Characterization of micro-fractures in carbonate Sarvak reservoir, using petrophysical and geological data, SW Iran

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A B S T R A C T

In this paper, an integrated study of micro-fractures is carried out in Sarvak Formation. To achieve this goal the data from three wells (A, B and C) in one of the southwestern Iranian oil fields were used. In this study petrophysical thin sections, porosity-permeability core data, image logs, Dipole Shear Sonic Imagier (DSI) log, Velocity Deviation Log (VDL), Hydraulic Flow Units (HFU) concept, resistivity logs and drilling mud reports were used to identify and analyze micro-fractures in Sarvak Formation. The micro-fractures were first detected in thin sections and image logs directly, then the results of other methods in micro-fracture zones were investigated. The results show there is an abnormal trend of porosity-permeability in core data which is compatible with micro-fracture zones. Also, the relationship between micro-fractures and flow units was studied. Eight HFUs were recognized using porosity-permeability core data and FZI* (Flow Zone Indicator-Star) method. Later each of the HFUs was divided into two sub-HFUs; one of them is well-matched with the micro-fracture zones. The negative parts of VDL were in good agreement with the micro-fracture zones. The slowness anisotropy was mainly affected by the micro-fracture zones, but the energy and traveltime anisotropies were under the influence of the other phenomena such as solution seams, shale layers and borehole washouts. The fast shear wave azimuth was mainly aligned with the $S_{\text{max}}$ (maximum horizontal stress) direction, however, in micro-fracture zones, the direction suddenly changes. It was also observed that the micro-fractures do not have a considerable effect on Stoneley wave reflection, while the borehole washouts and shale layers have a great impact on this. The mud loss and mud invasion were very low in micro-fractured zones, which is related to the lack of lateral continuity of micro-fractures in the formation. The measured fracture apertures using thin section and image logs are often less than 0.1 mm, but the calculated values using Pezard-Anderson equations are very high.

1. Introduction

More than 60% of the world’s oil and 40% of the world’s gas reserves are in carbonate reservoirs (Lee et al., 2015). In these reservoirs, a combination of depositional fabrics, diagenetic alterations and fracturing controls the reservoir quality (Abrahams, 2008). Most of the oil producing horizons of Iran is related to the Oligocene–Miocene Asmari Formation and the Upper Cretaceous Sarvak Formation (Rabbani et al., 2011). The Sarvak Formation in the southern Iran contains more than 20% oil-in-place of Iranian oil reserves, creating the second most important oil reservoir after the Asmari Formation (Bordenave et al., 2010; Pireh et al., 2015).

Despite its importance, few studies have addressed the fractures in Sarvak Formation. Those few studies often included only large scale fractures. Tavani et al. (2011) recognized four joint sets during the structural evolution study of the Bangestan anticline, based on outcrop observations. Lapponi et al. (2011) studied the dolomitized sections of the Sarvak Formation in outcrops in Lurestan province and concluded that dolomitization had a great impact on the final geometry of the fracture network. Movahed et al. (2016) used image logs to study the natural fractures of Sarvak Formation in the Gachsaran oil field and they identified two sets of conjugate fractures, with high densities and high apertures. Mollaian and Memarian (2016) classified some of the physical properties of Sarvak reservoir using Parzen classifier to recognize the three main porosities (interparticle, vuggy and fracture porosities). Moradi et al. (2017) proposed a clustering method based on k-nearest neighbor to study the facies types using well data in Sarvak Formation. Kosari et al. (2017) studied the origin of natural fractures of
Sarvak Formation around normal faults using seismic data in one of the oil fields in Persian Gulf. Moreover, Fracture Measure (FM) method was used to estimate fracture parameters using fullset logs and the neural network (Mazaheri et al., 2015, 2017). Misra et al. (2015) and Misra et al. (2016a) implemented electromagnetic measurements to characterize fractures in the borehole and in geological cores.

In general, studies on micro-fractures have focused mainly on their genesis (Scholz, 2016; Schultz et al., 2013), their size distribution (Guerriero et al., 2010; Hooker et al., 2014), paleostress assessment (Laubach and Diaz-Tushman, 2009; Ellis et al., 2012; Rempe et al., 2013), their relationship with faulting (Faulkner et al., 2011; Suzuki, 2012), diagenesis sequence determination (Ahr, 2008; Mehrabi and Rahimpour-Bonab, 2014) and hydrocarbon primary migration assessment in shale formations (Kobchenko et al., 2011; Fan et al., 2012; Teixeira et al., 2017).

Identifying micro-fractures commonly requires a detailed study of cores. However, their identification with other less costly methods is also of particular importance. In this study, the main goal is to investigate the application of different identification methods for micro-fractures in a carbonate reservoir. Moreover, this study addresses the effect of micro-fractures on reservoir quality.

Detailed fracture analysis needs a complete dataset, including core and petrophysical data, which are not always available. Due to lack of necessary data, the role of fractures (and especially micro-fractures) is still unknown in most of the Iranian reservoirs. For current study, an exceptionally comprehensive dataset from three wells (A, B and C) enabled us to characterize various petrophysical aspects of micro-fractures, delineate their effect on reservoir quality and investigate their effects on the petrophysical logs of the Sarvak Formation in one of the supergiant oilfields of southwestern Iran.

In this study, according to Anders et al. (2014), the fractures with apertures less than 0.1 mm were considered as micro-fractures.

2. Geological setting

The studied oil field is located in southwest Iran (80 km to the western of Ahvaz city) in Abadan Plain (Fig. 1). The main trend of the field is N-S, however the southern part shows somewhat NW-SE trend (Abdollahie-Fard et al., 2006). The Abadan Plain is located at the end of Southwest Zagros. The north and north-eastern borders of this plain are Zagros folds front and the southern border is located in the Persian Gulf. It belongs to Mesopotamian basin which is northern termination of the Arabian platform (Aghanabati, 2004). This plain is a flat area, with low elevation and covered by alluvial deposits; hence the subsurface...
geological information is achieved only from seismic, drilling and well logging data (Motiei, 2010).

The Abadan Plain shows three main structural trends: NE–SW, N–S and NW–SE which are related to deep-seated fault activities and the geological structures along these trends are believed to be related to the basement-rooted faults (Abdollahie-Fard et al., 2006).

The Sarvak Formation was deposited in upper Cretaceous during late Albian to early Turonian (Bordenave and Hegre, 2010) (Fig. 2). The Sarvak deposition is considered to be synchronous with a progressive relative sea-level fall during late Albian to Turonian, which was followed by a general uplift and emergence during Turonian (Emami et al., 2010; Aqrawi et al., 2010; Sharp et al., 2010; Hollis, 2011). In Abadan Plain the Sarvak Formation is overlain by Laffan shale with an unconformity and its lower contact is with Kazhdumi Formation. The thickness of the Sarvak Formation in Abadan Plain is 600-700 meters, and comprises thick limestone and dolomitic limestone with minor clayey and argillaceous intervals.

The Sarvak Formation is divided into 13 zones in the studied oil field. From top to base, Sar_1 to Sar_12 are its reservoirs and the lower 13th zone, Sar_Intra, is not a part of the reservoir. The upper part of the Sarvak Formation (Sarvak Reservoir) is dominated by bioclastic wackestone and packstone of shallow marine origin (Assadi et al., 2016).

3. Materials and methods

3.1. Materials

For the well-A, in total, 687 porosity-permeability data from core-plug samples were used from Sar_1 to Sar_10 (except Sar_2 which its main lithology is shale) reservoir units. Moreover, 834 thin sections were analyzed. The fullset log data such as CAL (Caliper), BS (Bit Size), GR (Gamma ray), RHOB (Bulk Density), NPHI (Neutron Porosity), DT (Compressional Sonic Slowness), PEF (Photoelectric Factor), HRLA (High-Resolution Laterolog Array) and MSFL (Micro-Spherically Focused Log) and advanced log data such as FMI (Fullbore Formation Microimager) (Schlumberger, 2002a) image log, NMR (Nuclear Magnetic Resonance) and DSI (Dipole Shear Sonic Imager) log data (The Stoneley and cross-dipole modes) were used for petrophysical evaluation and micro-fractures characterization. In addition the drilling mud loss data were analyzed.

In the well-B, 210 porosity-permeability data from core-plug samples (from Sar_3 and Sar_4 reservoir zones), fullset log data, OBMi (Oil-Base Microimager)-UBI (Ultrasonic Borehole Imager) (Schlumberger, 2002b, 2006) image logs, DSI log (Stoneley mode) and drilling data were used. Moreover, in well-C, fullset data, FMI image log, DSI log (Stoneley mode) and drilling mud loss data were used.

3.2. Methods

3.2.1. Image logs

The FMI, OBMi and UBI image logs of the studied wells were quality-controlled and corrections, such as speed, bad button, swing arm and gain, were applied to the raw image data. The corrected image was equalized and normalized (statically and dynamically), and then the static and dynamic images were used for the interpretation. Different borehole events such as fractures, breakouts, bedding surfaces, solution seams and stylolites were extracted using image log. Solution seams and stylolites (diagenetic features) are products of chemical compaction in sedimentary rocks and are common in carbonate rocks (Mehrabi et al., 2016).

3.2.2. Hydraulic flow unit (HFU)

Mirzaei-Paiaman et al. (2015, 2018) showed that rock types could be divided into two categories of static and dynamic based on their petrophysical attributes. A petrophysical static rock type (PSRT) was defined as a set of rocks with similar primary drainage capillary pressure curves or unique water saturation for a given height above the free water level. A petrophysical dynamic rock type or HFU was then
described as a collection of rocks having similar fluid flow behavior. They theoretically, conceptually and experimentally showed that the well-known FZI (flow zone indicator) (Amaefule et al., 1993) was not a correct indicator for appraisal of HFUs and proposed an alternative correct indicator as FZI* (FZI-Star) as:

$$FZI^* = 0.0314 \sqrt{\frac{k}{\phi}}$$  \hspace{1cm} (1)

In which FZI* is in μm, ϕ is porosity in fraction and k is permeability in md. This index is equivalent to the famous RQI (Reservoir Quality Index).

3.2.3. Velocity Deviation Log (VDL)

VDL is used for separation and characterization of different pore types in carbonate reservoirs. In this method, using Wyllie equation, a synthetic sonic velocity is constructed and compared with real velocity. The velocity deviation groups are:

- Positive deviation (VDL > +500): vuggy/moldic porosities are privilege.
- Zero deviation (−500 < VDL < +500): interparticle, inter-crystalline and micro-porosities.
- Negative deviation (VDL < −500): borehole washouts, free gas and fractures can create a negative VDL curve.
3.2.4. DSI log

The mode3 (Stoneley mode) and modeX (cross dipole) of DSI (Schlumberger, 2014) are used to natural fracture study. The transducers for the mode3 and modeX data acquisition are monopole and dipole, respectively.

Wellbore wall irregularity (like washouts), bedding and natural fractures reflect Stoneley wave. The reflected Stoneley wave creates chevron patterns in Stoneley full waveforms, which could be used as an indicator for natural fracture detection and characterization after appropriate processing and filtering (Zaree et al., 2016). As Stoneley wave travels in the wellbore wall, it is reflected by some events such as the washouts and natural fractures, therefore, some criss cross shapes are created in the Stoneley waveform which is called chevron patterns. In this study, time and depth average filters were applied to the Stoneley raw data and the direct Stoneley wave was removed by a band-pass frequency filter. Then, F-K filter was applied to separate the up-going and down-going components of the chevron patterns from remaining waveforms. The reflected part of Stoneley wave is considered as noise in Stoneley full waveform; however, these noises can be used for fracture detection (Haldorsen et al., 2006).

Anisotropy can be resulted from structural events such as aligned fractures, thinly-layered beds and unequal stress distribution within the formations (Panning et al., 2010). Natural fractures are one of the sources for anisotropy in carbonate reservoirs (Nelson, 2001; Maultzsch et al., 2003). Reservoir anisotropy can be studied by processing and analyzing DSI Xdipole (Cross Dipole) mode data (Plona et al., 2000, 2002). In an anisotropic formation, shear waves, whose polarization is aligned in the stiff direction, travel faster (Panning et al., 2010). There are three main kinds of anisotropy in rocks; slowness, traveltime and energy. Moreover, Homan et al. (2016) developed a triaxial electromagnetic coil apparatus for quantifying the anisotropy of hydrocarbon reservoirs.

3.2.5. Resistivity logs

The DLL (Dual Laterolog) tool operates by focusing electrical currents into the formation to create a deep (Laterolog Deep = LLD) and shallow (Laterolog Shallow = LLS) measurement in water-base drilling.

![Fig. 6. Porosity-permeability cross plot for the Sarvak reservoir zones, separately. The mentioned trend in previous figure was considered for each of the Sarvak reservoir zones.](image1)

![Fig. 7. The eight recognized HFUs on probability plot.](image2)
mud condition (Halliburton, 2007). HRLA (High-Resolution Laterolog Array Tool) measures resistivity (Schlumberger, 2000) in different depths (RLA0 to RLA5). RLA0 measures the mud resistivity, LLS reading is between RLA2 and RLA3, and RLA5 is approximately equal to LLD (Deng et al., 2012). Misra et al. (2016b) also described the use of another electromagnetic tool, referred as induction tool, for shale gas applications in the presence of natural fractures.

In order to use resistivity logs, natural fractures are divided into two categories: horizontal fractures, with the dip angle less than 60° and vertical fractures, with the dip angle more than 75°. There are different resistivity log separations for the two categories. Saboorian-Jooybari et al. (2016) used the Pezard and Anderson equations for fracture aperture estimation:

\[ b_h = \frac{R_m}{1.2 \times 10^{-3} \left( \frac{1}{R_{LLD}} - \frac{1}{R_{LLS}} \right)} \]  
\[ b_v = \frac{R_m}{4 \times 10^{-5} \left( \frac{1}{R_{LLS}} - \frac{1}{R_{LD}} \right)} \]  

Where \( b_h \) and \( b_v \) (\( \mu \)m) are the fracture apertures for the horizontal and the vertical ones, respectively. \( R_m \) (ohm/m) is mud resistivity, \( R_b \) is the maximum resistivity of the nearby non-fractured rock, \( R_{LLS} \) is resistivity from Laterolog Shallow (LLS) in ohm and \( R_{LD} \) is resistivity from Laterolog Deep (LLD) in ohm.

3.2.6. Mud loss

Several studies have been performed to investigate the relation between mud loss and natural fractures in hydrocarbon reservoirs (Majidi et al., 2010; Huang et al., 2011; Kang et al., 2012; Xia et al., 2015). The severity of mud loss categories is shown in Table 1. Generally, second, third and fourth mud loss categories (partial to total) are regarded as an indicator for the presence of natural fractures.

4. Results and discussion

In this study, micro-fractures were first identified directly using the thin sections and image logs. Then, the capabilities of different methods for micro-fractures evaluation were investigated. For example, in the case of DSI log, it is believed that the presence of natural fractures increases the anisotropy and creates chevron patterns in Stoneley waveform. In this work, we examined this assumption for the micro-fractures and how the other geological and wellbore phenomena affect it. It is also believed that considerable mud loss and mud invasion is happened in natural fracture zones. In this regard, the mud loss and mud invasion was checked for the micro-fractured zones. In this study, the capability of Pezard-Anderson method for fracture aperture calculation using electrical logs was investigated. Finally, in this study, the methods whose results are more consistent with the direct identification methods of micro-fractures were specified and the limitations of other methods were expressed.

4.1. Well A

This well has the most complete data in the studied oil field. Hence, its dataset were thoroughly evaluated and the results were compared with each other.

4.1.1. FMI image log

First, the wellbore wall events were picked using FMI image log. Some of the picked events by FMI are shown in Fig. 3. The picked open fractures, with narrow apertures, are called hairline fractures. The hairline fractures should not be confused with drilling induced tensile

Table 2

<table>
<thead>
<tr>
<th>HFU</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
<th>F21+ (μm)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>mean</td>
</tr>
<tr>
<td>1</td>
<td>2.226</td>
<td>16.972</td>
<td>6.128</td>
</tr>
<tr>
<td>2</td>
<td>1.544</td>
<td>15.351</td>
<td>7.713</td>
</tr>
<tr>
<td>3</td>
<td>2.360</td>
<td>28.819</td>
<td>12.868</td>
</tr>
<tr>
<td>4</td>
<td>1.741</td>
<td>25.887</td>
<td>15.576</td>
</tr>
<tr>
<td>5</td>
<td>2.033</td>
<td>32.016</td>
<td>17.791</td>
</tr>
<tr>
<td>6</td>
<td>2.642</td>
<td>29.327</td>
<td>17.590</td>
</tr>
</tbody>
</table>
fractures, as the borehole breakouts in this interval are parallel to the borehole axis, thus drilling induced fracture, if existed, must be parallel to wellbore axis (Zoback, 2010). On the other hand, the picked hairline fractures are inclined. The sinuses are also fitted well on these fractures that confirms further their natural source (Zoback, 2010).

Totally 52 open natural fractures (all hairline type) were picked using FMI image log along the Sarvak reservoir (Sar_1 to Sar_12). The

<table>
<thead>
<tr>
<th>Zones</th>
<th>A portion of HFUs (%)</th>
<th>B portion of HFUs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sar_1</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>Sar_3</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Sar_4</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>Sar_5</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>Sar_6</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>Sar_7</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Sar_8</td>
<td>12</td>
<td>88</td>
</tr>
<tr>
<td>Sar_9</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>Sar_10</td>
<td>46</td>
<td>54</td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>67</td>
</tr>
</tbody>
</table>

Table 3
The HFU percentages for the Sarvak reservoir zones.

4.1.2. Hydraulic Flow Units
Commonly there is no good correlation between porosity and permeability in carbonate reservoirs due to their complicated digenetic processes (Rezaee et al., 2007; Ahr, 2008). Likewise, the porosity-permeability correlation in the Sarvak Reservoir in the well-A was not satisfactory. In Fig. 5 a trend of porosity-permeability is marked by a red ellipse which shows that several low porosities are related to higher permeability than expected; Surprisingly, there were even some

Fig. 10. Some of the recognized micro-fractures in thin sections. The arrows are representative; blue for open micro-fracture, red for partially filled micro-fracture and green for filled micro-fracture. a: open micro-fractures in mudstone. b: a partially filled micro-fracture, the rock texture is Foraminifera-rich wackestone. c: an open micro-fracture and a cemented vug, the rock texture is mudstone to wackestone. d: a large Rudist fragment which is cut with an open micro-fracture, the rock texture is floatstone. e: An Echinoderm fragment with micro-fractures. f: a partially open micro-fracture in mudstone. g: an open micro-fracture which cuts a Rudist fragment and a partially filled micro-fracture which reached to a Rudist fragment. h: open micro-fractures that cut filled fractures, the rock texture is wackestone. i: a partially filled micro-fracture in wackestone. Note that figures a to e belong to Sar_4, f belongs to Sar_5, g belongs to Sar_6, h and i are belong to Sar_7. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Fig. 11. From left to right the Tracks are Depth, Caliper-Bit size, Lithology, OF (Open Fracture, from thin sections), PFF (Partially Filled Fracture, from thin sections), FF (Filled Fracture, from thin sections), OF plus PFF from the thin sections (FE), FZI*, HFUs, sub-HFUs, VDL, FMI Static Image and Fracture Density from the FMI image log.

Fig. 12. Some of the secondary porosity features (annotated by red arrows) in thin sections. a: moldic porosity in a benthic Foram and intercrystalline porosity in lower part of figure. b: wackestone to packstone texture with vuggy porosity. c: mudstone to wackestone texture with a large vug. d: detrital particles with large vugs. e: bioclast wackestone texture with moldic porosity. f: a Rudist fragment with intraskeletal porosity. a and b belong to Sar_3 and c to f belong to Sar_8. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
samples with porosities less than 10% and permeability higher than 100 md. Such unexpected porosity-permeability trend could be an indicator of micro-fracture presence in plug samples.

The porosity-permeability cross plot was separated for the Sarvak reservoir zones, and the zones that show the above-mentioned trend were marked (Fig. 6). Most of the Sarvak reservoir zones show the mentioned trend (Fig. 6). The Sar_1, Sar_4, Sar_5, Sar_6, Sar_7, Sar_9 and Sar_10 show such trend, while Sar_3 and Sar_8 zones do not.

In this study, the concept of HFU was used to determine whether micro-fracture zones could be associated with one or a few specific HFUs or not. The HFU concept was used to separate porosity-permeability data into the more coherent groups. The FZI* was calculated for the porosity-permeability from cores using Equation (1). Eight HFUs were recognized using probability plot for the FZI* data (Fig. 7). Results show that, from HFU1 to HFU8, FZI* increases, which accompany with higher permeability to porosity ratio.

The statistical properties of the mentioned eight HFUs are summarized in Table 2. From HFU1 to HFU8 the permeability and the FZI* increase significantly, but there is not much difference between their porosity. In general, the HFU8 has the highest ratio of permeability to porosity and consequently the highest average FZI*.

The porosity-permeability data were segregated based on the recognized HFUs (Fig. 8). Almost all the detected HFUs have some data points in the trend shown in Figs. 5 and 6. Therefore, it is not possible to relate just one of the HFUs to that trend. Each HFU represents samples that have the same flow behavior, and the first parts of these HFUs, with low porosity, have similar mean flow characteristics like those with high porosity in the same group. This is due to the fact that for

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Fig. 13. The tracks from left to right are Depth, Caliper-Bit size, FE, FMI Fracture and Bedding densities, sub-HFUs, VDL and the chevron patterns (which are extracted from Stoneley wave). A strong reflection is created by the borehole washout in Sar_2.
each HFU, the effect of low porosity with fracture is similar to high porosity without fracture on mean hydraulic radius. FZI∗ truly predicts such observation because a HFU predicted by this method can cover a wide range of porosity.

The porosity of the samples with micro-fractures range 1.3–19%, and 79% of them have 5–14% porosity. Moreover, based on the same mean hydraulic radius for each HFU, the left side of each HFU (with lower porosity) may have micro-fractures. According to Fig. 9, from HFU1 to HFU8 there is more deviation from linear porosity-permeability trend. Therefore, different porosity cut-offs were used to separate sub-HFUs where micro-fracture presence is more likely. For the HFU1 to HFU8, 3.5%, 4.5%, 6.5%, 10%, 12.5%, 14.5%, 16.5%, and 19% porosity cut-offs were used respectively (Fig. 9).

Moreover, fractures identified using FMI are located in Sar_1, Sar_4 to Sar_7, Sar_9, and Sar_10 zones (Fig. 4). These zones presented a porosity-permeability trend that possibly indicates the presence of micro-fractures (Fig. 6).

The A and B portions for each of the Sarvak reservoir zones are shown in the Table 3. The Sar_1, Sar_4 to Sar_7 and Sar_9 and Sar_10 reservoir zones have higher percentage of A-portion of HFUs, while for Sar_3 and Sar_8 the A-portion percentages are very low.
4.1.3. Micro-fractures in thin sections

Considerable number of micro-fractures with various shapes and fillings were found in thin sections. Some of the recognized micro-fractures are shown in Fig. 10. In this figure, open, partially filled and filled fractures are shown by blue, red and green arrows, respectively. In the thin sections, totally open (Fig. 10a, c and d), partially filled in

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**Fig. 15.** Some of the detected solution seams are shown in image log, core, plug and thin section. The presence of the solution seams has led to an increase in energy anisotropy.

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**Fig. 16.** The correlation of solution seams and stylolites density and energy anisotropy.

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**Fig. 17.** In this figure the direction of horizontal stresses, FMI fractures and fast shear wave directions are shown. a: \( S_{\text{min}} \) direction (from borehole breakouts), b: \( S_{\text{max}} \) direction (90° from borehole breakouts), c: the FMI fractures strike, d: fast shear wave travel direction (derived from DSI Xdipole mode). The FMI fractures strike and fast shear wave directions are almost in the same direction with \( S_{\text{min}} \), but in fast shear wave direction there is some dispersed directions (marked by red ellipses). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
fracture wall (Fig. 10b), partially filled discontinuously (Fig. 10f and i) and totally filled (Fig. 10h) micro-fractures were detected. In some thin sections, different kind of micro-fractures are coexisted (Fig. 10g) and in some cases, they cut each other (Fig. 10h).

Some of them are branched (the open micro-fractures in Fig. 10a and h) and some are straight (Fig. 10b, d and g). The intervals in which the micro-fractures were observed in the thin sections are shown in (Fig. 11). These fractures, similar to the FMI-detected fractures (Fig. 4), are mainly present in Sar_1, Sar_4 to Sar_7, Sar_9 and Sar_10 zones (Fig. 11).

4.1.4. Velocity Deviation Log (VDL)

The negative quantities of VDL are the indicators for the presence of open fractures. The presence of free gas and washouts also can move VDL to negative parts, but there was not any report of free gas in the studied field, hence only borehole failures and natural fractures can make this curve negative. In Fig. 11, a set of outputs are shown using the thin sections, HFU, FMI and VDL methods.

In Fig. 11, the negative parts of VDL and the A-portion of HFUs are in good agreement and both are relatively coincident with the fractures which are detected using thin sections and image log. The open and
partially filled micro-fractures (FE track) are mainly observed in Sar_4 to Sar_7 reservoir zones. In those intervals VDL is mainly negative, the A-portion of HFUs is present and most of the FMI-derived micro-fractures are located in them. FZI* is also high in the zones where micro-fractures existed. The micro-fractures are also detected in Sar_1, Sar_9, and Sar_10 zones, where negative VDL and the A-portion of HFUs are partially present. Note that from 3833 to 3839 m interval (in Sar_4) no plugs from core samples were recovered, due to the high fracture densities, which is visible in FMI image log (Fig. 11).

For the Sar_3 and Sar_8 zones the VDL is mainly positive, accordingly negligible quantity of micro-fractures were detected in thin sections and no fractures were picked in FMI image log. The positive values of VDL can be attributed to large pore sizes such as vugs and moldic porosities. Correspondingly, thin section study showed that such large porosities are dominant in Sar_3 and Sar_8 reservoir zones (Fig. 12).

4.1.5. The Stoneley wave response to the micro-fractures

The Stoneley wave is generally very sensitive to borehole washouts (Zaree et al., 2016), which cause strong reflections. This phenomenon was observed in Sar_2, where the main lithology is weak shale and major washouts were occurred (the well diameter is 14.8 inches in that zone, while the original diameter is in 8 ½ inches). Consequently, in this zone, Stoneley wave was strongly reflected and sharp chevron patterns were created (Fig. 13). On the other hand, in Sar_8, chevron patterns do not exist, where the borehole wall is in good condition, bedding density is zero and there is no indication for fractures.
There are some weak chevrons in the middle of Sar_4 (Fig. 13). This may be related to micro-fractures as there is no bedding, and caliper is equal to bit size. On the other hand, in lower and upper parts of this zone, the chevron patterns do not exist, whereas micro-fractures are present. The Stoneley wave has not been reflected in Sar_5 reservoir zone. The chevron patterns in Sar_6 and Sar_7 contact may be related to bedding contacts, micro-fractures or both. However, in Sar_6 and Sar_7 contact, a shale peak exists in lithology column which indicates the bedding contact reflection. In the middle of Sar_7 a weak chevron matches the FMI-detected fractures. The chevrons in the middle of Sar_10 are likely related to borehole wall condition.

4.1.6. Reservoir anisotropy and the micro-fractures

Solution seams and stylolites are common in Sarvak reservoir in this well (Figs. 14 and 15). According to Fig. 14, in most cases, as the density of the solution seams and stylolites increases, the difference in the minimum and maximum energies increases. This indicates an increase in energy anisotropy.

Fig. 15 shows solution seams in image log, core, plug and thin section. The energy anisotropy increases when solution seams exist.

The cross plot of maximum minus minimum energies versus solution seams and stylolite densities is shown in Fig. 16. The correlation coefficient is 0.64, therefore, it could be concluded that there is a meaningful relationship between the energy anisotropy and solution seams density. It seems that the strong effect of solution seams and stylolites on energy anisotropy overshadows the micro-fracture effects.

Also, according to Figs. 13 and 14, it seems that solution seams and stylolites have no effect on the chevron patterns creation.

The shear slowness anisotropy is a function of fast shear wave travel-time (DTS_Fast) and slow wave travel-time (DTS_Slow) differences. The slowness anisotropy increases in the main micro-fracture (Sar_4 to Sar_7) and the washout (Sar_2) zones. The slowness anisotropy curve was shaded by green for the quantities more than 4%. It was observed that shaded parts are in good agreement with the micro-fracture zones (Fig. 14).

The direction of AZIM_FAST (fast shear wave azimuth) curve in the Sarvak reservoir is not fixed, and in some depths, it has sudden and severe changes (spikes). These spikes in AZIM_FAST curve are mainly located in Sar_4 to Sar_7 and Sar_2 zones, where the slowness anisotropy is also high. Therefore, these spikes might have relation with the micro-fracture zones and washouts (Fig. 14).

In the Sar_2 a strong peak exists in the traveltime anisotropy which is related to washouts and the shale layer (Fig. 14).

In this well, the orientations of horizontal stresses were determined using the borehole breakouts (Fig. 17). The compressional stresses accumulate around the well in the direction of minimum horizontal stress, causing the wall to symmetrically fail on both sides of the well. This phenomenon (borehole breakout) is used as an indicator for SHmin (minimum horizontal stress) direction determination. A total of 66 distinct borehole breakouts were identified with NW-SE directions, therefore, it can be deduced that the direction of the SHmax (maximum horizontal stress) is NE-SW. The strike of the fractures detected by FMI.
is also compatible with the $S_{\text{Hmax}}$ direction (Fig. 17). Extension fractures are formed parallel to the $S_{\text{Hmax}}$ direction. The fast shear wave tends to move toward denser direction, which is mainly influenced by the $S_{\text{Hmax}}$ direction, hence the major parameter that controls the fast shear wave direction is in-situ horizontal stress. However, in fast shear wave direction rose diagram, there are some dispersed directions that are marked by red ellipses (Fig. 17d). These dispersed directions are mostly related to sudden changes (spikes) in fast shear wave direction (Fig. 14), which is probably due to the micro-fractures that change fast shear wave direction, locally. Micro-fractures are usually not aligned in parallel directions and they may create different angles with each other (Singhal and Gupta, 2010).

4.1.7. Mud loss and mud invasion in micro-fracture zones

Mud loss and mud invasion were evaluated in micro-fracture zones (Fig. 18). The mud weight during the drilling of Sarvak reservoir was approximately uniform (80–82 pcf). Generally, the mud loss in reservoir zones were less than the upper seepage limit (Table 1).

Unexpectedly the mud loss in Sar_4 to Sar_6 (zones with higher presence of micro-fractures) was the lowest (0.5 bbl/hr), whereas plug samples have considerable permeability in these zones (perm track in Fig. 18). Very low mud loss in these zones could be related to the absence of lateral continuity of the micro-fractures. In such condition, the fracture network does not exist to facilitate the fluids movement.

On the other hand, mud loss in lower part of Sar_11, and Sar_12 were highest (5.5 bbl/hr). These zones were not cored, since they were mainly water-saturated. Moreover, in these zones the VDL curve is strongly positive, secondary porosity curve is high and Nuclear Magnetic Resonance (NMR) T2 distribution is mainly situated to the right part of the track, hence in these zones pore sizes are large which may increase the mud loss. Sar_8 has positive VDL and T2 Distribution is situated to the right which shows the large pore size of this unit.

Fig. 21. The tracks from left to right are Depth, Caliper-Bit size, Lithology, Core porosity, Core permeability, UBI Image, OBMI Image, Fracture Dip, Fracture Density, Fracture Aperture using image log, Equations (2) and (3) and Velocity Deviation Log respectively. The micro-fractures were identified using image log only in the Sar_Intra zone.
However, pores in this zone were smaller than Sar_11 and Sar_12 zones.

In this study, in addition to the thin section and the FMI, Equations (2) and (3) were used to estimate the fracture apertures. In Fig. 19, a combination of different methods for fracture aperture calculation, mud invasion diameter (estimated using HRLA resistivity logs), mud loss and the reservoir fluids saturation are shown.

The apertures estimated by Equations (2) and (3) are much higher than the calculated aperture using thin sections and FMI image log (Fig. 19). For instance, the fracture apertures based on FMI and thin sections are mainly less than 0.05 mm, however, based on the equations, apertures are mostly larger than 1 and 10 mm in low and high angle conditions, respectively (Fig. 19). Moreover, using Equations (2) and (3), high fracture apertures would be calculated for Sar_8 and Sar_3 units while no considerable fractures were seen in the thin sections and FMI for these units. One possible explanation is that, such equations estimate fracture aperture in continues manner while in certain zones may not any fracture exist.

The invasion diameter (DI curve) in Sar_3 and Sar_8 is more extended than Sar_4 to Sar_7. This caused more separation between RLA3 and RLA5, hence based on Equations (4) and (5), larger fracture apertures are calculated for Sar_3 and Sar_8 (Fig. 19). Below the 4074 m depth, where the water saturation is prominent, RLA1, RLA3 and RLA5 are close to RXO resistivity, since all these curves read salt water.

Fig. 22. The porosity-permeability cross plot of well-B.

Fig. 23. The tracks from left to right are Depth, Caliper-Bit size, Lithology, Mud invasion (DI), Mud loss (ML), Secondary porosity (SEC_POR), Oil-water saturations, Solution seam and stylolite density, Solution seam and stylolite dip, VDL, Fracture and bedding density and Chevron patterns.
Therefore, the calculated fracture aperture by Equations (2) and (3) is very high (Fig. 19).

In Sar_4 to Sar_7 zones, RLA3 and RLA5 are proximally coincident and far from RXO, therefore the invasion is low (Fig. 19). This observation, similar to the mud loss amount in micro-fracture zones, further confirms the absence of the connected network of fractures in the formation.

The average calculated fracture aperture using thin sections, FMI image, Pezard-Anderson equations for high and low angle fractures are 0.023, 0.050, 1.96 and 41.70 mm, respectively (Fig. 20). Pezard-Anderson equations were proposed for a condition in which the fractures are elongated enough and form a network to transport the mud filtrate to considerable distance from the wellbore wall, however, it seems that this is not the case in this well.

4.2. Well B

4.2.1. Image log, VDL and core data

In this well, only 7 micro-fractures were identified in Sar_Intra zone using the image logs (Fig. 21). So the number of fractures in this well is very low. The average aperture of these fractures is 0.060 mm using the image log. While the average aperture using Equations (2) and (3) for high and low angle fractures are 15.09 and 128.25 mm, respectively (Fig. 21). So, the calculated apertures using this equation are very high for this well, similar to well-A.

In well-B, the VDL is mainly positive, however, at the 4241–4267 m depth interval, VDL is negative. The main washouts and micro-fractures are present in this interval. In addition to the fractures, borehole washouts also cause a negative VDL.

Core is taken only in Sar_3 and Sar_4 zones in this well. The porosity-permeability cross plot of this well shows a fairly linear trend (Fig. 22). Moreover, the mentioned micro-fracture trend in the well-A does not exist in the cored zones of the well-B. Therefore, according to image log, VDL and core data, there is no micro-fractures in Sar_1 to Sar_12 zones.

4.2.2. Drilling mud, stoneley wave and stress direction data

The mud loss was 0.5–5 bbl/hr for the Sarvak Formation drilling in this well, which is in seepage range (Fig. 23). In Sar_12 and Sar_Intra zones, the secondary porosity is increased and the mud loss is higher (Fig. 23). There is also not much mud invasion in the Sar_Intra zone where the micro-fractures are present. The Sar_Intra zone is water saturated (Fig. 23) and is not the reservoir throughout the entire field.

The major chevron patterns have been created in Sar_2 and Sar_Intra (Fig. 23). The presence of these patterns is due to the presence of weak shales and the borehole washouts. Moreover, in Sar_11 zone, there is some chevron patterns and as expected shale layer peaks in lithology track accordingly (Fig. 23). The solution seams and stylolites were also picked for this well. Like well-A, there is no correlation between the solution seams-stylolites density and the chevron patterns (Fig. 23).

Horizontal stress directions in the Sarvak Formation of this well were determined using 242 bore hole breakouts (Figs. 24 and 25). Like well-A, in well-B the SHmax direction is toward NE-SW (Fig. 25). While the strike of identified fractures using the image log is toward NW-SE.

4.3. Well C

4.3.1. Image log and VDL

In this well only two micro-fractures were identified in Sar_Intra zone using FMI image log. The average aperture of the two recognized micro-fractures is 0.05 mm. Whereas the calculated average aperture using Pezard-Anderson equations for high and low angle fractures are 2.76 and 199.542 mm, respectively (Fig. 26).

In the well-C, like well-B, the VDL is mainly positive, but in Sar_Intra in front of wellbore washouts and micro-fractures, VDL is negative (Fig. 26). Also in Sar_2 due to the washouts the VDL in negative (Fig. 26). Regarding to the FMI and VDL outputs there is no micro-fractures in Sar_1 to Sar_12 zones.
4.3.2. Drilling mud, stoneley wave and stress direction data

The mud loss was reported as 2 to 6 bbl/hr, for the Sarvak Formation in this well, which is in seepage range. There is also no considerable mud invasion in the Sar_Intra zone where the micro-fractures are detected.

Like well-B the major chevron patterns are present in Sar_2 and Sar_Intra (Fig. 27), where the main washouts exist. Also in Sar_7 zone there are some chevron patterns and the shale layer peaks in the lithology track accordingly (Fig. 27). There is also no relationship between solution seams-stylolites density and the chevron patterns in this well (Fig. 27).

The direction of the horizontal stresses in the Sarvak Formation of this well were determined using 112 bore hole breakouts (Fig. 28). Like well-A and well-B the SHmax direction is toward NE-SW for this well (Fig. 28). The strike of the two micro-fractures is toward NW-SE.

5. Conclusion

In this study, the micro-fractures of the Sarvak reservoir were evaluated in the three wells of one of the Abadan Plain's oil fields.

In the well-A micro-fractures were initially detected and characterized using FMI image log and thin sections. Sar_4 to Sar_7 reservoir zones have the highest micro-fracture density. Using HFU concept and probability plot, eight HFUs were recognized from the porosity-
permeability core data. The HFUs were divided into two portions (using the porosity cut-offs): A and B. The A-portion has a high compliance with micro-fracture zones. The VDL log had satisfactory compatibility with micro-fracture zones and its negative parts indicate the presence of micro-fractures. DSI data analysis revealed that the Stoneley wave reflections and chevron patterns cannot be linked to the presence of micro-fractures, while borehole washouts have a definite impact on them. The traveltime anisotropy was also mainly affected by borehole washouts and lithology changes. Energy anisotropy had a significant relation with the density of solution seams and stylolites. On the other hand, slowness anisotropy and sudden changes in fast shear wave azimuth, had meaningful relation with the micro-fracture zones. The average apertures of the micro-fractures are 0.050 and 0.023 mm based on FMI and thin sections, respectively. However, Pezard-Anderson equations overestimated the apertures in the micro-fracture zones. Unexpectedly, the mud loss and mud invasion in the micro-fracture zones was very low, which is due to the lack of a fracture network in the formation.

In the well-B and Well-C, using fullset logs, porosity-permeability core data, image logs and drilling mud data, it was found that micro-fractures presence are negligible. According to the results, VDL, slowness anisotropy and fast shear wave azimuth spikes are suitable for identification of micro-fracture zones, while energy and traveltime anisotropies, Stoneley wave chevron patterns, mud loss and mud invasion might not help to detect micro-fracture zones.

The existing fractures in the reservoir do not necessarily have effect on improving the quality of the reservoir. The length of these fractures may be limited and only affect the data obtained from the plugs. In order to have a considerable effect on reservoir quality, the fractures must create a network. In general, it could be stated that micro-fractures in the well-A does not have a considerable effect on the quality of the reservoir and in the wells B and C the presence of micro-fractures are very limited.

Fig. 27. The tracks from left to right are Depth, Caliper-Bit size, Lithology, Mud invasion (DI), Secondary porosity (SEC_POR), Oil-water saturations, Solution seam and stylolite density, Solution seam and stylolite dip, VDL, Fracture and bedding density and Chevron patterns. The chevron patterns are mainly created due to borehole washouts and shale layers.
Fig. 28. The horizontal stress and fracture directions. a: $S_{hmax}$ direction (from borehole breakouts), b: $S_{hmax}$ direction, c: the fractures stereonet (upper hemisphere), d: fractures strike.

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Nomenclature

- $b_h$: fracture aperture form Pezard-Anderson equations in horizontal condition
- $b_v$: fracture aperture form Pezard-Anderson equations in vertical condition
- $R_m$: maximum resistivity of the nearby non-fractured rock
- $R_{hi}$: mud resistivity
- $R_{LLD}$: resistivity from Laterolog Deep (LLD)
- $R_{LLS}$: resistivity from Laterolog Shallow (LLS)
- $\phi$: Porosity
- ANIS_DTS: slowness anisotropy
- ANIS_TIME: traveltime anisotropy
- AZIM_FAST: fast shear wave azimuth
- BS: Bit Size
- CAL: Caliper
- DI: Invasion Diameter, depth of penetration of mud filtrates into the formation
- DLL: Dual Laterolog
- DSI: Dipole Shear Sonic Imager
- DT: Sonic Slowness
- DTS: shear wave slowness
- DTS_FAST: fast shear wave slowness
- DTS_SLOW: slow shear wave slowness
- FE: Open Fractures plus Partially Filled Fractures
- FF: Filled Fracture
- FMI: Fullbore Formation Microimager
- FZI: Flow Zone Indicator
- FZI*: Flow Zone Indicator-Star
- GR: Gamma ray
- HFU: Hydraulic Flow Units
- HRLA: High-Resolution Laterolog Array
- K: Permeability
- LLD: Deep Laterolog
- LLS: Shallow Laterolog
- MAX_ENERGY: maximum cross energy
- MIN_ENERGY: minimum cross energy
- ML: Mud loss
- MSFL: Micro-Spherically Focused Log
- NMR: Nuclear Magnetic Resonance
- NPHI: Neutron Porosity
- OF: Open Fracture
- PA_H: Pezard-Anderson fracture aperture for high angle fractures
- PA_V: Pezard-Anderson fracture aperture for high angle fractures
- PEF: Photoelectric Factor
- PFF: Partially Filled Fracture
- RHOB: Bulk Density
- RQI: Reservoir Quality Index
- RXO: shallow resistivity from MSFL
- SEC_DEN: solution seams and stylolites densities
- SHmax: maximum horizontal stress
- Smin: minimum horizontal stress
- VDL: Velocity Deviation Log
- Xdipole mode: Cross Dipole mode of DSI tool

References


