Interpretation of aeromagnetic data to detect the deep-seated basement faults in fold thrust belts: NW part of the petroliferous Fars province, Zagros belt, Iran

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ABSTRACT

Detection and delineation of basement faults are fundamental exercises in petroleum geology. This is because such structures can guide later deformation and the associated structures within the younger overlying sediments. This work presents aeromagnetic data interpretation and a comparison with the Digital Elevation Model (DEM) to detect basement structures covering the NW part of the petroliferous Fars province, Zagros belt. Anticlinal axes deflect in the NW-part of the province. The reason for this deflection is debated. We identified basement faults from the airborne geomagnetic data. Tilt filtering was applied on the magnetic data to enhance such faults. Two NE-trending cross-sections perpendicular to the anticlinal axes were prepared to show the effect of the basement faults in the sequence stratigraphy. The results of this research indicate a major NW and another NE trending deep-seated fault. Most of the extracted magnetic lineaments correspond to these faults. These faults were confirmed by the high displacement of the layers and changes of the thickness in the sequence stratigraphy. The result of this research suggests that the deep-seated basement faults are the main controlling factor of structural style in the NW part of Fars province in terms of a thick-skinned tectonics.

1. Introduction

Two contrasting views have been available for interpretation of the main controlling factors of the structural styles in the Zagros Fold Thrust Belt, especially in the Fars province. One states that the Hormuz salt (basal decollement) as the salt diapir has an important role in the structural style (due to the deflection of the fold axes on the surface) especially in the Fars province (e.g., Letouzey and Sherkati, 2004). Analogue models of Bahroudi et al. (2003) and Jahani et al. (2009) show that the surficial faults or deflection along the folds could be due to salt diapirism the sedimentary cover without any relationship with the basement faults. The other view is that the basement might also be deformed (e.g., Lacombe and Moutheureau, 2002; Moutheureau et al., 2007; Lacombe and Bellahsen, 2016; Koyi et al., 2016) and that the basement faulting is the main controlling factor for the deformation for the overlying materials (Misra et al., 2014; Misra and Mukherjee, 2015).

These two possibilities, the thin-skinned and the thick-skinned tectonics, are likely to compete in the Zagros belt (Fig. 1). Seismotectonic studies have provided more reliable evidence for the thick-skinned deformation and the role of the basement faulting as the main controlling factor in the changes of surficial features (Jackson, 1980; Ni and Barazangi, 1986; Berberian, 1995).

Analogue models show that the superficial features or deflection along the folds could also be related to the presence of the deep-seated basement faults in the Fars province (Koyi et al., 2016). These models indicate that the deflection of the fold axis from NW-SE trending in the western part of the Fars province to the E-W trend in the eastern part are related to the rotation of the deep-seated basement faults. In other words, basement faults have been considered to be the main controlling factor of the structural style in the region.

The Fars region has been a critical location where several concepts of Zagros orogeny have come up (Sarkarinejad et al., 2018a, 2018b). Based...
on stratigraphic data, during Zagros orogeny in the Early Miocene, inversion of the pre-existing structural elements with N–S and NW–SE trending is the first stage of the deformation in the Fars region (Mouthereau et al., 2007). The relationship between the surficial deformation of the anticlines and the basement faults in the study area so far remained doubtful. This is because such faults have not been documented in the NW part of the Fars province.

In this article, the basement faults are detected using filtering of magnetic data in the southern part of Iran, at the NW part of the Fars province. Also, the effect of these faults is investigated at the surface and through stratigraphy. The deflection and offset of anticlines at the surface are investigated in relation to the detected basement faults.

2. Study area

The study area is located within longitudes 51° 32’ to 53° 59’ E and...
latitudes 29° 29′ to 31° 29′ N, in the Zagros Mountains, NW part of Fars province, Iran (Fig. 2). There are several gas fields in the Fars province that explore hydrocarbons from the Dehram Group (Kangan and Dalan equivalent to Khouf Formations as reservoir layers) from ~2600 to 5311 m depth (Rouhani and Zakeri, 2012) (Fig. 3). The deflection of the anticlinal axes is visible at the surface in the NW part of the province. However, the reason for the swing is not well understood. No salt diapirs have so far been mapped (Mouthereau et al., 2007; JahaniS, 2009) between the NW-trending High Zagros Fault and the N-trending Kazerun Fault. The thickness of the Hormuz salt is very low in the northern Fars province and is devoid of diapirs (Sherkati et al., 2006).

3. Geophysical background

Aeromagnetic data has classically been used for economic surveys (Blakely, 1995) and recently in the structural mapping (Saibi et al., 2016). The initial problems of structural mapping of a magnetic crystalline basement overlain by the non-magnetic sedimentary rocks have long been solved by the different methods of magnetic interpretation (review in Table 1).

Geophysicists define the basement based on the reflectivity pattern or physical properties (e.g., seismic wave velocities, magnetic or gravimetric signature) and compare them with those of the overlying sedimentary rocks (Lacombe and Bellahsen, 2016). Numerous geophysical studies have been performed worldwide to extract the basement faults using magnetic data (review in Table 2). The depth to the top of fresh igneous rocks is often named the magnetic basement. Sedimentary rocks are considered non-magnetic. In other words, the igneous basement is considerably more magnetized than the overlying sediments (Teknik and Ghods, 2017). No magnetic layers occur within the sedimentary package in the study area (in the NW part of Fars province). Lack of intrastriatal magnetic material is also the case with the Zagros belt. The magnetic map can be the base map for the extraction of the basement faults in Zagros (Bahroudi and Talbot, 2003).

Table 1
A list of references related to the methods of interpreting magnetic data.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Studied terrain</th>
<th>Findings</th>
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</thead>
<tbody>
<tr>
<td>Lyatsky et al. (2004)</td>
<td>The Alberta Basin, Canada</td>
<td>Detection of subtle basement faults with gravity and magnetic data</td>
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<tr>
<td>Salem et al. (2008)</td>
<td>Method</td>
<td>Tilt filtering of Magnetic data method is powerful method for detection of the basement fault</td>
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<td>Crawford et al. (2010)</td>
<td>The Wernecke Inlier, Yukon Territory, Canada</td>
<td>Structural connectivity between basement faults and mapped normal faults lead to detect fluid pathways during ca. 1590 Ma hydrothermal activity</td>
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<td>Ndougsa-Mbarga et al. (2012)</td>
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<td>Artsoy and Dikmen (2013)</td>
<td>Method</td>
<td>Total horizontal derivative of the tilt angle is valuable method for edge detection of magnetic sources</td>
</tr>
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<td>Shah and Crain (2018)</td>
<td>The crystalline basement in north-central Oklahoma</td>
<td>Significant structural differences between the crystalline basement and sedimentary cover, numerous seisimogenic faults, and highlighting previously unmapped basement faults or contacts</td>
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<td>Ibraheem et al. (2019)</td>
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<td>The result helps making decision in choosing the location of the boreholes for gas and oil exploration.</td>
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<td>Ariyo et al. (2020)</td>
<td>Precambrian gneisses of Ago-Jowo, southwestern Nigeria</td>
<td>A prospective hydro-geological center, fault zones according to Liberian orogenic compression and as an undesirable spot for high-rise building</td>
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Table 2
List of references related to the detection of basement faulting using magnetic methods.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Studied terrain</th>
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<tr>
<td>Cordell and Grauch (1985)</td>
<td>San Juan basin, New, Mexico</td>
<td>The detection of magnetization boundaries using linear filter based on the gradient of pseudogravity.</td>
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<tr>
<td>Jacobi (2002)</td>
<td>the Appalachian Basin of, New York State</td>
<td>Not only are there more faults than previously suspected in NYS, but also, many of these faults are seismically active.</td>
</tr>
<tr>
<td>Lyatsky et al. (2004)</td>
<td>The Alberta Basin, Canada</td>
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<td>Crawford et al. (2010)</td>
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<td>The result from integrated aeromagnetic and geological data indicate the Ordos block is not an entirety of Archean.</td>
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<td>Wang et al. (2015)</td>
<td>The Ordos hydrocarbon basin, North China Craton (NCC)</td>
<td>Basement faults are syn-depositional with continuous long-term activity during the basin’s evolution.</td>
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<td>Lin et al. (2015)</td>
<td>The Tarim Basin, China</td>
<td>Hydrocarbon distribution in the UAE basin appears to be controlled by the location of the basement ridges.</td>
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<td>Ali et al. (2017)</td>
<td>The UAE basin, United Arab Emirate</td>
<td>The giant oilfields and smaller oilfields in offshore Abu Dhabi, occur exactly above crests of salt pillows and at the margin of the northern basement high respectively. The basement morphology and mobilization of the Hormuz salts due to reactivation of the basements fault.</td>
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<td>Lenhart et al. (2019)</td>
<td>The Mäløy Slope, offshore west Norway</td>
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<td>Geng et al. (2020)</td>
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<td>The giant oilfields and smaller oilfields in offshore Abu Dhabi, occur exactly above crests of salt pillows and at the margin of the northern basement high respectively. The basement morphology and mobilization of the Hormuz salts due to reactivation of the basements fault.</td>
</tr>
<tr>
<td>Ikioda et al. (2021)</td>
<td>Anambra Basin, Nigeria</td>
<td>Determine the structural pattern and sedimentary thickness of the basin.</td>
</tr>
</tbody>
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4. Geology and tectonics

Iran is located within the active convergence zone between the Arabian and the Eurasian plates (Fig. 4A). In this country, the Arabia-Eurasia convergence trends N to NNE. Estimates of its velocity range from 22 mm yr\(^{-1}\) (Bayer et al. 2002) to 35 mm yr\(^{-1}\) (DeMets et al., 1990). The most reliable convergence vector is provided by the recent GPS studies at the Arabian plate scale and corresponds to a velocity of ~22–25 mm yr\(^{-1}\) towards N010°E (McClusky et al., 2003; Vernant et al., 2004; Lacombe and Moutheau et al., 2006; Masson et al., 2007, Fig. 5). The direction is oblique by ~20–30° to the principal long-term SW–NE shortening direction across the orogen (Agard et al., 2011). The northward convergence has accommodated a dextral strike-slip on the Main Recent Fault (Talebian and Jackson, 2004; Authemayou et al., 2009), the Kazerun Fault (Authemayou et al. 2006, 2009) and sub-ordinate faults of the Kazerun Fault (Lacombe et al., 2006). Overall, the direction of the convergence vector has controlled the deformation partitioning along the orogen (Fig. 4A). The exposed lithologies in the study area are the Tertiary and the Quaternary deposits (Fig. 4B).

The Zagros Fold and Thrust Belt (ZFTB) is ~1800 km in length, and is formed in the foreland of the collision zone between the Arabian and the Eurasian plates. The belt is a part of the Alpine-Himalayan orogenic system that evolved during the initiation and the closure stages of the Neotethys Ocean at the Tertiary time (e.g., Ricoull, 1971; Lacombe et al., 2011). The ZFTB has three provinces, towards SE these are: Lurestan province, Dezful embayment and the Fars province.

Within the Late Proterozoic to Paleozoic ~7–14 km in the thick sedimentary pile of the Zagros belt (Karasoz et al. 2018) and multiple decoulence levels complicate the deformation in the sedimentary cover and hides the subsurface faults (Sherkati et al., 2006). The effect of subsurface faults at the surface is manifested as clockwise ~70° rotation and several km of displacement of fold axes in the Fars province (Koyi et al., 2016). In this province, the main decoulence levels are the Dashtak and the Hormuz salt Formations (Sherkati et al., 2006) (Fig. 5). In the study area, the Hormuz salt is the main decoulamentat the base of the sedimentary cover (Mukherjee et al., 2010).

NW-trending faults and folds are the main structures in the Fars province. Towards the east of this province, structural trend swings to E-W. The Karah Basin, Saba-Pushan, Sarvestan, and Ghar Fault Zones are the master blind faults in the Fars province (Berberian, 1995, Fig. 2). The E-trending Ghir Fault is the SW–verging thrust (Sarkarinejad et al., 2018, 2018b). The other three faults trend N and display a right-lateral mechanism (e.g., HuberH, 1977; Sereh and Cosgrove, 2005). Whether any basement faults exist in the NW part of Fars province between the Kazerun Fault and the High Zagros Fault has remained indeterminate.

5. Methods

5.1. General points

Aeromagnetic data, acquired by the Geological Survey of Iran aerially from~ 343 m height, were used to detect the magnetic lineaments. The survey was conducted by the Aeroservice Company (Houston, Texas, USA) under the commission from the Geological Survey of Iran during 1974–1977. The survey was done using a twin-engine airplane by a cesium vapor magnetometer with a sensitivity of 0.02 gammas. The data were collected along the flight lines with an average line spacing of 7.5 km. The average spacing of the control flight lines was 40 km (Saleh, 2006).

Long-wavelength data of the magnetic intensity field were used since these data often correspond to deeper-crustal sources (Ten Brink et al. 2007). Oasis montajGeosoft software (Version 9.5, 2018) designed by the Geosoft Company was used to process the data. First, the aeromagnetic map was prepared using the aeromagnetic data (Fig. 6). This map is the basis for the interpretation of the magnetic lineaments and indicates different magnetic anomalies.

Information about the magnetic lineaments was obtained using filtering. Evidence of faulting along these detected lineaments were investigated using the tilt filtering map, Digital Elevation Model (DEM); prepared using the GIS software, version 10.5) and structural cross-sections (prepared using the 2D Move software, version 2013). Finally, a structural map of the study area was prepared using interpretation results of the filtering. In this map, the extracted basement faults (F1–F6) in this research were drawn.

The DEM is used to indicate the effect of the basement faults at the surface. This approach essentially relies on identifying the deflection of the fold’s axes and the offset of the markers (Saibi et al., 2016).

5.2. Tilt filtering

Airborne geophysical data must be filtered by the tilt filtering to detect regionally the lineaments and fractures. This filter is an upward filter normalizing the vertical deviation with respect to the horizontal deviation. Since the output in this filter is normalized in the range of 90° to ~90°, deep and surficial anomalies are detected uniformly. Deep and surficial structures are observed after that in terms of uniform anomalies (Miller and Singh, 1994). The tilt angle (θ) is defined as:

θ = \arctan \left( \frac{Z}{\sqrt{X^2 + Y^2}} \right)

where Z is the vertical component, X and Y are the horizontal components of the gravitational field. The tilt angles can be used to infer the direction of the basement faults and to identify the presence of faulting.
\[ \theta = \tan^{-1} \left[ \frac{\partial M}{\partial h} \right] \]  

\[ \frac{\partial M}{\partial h} = \sqrt{\left( \frac{\partial M}{\partial x} \right)^2 + \left( \frac{\partial M}{\partial y} \right)^2} \]  

Here \( M \) is the total magnetic field, \( \partial M / \partial Z \) is the vertical deviation field and \( \partial M / \partial Y \) and \( \partial M / \partial X \) are the horizontal deviations along X and Y-axes, respectively (Verduzco et al., 2004).

Tilt is zero at the boundary on the positive anomalies and it is negative outside the anomalies range. Thus, the zero value marks the anomaly’s boundary.

In Equation (3), \( h \) and \( z_c \) are the horizontal location and depth of the magnetic field, respectively. This equation indicates that \( \theta = 0^\circ \) (for \( h = 0 \)) above the edges of the contact and equals \( \pm 45^\circ \) for \( h = \pm z_c \). The contours of the magnetic tilt angle can identify both the location \( \theta = 0^\circ \) and depth (half the physical distance between \( \pm 45^\circ \) contours) of the contact-like structures (Salem et al., 2007, 2008).

Tilt filtering was performed on the Reduction To Pole (RTP). Also, the upward filter was performed on the RTP to remove the surficial noise for better investigation of the deep magnetic bodies. RTP transformation was applied to the magnetic data to minimize the polarity effects.
These effects are manifested as a shift of the main anomaly from the center of the magnetic source and result from the vector nature of the measured magnetic field. These filters are considered the most useful for defining the edges of bodies and amplifying the fault trends. The tilt filtering was performed on the magnetic data after processing the data. Two TDR (tilt derivative) and HD–TDR (horizontal tilt derivative) maps are the outputs of the tilt filtering (Fig. 7). The body’s boundaries are easily defined in the TDR map and, the lineaments are simply defined in the HD–TDR map.

The presence of a magnetic lineament does not always confirm a fault. Mostly, the basement lithology, granite-gneiss rocks in the present case, has more effect on the magnetic relief observed above the

(Blakely, 1995). These effects are manifested as a shift of the main anomaly from the center of the magnetic source and result from the vector nature of the measured magnetic field. These filters are considered the most useful for defining the edges of bodies and amplifying the fault trends. The tilt filtering was performed on the magnetic data after processing the data. Two TDR (tilt derivative) and HD–TDR (horizontal tilt derivative) maps are the outputs of the tilt filtering (Fig. 7). The body’s boundaries are easily defined in the TDR map and, the lineaments are simply defined in the HD–TDR map.

The presence of a magnetic lineament does not always confirm a fault. Mostly, the basement lithology, granite-gneiss rocks in the present case, has more effect on the magnetic relief observed above the
sedimentary basins than the topography (Okiwelu et al., 2012; Mohammadzadeh-Moghaddam et al., 2015; Olasunkanmi et al., 2018). Evidence of faulting must be investigated along-strike of the detected lineaments.

5.3. Cross sections

Two cross-sections (Fig. 8) were constrained based on (i) field studies, (ii) Landsat images, (iii) geological maps provided from the National Iranian Oil Company (1:1,000,000 scale maps), and (iv) available cross-sections produced by the Geological Survey of Iran and the National Iranian Oil Operating Company (Repository). The length of cross-sections AA’ and BB’ are ~ 130 and 38 km, respectively.

The study area is covered in the four maps with a scale of 1:100000. Names of these maps are Droudzan (provided by the Iranian Oil Operating Company), Sedeh (supplied by the National Iranian Oil Company), Sivand and Eghlid (produced by the Geological Survey of Iran). These were named as per the prominent locality these maps covered.

Cross-section AA’ runs across the Kuh-e Nabati, Kuh-e Darghook, Kuh-e Bakan, Kuh-e KushkZar, and the Kuh-e Gar anticlines. Cross-section BB’ goes across the NW part of the Kuh-e Kushk Zar anticline. Cross-section AA’ indicates the effect of the faults (F3, F4, F5 and F6) extracted from the tilt filtering map. Cross-section BB’ exhibits the effect of the F4 fault alone. The cross-sections demonstrate the role of the extracted basement faults in the sequence stratigraphy (Fig. 8).

Using the 2D Move software, the kink dip domain method was applied for the preparation of the cross-sections. In this method, the dip of layers in the folds changes at a small distance. The cross-sections demonstrate that folded layers got slipped by listric faults. Therefore, fault-related drag folds (Mukherjee, 2014) cannot be ascertained.

The detected faults in this work were shown in the existing cross-sections. But in the previous studies the cross-sections are in shallow depth and the detected faults were not considered as the basement faults. In other words, the attitude of the detected faults at a higher depth was not clear in the previous cross-sections. In this research, we indicate the faults have cut the basement at 9000–12000 m depths.

6. Results

6.1. Magnetic lineaments

Local anomalies of the magnetic data in the tilt filtering map indicate the location of the magnetic lineaments (Fig. 9). Magnetic lineaments can be considered as faults if there are evidence for faulting on the tilt filtering map or at the surface. In this work, lineaments were extracted on the tilt filtering map. Then the evidence of their surficial effects was studied.

Most of the extracted lineaments correspond to the given faults. The faults caused complexity in the structures in this area. In the HD-TDR map, these detected faults are visible as lineaments (e.g. F1, F2, F5 and F6) or between the different anomalies (F3 and F4). Detected faults in the HD-TDR map show the NE-SW and NW-SE trends in the study area (Fig. 9A). Rose diagram of the detected faults indicates NW-SE as their dominant trend (Fig. 9B).

6.2. Detected faults and their surficial effects

6.2.1. General points

The folds visible on the DEM (Fig. 10) trend NW in the NW part of the Fars province. However, some anticlines indicate a deflection of axial trace along the NE-SW faults. Detected faults on the tilt filtering map were overlaid on the DEM (Fig. 10) and the cross-sections (Fig. 8). This correlation shows the surficial effects of the main detected faults at the surface (as deflection of folds), although the faults are blind.

The surficial effects of few major detected faults are labeled (F1–F6; Figs. 9 and 10). F1 and F2 trend NE and F3–F6 trend NW. The major NW-trending anticlines are also visible on the DEM (Fig. 10) and in the cross-sections. These folds are Kuh-e Nabati, Kuh-e Darghook, Kuh-e Bakan,
Kuh-e KushkZar and Kuh-e Gar anticlines (Figs. 5 and 10). Few of these folds were presented in the geologic maps of the previous workers (Repository). Based on detail geological map (provided by Iranian Oil Operating Company, Droudzan sheet with a scale 1:100000), the basement fault in the SW part of the Kuh-e Kalb Ali anticline is a reverse fault.

The anticlines Kuh-e Tang-e Siah, Kuh-e Darghook, Kuh-e Nabati, Kuh-e Tange Goorak and Kuh-e Basiram anticlines trend NW-SE. These anticlines developed during the shortening of the Zagros orogeny. The forelimbs of these anticlines are cut by reverse faults. The interlimb angles of the Kuh-e Tang-e Siah and Kuh-e Darghook anticlines are more than those of the anticlines Kuh-e Nabati, Kuh-e Tange Goorak and the Kuh-e Basiram. In general, the anticlines are tighter in the NE part of the cross-section towards the High Zagros Zone. This is because deformation intensifies towards the High Zagros zone and the folds are tighter and more numerous (Bahroudi and Kovi, 2003; Sherkati et al., 2006). The forelimbs of the Kuh-e Tang-e Siah, Kuh-e Darghook and Kuh-e Nabati are cut by the F4, F5 and F6 reverse faults, respectively. The Kuh-e Tange Goorak and the Kuh-e Basiram anticlines are located outside the study area.

6.2.2. Surficial effects of the NE-trending subsurface faults

We document a clockwise rotation in the Sarvak Formation and an offset of ~2.5 km of the anticlinal axes across the detected NE-trending basement faults (Fig. 10). These faults manifest as magnetic lineaments. The main detected NE-trending basement faults are F1 and F2. The displacement of the F1 with respect to F2 is probably due to the NW-trending F4. The offsets of the Kuh-e Tang Siah anticline and the

**Fig. 7.** TDR (A) and HD-TDR (B) maps of the study area. TDR and HD-TDR maps indicate the border of magnetic mass and lineaments, respectively.
Deflection of the Kuh-e Gand Booie and Kuh-e Darghook anticlines occur as $F_1$ on the DEM. Deflection of the southwestern termination of the Kuh-e Bakan along the $F_2$ suggests its left-lateral slip.

6.2.3. Surficial effects of the NW-trending subsurface faults

In the study area, the foreland-dipping limb of the anticlines (e.g., Kuh-e Gar, Kuh-e KushkZar, Kuh-e Darghook and Kuh-e Nabati anticlines) is cut by NW-trending $F_3$–$F_6$ (Fig. 10). $F_6$ is the Zagros Main Thrust that separates the Far province from the Sanandaj-Sirjan metamorphic zone. In the Zagros belt, the NW-trending faults have cut the frontal limb of the anticlines and parallel the axial planes. These faults are listric within the basement with their dips decreasing with depth (Sarkarinejad and Goftari, 2019).

Enhancement of the NW-trending structures in the tilt filtering map plausible indicates that these deep-seated NW-SE faults originated from the basement and propagated towards the surface during the genesis of the anticlines. In other words, progressive compression leading to anticlines propagated these faults towards the surface and has cut the forelimb of the anticlines in the sedimentary cover.

The NW-SE faults could be detected in the sequence stratigraphy (Fig. 8). Slip is observed in the Late Cretaceous Ilam Formation in the upper part of the cross-section (near the surface) to the Precambrian.
basement and across F1–F6. Slip in the basement is ~1000–4000 m across the detected NW-SE detected faults. F5 and F6 have cut the forelimbs of the Kuh-e Darghook and Kuh-e Nabati anticlines, respectively, at a high-angle. F3 and F4 have cut at a high-angle the forelimb of the Kuh-e Kushk Zar and Kuh-e Gar anticlines, respectively. F3 is associated with the significant slip of the layers that and also continue within the basement.

Variations in the thicknesses of the layers are due to F4, F5 and F6 (Fig. 8). The Triassic Dashtak Formation with evaporate facies in the footwall of F4 is omitted in the hangingwall block of this fault. In the hangingwall of F4, Khaneh-Kat Formation with carbonate facies thickened within this time. Also, facies and thickness (1000–4000 m along NE-SW) in the sequence stratigraphy have shown changes in Permian, Jurassic and Lower Cretaceous deposits along with F5 and F6 (Fig. 8).

7. Discussions

Detection of deep-seated basement faults as the controlling factor of the structural style of the fold-and-thrust belts is a necessary step to predict their long and short-term dynamics, including seismic hazard, and to assess their potential of hydrocarbon exploration (e.g., Reeves, 1990; Misra and Mukherjee, 2015; Lacombe and Bellahsen, 2016). The studies on the basement faults in the fold-and-thrust belts, such as the Zagros Fold-Thrust Belt, have often been performed using indirect information, such as gravity (Aydogan, 2011), magnetic data (e.g., Ndougas-Mbarga et al., 2012), topographic anomalies (Leturmy et al., 2010), drainage network patterns (Leturmy et al., 2010), seismic tectonics studies (e.g., Jackson, 1980; Roustaei et al., 2010) etc.

Several techniques exist to interpret the aeromagnetic data and to detect the lineaments (Saithi et al., 2016; Boutirame et al., 2019). These techniques are consistent with Reduction To Pole (RTP) filtering and Tilt filtering.

In the Zagros belt, especially in the Fars province, the basement has controlled the surface structures only at the latest age of the tectonic evolution of the belt (e.g., Sherkati and Letouzej, 2004; Leturmy et al., 2010). In other words, the current thick-skinned style of the Zagros deformation succeeded a more general thin-skinned orogenic phase (Ovissi et al., 2009). This chronology is well illustrated by the spectacular structural interference where the folds are cut by the late oblique basement faults. These faults are covered by the Quaternary sediments at the surface and are dominantly blind. The mentioned faults, e.g., the Zagros Mountain Front Fault and the Zagros Main Thrust Fault (Fig. 2), trend NW. Such a pattern repeats throughout the Fars province (Leturmy et al., 2010).

Several authors have attributed the deformation of the Zagros sedimentary cover to the pre-existing basement faults (review in Table 3). Basement faults in the Zagros belt are usually beneath the sedimentary units within ~7–14 km depth and rarely reach the surface (Berberian, 1995). In the Fars province, the folded sediment cover was detached in the Hormuz salt over the Precambrian basement. The basement was also shortened but how far it governed the tectonics has remained indeterminate (Mouthereau et al., 2012).

The anticlines trend NW in the study area. Some of the anticlines (e.g., Kuh-e Tang-e Siah, Kuh-e Bakan, and Kuh-e Gand Booie anticlines) deflect their axial trends along the NE-SW trending faults possibly due to the drag effect of those faults (Mukherjee, 2014). Such deflections are frequently observed in the fold axes in the Fars province and have been classically interpreted as a result of strike-slip along the underlying basement faults that manifests so in the cover (Ricoult, 1974; Hessami et al., 2001). The influence of these strike-slip faults in accommodating the cover deformation has also been demonstrated in several parts of the Zagros fold-and-thrust belt (e.g., Kuhn and Reuther, 1999; Sarkarinejad et al., 2018a, 2018b; Razavi Pash et al., 2020). Lateral offset of the fold axes and geomorphic features along the strike-slip faults in the Zagros Fold-Thrust Belt has also been frequently demonstrated (e.g., Barzegar, 1994; Hessami et al., 2001; Koyi et al., 2016).

The NE-trending faults deflect and offset the antclinal axes as the left-lateral slip. On the other hand, the NW-trending faults cut the forelimb of the anticlines and slipped layers right-laterally as thrust. These faults usually act as blind ramps (Leturmy et al., 2010).

Overall in the Zagros belt, and also in the Fars province, the NW-SE trending faults are the thrusts/reverse faults, or thrusts with the dextral strike-slip component, such as the Main Zagros Thrust (Hessami et al., 2001). They cut the forelimb of the folds as the thrust faults in the Zagros. In the study area, these faults have cut the forelimb of the Kuh-e Nabati, Kuh-e Darghook, Kuh-e Tang-e Siah, Kuh-e Bakan, Kuh-e KushkZar, and the Kuh-e Gar anticlines. The Kuh-e Bakan, and Kuh-e Laye anticlines developed above the middle detachment (Dashtak Evaporation Formation) are typical breakthrough fault-propagation folds.

8. Conclusions

Deep-seated basement faults mainly govern structural style in the NW part of the Fars province. In this region, NW-SE and NE-SW are the trends of the basement faults. The NW-SE trending faults are sub-parallel to the Zagros Fold-Thrust Belt. Anticlinal axes deflected at the surface due to the faulting of the basement. The deep-seated faults changed the
trolling factor of tectonics in the NW part of the Fars province. In other
of their adjacent litho-units. These faults are the main con-
deformation of the Zagros sedimentary cover. thickness of their adjacent litho-units. These faults are the main con-
trolling factor of tectonics in the NW part of the Fars province. In other
words, thick-skinned tectonics dominated the area.

Table 3
A list of references related to the effect of pre-existing basement faults on the
deformation of the Zagros sedimentary cover.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Studied terrain</th>
<th>Applied Method</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hessami et al. (2001)</td>
<td>Zagros Fold and Thrust Belt</td>
<td>Landsat satellite images, in conjunction with the spatial distribution of earthquakes and their focal mechanism solutions</td>
<td>Reactivated basement faults, which are inherited from the Pan-African construction phase, controlled both deposition of the Paneranozoic cover before Tertiary. Recent deformation of the Zagros and probably the entrapment of hydrocarbons on the NE margin of Arabia and in the Zagros area</td>
</tr>
<tr>
<td>Sherkati and Letouzey/J (2004)</td>
<td>Dezful Embayment in the central Zagros belt</td>
<td>Interpretation of the seismic profiles, isopach maps and stratigraphic correlation</td>
<td>Geometric and kinematic evolution of the Zagros fold thrust belt was strongly affected by reactivation of pre-existing basement faults</td>
</tr>
<tr>
<td>Moutheau et al. (2006)</td>
<td>The Zagros folded belt (Fars, Iran)</td>
<td>Constraints from topography and critical wedge modelling</td>
<td>Basement thrusting produce locally significant deformation in the cover</td>
</tr>
<tr>
<td>Abdollahie Fard et al. (2006)</td>
<td>Abadan Plain and the Dezful Embayment in the central Zagros belt</td>
<td>Interpretation of the seismic profiles</td>
<td>Deep seated anticlines in the Zagros belt (in the Abadan Plain and the Dezful Embayment) show the basement is involved in the faulting</td>
</tr>
<tr>
<td>Leturny et al. (2010)</td>
<td>Fars Arc of the Zagros (Iran)</td>
<td>Morphotectonics study</td>
<td>Basement involvement occurred at a late stage of deformation (early detachment folds are cut by late oblique basement faults)</td>
</tr>
<tr>
<td>Nissen et al. (2011)</td>
<td>Zagros fold-and-thrust belt</td>
<td>Interpretation of earthquake data: focal mechanisms, magnitudes and depth</td>
<td>Local network earthquake data demonstrate that microseismicity occurs within the basement (activity of basement faults)</td>
</tr>
<tr>
<td>Razavi Pash et al. (2021)</td>
<td>BalaRud Fault in Central Zagros</td>
<td>Analogue Modelling</td>
<td>The BalaRud Fault as oblique basement has been controlled the deformation style on the border of the northern Dezful Embayment and Southern Lurestan province</td>
</tr>
</tbody>
</table>

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Soumyajit Mukherjee reports financial support was provided by Indian Institute of Technology Bombay. Soumyajit Mukherjee reports a relationship with Indian Institute of Technology Bombay that includes: employment. Soumyajit Mukherjee has patent None pending to None. None.

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Appendix A. Supplementary data

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References