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Accommodation of late Cenozoic oblique shortening in the Alborz range, northern Iran

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Abstract

The Alborz range, northern Iran, deforms by strain partitioning of oblique shortening onto range-parallel left-lateral strike-slip and thrust faults. Deformation is due to the north–south Arabia–Eurasia convergence, and westward motion of the adjacent South Caspian relative to Iran. Roughly north–south shortening occurs on thrusts that dip inwards from the range margins. Precambrian basement is not exposed because of detachment along upper Proterozoic evaporites and the thickness of overlying strata (~10 km). Other detachments occur within Phanerozoic sediments. Active left-lateral strike-slip faults trend ENE in the east of the range, WNW in the west. The eastern Mosha Fault has a left-lateral offset of ~30–35 km. Shortening across the range is ~30 km (25–30%) at the longitude of Tehran. This is hard to reconcile with the crustal thickness of ~35 km, which is similar to adjacent basins. Percentage shortening across the Alborz is similar to the adjacent Kopet Dagh, but because the latter is twice as wide, finite shortening is roughly half. The difference may be accommodated by subduction of the adjacent South Caspian Basin northwards under the middle Caspian. South Caspian sediments began folding in the Pliocene; the present kinematics of the Alborz may have begun at this time, including a reversal from range-parallel right-lateral to left-lateral strike-slip faulting, but the regional stratigraphy indicates uplift as early as the mid Tertiary.

Keywords: Strain partitioning; Transpression; Alborz; Iran

1. Introduction and geological setting

The Alborz range of northern Iran is a region of active deformation within the broad Arabia–Eurasia collision zone. The range is also an excellent example of coeval strike-slip and compressional deformation, and as such can be an analogue for inactive fold and thrust belts thought to involve a component of oblique shortening (transpressional deformation) (e.g. Harland, 1971; Vauchez and Nicolas, 1991; Dewey et al., 1998). It is roughly 600 km long and 100 km across, running along the southern side of the Caspian Sea. Several summits are >4000 m in altitude. Damavand, a dormant volcano, reaches 5671 m. The highest non-volcanic summit is Alam Kuh, at 4830 m (Fig. 1).

The paper describes the late Cenozoic structural geology of the Alborz (Figs. 1 and 2). The approach is to integrate many decades of field-based observations by the Geological Survey of Iran (e.g. Geological Survey of Iran, 1985, 1987, 1991a,b,c) with recent seismicity studies (Priestley et al., 1994; Berberian, 1997; Berberian and Yeats, 1999; Jackson et al., 2002), and data derived from our own fieldwork, satellite image and aerial photograph studies.

Upper Proterozoic clastics of the Kahar Formation are the oldest known rocks; unequivocally Precambrian metamorphic basement is nowhere exposed. The Kahar Formation passes conformably into a Cambrian–Triassic platform succession (Fig. 3). The Proterozoic–Triassic sedimentary succession is ~6 km thick in places (Geological Survey of Iran, 1991b). Stampfli et al. (1991) suggested that an Alborz block separated from Gondwanaland in the Ordovician–Silurian. It collided with Eurasia in the Late Triassic (Sengör et al., 1988). Metamorphic relics of this Palaeo–Tethyan collision are preserved in discontinuous outcrops along the northern margin of the present range, such as the Gorgan Schists in the northeast (Fig. 1).

South of these metamorphic units there was widespread deposition of the Lower Jurassic, locally Rhaetic, Shemshak Formation, which predominantly consists of fluvial and

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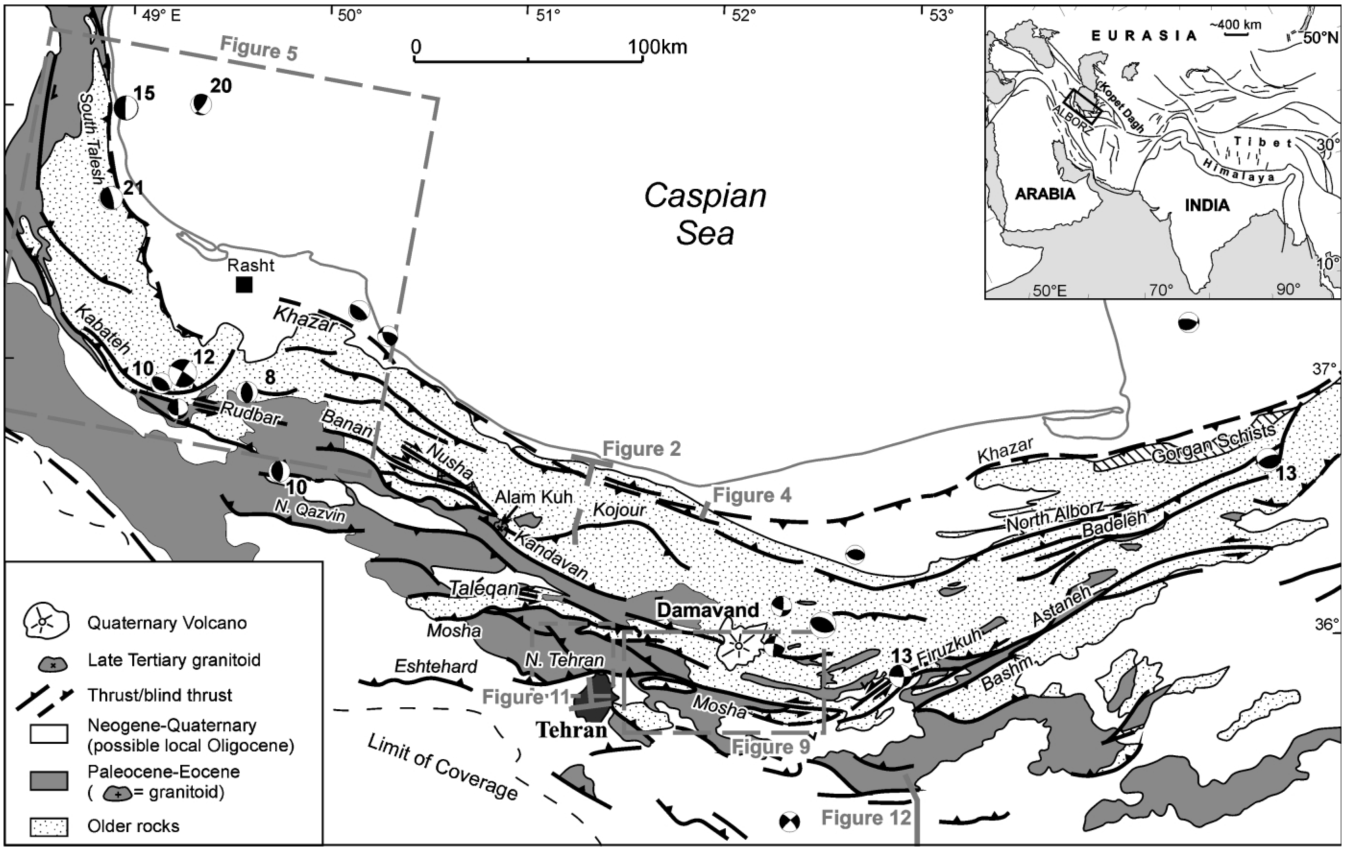

Fig. 1. Geology of the Alborz and, inset, its location within the Arabia–Eurasia collision. Geology derived from the National Iranian Oil Company (1977, 1978). Focal mechanisms are from Jackson et al. (2002). Adjacent numbers are earthquake depths in kilometres.

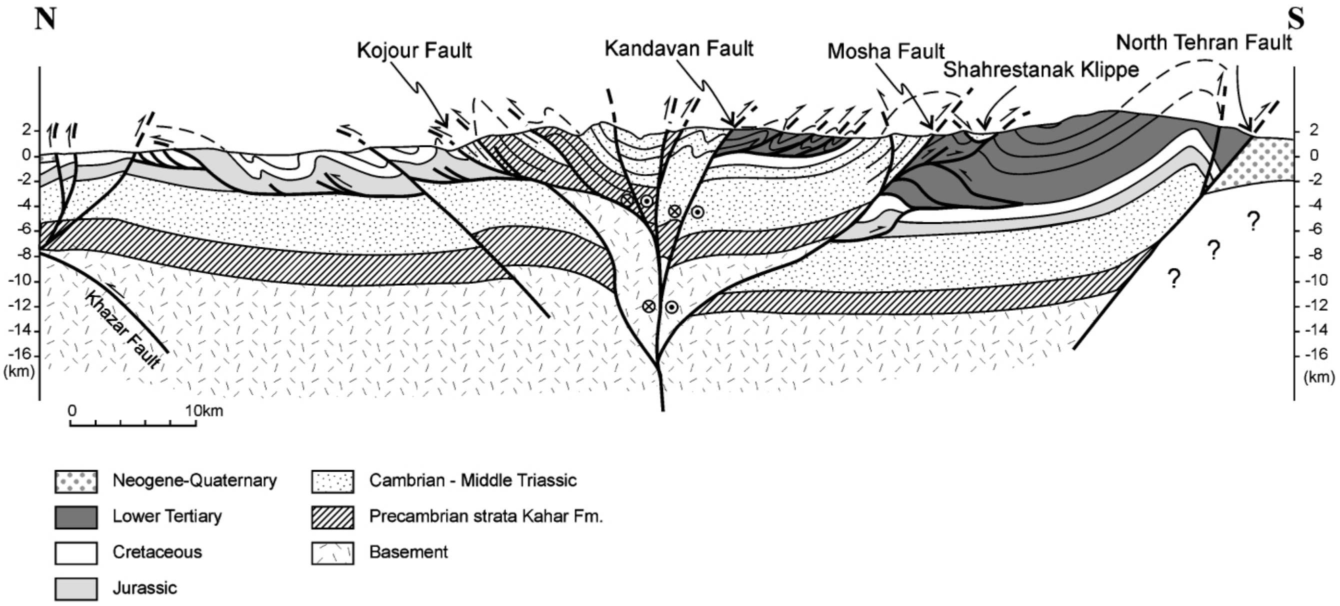

Fig. 2. Cross-section through the Alborz at the longtidue of Tehran (51°30′ E). Based on Stöcklin (1974), Geological Society of Iran (1987, 1991b) and our fieldwork. There are no indications that the late Cenozoic right-lateral faults in this part of the Alborz are active, in contrast to the left-lateral faults elsewhere in the range.

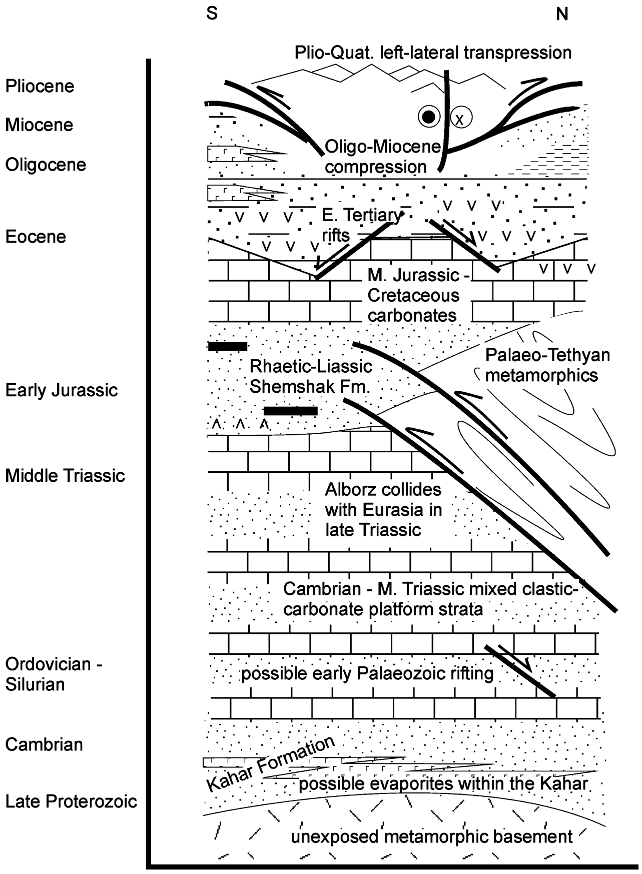

Fig. 3. Simplified tectonostratigraphy of the Alborz.

deltaic clastics, including coals. Marine Middle Jurassic–Early Cretaceous carbonates and clastics were followed by Late Cretaceous carbonates, basaltic and andesitic volcanics across large parts of the Alborz. In the northeast, sedimentation across the Gorgan Schists began diachronously between the Early Jurassic and the Late Cretaceous (Geological Survey of Iran, 1991a). Neogene clastics cover Mesozoic strata disconformably. It is questionable whether there ever was any early Tertiary deposition in this area, or if it was eroded prior to the Neogene sedimentation.

Elsewhere in the range, Paleocene deposition of the Fajan conglomerate heralded the Eocene Karaj Formation. This locally reaches 5 km in thickness, and is principally exposed in the southern Alborz (Fig. 1), where it consists of interbedded andesitic volcanics and clastics. Gypsum and anhydrite occur locally, especially at the base and top of the unit. Large scale slumps and organic-rich mudstones in the middle of the succession may indicate a deep-water basin, consistent with the existence of thick (>5 km) Paleocene–Eocene turbidites and sub-aqueous basalts in the neighbouring Talesh (Talysh) region of Azerbaijan (unpublished CASP data).

Few Oligocene strata are known from the Alborz, but to the south there are terrestrial red beds of this age in the interior of central Iran (Lower Red Formation). Mud volcanoes are present near the border with Turkmenistan. These resemble mud volcanoes in the Azerbaijan sector of the South Caspian Basin. It is probable that they indicate the presence of the mud-prone Oligocene–lower Miocene Maikop Suite in the sub-surface.

Miocene fluvial and lacustrine clastics are present in intermontane basins within the Alborz and at its southern margin. Middle and upper Miocene marine clastics occur in the foothills in the northeast of the range. Evaporites are present at several Tertiary intervals to the south of the range, but not the north. Central Iran and the southern margin of the Alborz were also affected by a short-lived latest Oligocene–early Miocene marine transgression, which resulted in the deposition of Qom Formation limestones. This unit is not known in the north. In general, the Cenozoic succession within and adjacent to the Alborz coarsens upwards, suggesting increased sub-aerial relief in the range over time, and consistent with the abundant evidence for young and active compressional deformation (Stöcklin, 1974; Alavi, 1996). This Cenozoic deformation is caused by the Arabia–Eurasia collision, which began as early as the middle Eocene (Hempton, 1987), but has increased its regional effects in the late Cenozoic. Deformation within the cover of the South Caspian Basin began in the late Pliocene offshore (Devlin et al., 1999) but possibly slightly earlier onshore (Aliev, 1960).

Two features of the Alborz are surprising for an active fold and thrust belt with such high relief: the young magmatism and relatively thin crust. The Alam Kuh granite (Fig. 1) was intruded at ca. 7 Ma (Axen et al., 2001), but no other late Miocene intrusions are known from the range. Damavand (Fig. 1) is a unique dormant volcano within the range. Its oldest products are probably no older than Pliocene. The lavas are shoshonitic, i.e. high K (Aftabi and Atapour, 2000). It is enigmatic why there should be recent magmatism at all in the Alborz, and whether the Damavand and Alam Kuh centres are related. Recent magmatism occurs in other areas of Iran, such as the Sabalan and Sahand volcanoes west of the Alborz. In broad terms, all of this magmatism is likely to relate to the Arabia–Eurasia collision, but the details remain poorly understood. The crust of the Alborz is ~35 km thick (Tatar, 2001), which is no thicker than the basins to its north and south.

North of the Alborz, the South Caspian Basin is underlain by basement with the geophysical properties of thick oceanic crust or thinned, high velocity continental crust (Neprochnov, 1968; Mangino and Priestley, 1998). Its sedimentary cover is >20 km thick in places, and is mostly mid-Tertiary and younger in age. South of the Alborz, Tertiary clastics and volcanics obscure its relationships to the continental blocks of Central Iran.

2. Structure

2.1. Overview

The Alborz is a stack of thrust sheets, produced by late Cenozoic compressional deformation (Alavi, 1996). Thrusts on the northern side of the range are principally directed northwards, those in the south towards the south (Figs. 1 and 2; National Iranian Oil Company, 1977; Stöcklin, 1974). Exposed thrusts with the greatest throw generally occur in the south of the Alborz, where Precambrian strata overthrust Tertiary strata in several places. The trend of the main folds and thrusts varies along the length of the range, changing from an ENE strike in the east to a WNW strike in the west. Prominent left-lateral strike-slip faults occur along the length of the Alborz, trending parallel to the thrusts and folds in each region. Structures at both the eastern and western ends of the Alborz change in strike to pass into adjacent fold and thrust belts: the Talesh in the west and the Kopet Dagh in the east (e.g. Berberian, 1997). Frontal structures encroach upon adjacent foreland basins: the South Caspian Basin in the north and, along a less linear topographic front at the southern margin, a series of basins across northern Central Iran.

In this account, the main structures of the Alborz are described from north to south. The division of northern, central and southern sections is somewhat arbitrary. There is a division between regions with exposed basement generated during the late Triassic collision, and regions where there was little or no deformation at that time. From east to west, this boundary lies along the line of the North Alborz, Khazar and Kabateh faults (Fig. 1). It does not have an important role in the late Cenozoic deformation.

2.2. Northern structures

The northern margin of the Alborz is linear and commonly steep. The main structures are the North Alborz and Khazar faults, which are only separate structures east of ~51°30′ E (Fig. 1). In its eastern section the Khazar Fault breaks the surface as a south-dipping thrust (Geological Survey of Iran, 1991a), which locally places the Gorgan Schists against Quaternary strata. There is not a continuous, exposed, south-dipping structure all along the northern side of the Alborz. The most basinward exposures of pre-Quaternary strata between 50°E and 52°30′ E typically dip northwards. Exposed thrusts in this region also dip northwards (Fig. 4), and imbricate Permian and Mesozoic strata, in particular a zone of right-stepping faults between 51°30′ and 52°30′ E (Geological Survey of Iran, 1991b). Sheared Lower Jurassic coal seams suggest major bedding parallel slip at this stratigraphic level, but another detachment horizon is needed to account for Permian outcrops. It is plausible that the Khazar Fault in this region is a blind, south-dipping structure at depth, with shallower foreland-dipping panels of imbricated Mesozoic and Neogene–Quaternary strata (Figs. 2 and 4). Centroid moment tensor (CMT) solutions for two earthquakes along the western part of the Khazar Fault, around 50° E are consistent with north-directed thrusting, although there are no reliable centroid depths (Fig. 1).

Berberian et al. (1992) noted four historic earthquakes along the western part of the Khazar Fault as far west of 50° E, and suggested that the fault extends west of this longitude under the plains around Rasht (Fig. 5).

A re-entrant in the northern mountain front south of Rasht (Fig. 1) is shown on some tectonic maps as a major northeast–southwest fault zone, the Lahijan Fault, offsetting Palaeo–Tethyan metamorphics rocks in a left-lateral sense (Karakhanian et al., 1997). However, there is no seismicity evidence for such a structure, nor clear geomorphic evidence for recent fault activity along this line. The topographic front steps south, to the south end of the South Talesh Fault (Fig. 5; Berberian and Yeats, 1999). This thrust is convex to the southwest, and directed towards the South Caspian Basin. It is associated with earthquakes with hypocentres in the region of 15–21 km (Jackson et al., 2002), which indicate very gently dipping east-directed thrusts.

The North Alborz Fault is mapped as a south-dipping thrust (Geological Survey of Iran, 1991a,c). It changes strike at ~53° E from ENE to WNW (Fig. 1). At ~54° E the fault has a linear trace and dips sub-vertically at present exposure levels. Pre-Jurassic rocks to its north are deformed beneath the basal Jurassic unconformity, while those to the south show little evidence of the Late Triassic deformation event. The Badeleh Fault lies 7–10 km south of and parallel to the North Alborz Fault (Fig. 1). It overthrusts in the opposite direction to the North Alborz Fault, with intervening rocks forming a pop-up zone. This pattern of major exhumation in pop-up zones between divergent thrusts occurs elsewhere in the range.

There may be a component of strike-slip associated with faults in this region, based on the linear trace and sub-vertical dip of at least part of the North Alborz Fault, the lack of relief between the strata to its north and south and the 1985 earthquake between the North Alborz and Badeleh faults (Fig. 1), for which a focal mechanism shows a small component of left-lateral motion on a steeply north-dipping nodal plane at a depth of 13 km (Priestley et al., 1994).

Anticlines between the Khazar and North Alborz faults deform Upper Cretaceous and Neogene strata. Basal Upper Cretaceous marls are locally sheared, where they are unconformable over the Gorgan Schists, and so each of the anticlines may be detached from the basement along the basement/cover unconformity. Shearing of this type gives the impression that there has been transport of younger over older rocks (Alavi, 1996), but this is not necessarily the case. Some of the individual folds extend for over 20 km, are typically upright, with wavelengths of 2–3 km. The fold belt dies out westwards, where the Caspian coastal plain is broadest.

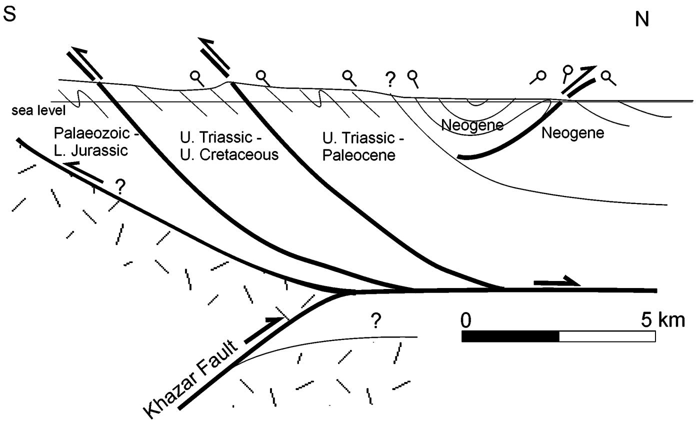

Fig. 4. Structural interpretation of the Galand Rud section, northern Alborz. Exposed faults in this area include north-dipping thrusts in Mesozoic strata, which appear to root into Upper Triassic carbonates. Speculatively, these faults are in the hanging wall of the basement-cored Khazar Fault. The Lower Jurassic Shemshak Formation does not crop out north of the northernmost of these thrusts, which may indicate a Mesozoic facies boundary. Location shown in Fig. 1.

2.3. Range interior structures

Most of the highest terrain of the Alborz and the oldest exposed rocks lie in a zone between the North Alborz/Khazar faults, and a line roughly following the Astaneh, Mosha and Rudbar faults—which are described in the next section (Fig. 1). The presence of folded and thrust lower Tertiary strata indicates that the region has experienced late Cenozoic compressional deformation (Stöcklin, 1974; Geological Survey of Iran, 1985, 1991c). There are focal mechanisms for earthquakes east of Damavand volcano (Fig. 1), which suggest left-lateral movement on WNW-trending structures, parallel to folds and faults in this region (Jackson et al., 2002). It is not clear which exposed faults, if any, correspond to these events. An earthquake in the same region in 1957 was probably a thrust (McKenzie, 1972); an exposed thrust east of the epicentre dips south and may be the same structure (Geological Survey of Iran, 1991c). Most folds in the area east of Damavand verge south (Geological Survey of Iran, 1987).

The adjacent Nusha and Banan faults (Fig. 1) appear to offset Mesozoic strata and an early Tertiary granite by ~10 km each, in a right-lateral sense (Geological Survey of Iran, 1985). To the southeast, right-lateral faults cut the ca. 56 Ma Akapol pluton, but are intruded by the ca. 7 Ma Alam Kuh granite (Axen et al., 2001). There is no major historic seismicity recorded on any of these structures, nor other indications that they are active.

Stöcklin (1974) noted right-lateral displacement along the Kandavan Fault and sub-parallel faults to its north also show right-lateral offsets on map patterns (Geological Survey of Iran, 1991b). The Kandavan Fault thrusts Jurassic clastics southwards over tightly to isoclinally folded, cleaved and imbricated Eocene turbidites in the section line of Fig. 2. These folds verge to the south, and the intensity of deformation decreases southwards over ~10 km. Roughly 25 km to the west-northwest, Ordovician strata are in the immediate hanging wall of the Kandavan Fault. The throw in this area must be ~5 km or more. Along strike to the east of the section line, the Kandavan Fault passes into a sub-vertical or even south-dipping structure (Geological Survey of Iran, 1991b).

Precambrian strata lie at the base of the hanging wall to the south-dipping, arcuate, Kojour Fault (Fig. 1). The structural relief between these rocks and Cretaceous strata in the footwall is ~10 km (Fig. 2). The hanging wall nappe is >20 km across at its maximum. In map view, the Kojour Fault and its nappe have the geometry of a right-lateral push-up structure, located north of the Kandavan Fault. The combination of right-lateral faults, a major push-up zone and divergent thrusts indicates that this central part of the Alborz was a right-lateral transpressional zone in the late Cenozoic, although it does not appear to be deforming actively with these kinematics. Lower Jurassic strata are commonly tightly folded across the northern Alborz on kilometre scale wavelengths (e.g. Geological Survey of Iran, 1991b), whereas older strata are not mapped with the same structures. Lower Jurassic coals and mudrocks display bedding-parallel shearing, and may form a regional décollement horizon at this level.

West of the Sefid Rud, major convex-southwest thrusts imbricate Palaeozoic, Mesozoic and Tertiary strata (Figs. 1 and 5). Thrusts change orientation as they approach the Sefid Rud from the west, and several become parallel to the river. We infer that this region represents a lateral ramp, but the timing of deformation is not clear. At least some faulting is Cenozoic, given the presence of the Karaj Formation in the thrust sheets.

At the western margin of the Alborz, thrusts that transport broadly to the southwest change in strike to merge with the NNE-trending, right-lateral Sangavar Fault (just west of Fig. 1) (Berberian and Yeats, 1999) and several sub-parallel, linear structures to its east, which we infer to be other right-lateral faults. Segments of the Sangavar Fault may have ruptured in 1863 and 1896. It has an orientation and sense of motion to allow northward motion of the

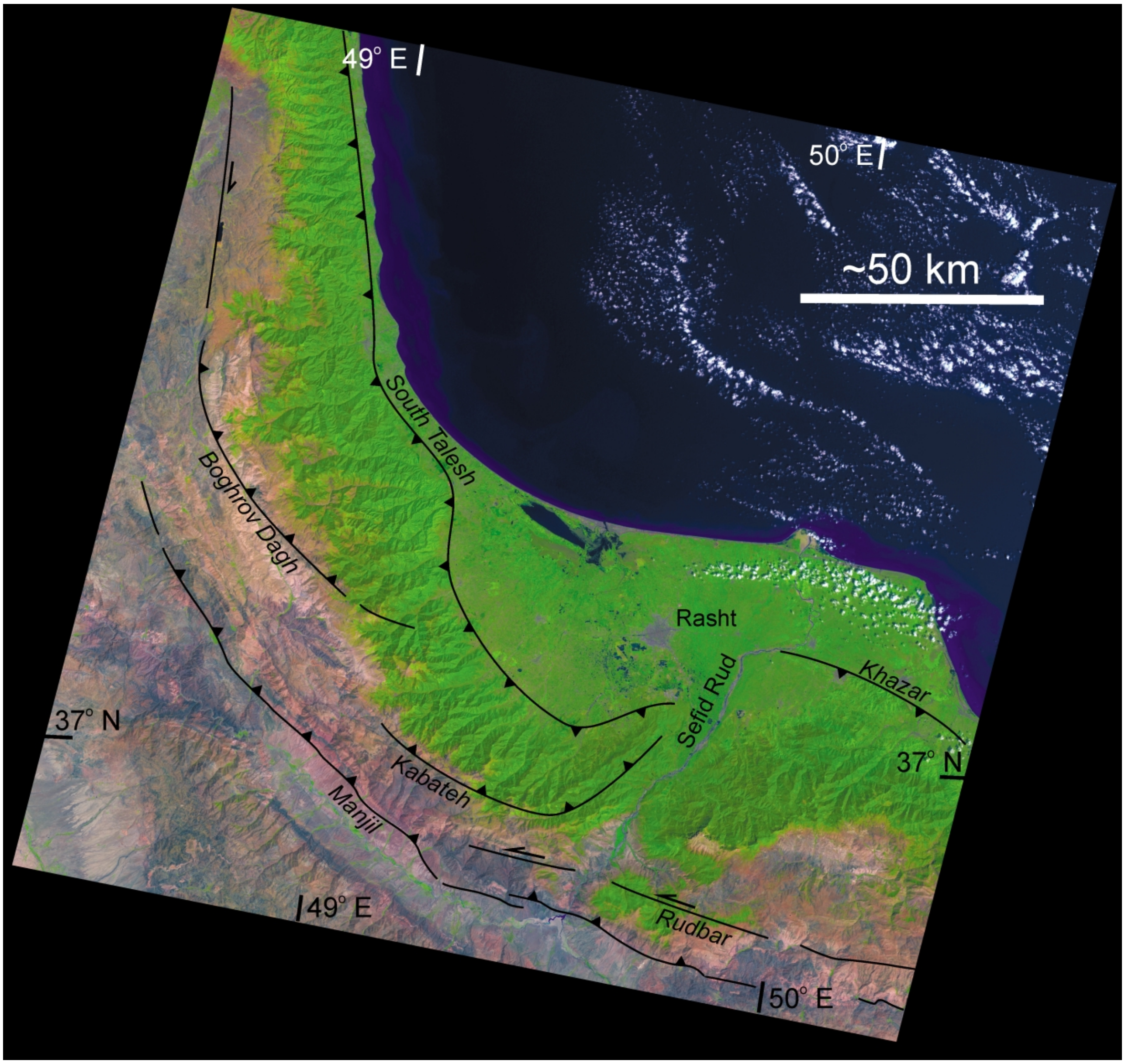

Fig. 5. Landsat 7 scene, showing the northwest Alborz. Selected faults are shown, modified from Berberian (1997) and National Iranian Oil Company (1978). The re-entrant in the range along the line of the Sefid Rud (White River) may be a Mesozoic structure, reactivated in the Cenozoic. The abrupt change in vegetation across the range highlights the climatic contrast, with the northern margin receiving 1500–2000 mm/yr of precipitation and the southern margin only 200–400 mm/yr. Location shown in Fig. 1.

interior of the Talesh relative to the Alborz and the South Caspian. Some tectonic maps (e.g. Philip et al., 1989) indicate a parallel right-lateral fault at the western margin of the present Caspian Sea, but there is no evidence for this from the seismicity data, or our fieldwork in the Azerbaijan sectors of the Talesh and eastern Greater Caucasus.

2.4. Southern structures

A segmented zone of broadly southward-directed thrusts and left-lateral strike-slip faults separates the main exposures of Eocene rocks in the southern Alborz from predominantly older rocks to its north (Fig. 1). In the east of the range, the Astaneh Fault trends ENE–WSW, but swings into a more east–west orientation near its terminations (Fig. 1). The eastern part of the fault offsets an anticline cored by Cambrian strata by ~20–25 km in a left-lateral sense, based on a restoration of the map patterns of Geological Survey of Iran (1991a). East–west-trending folds and faults north of the main fault trace are oblique to the regional ENE–WSW structural trend in this part of the Alborz, typical of splays at the ends of major strike-slip faults (Woodcock and Fischer, 1986). Offset drainage further west, roughly at 53.5° E, indicates recent left-lateral motion along this part of the Astaneh Fault (Berberian et al., 1996; Jackson et al., 2002).

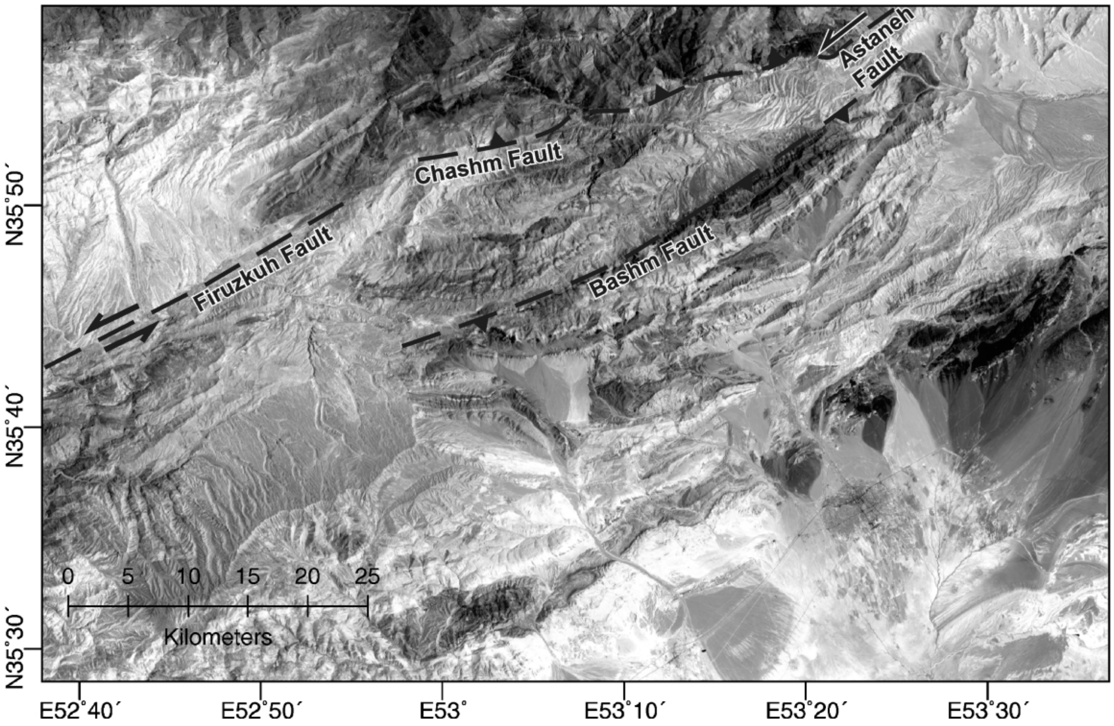

Fig. 6. Partial Landsat 5 scene, showing the Firuzkuh, Astaneh, Chashm and Bashm faults. A sinistral push-up zone lies at the intersection of these faults.

At the western end of the Astaneh Fault several east–west thrusts splay off the main fault. Folded Miocene, lower Tertiary and Mesozoic strata are exposed between these thrusts, and present drainage incises into the sediments (Fig. 6). The northernmost thrust, the Chashm Fault, is an imbricate zone, which has exhumed a sliver of the Proterozoic Kahar Formation among sheets of Lower Cambrian strata. Transport is broadly towards the south. Individual faults in this region are picked out by discontinuous lenses of gypsum and anhydrite (Fig. 7a). These evaporites may indicate a major detachment level in the succession. We think that they originate within or beneath the Kahar Formation, and represent the major detachment horizon, which decouples the Kahar Formation and all younger strata from the basement. The Bashm Fault is a southeast-dipping thrust that places Lower Cambrian over Eocene strata, with a throw of roughly 8 km (Geological Survey of Iran, 1988).

North of these splays, the Firuzkuh Fault is another active left-lateral fault (Berberian et al., 1996; Jackson et al., 2002). The region between the Firuzkuh and Astaneh faults is a right-stepping jog between two active left-lateral faults (Fig. 6), consistent with the uplift and compressional deformation in this area.

The western termination of the Firuzkuh Fault is at approximately 52.5° E (Fig. 8). In this same region there is the eastern limit of the Mosha (Mosha–Fasham) Fault, which has a WNW strike (Fig. 9). The two structures appear to continue into each other. Folds further north swing smoothly in strike to pass between the ENE and WNW trends. Three earthquakes may have activated segments of the Mosha Fault in 958, 1665 and 1830 AD (Berberian and Yeats, 1999). Published maps show the Mosha Fault as a thrust dipping NNE (Geological Survey of Iran, 1987), implying that the eastern part of the structure thrusts younger rocks over older rocks. Several lines of evidence suggest that it is a left-lateral fault, at least in its eastern part.

Our field observations of the Mosha Fault south of Damavand volcano show a sub-vertical fault zone, with entrained, fault-bound lozenges of various lithologies, including gypsum. Both steeply-dipping and sub-horizontal slickenlines are present on fault surfaces. Tar Lake (35°43.50′ N 52°14.00′ E) lies along the Mosha Fault, on the watershed between axial streams flowing WNW and ESE (Fig. 10). Individual faults are prominent along the northern and southern sides of the lake, with the lake itself occupying a left-stepping jog between them. The lake appears to occupy an overlap zone between fault segments, consistent with it being a small pull-apart structure. West of Tar Lake, the Mosha Fault has disrupted and beheaded drainage (Figs. 7b and 10) and is a prominent, linear topographic feature. The drainage offset appears to be left-lateral, but we have not measured precise displacements.

A possible offset marker is provided by the larger-scale drainage in the region. The Damavand River runs north to south through Damavand town (Fig. 9). It is presently fed by streams that pass axially along the Mosha Fault from both the west and east. There is also an air (wind) gap on the northern side of the fault, on the Emamzadeh–Hashem pass, roughly 4 km west of the present north–south drainage. If the original drainage through the air gap once fed the Damavand River, it implies a ~4 km left-lateral offset along

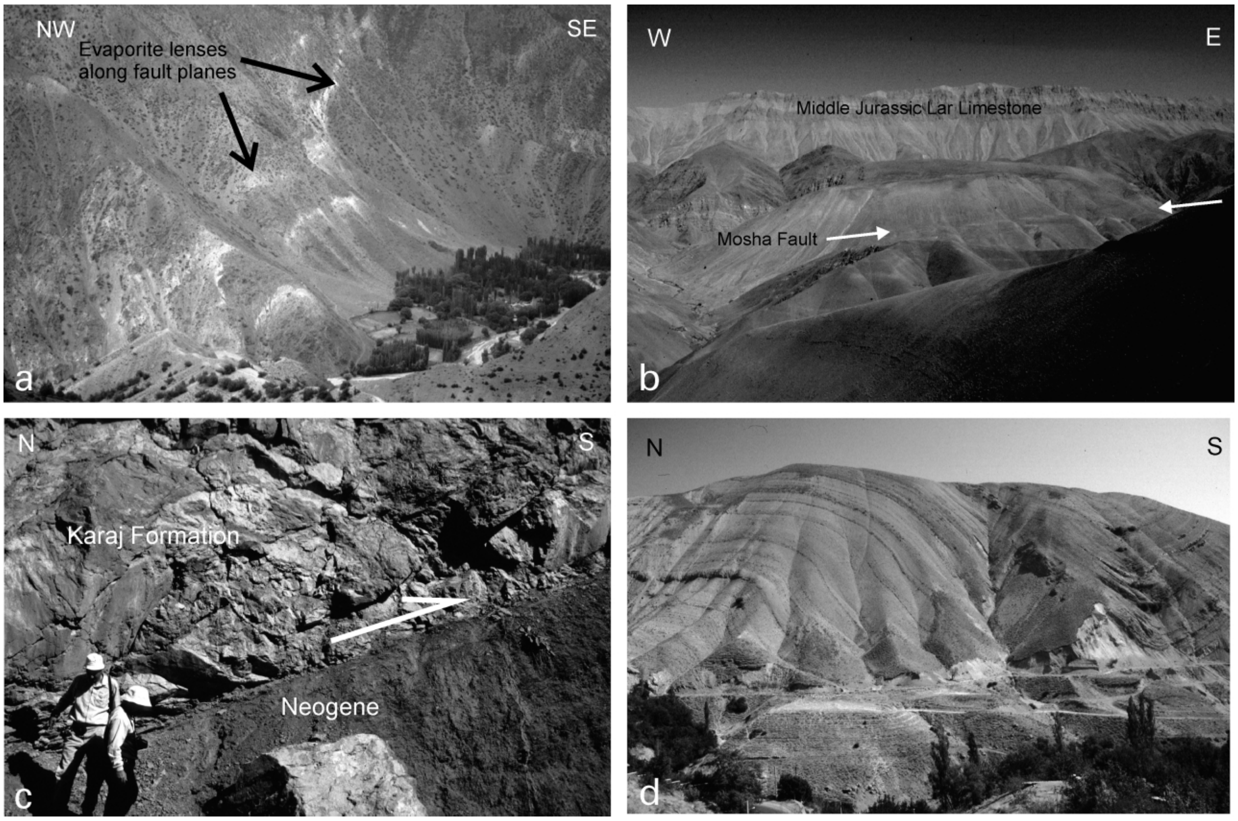

Fig. 7. Field photographs of Alborz structures. (a) Gypsum/anhydrite along planes of the Chashm Fault at 35°54.34′ N 53°06.52′ E. See Fig. 6 for a Landsat image of this structure. The Proterozoic Kahar Formation is imbricated with Cambrian strata along this part of the fault. These evaporites may indicate the presence of a decollement horizon within the Kahar Formation, which allows regional detachment of the sedimentary cover from underlying and unexposed basement. (b) View northwards of the Mosha Fault, ~5 km west of Tar Lake. Drainage is disrupted along the line of the fault, with apparent left-lateral offset, although we have not precisely measured the offset. (c) One of the planes of the Mosha Fault, 35°51.53′ N 51°41.55′ E. In this region the Mosha Fault is a thrust dipping to the NNE, with entrained slivers of Neogene strata. Overall, the fault juxtaposes different parts of the Eocene Karaj Formation. (d) Asymmetric, south-vergent folds in Karaj Formation strata, between the North Tehran and Mosha faults, ~20 km northeast of Tehran.

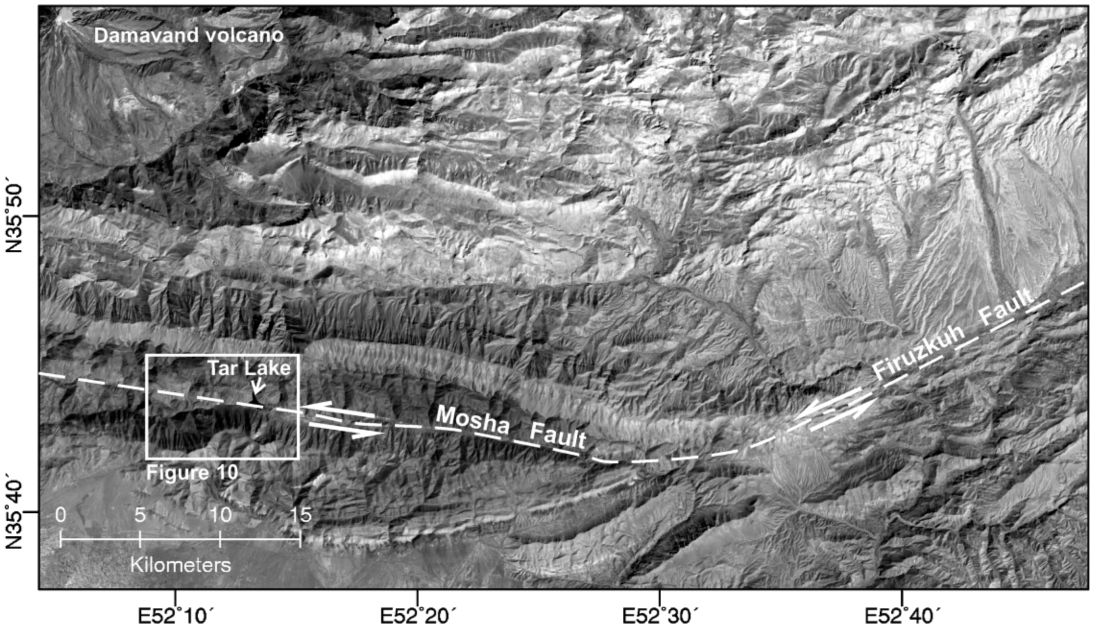

Fig. 8. Partial Landsat 5 scene, showing the eastern part of the Mosha Fault and the Firuzkuh Fault.

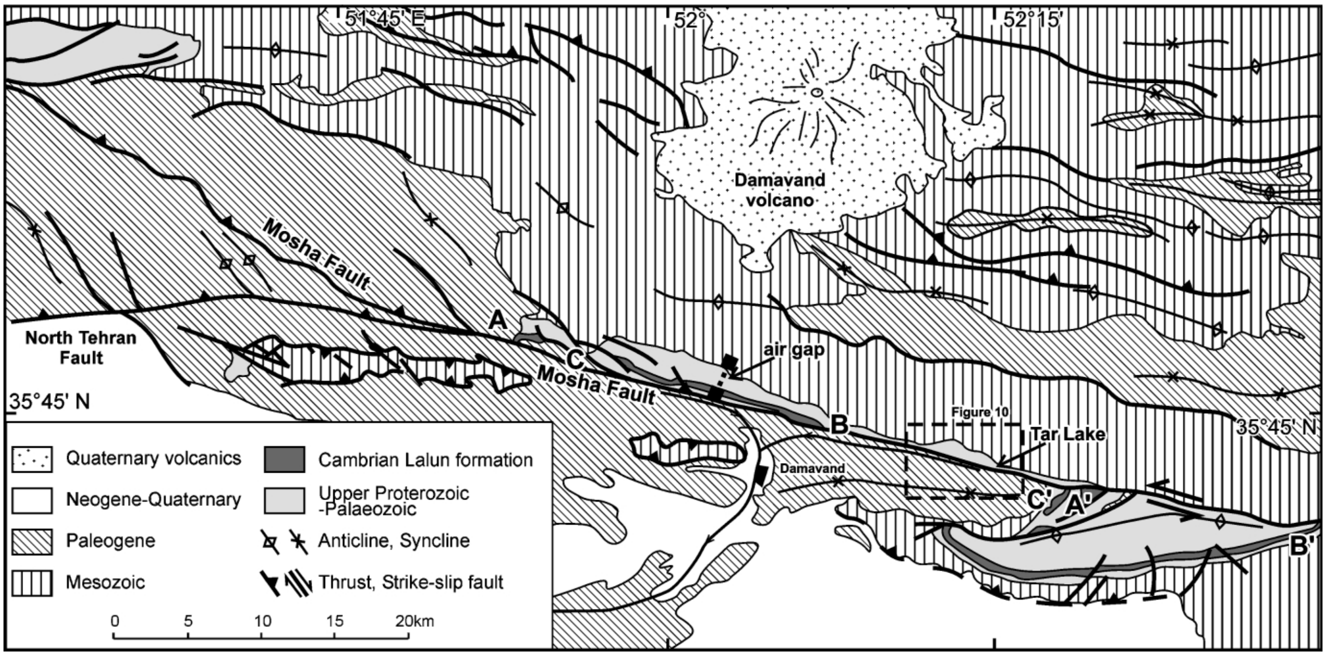

Fig. 9. Map of the Mosha Fault and surrounding regions, northeast of Tehran. Derived from the 1:250,000 geological map of the Tehran region (Geological Survey of Iran, 1987), with data from our field observations and satellite imagery. A–A′, B–B′ and C–C′ are piercing points along the Mosha Fault, which restore to give an offset of 30–35 km. Location shown in Fig. 1.

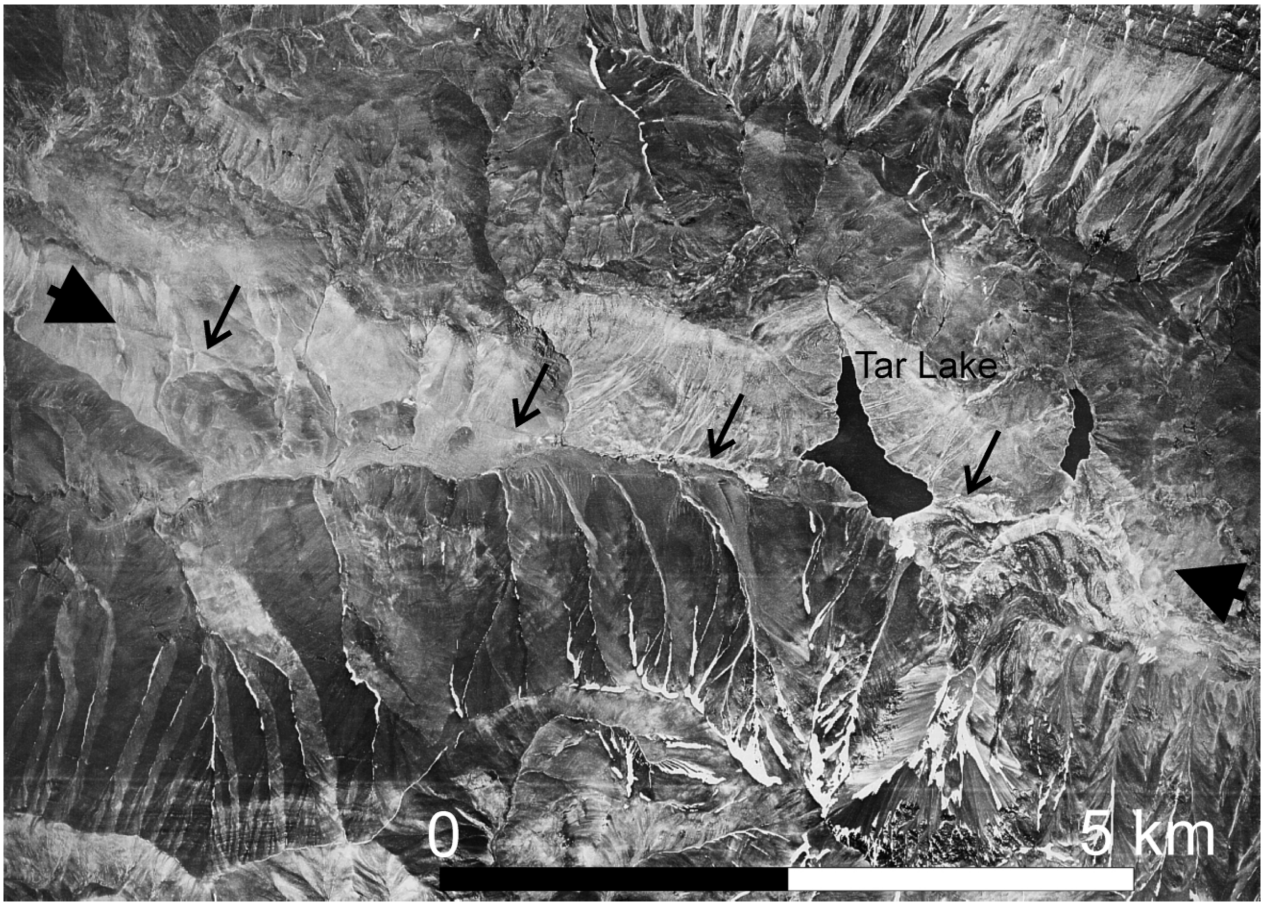

Fig. 10. Aerial photograph, showing the Mosha Fault in the vicinity of Tar Lake. The lake itself may represent a small pull-apart, developed between two overlapping segments of the fault zone. Note the disrupted drainage to the west of the lake. The large arrows highlight the overall fault trend in this area; the small arrows highlight examples of recent scarps. Location shown in Figs. 8 and 9.

the fault since the drainage reorganisation. Total left-lateral offset on the fault is constrained by piercing points to be ~30 35 km (Fig. 9). Lower Palaeozoic strata, presently displaced by the fault, form a domal anticline when this amount of slip is restored. The unconformity at the base of the Eocene rocks is offset by the same amount. The time of initiation and present slip rate are not constrained by the available outcrop data.

The Mosha Fault diverges west of the western limit of Palaeozoic strata exposed along it. One splay continues to the WNW, where it is a low angle thrust, dipping to the northeast (Fig. 7c). There is a topographic break along the fault, but no definite signs of recent faulting. The North Tehran Fault branches off to the west, where it forms an active, left-lateral oblique thrust running along the northern side of Tehran (Fig. 2; Berberian and Yeats, 1999). Numerous sub-parallel thrusts deform Plio–Quaternary strata in the Tehran plain to the south of the North Tehran Fault. Some of these have a left-lateral component of motion (Berberian and Yeats, 1999).

Folds in the Eocene rocks north of the North Tehran Fault strike both northwest and northeast (Figs. 7d and 11; Geological Survey of Iran, 1987). Several northwest-trending thrusts are present, which merge into the North Tehran Fault at their southern limits. Some of the northeast-trending fold axes are deflected by northwest-trending folds and thrusts, which suggests that the latter are younger. The northwest-trending set is consistent with left-lateral oblique shortening on the North Tehran Fault, which fits the present nature of this fault. The northeast-trending set is harder to explain; its orientation implies a phase of earlier right-lateral motion on the North Tehran Fault or a similar structure, which in turn implies a change at some post-Eocene time from right-lateral to left-lateral slip in this part of the Alborz.

There is much less evidence for range-parallel left-lateral faulting in the western Alborz than in the east. The catastrophic Rudbar–Tarom earthquake of 1990 had a left-lateral mainshock ($Mw = 7.3$). Up to 80 km of co-seismic surface ruptures occurred in three main, discontinuous fault segments, known collectively as the Rudbar Fault (Figs. 1 and 5). These had not previously been recognised as active structures (Berberian et al., 1992; Gao and Wallace, 1995), and the fault system does not seem to exert a strong control on the local geomorphology. The fault ruptured both east and west of the Sefid Rud, and it does not have the variation in strike possessed by many of the faults to the west of the river. Large parts of the ruptures are at altitudes of around 2000 m. Two of the aftershocks show thrusting on planes perpendicular to the regional strike, which presumably acted to accommodate the strain generated along the main structure (Jackson et al., 2002).

Klippen are present within the southern part of the Alborz. The Shahrestanak (Sharistanak) Klippe (Stöcklin, 1974; Geological Survey of Iran, 1987) exposes Cambrian to Triassic strata, south of the Kandavan Fault (Figs. 1 and 2). It lies across part of the Mosha Fault, and Asserto (1966) suggested that it was derived from the Kandavan Fault. This requires southward transport of ~15 km. Klippen further west principally consist of the Kahar Formation (Geological Survey of Iran, 1985), but it is not clear where these slices come from. Other klippen may exist to the south of the eastern part of the Mosha Fault (Fig. 9), where isolated areas of Mesozoic strata are in fault contact with Tertiary rocks around them. These klippen imply thin-skinned overthrusting for considerable distances within the Alborz.

East–west-trending thrusts are present within the southwest Alborz. They rarely expose pre-Tertiary rocks; the main exception is a pop-up zone between the Taleqan Fault and the western Mosha Fault (Fig. 1). Both dip-slip and oblique-slip (left-lateral) slickenlines are present on fault surfaces examined at the western margin of the Taleqan Fault, but were not seen in enough numbers to justify a quantitative analysis. Several of the east–west structures appear to die out laterally westwards, or at least disappear beneath the Quaternary cover. An exception is the North Qazvin Fault, where the Karaj Formation is thrust southwards over a syncline of Neogene and Quaternary clastics in its footwall. These east–west thrusts tend to occur southwest of WNW–ESE-trending thrusts, such as the Kandavan Fault described above, which separate the main exposures of early Tertiary from older rocks to the ENE.

Intermontane basins within the southwestern part of the Alborz (Fig. 1) contain terrestrial Neogene and Quaternary alluvial clastics and, locally, evaporites. These basins are being deformed as marginal thrusts propagate into the basin interiors. Around them, the Karaj Formation is ubiquitously folded across the southern Alborz. Finer-grained units close to major thrusts are cleaved, but nowhere are the exposed rocks metamorphosed.

Oligocene evaporites source numerous diapirs east of 52° E along the southern side of the Alborz, but not further west (Geological Survey of Iran, 1985, 1987). These evaporites have allowed deformation to propagate southwards into central Iran, leading to the development of emergent anticlines tens of kilometres to the south of the main mountain front (Fig. 12). West of 52° E, isolated ridges to the south of the Alborz are uplifted by active thrust and oblique slip faults, which have exhumed strata as old as the early Palaeozoic; basement involvement in these structures is indicated by hypocentres in the region of 10 km (Priestley et al., 1994).

3. Discussion

3.1. Stratigraphic evidence for the timing of deformation

The regional stratigraphy suggests uplift in the Alborz possibly as early as the Oligocene, with distinctly differing stratigraphies to its north and south from this time on, and few preserved Oligocene strata within the range itself. The

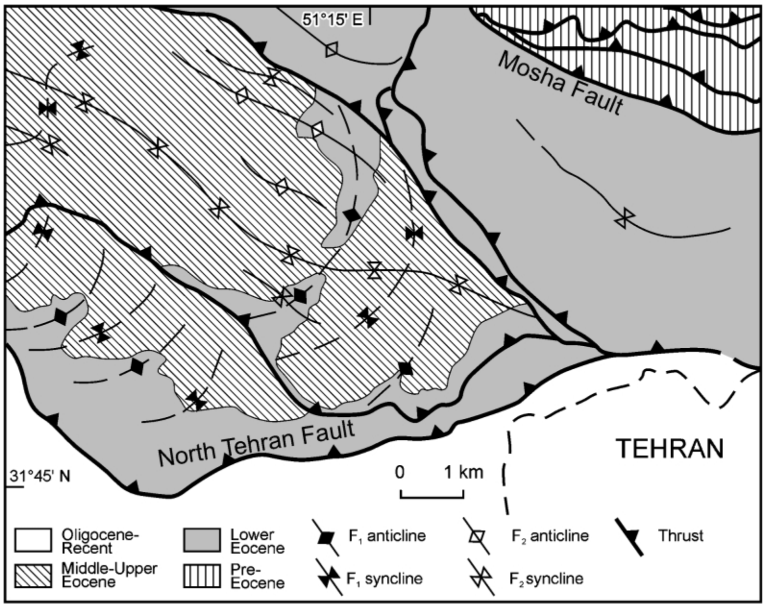

Fig. 11. Structure of the region northwest of Tehran, showing two generations of late Cenozoic folds. F1 appears to be associated with right-lateral oblique shortening; F2 appears to be part of the active, left-lateral deformation. After Geological Survey of Iran (1987) and Alavi (1996).

Qom limestone suggests there was little relief in the southern Alborz in the early Miocene, but overlying clastics of the Upper Red Formation represent considerable (>2 km thick) terrestrial sedimentation through the remainder of the Miocene, presumably as the result of uplift and compressional deformation in the Alborz. Syn-tectonic deposition in the Pliocene in the South Caspian Basin indicates an acceleration or reorganization of regional deformation at this time, continuing to the present day (Aliev, 1960; Devlin et al., 1999). This presumably marked the start of major motion of the South Caspian relative to adjacent areas, and so the initiation of left-lateral deformation along the Alborz (Axen et al., 2001; Jackson et al., 2002).

3.2. Crustal thickness

Whereas crustal roots are developed for other mountain belts within the broad Arabia–Eurasia collision, the Moho under the Alborz appears to be flat and the crust similar in thickness to adjacent basins (Tatar, 2001). This is surprising in a range with such high elevations, and a record of clastic sedimentation to its south and in intermontane basins going back to the early Miocene. A possible explanation is flow of the lower crust, a process favoured by crustal thickening and magmatic activity, both of which lower the viscosity of the lower crust (McKenzie et al., 2000). While crustal thickening is obviously a feature of other active mountain belts in the Arabia–Eurasia collision zone and beyond, the Alborz is distinctive because of its magmatism throughout the Cenozoic. However, to work, this mechanism would require the lower crust to be weak enough to flow, while the upper crust remained strong enough to support the relief between the Alborz and its forelands. Support by underthrust South Caspian basement may play a role (Axen et al., 2001), although there is no seismicity evidence to confirm that this is happening (Jackson et al., 2002).

3.3. Kinematics and finite shortening

Range-parallel left-lateral faults are present along the

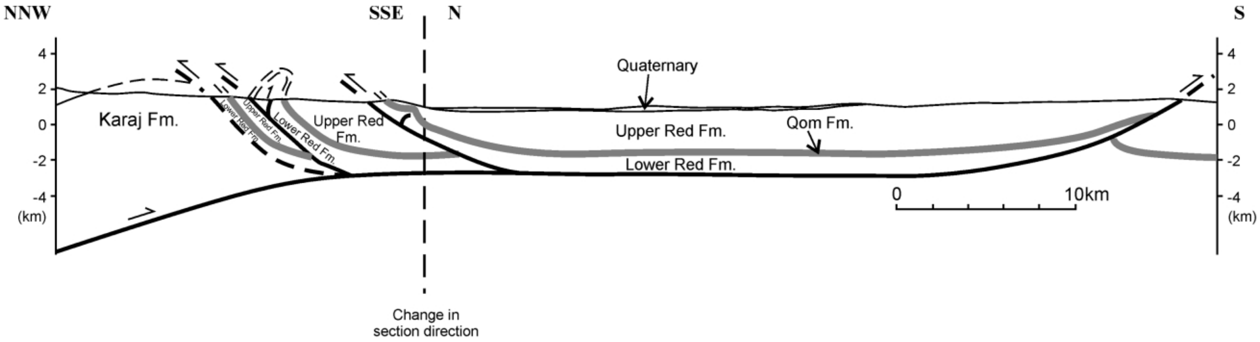

Fig. 12. Interpretation of the structure of the southern margin of the Alborz at the Abdolabad section (Fig. 1). Geology based on our fieldwork observations and data in Geological Survey of Iran (1988).

Alborz, while thrusts indicate shortening across it (Fig. 1; Priestley et al., 1994; Jackson et al., 2002). This is an example of strain partitioning of oblique shortening (transpressional deformation) across a mountain belt. The oblique shortening occurs because the Alborz is affected by both the regional Arabia–Eurasia convergence and the western component of the South Caspian's vector relative to Iran (Jackson et al., 2002).

Restoring the Kahar Formation in Fig. 2 gives an estimate of ~25–30% north–south shortening across the Alborz at this longitude, equivalent to a finite contraction of ~30 km. The caveats in this estimate are important: the undoubted transport of material out of the plane of the section and the scarcity of constraints on the sub-surface structure. However, this estimate is similar to the 25% shortening across the range given by Berberian (1983). It also matches the percentage shortening across the Talesh (30%; Jackson et al., 2002), and the Kopet Dagh (30%; Lyberis and Manby, 1999). Finite shortening of the Kopet Dagh is greater: ~75 km. Possibly the difference is accounted for by underthrusting of the South Caspian basement northwards under the middle Caspian. Underthrusting is suggested by the intermediate depth (<80 km) hypocentres under and to the north of the northern margin of the South Caspian Basin (Priestley et al., 1994).

Faults in the Alam Kuh region show clear evidence of late Cenozoic right-lateral displacement (Axen et al., 2001), while there are other indications of right-lateral transpression, such as the major push-up zone between the Kandavan and Kojour faults. There are no reported earthquakes or geomorphological features to suggest that any of these features are active in a right-lateral sense. On the contrary, the Rudbar–Tarom earthquake indicates active left-lateral slip in the western Alborz. Left-lateral slip was not recognized in this region prior to this event. Folds northwest of Tehran appear in two sets, with a northeast-trending set of folds refolded by a northwest-trending set (Fig. 11). We relate the latter to the present left-lateral oblique shortening, and the former to a putative earlier phase of right-lateral oblique shortening. Such refold patterns may be a general result of reversals of the sense of oblique shortening (Allen et al., 2001).

There is substantial evidence for active left-lateral strike-slip east of Tehran, on the Astaneh, Firuzkuh and Mosha faults (Fig. 1). If all of the Mosha Fault's cumulative 30–35 km of displacement occurred in the last ~5 million years it would imply a slip rate of 6–7 mm/yr. Jackson et al. (2002) estimate the current motion of the South Caspian to be ~13–17 mm/yr to the southwest (~210°) relative to Iran. Therefore a slip rate of 6–7 mm/yr on the Mosha Fault would take up all of the westward movement between the South Caspian and Iran. There is seismicity evidence for other left-lateral faults further north (Fig. 1), but no major left-lateral fault has been identified in this region, suggesting that the Mosha Fault takes up the bulk of the left-lateral slip in this part of the Alborz. If the offset on the Mosha Fault began prior to 5 Ma, the slip rate becomes correspondingly lower.

The main strike-slip faults lie within the interior of the range, with divergent thrusts to the north and south. At each part of the Alborz there is no more than one principal, active left-lateral strike-slip fault, and there is a major section of the range between 50 and 52° E where no such structure has yet been identified. It may be an implication for ancient transpressive zones that the strike-slip component is taken up along such a localised part of the mountain belt.

Fig. 13 shows a speculative kinematic model for the late Cenozoic evolution of the Alborz. Compressional deformation began in the Miocene, or even earlier, as the result of the early stages of the Arabia–Eurasia collision. Consequent uplift caused the deposition of clastics in the basins to the north and south of the range, and in intermontane basins. The Alborz seems to have created a climatic contrast to its north and south from Miocene times onwards: Miocene evaporites are only known from the southern Alborz, while marine strata occur to its north. Possibly, conjugate right-lateral and left-lateral faults were active during this phase, the former in the west of the range with a WNW strike, the latter in the east with an ENE strike. Such movements would be consistent with broadly north–south shortening across the range; they contribute to shortening by allowing extension parallel to the range, and are also consistent with the sense of shear to be expected if pre-existing faults of these orientations became reactivated during north–south compression. During this period there was little or no lateral movement of the South Caspian relative to Iran. Once the South Caspian began to move westwards relative to both Eurasia and Iran in the Pliocene, right-lateral faulting in the west of the Alborz ceased, and was replaced by left-lateral faulting along the range at least as far west as 49° E. We note that there is no definite evidence that any of the finite left-lateral slip is pre-Pliocene in age; it is possible that there was a complete reversal in slip along the Alborz at about 5 Ma.

3.4. Basement faulting and décollement horizons

Seismicity data indicate centroid depths in the range 8–13 km (Fig. 1; Priestley et al., 1994; Jackson et al., 2002). These earthquakes have magnitudes of $Mw > 5$. It is therefore likely that the basement is deforming seismically. Along strike-slip faults, earthquakes can be closely matched either to coeval surface ruptures (e.g. Rudbar) or obvious neotectonic scarps (e.g. Mosha, Firuzkuh). No similar ruptures are associated with thrust events, which suggests that one or more detachment horizons decouple the sedimentary cover from the basement (Fig. 2), and that many of the major thrusts remain blind, within the sedimentary cover. This is consistent with the exposed structural style (Fig. 4). The lack of outcrops of Precambrian metamorphic basement, and common appearance of the late Proterozoic Kahar Formation at the base of nappes is a strong indicator that there is a major detachment horizon

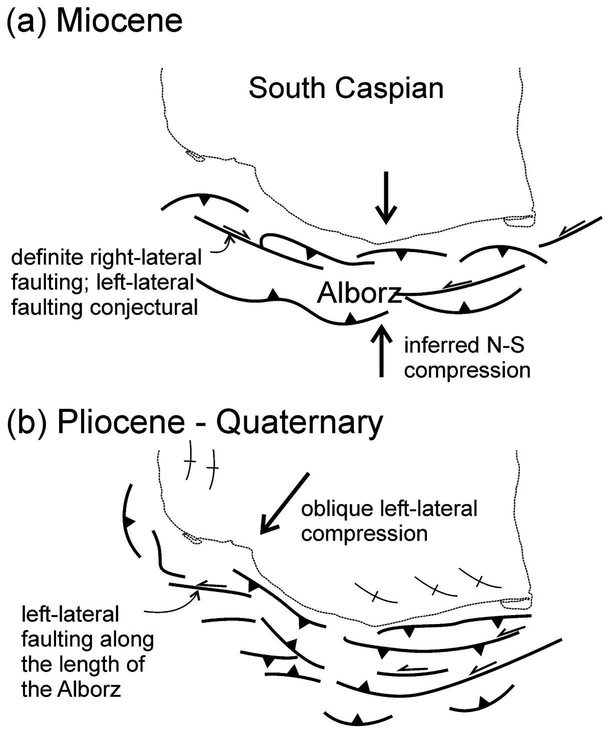

Fig. 13. Late Cenozoic structural evolution of the Alborz. (a) Miocene(?). Compressional deformation is accompanied by limited strike-slip faulting, possibly on conjugate right- and left-lateral faults. An alternative hypothesis is that only right-lateral faults were active within the range. (b) Pliocene–Recent. Continued compressional deformation is accompanied by left-lateral strike-slip along the length of the Alborz, which accommodates the westward motion of the South Caspian basement relative to Iran. Folding begins in the cover of the South Caspian Basin.

below the exposed Kahar clastics: the Kahar Formation appears at the base of at least six separate nappes and klippen in the Alborz. Gypsum and anhydrite lenses, localised along thrusted Kahar sediments near Bashm (Fig. 7a), suggest that this décollement consists of such evaporites. Such a succession is not completely unexpected: other Gondwanaland strata of similar age contain thick evaporites, such as the Hormuz Salt deposits of the Arabian plate.

Other décollement horizons operate within the Phanerozoic stratigraphy. Several thrust sheets on the northern side of the Alborz expose Upper Triassic carbonates immediately above the thrust plane, suggesting that there is a décollement horizon at this stratigraphic level. However, it is not clear what this might be. Lower Jurassic coals of the Shemshak Formation are visibly sheared at outcrop, and may be responsible for more regional detachment faulting where the Shemshak Formation is in the immediate hanging wall of major thrusts (Fig. 2). Cretaceous marls may act as a décollement horizon in the northeast, allowing the detachment of overlying strata from Palaeo–Tethyan metamorphics. Lower Tertiary evaporites in the southern side of the Alborz may allow detachment near the base of the Karaj Formation. Mid and upper Tertiary evaporites in the same region are certainly involved in both diaprisim and thrusting (Fig. 12). Collectively, these Tertiary evaporites may allow the propagation of thrusting south of the main Alborz, into the isolated uplifts of northern central Iran.

4. Concluding remarks

Many fold and thrust belts that are interpreted to result from oblique shortening are inactive, including the Caledonian example for which the term transpression was invented (Harland, 1971). The Alborz range is tectonically active and, as such, seismicity and geomorphology provide important constraints on the style, rate and vectors of deformation. Other regions of partitioned deformation within the Arabia–Eurasia and India–Eurasia collision zones have been described in this way (Jackson, 1992; Cunningham et al., 1996).

Both field observations and seismicity data for the Alborz demonstrate the partitioning of strain into dip-slip and strike-slip components. The principal strike-slip faults produce prominent surface ruptures, but major thrusts are commonly blind. While seismicity data indicate deformation within the basement, no unequivocal Precambrian basement is exposed. In some cases this is perhaps because of insufficient throw, but it is also likely that basement-involved thrusts pass into one of several possible detachment horizons within the thick sedimentary cover (Fig. 2). Other thrusts may be completely thin-skinned (Fig. 12). Thus the overall oblique convergence is simply partitioned into strike-slip and compressional components, but the compressional deformation involves ramps and flats and locally complete detachment between the basement and cover. Major strike-slip faults do not have this complication; hypocentres at depths of ~12 km are coeval with surface ruptures.

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