**IJES** *Irish Journal of Earth Sciences*

**Vol. 12, No. 3, 2020, 205-217.**

**Determination of in-situ stresses direction in the Sarvak formation in one of the West Iranian oil fields**

Mohsen Shourah¹, Mehdi Yousefi¹², Ali Faghih³

1. Sarvak Azar Engineering and Development (SAED), Tehran, Iran
2. Department of Geology, College of Sciences, University of Birjand, Birjand, Iran
3. Department of Earth Sciences, College of Sciences, Shiraz University, Shiraz, Iran

Received 11 May 2019; accepted 26 November 2019

**Abstract**
The image logs interpretation from two wells in a fold hosting a west Iranian oil field located in the Dezful Embayment, SW Iran reveal the occurrence of two major systems of natural fractures. In the central part of the fold, the fold-related fractures include two sets of fractures trending N53°E and N34°E. In the eastern and also curved part of the fold, the strike of open fractures varies from N85°E to S85°W with average dip of 63 degrees. Due to operation of the sinistral strike-slip fault, the mean present-day maximum horizontal stress orientations varies from N55°E to N30°E in the central and eastern parts of the fold. The SHmax orientations observed in wells located in the central and eastern parts of the fold are nearly consistent with SHmax orientations derived from nearby earthquake focal mechanism solutions and also with the absolute plate motion direction of the Arabian plate in the Dezful Embayment. Due to reactivation of the NE–SW oriented strike-slip faults, the mean shortening direction in the Zagros folds and thrust belt can be changed in the south Dezful Embayment. Drilling of production wells that are highly-deviated or horizontal and oriented approximately towards the present-day stress SHmax are likely to both intersect more hydraulically conductive fractures and reduce wellbore instability problems.

**Keywords**: FMI Logs, Fracture systems, In-situ stresses, Sarvak formation.

**1. Introduction**

Knowledge of the present-day tectonic stress is an essential issue in petroleum exploration and production, and, in particular, is a key parameter in: borehole stability; reservoir drainage and flooding patterns; fluid flow in naturally-fractured reservoirs; hydraulic fracture stimulation, and; seal breach by fault reactivation (Tingay et al. 2009, Rajabi et al. 2010). The present-day state of stress is described by determination of the stress tensor. It is commonly assumed that one principal stress acts vertically in sedimentary basins and thus the stress tensor can be simplified to consist of four components, the magnitudes of the vertical, maximum horizontal and minimum horizontal stresses in addition to the orientation of the maximum horizontal stress (Bell 1996; Tingay et al. 2009, Rajabi et al. 2010). Of these four components, determination of the maximum horizontal stress (SHmax) orientation has received extensive attention in recent 20 years, particularly with regards to the control of in-situ stresses on subsurface fluid flow and fault reactivation (Barton et al. 1995; Tingay et al. 2010). Fractures that are most susceptible to tensile or shear failure in the present-day stress, typically those striking approximately parallel or within 30° of the maximum principal stress orientation, are often observed to transmit the largest volumes of fluids.

Furthermore, extensive analysis of flooding operations has observed that fluid flow is enhanced and pumping rates more strongly correlated between well pairs that are located parallel to the present-day SHmax orientation (Heffer et al. 1997). The scientific importance of understanding the present-day maximum horizontal stress orientation is further highlighted by the findings of the World Stress Map (WSM) Project, which has spent over 20 years building an extensive freely-available repository of present day stress information. The 2008 release of the World Stress Map Project contains 21750 present-day stress indicators from all over the world and reveals the complexity of the global stress pattern (Heidbach et al. 2010). Early studies of the present-day stress field revealed that the primary, plate-scale stress field is controlled by plate boundary forces such as ridge push, slab pull and resistance at continental collision zones coupled with large intra-plate forces such as gravitational body forces near mountain ranges (Zoback 1992). However, more recent studies have highlighted the significance of smaller-scale perturbations in the stress field, superimposed upon the plate-scale stress pattern, that are often observed at the basin to field scale (Heidbach et al. 2009; Tingay et al. 2009). Furthermore, it is knowledge of stress orientations at smaller basin and field scales that has critical importance for petroleum applications such as wellbore stability, and hydraulic fracture stimulation (Bell 1996; Tingay et al. 2008). Knowledge of the

*Corresponding author.
E-mail address: mohsen_shourah17@yahoo.com*
present-day stress orientation is particularly important in Iran, which has an extensive and mature petroleum exploration and production industry, and is also prone to stress-related geo hazards such as earthquakes. Yet, the 2008 World Stress Map database contains very little present-day stress information for Iran and no stress data from petroleum wells (Heidbach et al. 2009). Indeed, all of the stress data currently available for Iran is derived from earthquake focal mechanism solutions from events that are typically at depths of ten kilometers or more, and which might not be relevant for petroleum applications, particularly in areas possibly detached by salt or low-angle faults. Furthermore, the majority of these earthquake focal mechanism solutions are located along the boundary between the Arabian and Eurasian plates, and there are concerns surrounding the reliability of stress information derived from earthquakes near plate boundaries (Heidbach et al. 2010). For example, stress orientations derived from earthquake focal mechanism solutions along the San Andreas Fault Zone and Great Sumatran Fault are often highly inconsistent with those obtained from more reliable petroleum industry data (Zoback et al. 1987; Mount and Suppe 1992; Heidbach et al. 2010). In this study we examine resistivity image logs to analysis of fold and fault-related fracture systems. Also the present-day stress (S_{max}) orientations will be obtained by borehole breakout and induced fractures in the Sarvak carbonates formation in the west Iranian region.

2. Geological Setting

The Zagros is a young (Mio-Pliocene) NW-SE trending fold-thrust belt located along the northern margin of the Arabian Plate. This belt is currently undergoing 20–25 mm/a shortening (Jackson and McKenzie 1984; Vernant et al. 2004) and thickening as a result of collision of the Arabian and central Iran plates (Berberian and King 1981). This belt provides a good example of convergence partitioning in its NW part. The overall N-S convergence between the Arabian and Eurasian plates being accommodated by dextral strike-slip movement at the rear of the belt along the Main Recent Fault (MRF) (Talebian and Jackson 2002) and by belt-perpendicular shortening leading to the formation of N140 trending folds (Agard et al. 2005; Vernant and Cherry 2006). The Zagros folded belt has been divided into several morphotectonic regions (Berberian 1983). These main morphotectonic regions are limited by deep-seated basement faults (Fig 1a). Two dominant tectonic trends, respectively N-S and NW-SE, are well known in the Arabian Shield and there is evidence for the continuation of these trends northward into the Zagros belt (Hessami et al. 2001; Bahroudi et al. 2003). In the Zagros belt, the approximate locations and geometries of the basement faults have been defined using geodetic survey, more or less precise epicenter/hypocenter locations, as well as topographic and morphotectonic analyses (Berberian 1995). The first group of basement faults includes the Mountain Front fault (MFF), the Dezful Embayment fault (DEF), and the Zagros Foredeep fault (ZFF). Fault plane solutions for earthquakes along these faults indicate that they all dip about 60\(^{\circ}\) NE, suggesting that they now act as reverse faults although they may have acted as normal faults during the Permo-Triassic opening of Neo-Tethys (Jackson 1980; Berberian 1995). Another group of basement faults are N-S trending faults which developed during the latest Proterozoic and early Cambrian in the Arabian basement (Beydoun 1991). These faults are steeply dipping and currently undergo right-lateral strike-slip motion (Hessami et al. 2001; Sepehr et al. 2002). Some of these faults, located in the Zagros belt, are the Hendijan- Izeh Fault (HIF), the Kharg-Mish Fault (KMF) and the Kazerun Fault (KZ). The Balurad Fault (BR) is an E-W left-lateral shear zone northwest of the Dezful Embayment. Structural information derived from seismicity within the Zagros belt indicates that these faults are still active as right lateral strike-slip faults in the basement underlying the folded cover. The study area is located in the North-West margin of the Dezful Embayment (Fig 1b). The Dezful Embayment primarily corresponds to a morphotectonic region stepped down with respect to the Izeh zone, surrounded by three of the major basement structures described above. The north-northeastern limit is the Balaroud flexure, the east-northeastern limit is the Mountain Front Fault (MFF) and its south-southeastern limit is the Kazerun Fault (Sepehr and Cosgrove 2005).

Generally three main lithological series are exposed in this area from Lower Cretaceous up to Pliocene: (i) Carbonate series, including part of the Khami Group (Fahlidi and Darjan Formations, of Neocomian and Aptian age, respectively), Ilam and Sarvak Formations (Cenomanian to Santonian) and the Asmari Formation (Oligocene-Lower Miocene); they form the main reservoir rocks in southwest Iran. (ii) Clastic and argillaceous series, including the Gadvan Formation of the Khami Group (Neocomian-Aptian), Kazhdum (Albian), Gurpi (Campanian-Maastrichtian), Pabdeh (Paleocene-Eocene), Mishan, Agha-Jari and Bakhtiari Formations (Upper Miocene-Lower Pleistocene). (iii) Evaporitic series, including the Kalhur member (Lower Miocene) within the Asmari Formation and the Gachsaran Formation (Middle Miocene), which is the main cap rock of the Asmari reservoirs in Iran. This antcline is an asymmetric fold that the overall its axial trend is about NW-SE; however, the eastern part of this antcline has E-W trend. This fold characterized by a high angle southwestern forelimb due to faults development in this limb (Fig 1b). Surface outcrop in this fold is Aghajari formation and also the Asmari, Gachsaran and Bangelan group are drilled in this structure. In the north dezful embayment, detachments surface is more active than north dezful embayment (Fig 2).
Detachmental role of the Ghachsaran and kalhur units provided disharmonic folds and thickness increasement in these horizons (Fig 3).

3. Methodology
Due to the absence the surface outcrop of the Sarvak reservoir formation, we used image logs for fracture analysis in this area. We have analyzed the spatial distribution, orientation, scale, and kinematic significance of the fold-and fault-related fracture systems applying Formation Microimages (FMI) & Formation microscanner (FMS) images log, UGC map (underground contour map), seismic cross-section and the Rockwork and Move softwares. Imaging tools can be used in a wide variety of geological and drilling environments, providing borehole images of rock, from the karstic carbonates to soft thinly laminated sand/shale sequences (Aghli et al, 2016). Their advantage aspects are high resolution and often complete borehole coverage images. Image log is a pseudo-picture of
borehole wall which image the physical property of borehole wall such as electrical resistivity or acoustic impedance. In the first method resistivity of borehole wall is converted into high resolution resistivity image of wall. There are 2, 4, 5 or 8 pads on an imaging tool (Fig 4a). Each pad covers limited part of borehole wall (Serra 1989). The FMI tools have an azimuthal resolution of 192° capable of radial micro resistivity measurements (vertical resolution: 0.2′′, vertical sampling: 0.1′′, depth of investigation: 30″) (Schlumberger 2003). The EMI Electrode arrays are mounted on six independent arms providing excellent pad contact. This produces very high resolution images for stratigraphic and structural analysis (Halliburton 1996). Bedding, fracture features, faults, stratigraphic features can often be manually or semi- automatically identified and quantified (Ye and Rabiller 1998).

Besides identifying the fractures and faults, borehole imaging tools are routinely used in the support of detailed core analysis for a variety of other applications such as sequence stratigraphy, facies reconstruction, and diagenetic analysis. In general, the electrical images appear to be sensitive to variations in mineralogy, porosity, and fluid content that highlight both natural fractures and rock fabric. In this study, image logs were processed and interpreted by the CIFLOG GEOMATRIX software. When the image is "unrolled" and displayed from 0″ to 360°, linear natural features intersecting the borehole appear as sinusoids (Rider 1996). Assuming that the images are properly oriented to the geographic north, the peaks and troughs of the sinusoids can be related to the dip and azimuth of the associated feature, respectively (Fig 4b). This consequently provides fundamental information regarding the formation encountered that other petrophysical logs are unable to provide. Images were produced in the two well A&B sites. Detailed post-acquisition analysis of the image data was done with high-performance interview analysis software. Image analysis and enhancement techniques were available to identify precisely the characteristics of the formation reservoir. The main purpose of this study is to systematically study the Sarvak reservoir fracturing and bedding, their direction and type, methods to extend the fracture in the reservoir, their generation mechanisms, determination of the in situ stress direction, borehole breakouts induced fracture and determination of the the maximum horizontal stresses. This study is important because the optimal production from naturally-fractured reservoirs is, in essence, a function of drilling wells to intersect as many hydraulically conductive fractures as possible. Hence, horizontal wells drilled approximately towards the $\sigma_{\text{max}}$, would be expected to encounter the greatest number of open fractures in the wells within the study region. Also deviation of wells towards the present-day $\sigma_{\text{max}}$ reduces both the absolute stress and differential stresses acting on the borehole, resulting in the least possible circumferential stress concentration around the wellbore and thus reducing the likelihood of breakout and associated drilling problems such as struck pipe and wellbore collapse.

4. Results
4.1. Bed boundary in well A and B
As mentioned above a bed boundary forms due to changing in adjacent beds characteristics such as texture, mineralogy, color, grain size, etc. Physical variation of adjacent beds reflects in resistivity contrast in the FMI logs. Therefore, bed boundary appears as sudden change in FMI tones that usually observable in all pads. Two types of them are observed: The first set, in which the dips correspond to sharp and well planar bed/layer boundaries are categorized as High Confidence (HC) whereas in the second set the dips corresponding to vague and uneven bed/layer surfaces are categorized as Low Confidence (LC) (Figs 5a,b). In the FMI of studied wells ~290 bed boundaries were recognized. 232 bed boundaries were Low Confidence Bedding and 58 bed boundaries were high Confidence Bedding. Most bed boundaries are not sharp and diagenesis processes or variation in shale content of beds made them vague. The sharp and vague bedding was categorized as High Confidence and Low Confidence Beddings, respectively. Picking these bedding was erroneous and it was tried to set them in agreement with sharp beddings. Figures 5 and 6 show the orientation of low and high confidence bedding. Based on HC and LC, in well A situated in central part of anticline, the structural dip azimuth is S64°E and the magnitude of dip is 4°. The dip of bedding varies from 0.5-17.2.
4.2. Fractures characterization in the Well A and well B

Fractures are planar features with no apparent displacement of blocks along their planes. Generally, they have a steep dip in tensional and wrench regimes (Rider 1996). Whereas in compressional regimes, they may have high to low angle dips. Based on the interpretation of the seismic reflection profile across the anticline, the southern limb has a more dip than the northern limb and fractures were developed highly in the southern limb.

Generally on the FMI and EMI images, fractures tend to occur as linear features that generally have a dip steeper than the structural dip. Open fractures, in a clay free formation, have a conductive appearance on the images due to invasion of their aperture with the conductive drilling mud. While the mineralized or sealed fractures appear resistive if the filling material of their apertures is dense like calcite or anhydrite (Ye and Rabiller 1998). However, the fractures having a clay or pyrite filling have a conductive response. To differentiate between the mud filled and clay/pyrite filled conductive fractures, knowledge of the depositional and stratigraphic setting of the study area is imperative. In some cases, open hole logs can also be very helpful for such kind of differentiation. If a well is drilled by saline water, apertures of open fractures will be filled with conductive mud. Trace of open fractures in borehole wall seems as a sinusoidal wave in FMI. Resistivity of saline mud that fills open fractures is lower than matrix so an open fracture appears as a dark sinusoidal wave in a bright background. These dark features might be continuous or discontinuous and vertical or oblique with high dip.
Different types of observed fractures in this anticline are major open fracture, medium open fracture, minor open fracture, possible open fracture, vertical open fracture, vuggy open fracture, non-systematic crack, filled fracture. 536 different fractures detected in FMI of this fold. The minor open fractures are the dominant fractures in FMI (Fig 7). Based on the average orientation of fractures, two main fracture sets can be classified in well A located in the central part of fold (Fig 8), the first set is high angle systematic fractures and another set is an approximately vertical fracture set. Relative orientation of fractures with respect to beddings is presented in Figure 8.

Fig 6. High (a) and Low (b) confidence bedding in well B.

Fig 7. Examples of minor open fractures
Fig 8. UGC map for top of the Sarvak formation and illustration of fractures development in the fold. Note the strikes of bedding are shown by black lines. Also strikes of cross-axial and oblique fractures are shown by red and white lines respectively.

Fig 9. Iso dip (a) and curvature (b) map of top of the Sarvak formation. Each color shows the same slope value.
These fracture sets have trending N53E and N34E that are cross-axial and oblique fractures respectively. Fractures’ dip was found to be varied from 5.7° to 89.3° with the average of 70.7°. In well B situated in eastern and also curved part of fold, the dominant strike direction of open fractures is toward N85E-S85W with average dip inclination of 63 degrees. The consistent relationship between the strike of conductive fractures and bedding indicates oblique nature of these natural fractures (Fig 8). Also can be said that due to operation sinistral strike-slip fault, anticlockwise rotation of anticline axis, change in fractures orientation and also development and increase the density of fractures in the curved part of this anticline was occurred (Fig 8).

Fracture density around a fold may be directly related to the fold curvature, and variations in fracture density can therefore be inferred by plotting variations in curvature (Lisle 1994; Roberts 2001, Al-Dossary and Marfurt 2006; Chopra and Marfurt 2007; Gao 2013, Vatandoust and Farzipoursaein 2017). Curvature can be expressed in terms of the second derivative of the curve (Thomas 1972). Increased curvature of a surface results in increased tensional stresses and consequently causes more jointing. Therefore slope and curvature maps of a folded surface may help to identify areas which contain open fractures which may in turn increase the porosity and permeability (e.g. Fischer and Wilkerson 2000; Stewart and Wynn 2000, Vatandoust and Farzipoursaein 2017). In the figure 9 the slope and curvature map of the top sarvak formation in the studied anticline is presented. These maps are generated in move software using the UGC data. Based on iso-curvature map of the sarvak Formation in the field (Figs.7 and 8), maximum curvature occurs in the southern limb of the anticline, and near the sinistral strike-slip fault. The map also demonstrates (red dashed lines in Fig 8) the juxtaposition of high positive and high negative curvature values which may be interpreted as major fracture lineaments. Since high curvature areas have undergone significant outer-arc stretching during folding, they may be zones of well-developed hinge-parallel fractures (Price 1966).

In high curvature regions, fracture intensities are high and fractures are oriented parallel to the fold hinges (E-W striking fractures in the well B and NW-SE striking fractures in the well A). The effect of the strike slip fault on the anticline structure demonstrated by the fold curvature map, change in fracture strikes and the orientation of the bedding in the central and NW part of the anticline.

4.3. Determination of in-situ stress directions using image logs

Borehole breakouts and drilling-induced fractures (DIFs) are important indicators of horizontal stress orientation, particularly in aseismic regions and at intermediate depths (<5 km). Approximately 19 % of the stress orientation indicators in the World Stress Map (WSM) database have been determined from borehole breakouts and DIFs. Furthermore, borehole breakouts and DIFs provide the majority of stress orientation indicators in petroleum and geothermal systems (Tingay et al. 2008). Borehole breakouts are stress-induced enlargements of the wellbore cross-section (Bell and Gough 1979). When a wellbore is drilled, the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the surrounding rock (i.e. the wellbore wall) (Tingay et al. 2008). Borehole breakout occurs when the stresses around the borehole exceed that required to cause compressive failure of the borehole wall (Zoback et al. 1985; Bell 1990). The enlargement of the wellbore is caused by the development of intersecting conjugate shear planes that cause pieces of the borehole wall to spall off (Fig 10). The stress concentration around a vertical borehole is greatest in the direction of the minimum horizontal stress (Sh). Hence, the long axes of borehole breakouts are oriented approximately perpendicular to the maximum horizontal compressive stress orientation (SH; Plumb and Hickman 1985). DIFs are created when the stresses concentrated around a borehole exceed that required to cause tensile failure of the wellbore wall (Aadnoy 1990). DIFs typically develop as narrow sharply defined features that are sub-parallel or slightly inclined to the borehole axis in vertical wells and are generally not associated with significant borehole enlargement in the fracture direction (note that DIFs and breakouts can form at the same depth in orthogonal directions (Aadnoy and Bell 1998). The stress concentration around a vertical borehole is at a minimum in the SH direction. Hence, DIFs develop approximately parallel to the Sh orientation (Aadnoy and Bell 1998).

Borehole breakout typically appears on resistivity image logs as broad, parallel, poorly resolved conductive zones separated by 180° (i.e. observed on opposite sides of the borehole) and often exhibiting caliper enlargement in the direction of the conductive zones (Bell 1996). Breakouts are typically conductive and poorly resolved because the wellbore fracturing and spalling associated with the breakout results in poor contact between the tool pads and the wellbore wall, which in turn causes the tool to partially or fully measure the resistivity of the electrically conductive drilling mud rather than the formation. Drilling-induced fractures can only be observed on image logs. DIFs typically become infiltrated by drilling mud and, thus, appear on resistivity image logs as pairs of narrow, well defined conductive features (resistive in oil-based mud images) separated by 180° (Aadnoy and Bell 1998). Furthermore, unlike natural fractures that tend to cross-cut the wellbore, DIFs are usually aligned sub-parallel or slightly inclined to the borehole axis in vertical wells (Tingay et al. 2008).
4.3.1. Present-day maximum horizontal stress orientations

In this part of our study we used resistivity image logs to determine the present-day stress orientations in the study anticline in the north Dezful embayment. The elongation of the the maximum circumferential stress around a vertical borehole occurs perpendicular to SH\textsubscript{max} (Kirsch 1898). Hence, borehole breakouts are elongated perpendicular to the present day S\textsubscript{Hmax} direction (Bell and Gough 1979). Image logs can also be used to interpret drilling-induced fractures (DIFs) which are oriented parallel to the in-situ S\textsubscript{Hmax} orientation (Bell 1996). To identify present-day maximum horizontal stress orientations, we interpreted 184 breakouts and 16 tensile fractures with a total length of 197 m in the FMI of well A in the central part and well B in the eastern part of the anticline (Figs. 11 and 12). Figure 10 show a typical breakout and tensile fractures detected in the FMI of well A. 161 breakouts and 2 tensile fractures were interpreted in this well. The mean dip azimuth of breakouts is N325°. Induced fractures in the well A have trending N55°. Based on the orientation of the induced fractures situated parallel to the maximum horizontal, the mean present-day maximum horizontal stress orientation is N55° in the central part of the fold. The mean strike azimuths of the breakouts and induced fractures in the well B have trending N300° and N30° respectively (Fig 12). Based on the orientation of the borehole breakout fractures situated perpendicular to the maximum horizontal stress, the present-day maximum horizontal stress orientation is N30° in the eastern part of the fold (Fig 13).

5. Discussion

In the studied anticline we have identified two systems of fractures that relate to either folding or faulting. In the central part of fold, the first fold-related system, includes two sets of fractures are created by NE contraction that developed the overall Zagros folds. The second system of fractures includes sets formed due to operation of the strike slip fault. Reactivation of this fault caused anticlockwise rotation of the anticline axis, change in fractures orientation (fold related longitudinal fractures, NW-SE, and E-W sets) and also develop and increase the density of traversal fractures (NE-SW set) in the eastern part of the anticline. Furthermore in this study the maximum horizontal stresses obtained by interpretation of the borehole breakouts and induced fractures in image logs.
The correlation between $S_{Hmax}$ orientations derived from breakouts herein and earthquake focal mechanism solutions in the WSM project is also scientifically significant. Earthquake focal mechanism solutions make up 72% of the 2008 WSM database (Heidbach et al. 2010). However, the reliability of using focal mechanism solutions near plate boundaries as present-day stress indicators has recently been brought into question (Heidbach et al. 2010). Stress orientations inferred from focal mechanism solutions assume that the earthquake motion is along faults that are sub-optimally oriented with the present-day stress orientation. Yet, analysis of stress orientations from different methods near plate boundaries has revealed that some plate boundaries, most notably the San Andreas Fault Zone and Great Sumatran Fault, are mechanically weak (low coefficient of friction) and may thus be reactivated by non-optimal and highly-oblique stress fields (Zoback et al. 1987; Mount and Suppe 1992). Hence, there exists a higher likelihood for errors in stress orientations derived from earthquake focal mechanism solutions near plate boundaries and these data must be considered as potentially unreliable (Heidbach et al. 2010; Rajabi et al. 2010).

6. Conclusion
In the central part of fold induced tensile fractures and borehole breakout directions are N55° and N145° respectively. Also tensile-induced fractures direction was inclined in the eastern part of anticline and showing N30° direction and borehole breakout direction is perpendicular to tensile fracture and has N120° orientation. Based on the orientation of the induced fractures and borehole breakouts, the mean present-day maximum horizontal stress orientations are N55° and N30 in the central and eastern parts of the anticline (Fig 14 and Table 1). The $S_{Hmax}$ orientation observed in the well located in the central part of the anticline is consistent with $S_{Hmax}$ orientations derived from nearby earthquake focal mechanism solutions and with the
absolute plate motion direction of the Arabian plate in north Dezful emplacement and it emphasize that this part of structure is deformed under the Zagros orogeny tectonic phase. Also the $H_{\text{max}}$ orientation observed in the eastern part of fold can be related to reactivation of strike slip faults in the post collisional phase. We propose that in effect of reactivation of the NE–SW oriented, strike–slide faults, beside the rotation in fold axis, the mean shortening direction in the overall Zagros folds and thrusts belt (NE trend) can be changed in the north Dezful emplacement. Finally we suggest that drilling of production wells that are highly-deviated or horizontal and oriented approximately towards the present-day stress $H_{\text{max}}$ are likely to both intersect more hydraulically conductive fractures and reduce wellbore instability problems. Comparing our results with other studies in the Zagros, such as Rajabi et al. (2010), shows that the maximum present-day stress direction in North Dezful is consistent with the general direction of compression and continental collision, although under the influence of faults operation, these maximum present-day stress direction can be changed. Optimal production from naturally-fractured reservoirs is, in essence, a function of drilling wells to intersect as many hydraulically conductive fractures as possible (Rajabi et al. 2010). Hence, horizontal wells drilled approximately towards the N30°E in the eastern part of fold and towards the N55°E in the central part of the fold, would be expected to encounter the greatest number of open fractures in the wells within the study region. Deviation of wells towards the present-day $H_{\text{max}}$ reduces both the absolute stress and differential stresses acting on the borehole, resulting in the least possible circumferential stress concentration around the wellbore and thus reducing the likelihood of breakout and associated drilling problems such as stuck pipe and wellbore collapse (Peska and Zoback 1995). Hence, we suggest that drilling of production wells that are highly-deviated or horizontal and oriented approximately towards the present-day stress $H_{\text{max}}$ are likely to both intersect more hydraulically conductive fractures and reduce wellbore instability problems.

References
Fischer MP, Wilkerson MS (2000) Predicting the orientation of joints from fold shape: Results of pseudothree- dimensional modeling and curvature analysis, Geology 28: 15-18.
Ghanadian M, Faghhi A, Abdollahie Fard I, Kusky T, Maleki M (2017) On the role of incompetent strata in...
the structural evolution of the Zagros Fold-Thrust Belt, Dezful Embayment, Iran, *Marine and Petroleum Geology* 81:320–33


Schlumberger (2003) Using borehole imagery to reveal key reservoir features, Reservoir Optimization Conference p. 137, Chester, Tehran, Iran.


