj (Guest et al., 2006). The E–W trending North Teheran and Qazvin faults, located in the southern frontal part of the belt along the western continuation of the Mosha Fault, are characterized by reverse motion, and show clear evidence of recent tectonic activity (De Martini et al., 1998; Jackson et al., 2002; Allen et al., 2003a; Bachmanov et al., 2004; Ashtari et al., 2005). The Alborz still represents a region of strong active deformation between the more stable Iranian Plateau and the Eurasian plate to the north. N–S shortening across central Alborz has been evaluated to 5 ± 2 mm/yr using GPS measurements (Vernant et al., 2004).

4. The Shahrestanak "klippe"

In the southern part of central Alborz an isolated, 30 km long and 5 to 2 km wide, E–W oriented ridge, composed of the Permo-Triassic carbonates of the Ruteh and Elika Formations, outcrops between the villages of Shahrestanak and Lalun (Fig. 3). This structure, known as the "Shahrestanak klippe", was interpreted as an isolated thrust sheet by Assereto (1966b), and has since been considered as the most important evidence of severe crustal shortening in the Alborz (Alavi, 1996). In this interpretation, mainly based on the high topographical relief of the structure and on the complex tectonic relationships with the surrounding units, previous authors interpreted the "Shahrestanak klippe" as the relict of an allochthonous thrust sheet rooting in the Kandevan Thrust (Assereto, 1966b).

The "Shahrestanak klippe" is mainly formed by the Triassic platform carbonates of the Elika Formation. The Permian units of the Dorud and Ruteh Formations outcrop at the core of two ENE–WSW oriented anticlines, along the southern part of the ridge. Both the northern and the southern boundaries of the graben show variable stratigraphic separations along the strike, and their geometry is complicated by secondary strike-slip faults (Fig. 4).

The steep (>70°) E–W trending border faults of the "klippe" dip inward the axis of the structure. The trace of the faults cross a young topographic relief characterized by high crests and deeply dissected valleys, giving a sinuous fault trace despite the straight geometry of the structures. To the north, the boundary fault separates the Triassic carbonates of the Elika Formation in the hanging wall, from Cambrian to Upper Palaeozoic sequences in the footwall, generally with a normal stratigraphic throw in the western part. Eastward the border faults of the structure became vertical, due to more intensive strike-slip reactivations (Fig. 5). The Elika Formation is in contact eastward with the Shemshak formation along a high angle fault, showing a reverse stratigraphic throw. The fault at the southeastern border of the klippe separates the Permo-Triassic Ruteh and Elika Formations in the hanging wall from the Lower Palaeozoic to Precambrian successions in the footwall (Fig. 4). Toward the west the geometry of the southern boundary of the "klippe" is more complex. North of Maygoon, the high angle normal fault, which bounds the "klippe" to the south, is clearly sealed by Palaeocene conglomerates which overlie both the hanging wall and the footwall (Fig. 6). This evidence clearly proves a pre-Palaeocene age of the "Shahrestanak klippe" bounding faults. At the western tip of the structure, the Palaeocene conglomerates and the overlying Karaj Formation are intensively folded and partially detached from the Elika Formation which is stacked southward on the Miocene red beds.

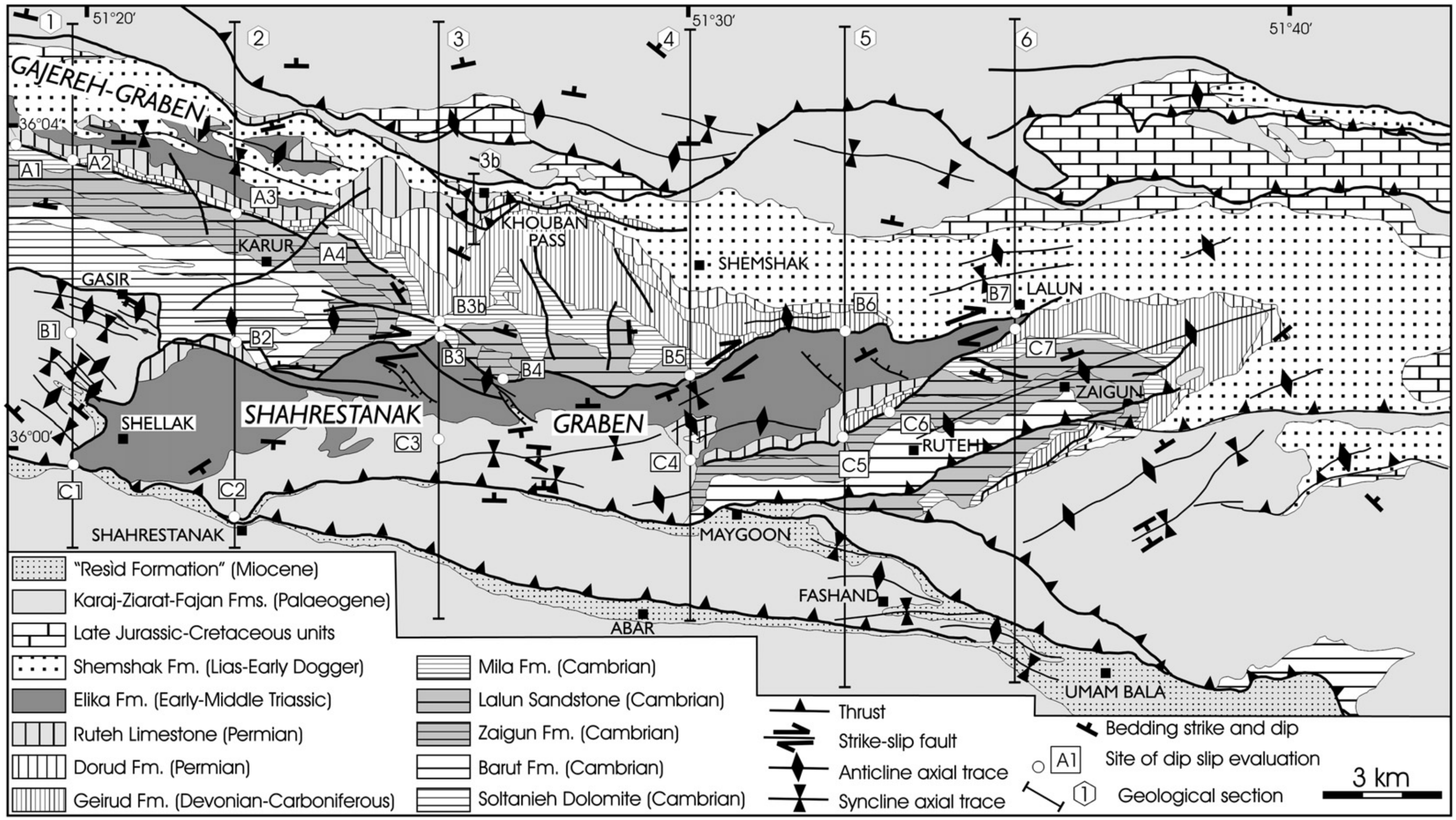

Fig. 3. Simplified geological map of the Shahrestanak area, from Assereto (1966b) and our own observations.

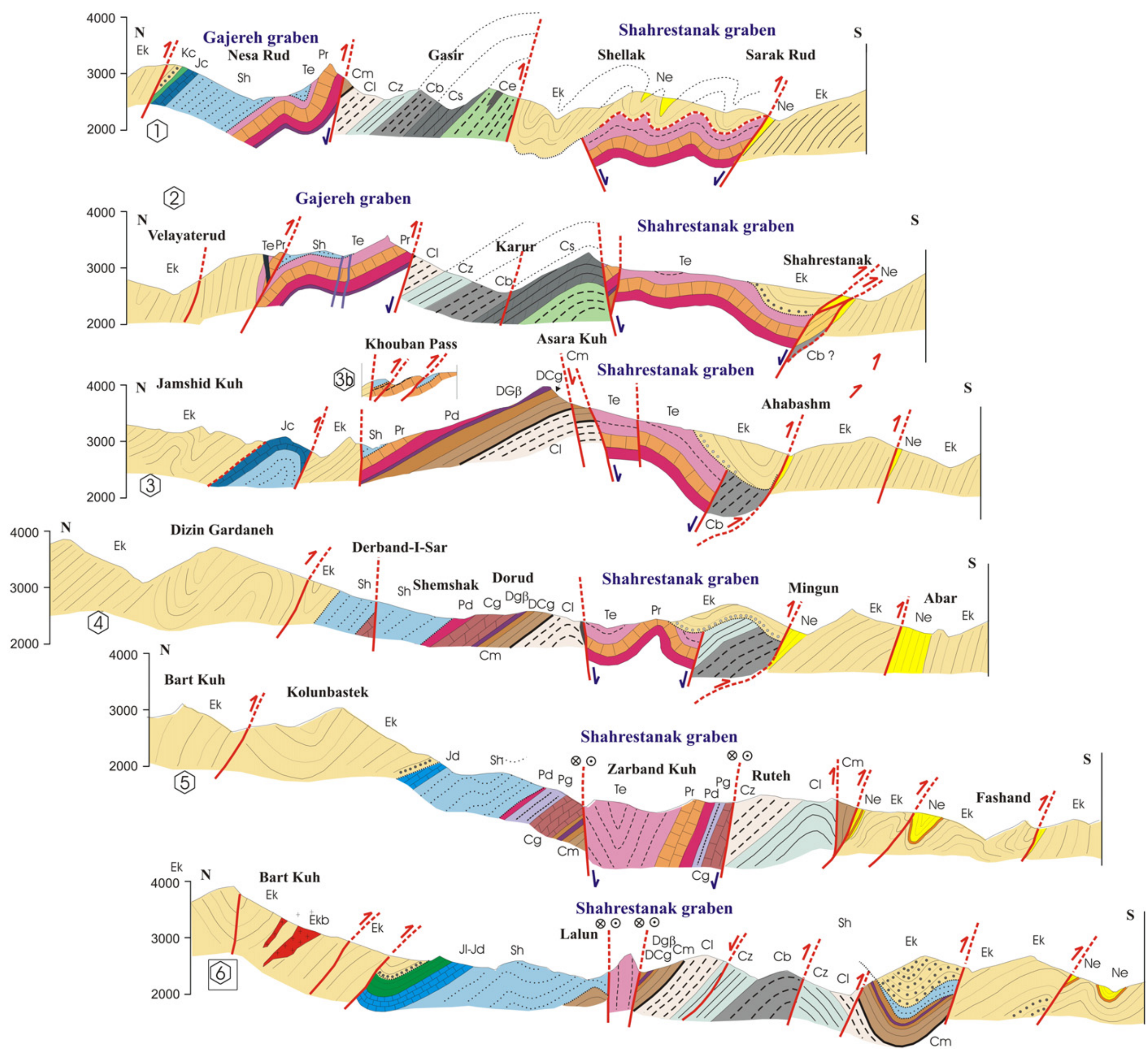

Fig. 4. Selected cross-sections for the "Shahrestanak Klippe", now interpreted as an inverted-reactivated graben; traces of the sections in Fig. 3. Cs, Soltanieh Dolomite (Precambrian–Early Cambrian); Cb, Barut Formation (Early Cambrian); Cz, Zaigun Formation (Early Cambrian); Cl, Lalun Sandstone (Early–Middle Cambrian); Cm, Mila Formation (Middle–Late Cambrian); DCg, Geirud Formation, member A; DgB, Member A basaltic flows (Pre-Devonian–Tournaisian); Cg, Geirud Formation, Member B (Early Carboniferous); Pd, Dorud Formation (Early Permian); Pr, Ruteh Formation (Late Permian); Te, Elika Formation (Early–Middle Trias), Sh, Shemshak Formation (Late Trias–Dogger); Jc, Abnak and Lar Limestone (Late Dogger–Malm); EK, Fajan Conglomerate and Karaj Formation and (Palaeocene–Eocene); Ne, Red Formation (Miocene). Age determinations according to Assereto (1966b).

The structural and stratigraphic features of the "Shahrestanak klippe" suggest that it is indeed a reactivated extensional structure. This interpretation is supported by several lines of evidence. Where the boundary faults show minor or no reactivation, their stratigraphic throw is normal and the vertical normal displacement, evaluated on the basis of the stratigraphic throw, can be more than two kilometres (Fig. 7). This indicates that the Permo-Triassic succession was bordered by normal faults and that the "Shahrestanak klippe" was originally a graben.

Another structure which resembles the "Shahrestanak klippe" is the Gajereh half-graben (Figs. 3 and 4, sections1, 2), exposed to the north. It is bordered by the Nesa Fault, that still displays a stratigraphic normal throw, separating Permo-Triassic rocks in the hanging wall from Cambrian units in the footwall.

The age of the extensional structures is constrained by the different stratigraphic record within and outside the two grabens. The Elika Formation is preserved only in the Shahrestanak and in the Gajereh grabens; in the latter the Triassic carbonates are capped by the Shemshak Formation. Outside the grabens, the Elika Formation has been completely eroded before the deposition of the Shemshak Formation, which

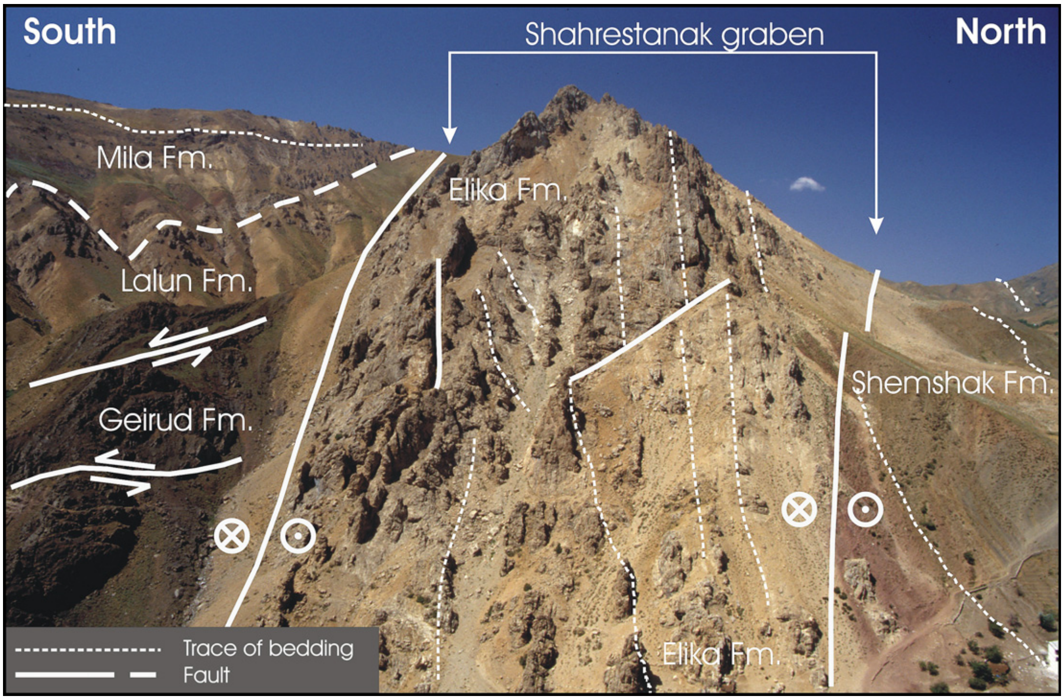

Fig. 5. View of the eastern closure of the Shahrestanak graben, here bordered north and south by vertical strike-slip faults, Lalun Village site Lalun 1; symbols as in previous figures.

covers with a low-angle unconformity Permian or Carboniferous units. This suggests that the Shemshak Formation sealed an existing horst and graben setting. In other part of the belt, synsedimentary normal faults and neptunian dikes with an E–W present-day trend have been recognized in the Shemshak Formation (Barrier et al., 2004), suggesting that extensional tectonics persisted during its deposition. Fursich et al. (2005) suggested that the upper part of the Shemshak Formation of the eastern Alborz was deposited in an extensional basin.

Therefore, the normal faulting event occurred after the deposition of the Elika Formation, which does not show evidence of syn-depositional tectonics. This indicates a Middle-Late Triassic age for the extensional event forming the Shahrestanak graben and the Gajereh half-graben, which likely represent the faraway response to the Eo-Cimmerian orogeny active along the northern margin of the present-day Alborz belt (Fig. 8).

The complex history of inversion and reactivation of the graben occurring during the formation of the present-day belt is described in detail in the next section.

5. Structural analysis around the Shahrestanak graben

Detailed structural analyses have been performed in the region of the Shahrestanak graben located around the Shemshak

Fig. 6. View of the western side of the Djadje Rud just north of the village of Maygoon. The normal fault between the Lalun and the Ruteh Formation is sealed by the Fajan Conglomerate and by the Karaj Fm; symbols as in previous figures.

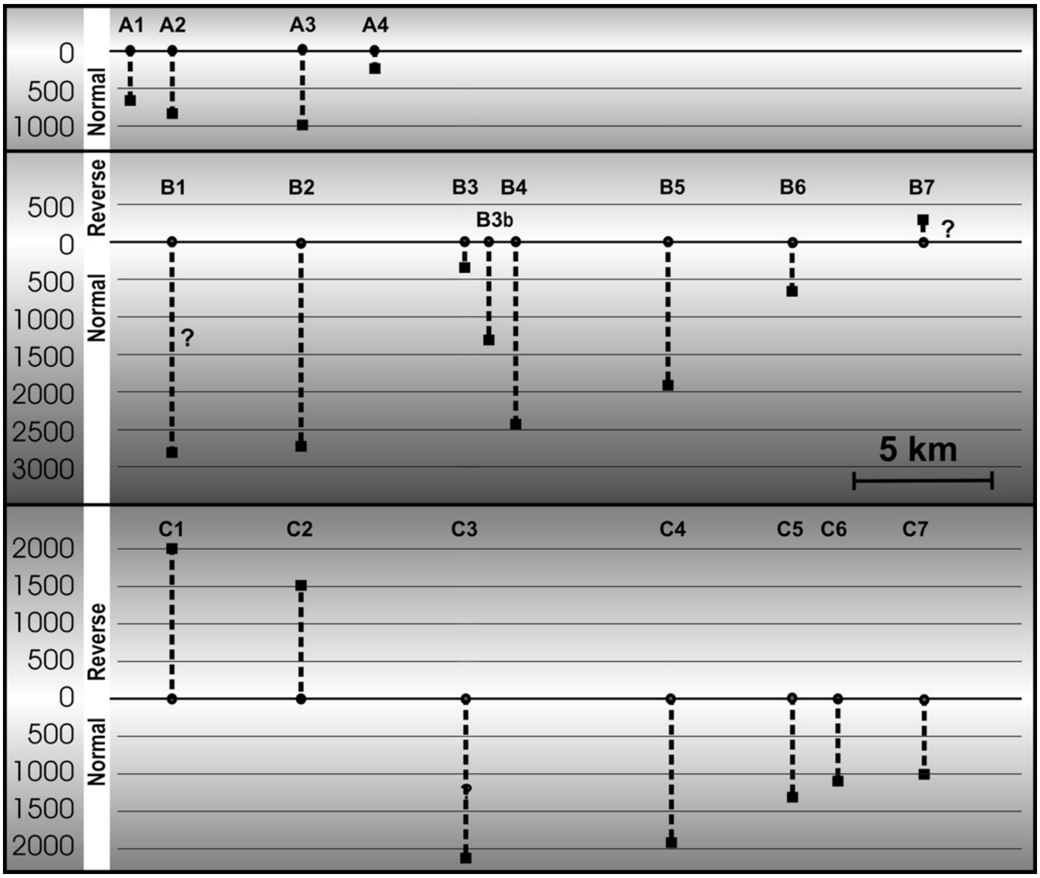

Fig. 7. Separation diagram for the border faults of the Shahretsanak and Gajereh grabens. Reference points are shown in Fig. 3.

ski-resort and along the Karaj-Chalus road in the central part of the chain. We focused on the analysis of the main faults and folds reported in published geological maps (Assereto, 1966b; Geological Survey of Iran, 1991, 1997) in order to reconstruct the kinematics of the main faults, to understand their geometrical relationships, and their evolution during the structuration of the central Alborz. Folds have been also analysed in order to define their relationships with the general

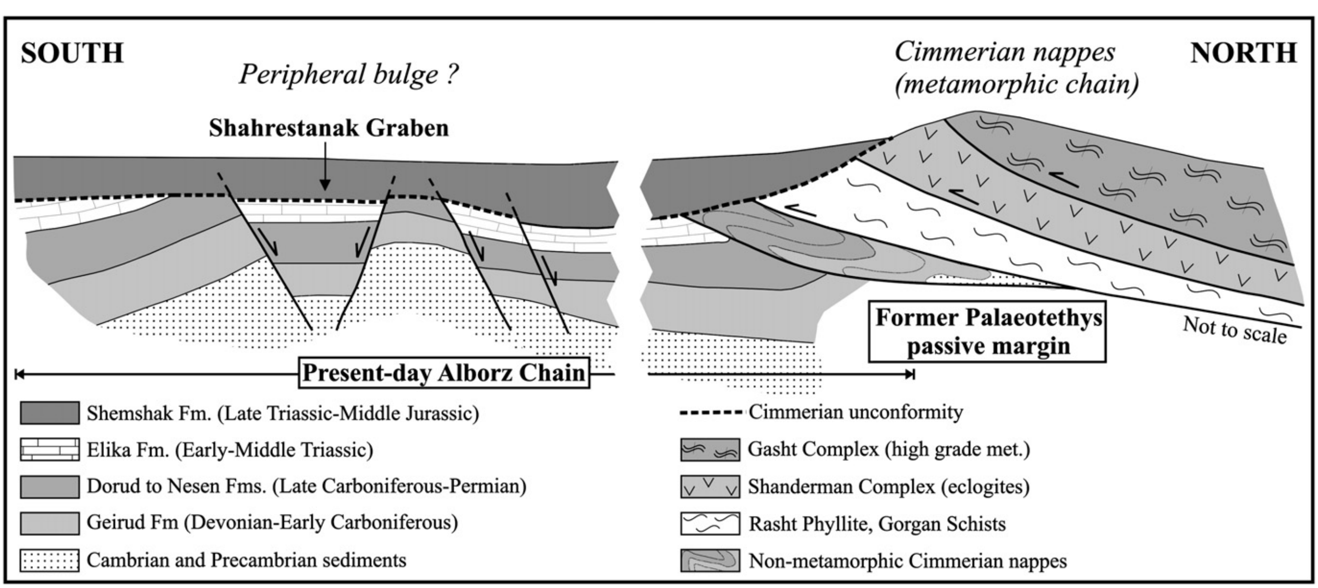

Fig. 8. Tentative sketch of the relationships between the Shahrestanak and Gajereh grabens and the Cimmerides.

fault kinematics. About 1000 mesoscopic tectonic structures were measured in the area. Several kinds of mesoscopic tectonic structures have been analysed, including striated and not striated faults, folds, axial plane foliations (slaty and stylolitic cleavages) and mylonitic foliations with S-C structures along the main thrust faults. As most of the faults show polyphase movements, a relative chronology has been established, according to cross-cutting relationships among fractures and/or striations, their relationships with the main stratigraphic unconformities, and reactivations of previously formed planes.

Fault populations measured in several sites were used for palaeostress reconstructions. We used the direct inversion INVD (Angelier, 1990) and the stress tensor research through iterative procedures R4DT (Angelier, 1984) for palaeostress reconstruction with striated fault populations, choosing for each site the best fitting solution.

Palaeostress analyses are known to be good tools to unravel the structural evolution of mountain chains, especially in the case of brittle deformation (Chang et al., 2003). Moreover, palaeostress reconstruction helps to constrain the kinematic compatibility among different fault sets when fault populations are complex and allows to differentiate polyphase fault associations. This technique eventually describes stress variations across regions of complex deformation, as in the case of the study area, where block rotations along vertical axes can be likely associated to strike-slip fault activity.

Table 1 contains all the results for stress tensor determinations, which include the adopted numerical method (R for iterative procedure and I for direct inversion), faults number (N), ratio φ between the differences of the principal stress eigenvalues, $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, average (av) and maximum (M) angle between computed shear stress and slip vector (ANG), average (av) and maximum (M) value for the quality estimator parameter (RUP) for solutions obtained with INVD. We generally accepted numerical solutions for average and maximum value of ANG respectively of 10–12° and 20–22° and average and maximum value of RUP of 35 and 55. For complex and polyphase fault populations, we considered larger deviations and solutions obtained with less than 8 faults, which must be considered as a broad indication of the palaeostress state.

Folds have been described measuring the attitude variations of bedding, axes, hinge lines, axial plane cleavage and of axial surface.

Three main associations of compressive structures have been identified. The Eo-Cimmerian extension is not

Table 1
Information on stress tensor determinations in the Central Alborz

Site	Method	No. of data	σ_1 plunge/dip	σ_2 plunge/dip	σ_3 plunge/dip	Ratio φ	ANG av (°)	M (°)	RUP av (%)	M (%)	Fm.	
Thrust stacking and folding												
Gazir-A (17)	R	12	181/15	273/04	016/74	0.44	16	26			Karaj (Eo)	Fig. 9a
Khouban2A (2)	R	14	190/13	099/03	356/76	0.511	7	22			Ruteh (M-Per)	Fig. 9a
Khouban-3A1 (3)	R	5	023/04	114/08	265/81	0.32	11	19			Tiz Kuh (Cre)	Fig. 9a
Khouban-3A2 (3)	R	16	201/13	052/75	293/07	0.15	7	17			Tiz Kuh (Cre)	Fig. 9a
Khouban-4A (4)	R	4	196/26	015/64	106/00	0.41	2	5			Shemshak (L Tr–M Ju)	Fig. 9a
Right-lateral transpression												
Lalun1 (5)	R	8	294/11	186/58	031/30	0.25	13	24			Elika (E–M Tr)	Fig. 9b
Ruteh (6)	R	8	336/25	098/49	231/30	0.45	6	15			Zaigun (Cam)	Fig. 9b
Kohestan-1 (9)	R	16	317/03	053/62	225/27	0.046	13	29			Ruteh (M Per)	Fig. 9b
Kohestan-2 (10)	I	7	315/03	217/71	046/19	0.29	18	39	45	65	Ruteh (M Per)	Fig. 9b
Geirud (13)	R	14	324/20	201/56	064/26	0.08	5	12			Mila (Cam)	Fig. 9b
Dorud-2 (14b)	R	14	123/17	239/56	023/29	0.85	11	35			Dorud (E Per)	Fig. 9b
Dorud-1 (14a)	R	8	128/15	259/67	034/16	0.06	10	21			Dorud (E Per)	Fig. 9b
Karur-A(16)	R	8	145/05	002/83	235/04	0.001	12	19			Elika (E–M Tr)	Fig. 9b
Gazir-B (17)	I	4	155/11	063/10	292/75	0.17	7	12	28	37	Karaj (Eo)	Fig. 9b
Khouban-1	R	7	143/15	025/61	240/24	0.001	8	19			Karaj (Eo)	Fig. 9b
Left-lateral transpression												
Khouban-2B (2)	R	14	190/13	099/03	356/76	0.51	7	22			Ruteh (M Per)	Fig. 10
Khouban-3C (3)	R	7	251/11	128/71	345/15	0.12	18	40			Tiz Kuh (Cre)	Fig. 10
Khouban-4B (4)	R	10	245/28	147/14	033/58	0.25	11	24			Tiz Kuh (Cre)	Fig. 10
Fashand (7)	R	6	049/03	319/04	177/84	0.55	7	14			Karaj (Eo)	Fig. 10
Sharistanak (15)	R	6	030/12	299/01	203/78	0.57	5	8			Karaj (Eo)	Fig. 10
Unam (8)	R	9	053/02	323/07	159/82	0.64	6	13			Karaj (Eo)	Fig. 10
Afjah (18)	R	11	028/28	120/04	217/62	0.93	21	39			Karaj (Eo)	Fig. 10
Bafkijan (19)	R	8	209/13	317/74	111/33	0.56	8	16			Karaj (Eo)	Fig. 10
Ira (20)	R	5	223/66	042/24	132/00	0.27	10	19			Karaj (Eo)–L Pleist	Fig. 10

The following indications are reported: name of site; inversion method: I (INVD), R (R4DT); number of data used for stress tensor determination; plunge/dip of the main stress axes σ_1, σ_2, σ_3 ($\sigma_1 > \sigma_2 > \sigma_3$); ratio φ: $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; average value av (°) and maximum value M (°) of ANG; average value av (%) and maximum value M (%) of RUP; name of the formation (Fm); reference figure.

documented by mesoscopic structures, due to strong overprinting during the Cenozoic compression.

5.1. E–W reverse faults and folds

The oldest compressive structures recognized in southern-central Alborz are E–W trending folds and north-dipping reverse faults (Fig. 9). Structures related to this event form a small imbricate thrust fan exposed south of the Kouban Pass, causing the tectonic repetition of the ironstone beds at the top of the Ruteh Formation (Fig. 4, section 3b). Faults are low-angle dip-slip thrusts. Similar faults are represented by conjugate thrust and strike-slip faults in the limestones of the Cretaceous Tiz Kuh Formation along the splays forming the eastern continuation of the Taleghan Fault. The main folds affecting the Ruteh Formation, at the axial part of the ‘‘Shahrestanak graben’’, can be related to this event, as suggested by cross-cutting relationships with subsequent right-lateral strike-slip faults. Mesoscopic E–W thrust faults with dip-slip motion occur along the Gazir fault, which stacks Cambrian units upon the Eocene volcanics.

5.2. E–W dextral faults (dextral transpression)

The most important tectonic structures recognized in this area are E–W trending dextral strike-slip faults which occur especially along the borders of the Eo-Cimmerian grabens (Fig. 9). Most of the main faults of the area show right-lateral cinematic indicators, which record this important tectonic event recognized in the whole Alborz belt (Axen et al., 2001; Allen et al., 2003a; Guest et al., 2006). E–W oriented right-lateral strike-slip faults overprint the northern boundary fault of the ‘‘Shahrestanak graben’’ from the Gazir valley eastward to Lalun. A strong reactivation with a right-lateral sense of movement can be observed everywhere with an almost horizontal slip vector. This suggests that the normal offset, which in some part exceeds 2 km, has been mostly achieved during previous extension when the graben formed.

Dextral and high-angle NNE–SSW reverse faults clearly overprint previous E–W folds within the Shahrestanak graben in the deep gorge south of Shemshak. Dextral faults are often associated with minor NNW–SSE to N–S trending left-lateral strike-slip faults which suggest a NW–SE compression in a strike-slip regime. ENE–WSW en échelon normal faults also occur within the Elika Formation in the Sahhrestanak graben, also suggesting dextral shearing (Fig. 3). In several sites high-angle reverse and dextral reverse faults are subordinately associated to pure strike-slip faults indicating a transpressive regime also at the mesoscopic scale. The importance of the dextral transpression is also enhanced by the occurrence of curved en échelon WNW–ESE trending folds that are geometrically consistent with E–W right-lateral fault parallel to the main trend of the belt. These folds are evident in the eastern part of the klippe, where the Cambrian and the Eocene beds are strongly deformed and uplifted.

Palaeostress tensors obtained for this stage are the most reliable and consistent within the whole analysed fault populations, indicating a NW–SE compression in a strike-slip tectonic regime.

5.3. E–W left-lateral strike-slip and NE–SW thrust faults

These structures consist of ESE–WNW to SE–NW oriented thrust faults with dip-slip motion occurring in the southern part of the study region (Fig. 10). This stage, which is the youngest deformational event in the Alborz belt, is also responsible for the inversion of the shear sense along some of the E–W strike-slip faults, from right- to left-lateral. This phenomenon has been described in terms of transpressive inversion which has been related, as in our case, to the reactivation of pre-existent shear zones (Allen et al., 2001). The most important structure related to this stage is the Shahrestanak-Maygoon-Afjah fault, a branch of the Mosha thrust. This pure dip-slip thrust fault stacks southwards the Cambrian units—forming the southern shoulder of the Shahrestanak graben—on Miocene beds (Figs. 4, 7, 9). We interpret this fault as a deep shortcut propagating from the southern boundary fault of the Shahrestanak graben. This thrust forms a restraining bend of the active Mosha Fault (Guest et al., 2006). West of the village of Ira, the Mosha fault becomes a vertical left-lateral strike-slip fault, locally forming a releasing bend associated to normal faults (Fig. 9). The fault plane, which is well exposed along an artificial trench, displaces recent alluvial deposits covered by red palaeosoils with a vertical offset of at least 5 m. Faults are sealed by a recent soil.

Striations indicating left-lateral motions along E–W trending previous right-lateral faults were observed along some of the northern faults of the Shahrestanak graben (Karur16, Fig. 9) and in the Shemshak area close to the Khouban Pass along a splay of the Thalegan Fault. Overprinting relationships confirm that this stage is the most recent one. The E–W branch of the Mosha Fault joins the seismically active North Teheran Fault, whereas the Maygoon-Shahrestanak-Afjah branch seems less active. S-vergent NE–SW folds formed in the Eocene Karaj Formation along the Shahrestanak-Maygoon-Afjah thrust can be related to this event. These folds show a strong asymmetry and a shorter wavelength than the ones related to the dextral transpression. They are well exposed around Fashand and west of Shellak, where the Eocene volcanics are clearly detached from the Triassic substratum.

The obtained palaeostress tensor solutions suggest a pure compressional regime related to NW–SE reverse faults as well as a strike-slip regime with a permutation between the intermediate and minimum axis. The horizontal projection of σ_1 is close to the present-day direction of maximum shortening (N30°E) obtained by Vernant et al. (2004) from geodetic data.

5.4. Tectonic inversion of the Shahrestanak Graben

Structural data indicate that central Alborz is characterized by different episodes of transpressive deformation since Oligocene, that postdate older events. Field evidence in the area around Shemshak has shown the occurrence of old extensional

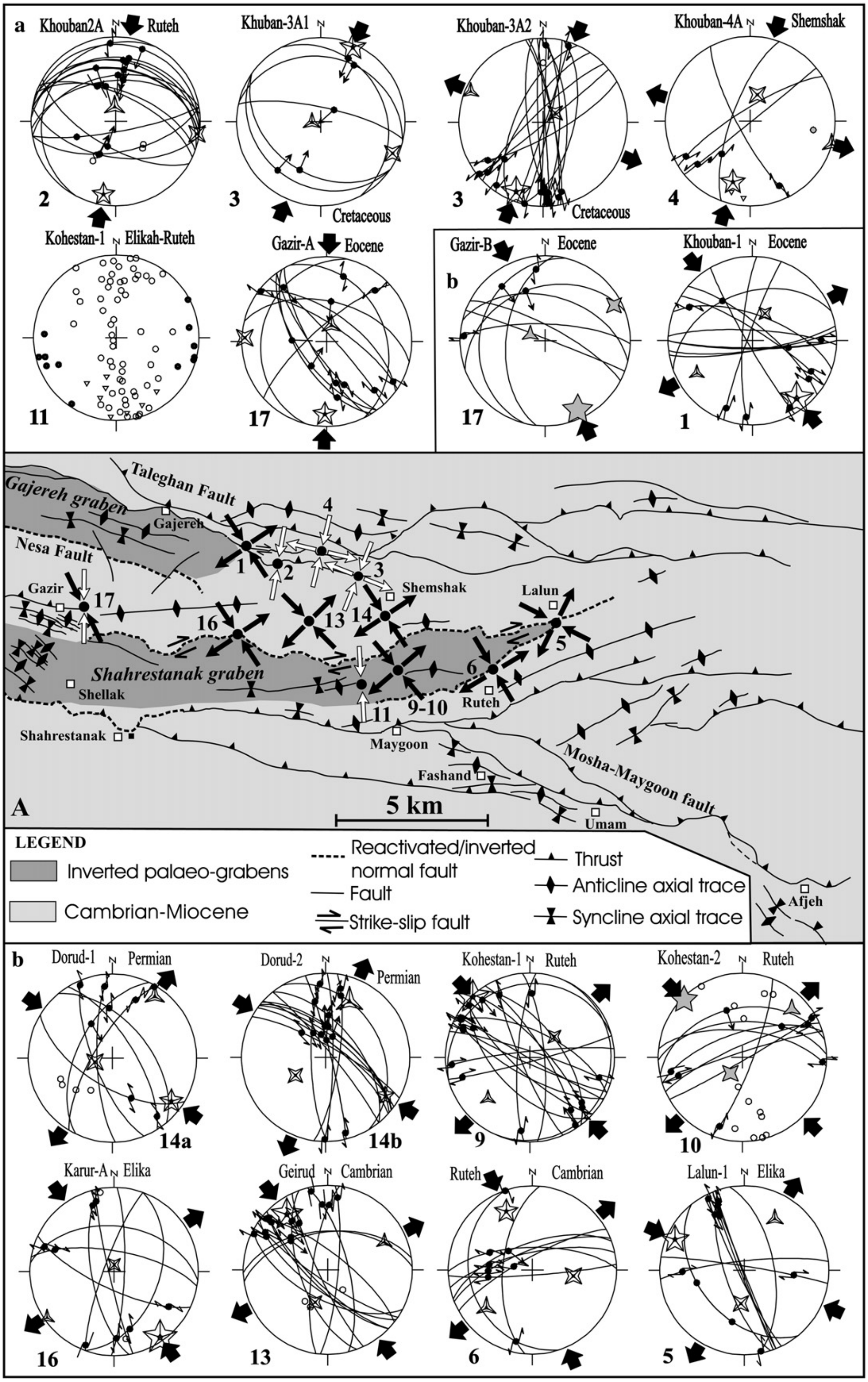

Fig. 9. Examples of fault populations and folds for the N–S to NNW–SSE compression (white arrows) and for the dextral transpression (black arrows) with palaeostress determinations from fault inversion. Schmidt's projection lower hemisphere. Thin lines are faults, black dots represent striations with relative sense of motion, triangles are poles to axial plane cleavage and axial surfaces, large dots are poles to bedding planes. Convergent black arrows represent the horizontal projection of the σ_1 axis obtained by stress tensor determinations of good quality; grey arrows refer to stress directions deduced through geometrical criteria. σ_1, σ_2, σ_3 axes ($\sigma_1 > \sigma_2 > \sigma_3$) are respectively represented by five-, four- and three-point stars. Complete results are given in Table 1.

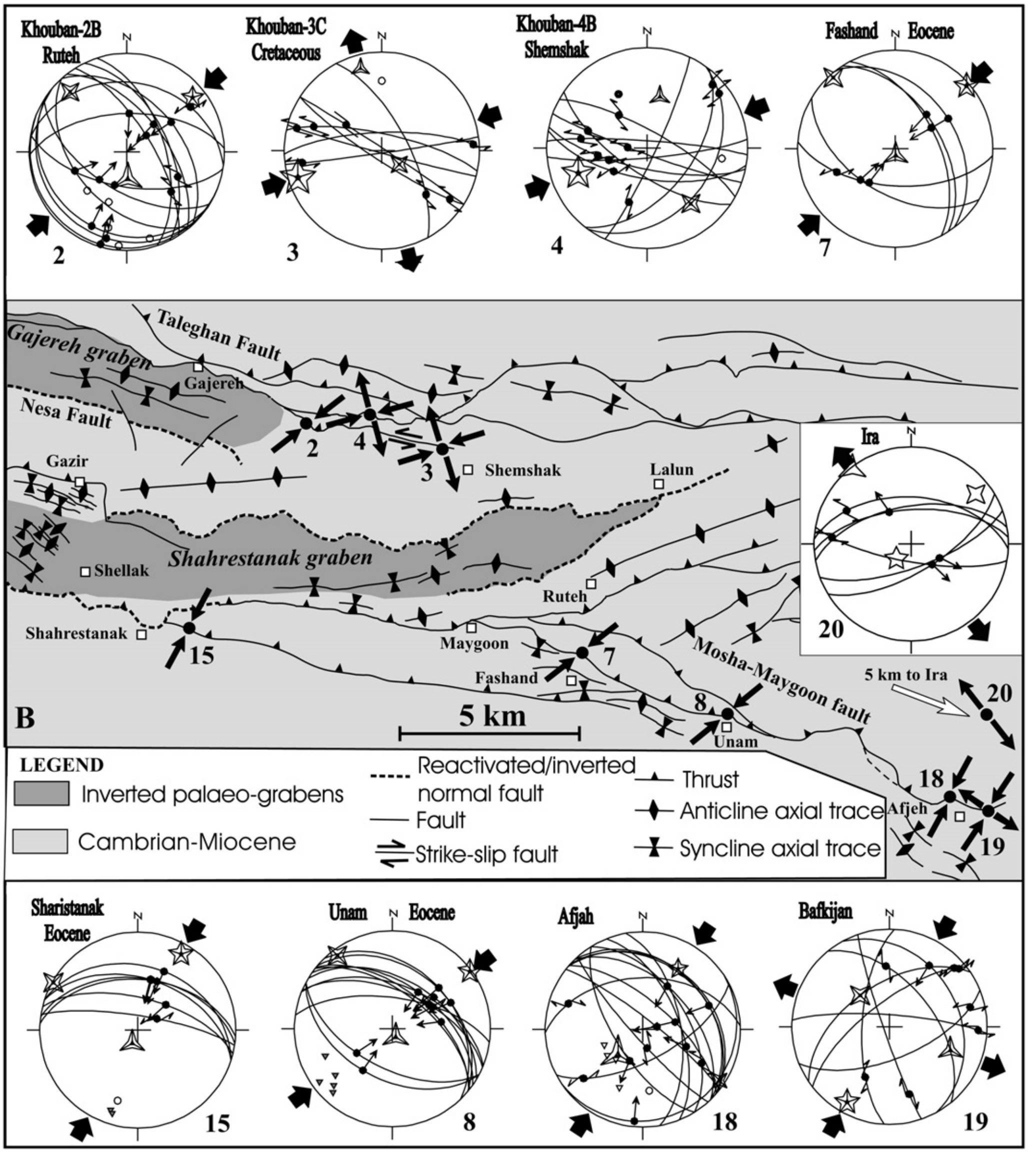

Fig. 10. Palaeostress determinations from fault inversion for the NE–SW compression.

structures that were activated after the deposition of the Elikah Formation and before the end of the deposition of the Shemshak Formation Fig. 11(1). Grabens formed during the Eo-Cimmerian orogeny within the stable foreland of the Iranian block, possibly due to peripheral bulging of the stable area located south of the main collision zone.

The evaluated throw of the border faults of the graben exceeds the stratigraphic separation between the units sealed by the Shemshak Formation (Elika Formation to upper Geirud Formation) that is surely less than 1 km. This can be explained invoking a partial reactivation of the normal faults before and during the deposition of the Palaeocene–Eocene beds, which show significant thickness variations across the area due to syn-sedimentary tectonic activity Fig. 11(2). During Cenozoic, normal faults have been reactivated as strike-slip or high-angle reverse faults.

The first deformational event formed E–W trending tight to isoclinal folds with steep axial planes within the Shahrestanak and Gajereh grabens, interpreted as buttressing structures causing a plain strain deformation with vertical extension (Gillcrist et al., 1987; Butler, 1989) in response to the obstacle created by pre-existent high-angle normal faults which are unsuitable to thrust propagation. These folds are crossed by dextral strike-slip faults reactivating the northern border faults of the Shahrestanak and Gajereh grabens. Such faults strongly overprint the border faults of the Shahrestanak Graben between Ruteh and Lalun (Fig. 7).

The most recent and active tectonics (Allen et al., 2003a) are characterized by a NE–SW compression causing an inversion of the sense of motion of longitudinal faults from right- to left-lateral and the associated activation of ESE–WSW thrust faults. During this event shortcut thrust planes developed along the Maigoon-Shahrestanak branch of the Mosha thrust south of the Shahrestanak graben. These deep faults, branching from the north-dipping normal faults bounding the

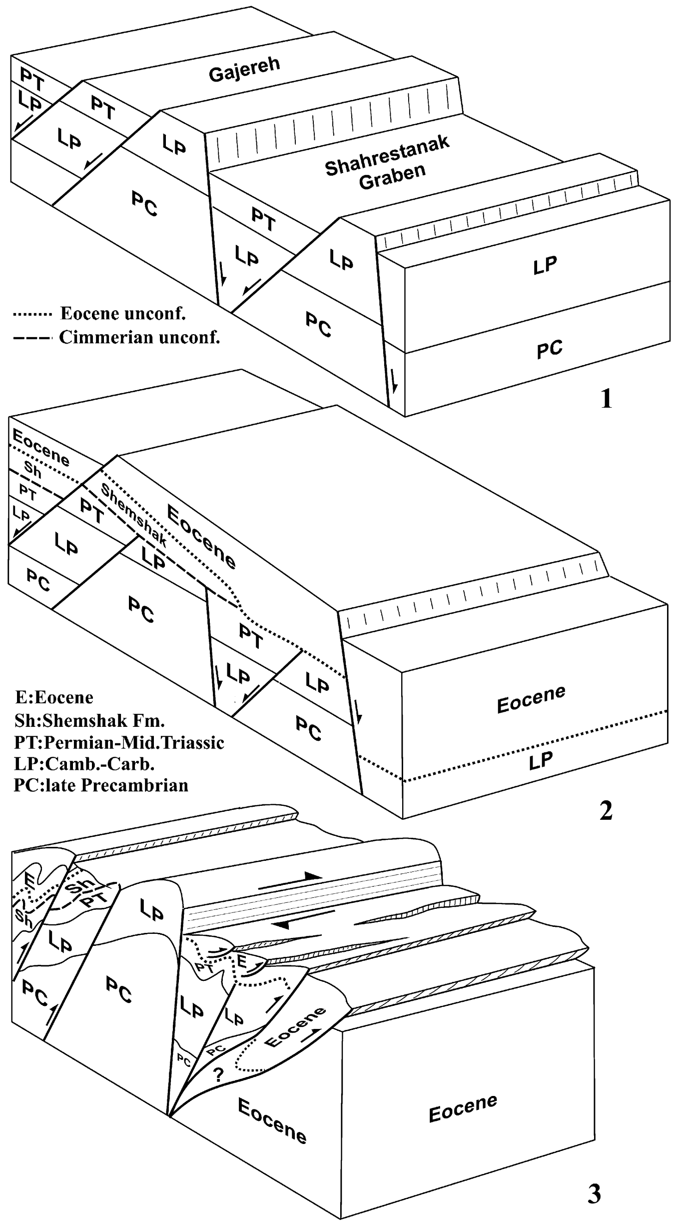

Fig. 11. Evolution of the Shahrestanak structure during Mesozoic and Tertiary. (1) early Late Triassic, when grabens formed in the Cimmerian foreland due to peripheral bulging; (2) sealing of the grabens after the deposition of the Shemshak and of the Eocene volcanics; (3) Neogene-Quaternary inversion, enhancing strain partitioning along pre-existent normal faults.

southern part of the graben, form small "floating horses" (Gillcrist et al., 1987) of Cambrian to Precambrian rocks, which are stacked along the palaeo-graben shoulders above the Tertiary successions. In this case, an apparent offset of several kilometres is shown between the Cambrian and the Miocene; if we assume that the exhumation of the graben shoulder occurred during extension, the throw is reduced to a maximum of 1 to 2 km, resulting from the Cenozoic inversion (Fig. 7).

6. Tectonic implications for the central Alborz

Different structural models have been presented for the Alborz. Alavi (1996) presents a model in which the belt is interpreted as an antiformal stack affected by extensional detachments on its Caspian side. According to Allen et al. (2003a), vertical right-lateral strike-slip fault characterize the central part of the Alborz mountain belt, whereas imbricate thrusts and complex triangle zones formed in the external zones, with the "Sharestanak klippe" resting on the top of the thrust pile. N–S shortening at the longitude of Teheran is evaluated to about 30 km. Guest et al. (2006), basing on detailed mapping, emphasize the importance of unconformities and of pre-Late Cenozoic tectonics, obtaining a shortening of about 50–55 km across the belt, considering also folding and strike-slip components.

We present a regional cross section of the central Alborz (Fig. 12), based on structural and geological observations along the Karaj-Chalus road and on detailed analysis in the Shahrestanak region. Our reconstruction indicates that most of the shortening across the belt is achieved along its frontal parts, as suggested by thrust activity around Teheran and recent tectonic activity along the Kazar fault to the north (Berberian et al., 1992; Vernant et al., 2004; Ashtari et al., 2005). High-angle and vertical faults dominate the axial zone of the belt, showing reverse motions and subsequent right-lateral motions. In the case of the Kojour, Dashband and Kandevan Faults the throw is reverse, whereas a normal stratigraphic separation is evident along the N- and S-axial faults and Nesa fault and across the Shahrestanak Graben. The Thalegan fault has a complex development showing left-lateral motions (Guest et al., 2006); around Gajereh, the stratigraphic separation is reverse, as folded Cretaceous beds are stacked on the Eocene units, whereas along the section it shows a normal separation. Due to strong thickness variations of the Eocene volcanics across the structure, this fault was possibly active as a normal fault during the deposition of the Eocene volcanics.

According to our interpretation, most of the internal part of the central Alborz is characterized by high angle faults associated to the reactivation and inversion of previous normal faults in a transpressive regime which can account for most of the "anomalous" contacts. Complex inversion of the Eo-Cimmerian extensional faults can explain the uplift of Precambrian and Palaeozoic units along the Fashand branch of the Mosha fault and their juxtaposition with the Permo-Triassic units in the Shahrestanak graben. A similar scenario can help to explain the uplift of the Precambrian basement in the Kahar Mountains to the west.

7. Conclusions

Central Alborz is a significant example of a transpressive belt dominated by strain partitioning between distinct strike-slip and thrust faults which result from inversion and reactivation of pre-existing structures inherited from the long and complex evolution of this segment of the Alpine–Himalayan orogenic system. Structural data and stratigraphic constraints demonstrate that the general structure of the Southern Central Alborz is strongly controlled by the geometry of pre-existing zones of weakness, which mainly consist of extensional faults

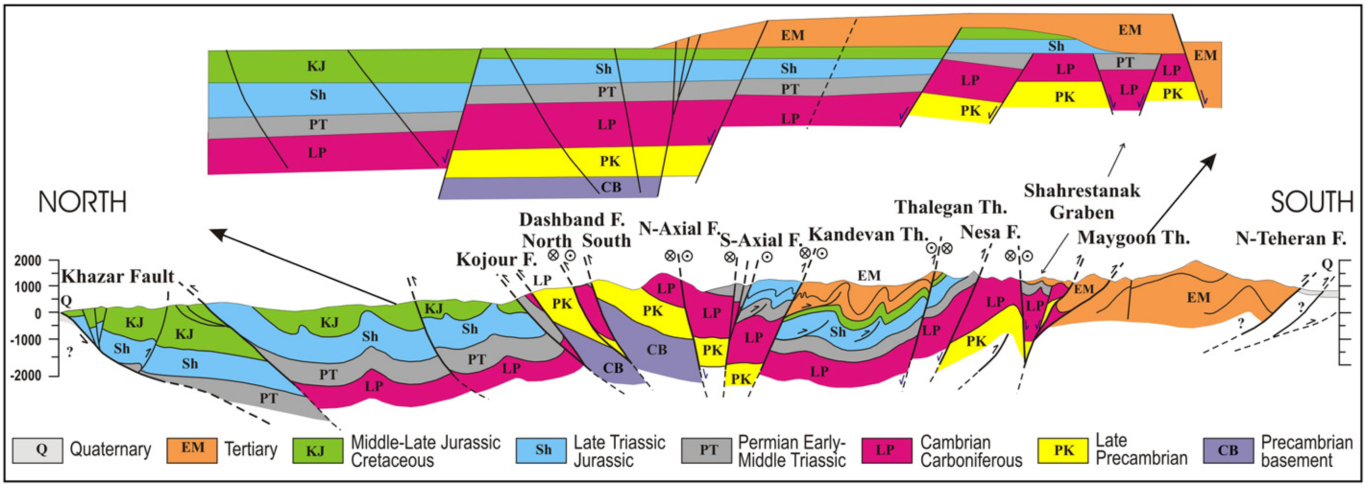

Fig. 12. Interpretative geological section across the central Alborz; trace in Fig. 2.

related to the pre-Neogene evolution of the area. In the Shahrestanak and Gajere grabens stratigraphic evidence testifies that these extensional structures were formed during the Eo-Cimmerian orogeny. The tectonic history of the southern central Alborz can be extrapolated also to other parts of the belt, where some of the main faults still stack young units above older ones. Reactivation of normal faults in other parts of the Alborz are not necessarily related to the Cimmerian extension only, but can be linked to other extensional events predating the Neogene compression. The existence of different extensional episodes is also suggested by important thickness changes across the whole Phanerozoic stratigraphy. The reconnaissance of these extensional structures can also explain the presence of strongly uplifted portions of the Palaeozoic and pre-Palaeozoic basement along the southern margin of the belt, without forcing the occurrence of isolated thrust sheets moving from a long distance.

Fault analyses and palaeostress reconstruction suggest that extensional structures in the central Alborz have been reactivated during different tectonic stages which are consistent in the whole study area. A N–S compression activating E–W thrust and forming E–W folds evolves into a right-lateral transpression during Late Miocene, which is related to a NW–SE direction of maximum compression. This stage is followed by a second transpressive event that is still active. Pre-existent structures have been inverted as E–W trending strike-slip or NW–SE high-angle reverse faults, depending on their attitude. Pre-existing discontinuities thus controlled the partitioning of strain along faults parallel to the trend of the belt, in response to an oblique convergence, as shown by the present-day evolution of the belt, where both left-lateral and reverse faults are active.

The tectonic framework of the belt is thus characterized by positive flower structures, which contributed to the high topographic relief of the chain and to its rapid uplift since the Miocene. Uplift has been favoured by inversion as a consequence of buttressing related to high-angle pre-existent discontinuities, and to the formation of positive flower structures related to oblique reactivation of pre-existing normal faults, without necessarily implying important shortening and thickening of the basement. Dry climatic conditions, persisting during the latest Cenozoic in the southern part of the belt, favoured the preservation of the topographic relief, which suddenly decreases towards the rainy Caspian side of the belt.

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