Fracture intensity vs. mechanical stratigraphy in platform top carbonates: the Aquitanian of the Asmari Formation, Khaviz Anticline, Zagros, SW Iran

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ABSTRACT: Outcrop analogue studies can significantly improve the understanding of fracture distribution and their impact on fluid flow in hydrocarbon reservoirs. In particular, the outcrops may reveal details on the relationships between mechanical stratigraphy and fracture characteristics. This has been investigated in an integrated sedimentological-structural geological study in the Aquitanian sequence of the Asmari Formation on the NE limb of the Khaviz Anticline in the Zagros foothills in SW Iran. The Aquitanian sequence was deposited in a platform top setting and is characterized by well-defined bedding planes and relatively thin layers (<4 m) with rapid changes in textures from laminated peritidal mudstones to bioclast and ooid grainstones. Fractures in the studied area dominantly strike parallel to the fold axis, have a high angle to bedding and are stratabound. In the literature it is often reported that fracture spacing or the inverse fracture intensity (FI) is controlled by the mechanical layer thickness (MLT). However, in the present study area a rather poor correlation between FI and MLT was observed. Instead, the Dunham texture appears to be more important for the FI. Mud-supported textures (mudstone and wackestone) have higher FI than grain-supported (packstone and grainstone) ones. The degree of dolomitization does not appear to have any significant effect on FI within each texture class. A strong relationship between FI and MLT is observed generally in cases where there has been one single phase of extension and when interbed contacts are weak, e.g. interbedded competent limestones and incompetent shales. However, in the present study area a rather complex deformation history exists and well-developed shales between fractured carbonate layeres are lacking. It is suggested that in such cases the MLT is of minor importance for the FI, which is controlled by the texture.

KEYWORDS: *Zagros, carbonates, mechanical stratigraphy, fracture intensity, Dunham texture*

INTRODUCTION

Fractured reservoirs are strongly heterogeneous at all scales from micro-scale to full field, and well performance may vary dramatically between nearby wells. An understanding of the spatial distribution of fractures is necessary to predict fluid flow and to develop drainage strategies in such reservoirs. Generally, several fracture parameters are difficult or impossible to observe in core or image logs from wells (e.g. fracture length, cross-cutting relationships) and observations from wells are also influenced strongly by directional sampling bias. Recent advances in acquisition, processing and analysis of reflection seismic data have improved the characterization of fractured reservoirs significantly (e.g. Angerer *et al.* 2003; Lynn 2004*a*, *b*). Nevertheless, reflection seismic data have a limited resolution and details on parameters controlling the production and recovery of fractured reservoirs, such as fracture orientation, spacing and length, cannot be resolved. Therefore, outcrop studies can improve the understanding of fracture formation and spatial distribution to be used in the characterization of a subsurface reservoir significantly.

Many studies show that fracture pattern in sedimentary successions is controlled by mechanical stratigraphy, i.e. spatial variation in mechanical properties due to changes in lithology. Mechanical stratigraphic control on fracture characteristics has been applied for layered rocks both in carbonates (e.g. McQuillan 1973; Huang & Angelier 1989; Underwood *et al.* 2003) and siliciclastic sequences (e.g. Ladeira & Price 1981; Ruf *et al.* 1998; Silliphant *et al.* 2002). The concept of mechanical stratigraphy consists of several elements. The material properties of each individual bed are dependent on lithology and texture, which is controlled by the depositional environment and diagenetic history of the host rock. In addition, bed thickness is an important factor, as demonstrated in numerous papers (e.g. McQuillan 1973; Narr 1991) and modelled for Mode 1 fractures by Hobbs (1967) and Gross *et al.* (1995). Finally, the influence of the strength of the interfaces between

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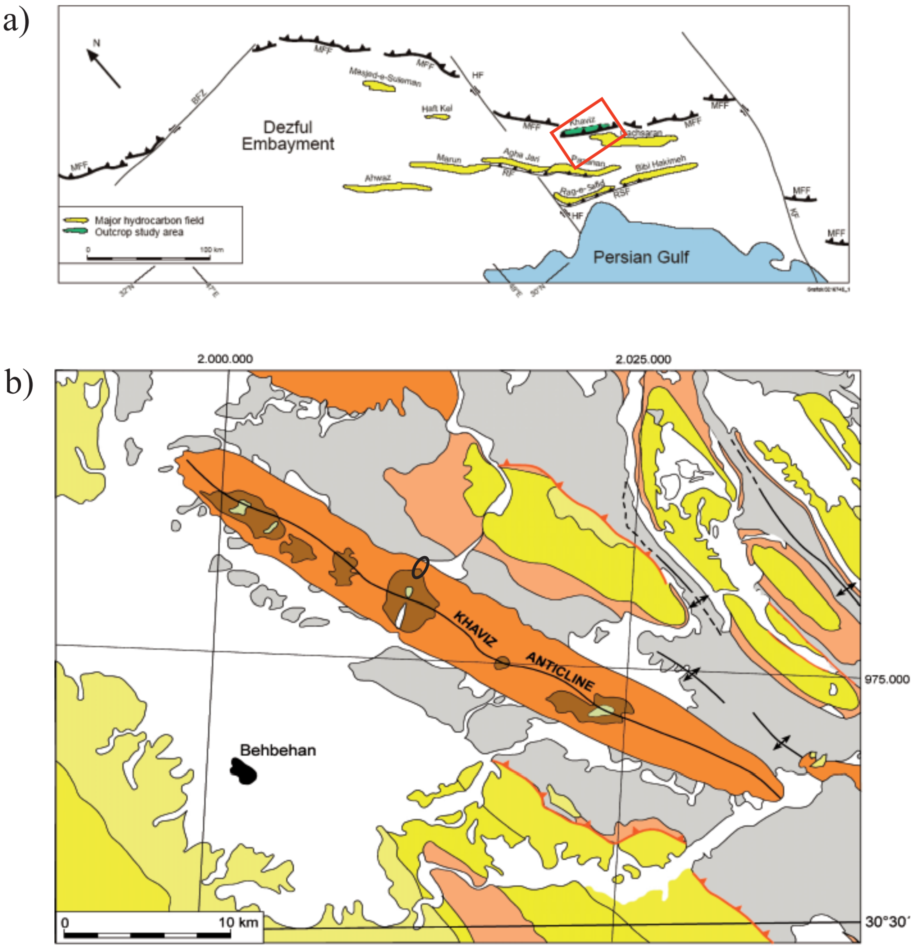

Fig. 1. (**a**) Overview map of the Dezful Embayment. (**b**) Geological map of the Khaviz Anticline.

different layers on the fracture mechanics was discussed by Cooke & Underwood (2001).

The most prolific oil reservoir in SW Iran is the Asmari Formation (Late Oligocene–Early Miocene), where production properties depend strongly on the existence of fracture networks. Outcrops of the Asmari Formation are found in close proximity to giant oil fields in the outer part of the Zagros Mountain Chain, and one of these outcrops is the Khaviz Anticline – the focus for this paper.

The spatial distribution of fractures in folded carbonate units such as the Asmari Formation is a truly multivariate problem, where fracture parameters for each fracture set (such as orientation, length, spacing, aperture etc.) are functions of position within the fold, sedimentary texture, mechanical bed thickness and so on. The purpose of this paper is to focus on the relationship between mechanical stratigraphy and 1D fracture intensity, which is related to the fracture spacing. The structural position of the studied outcrop is limited in the backlimb of a major anticline in the Zagros fold belt, the Khaviz Anticline, which has a relatively simple fracture pattern (Wennberg *et al.* 2006). The focus is also on one particular depositional setting – the platform top sediments of the Aquitanian of the Asmari Formation.

GEOLOGICAL SETTING

Structural background

The study area is located in the foothills of the Zagros Mountain Chain in the northeastern part of the Arabian Plate (Fig. 1a). The mountain chain was developed as a result of plate convergence, particularly during the Late Miocene–Pliocene orogenic phase (e.g. Hessami *et al.* 2001). The structural evolution has been controlled by a combination of thin-skinned tectonics above a main detachment zone and thick-skinned tectonics involving the crystalline basement by inversion of pre-existing normal faults (e.g. Blanc *et al.* 2003; Sherkati & Letouzey 2004; Sepehr & Cosgrove 2004).

The Khaviz Anticline represents a typical Asmari Formation fold in this area (Wennberg *et al.* 2007). It is approximately 40 km long and 6–8 km wide, displaying a periclinal geometry, trending WNW–ESE (Fig. 1b). In general, the southern limb (*c.* 40°) is somewhat steeper than the northern limb (*c.* 30°). Normal faults striking sub-parallel to the fold axis are present in the fold limbs, but are particularly well developed in the crest area.

The study area is located on the NE limb of the Khaviz Anticline in the Tang-e Takab (Fig. 1b). Here, a profile through the anticline has a box-fold-like geometry with two hinges. The most marked hinge is between the NE limb, with an average dip angle of 38° towards an azimuth of 029° and the crest area.

Measured fractures have been grouped into two major types based on their inferred influence on fluid flow behaviour: **diffuse fracturing** describes distributed fracture populations, which in general contain several fracture sets with distinct spatial characteristics. Diffuse fractures are, to a large degree, stratabound. **Fracture swarms** are larger-scale features, which dissect significant parts of the reservoir stratigraphy. Furthermore, the normal faults, with displacements up to 150 m, are associated with relatively narrow damage zones with locally very high fracture frequency.

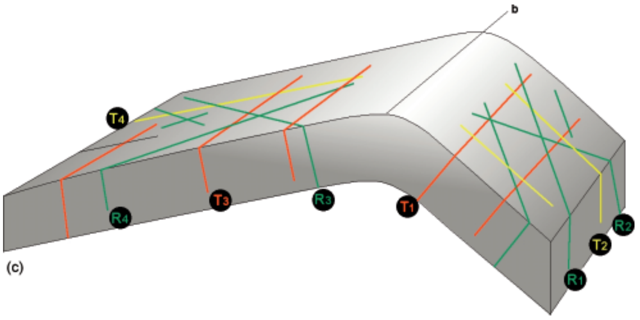

Fig. 2. Price's (1966) classification of fracture sets typical for asymmetric anticlines. See text for discussion. Modified from Price (1966).

Diffuse fractures are, in general, sub-perpendicular to bedding and have been subdivided according to the scheme of Price (1966) into **T fracture** sets and **R fracture** sets (Fig. 2). T fracture sets are generally tensional and occur in one set sub-perpendicular to the axis of the fold (T2 in the forelimb and T4 in the backlimb) and one set striking parallel to the axis (T1 in the forelimb and T3 backlimb). R fracture sets develop as conjugate sets: R1 & R2 in the forelimb R3 & R4 in the backlimb. A clear relationship was found between fracture attributes and structural position on the Khaviz Anticline, suggesting that the fracture formation was related to the folding (see Wennberg *et al.* 2007 for details). This paper focuses on the T3 fracture set, which is the dominating one in the backlimb of the anticline.

Wennberg *et al.* (2007) indicated that all the measured fracture sets formed during the same time interval, based on the lack of systematic termination or abutting relationships between different fracture sets. The main factors controlling the effective stress and fracture formation during the folding of the Khaviz Anticline are suggested to have been plate-scale NNE–SSW contraction, orthogonal flexure folding, flexural slip folding, stress perturbation around active faults and fluid pressure variation. This implies that the resulting effective stress field responsible for the fracture generation in the Khaviz Anticline was in a continuous state of flux and varied temporally and spatially.

The Asmari Formation: the Aquitanian sequence

Fracture network characteristics are related to mechanical stratigraphy, which is controlled by the depositional environment and diagenetic history of the fractured unit. The Asmari Formation in the Khaviz Anticline is described mainly based on field logging and analyses of a complete 378 m long profile through the Asmari Formation in the NE limb of the anticline (Tang-e-Takab). Using micropalaeontological investigation, strontium isotope age dating (Ehrenberg *et al.* 2004) and regional correlation (Neil Pickard, pers. comm.), three sequence stratigraphic units have been defined (Svånå *et al.* 2005; Figs 3, 4):

- The lowermost **Chattian sequence** (213 m) consists of thick massive cliff-forming beds with mainly open-marine coral, red algae and a special bryozoan-bearing facies.
- The **Aquitanian sequence** is the unit studied in most detailed here, and a log through the sequence is shown in Figure 4. This sequence is 99 m thick and reflects important changes both in depositional evolution and corresponding changes in mechanical stratigraphy relative to the underlying unit. The base sequence boundary marks the transition into overall lower sedimentation rates in a platform top setting. More well-defined bedding planes and generally thinner layers (up to 4 m thick), with rapid changes in texture, cover the range from marl and laminated peritidal mudstone deposits to bioclast and ooid grainstones. The thicker grainy layers are cliff forming, while the recessive intervals contain more mudstones. Strata-bound intervals with vugs, resulting from dissolved anhydrite nodules, are indications of periods with sabkha-type deposition. In addition, several indications of periods with subaerial exposure (e.g. early karstification and speleothemes) occur in this sequence.
- The overlying **Burdigalian sequence** (66 m) contains generally thicker and cliff-forming with well-defined planar bedding interfaces, characterized by moderate energy deposits and periodically restricted marine conditions. Fine-grained mud-, wacke- and packstones characterize this sequence.

Fig. 3. Photo showing the Asmari Formation in the NE limb of the Khaviz Anticline. Base and top of the Aquitanian are indicated with arrows. View from ESE more or less along structural strike.

The Aquitanian succession has been affected by a variable degree of dolomitization (Fig. 4, see Aqrawi *et al.* 2006 for details). The thickness of dolomitized beds was variable and the dolomite is generally fine-grained with crystal size ranging from 5 μm to 20 μm. The beds of grainy dolomitized facies are relatively thick, but usually consist of leached grains (i.e. vuggy pores), while the dolomitized muddy textured beds are thinner. The dolomites in the Aquitanian were interpreted mainly as having originated in early diagenetic stages from both tidal flat and subtidal/platform environments (Aqrawi *et al.* 2006).

DATA SAMPLING

A line sampling (scan-line) technique was used for the main data collection, following the procedures of Priest (1993). The data presented in this paper are condensed from measurements obtained on a series of 11 scan lines in both vertical and bed-parallel sections. For most of the scan-line stations 40 to 60 fractures were sampled; sampled parameters include intersection distance, dip and dip azimuth, length, type of termination and mineral fill.

To have a continuous dataset of fracture attributes over a longer interval of the Asmari Formation a fracture log was collected over an interval of 72 m in the Aquitanian sequence, including 77 mechanical beds. This part of the Asmari Formation was nearly continuously exposed (98%). The fracture logging was carried out closely together with a sedimentological study, with the aim being to relate fracture parameters to the lithology and depositional setting of the individual beds. The following parameters were recorded in the fracture log:

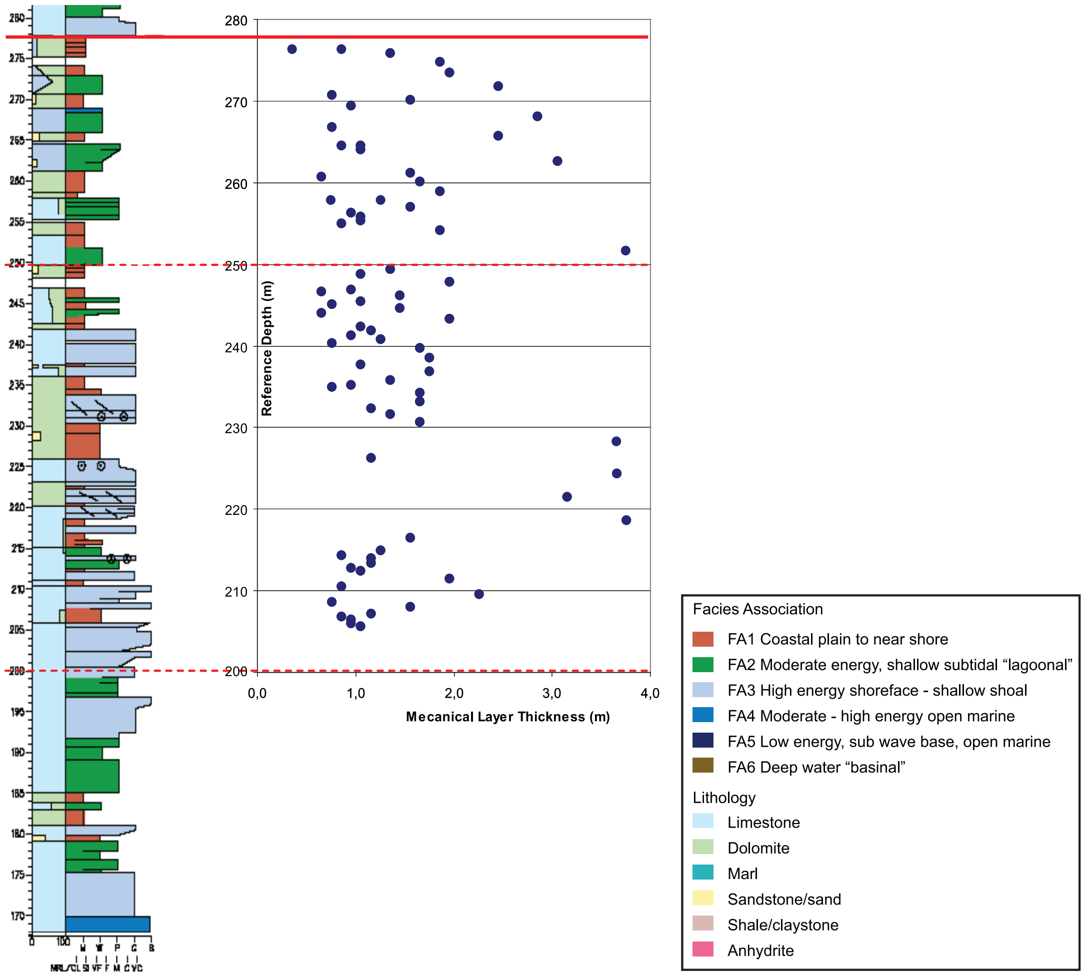

Fig. 4. (**a**) Sedimentological section through the Aquitanian sequence of the Asmari Formation; (**b**) Mechanical bed thickness variation through the logged section.

thickness of the mechanical layer; fractures per metre for each of the different sets; type of fractures (filled, partly open, not conclusive); and percentage of stratabound fractures.

RESULTS

Fracture occurrence

The vast majority of fractures appear to be dilational, since they do not show any indication of shear movement. Shear fractures displaying a clear lateral offset are observed at only a few localities. However, minor shear displacement on the conjugate R fracture sets has been inferred based their orientation. Fractures are, in general, observed to be relatively planar. Dissolution features are present along all the fracture sets, indicating localized channel-like openings along most fracture planes. Whenever it is possible to observe fracture fills, the fractures are partly or totally filled with calcite. Most of the diffuse fractures in the Aquitanian sequence are found to be stratabound, i.e. confined to one mechanical layer. The amount of stratabound fractures varies between 80% and 100%. This indicates moderate strength interfaces according to Cooke & Underwood (2001).

Fracture orientation

Analysis of fracture orientation and definition of fracture sets have been performed using standard stereograms and rose diagrams (Fig. 5), as well as using bias correction (Terzaghi 1965) and length weighting (figure not included). The T3 set striking parallel to the axis of the anticline (WNW–ESE) is clearly the best developed fracture set in all scan-line stations. In most cases the orthogonal T4 set is the second most important set (striking NNW–SSE). Hence, an orthogonal fracture pattern is commonly observed on bedding surfaces (Fig. 6a). It is also clear that most fracture sets, including the T3 set, have a high angle to bedding (Fig. 5).

Mechanical stratigraphy

A mechanical layer represents one or more stratigraphic units that fracture independently of other units (e.g. Underwood *et al.* 2003). In layered carbonates, such as the Aquitanian sequence of the Asmari Formation, fractures are typically stratabound and span the thickness of the mechanical layer and commonly abut the bounding stratigraphic horizons. The bounding stratigraphic horizons are here termed mechanical layer boundaries.

Mechanical layer boundaries in the study area are characterized by:

1. interfaces between layers with different lithology, e.g. between mudstone layers and grainstones. These interfaces may be laterally extensive;
2. relatively thin carbonate mud layers (1–5 cm) separating more brittle grainstones. These often represent exposure surfaces, which do not necessarily have a large lateral extent;

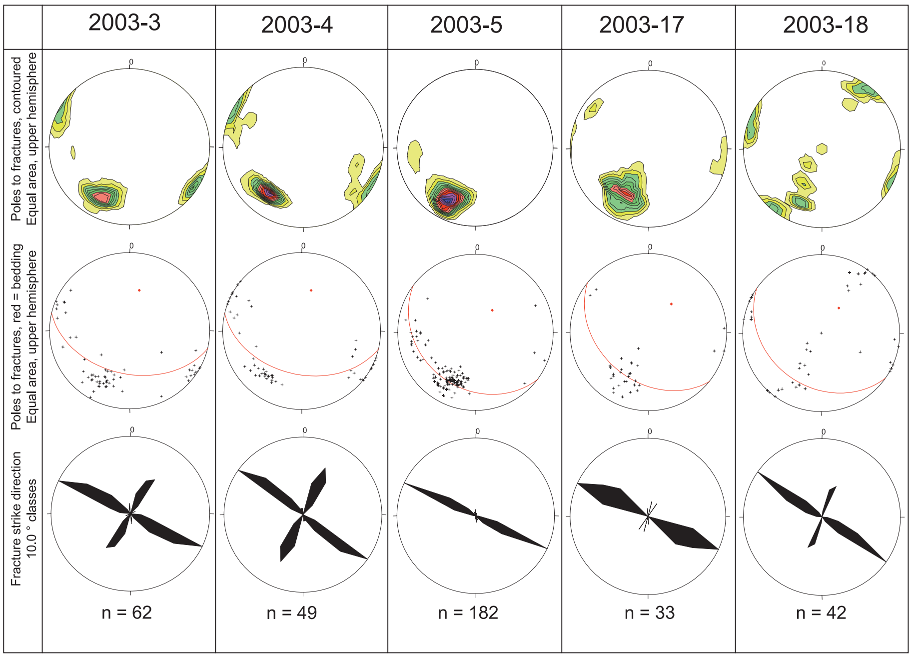

Fig. 5. Stereograms and rose diagrams of selected scan-lines. See Figure 4 for stratigraphic position.

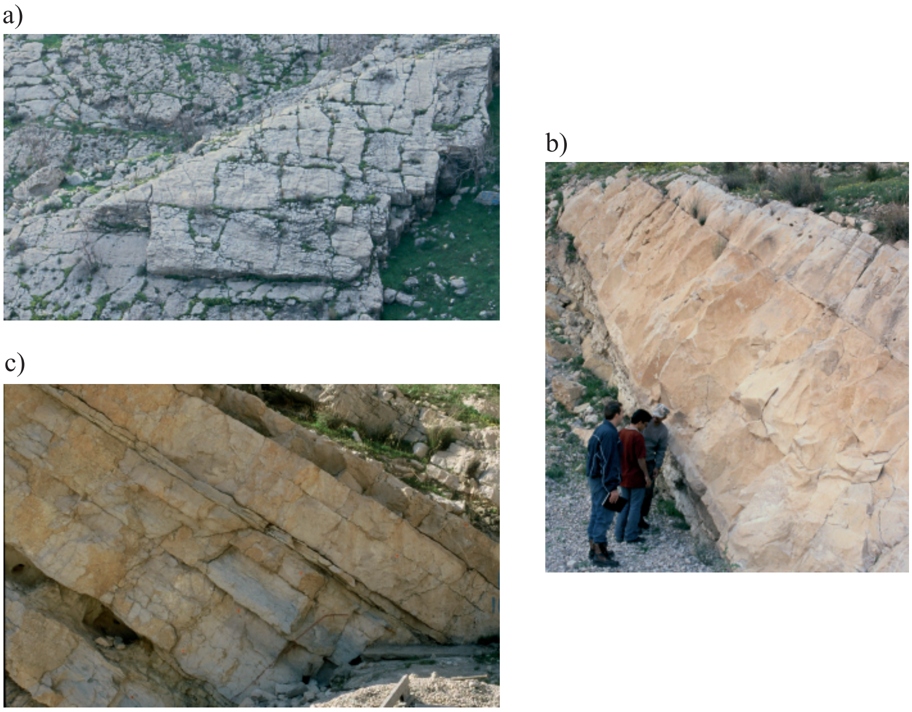

Fig. 6. Outcrop photos from the backlimb of the Khaviz Anticline: (**a**) fracture pattern on bedding surface; (**b**) and (**c**) examples of layering in the platform top carbonates.

3. thin (1–5 cm) layers with frequent layer-parallel stylolites. These also tend to be relatively local with a limited lateral extent.

Examples of mechanical layering are shown in Figures 6b and c.

Consequently, the mechanical layer thickness (MLT) varies laterally as mechanical layer boundaries disappear, e.g. two mechanical layers may be replaced by one layer laterally. Furthermore, the mechanical layer boundaries are irregular, undulating surfaces and the texture commonly changes rapidly laterally in platform top settings. These features also cause lateral variations in the MLT. Low competent or ductile shale/marl layers are rare in the Aquitanian succession.

In the investigated part of the Aquitanian sequence the MLT varies between 0.10 m and 3.70 m, with a mean of 0.94 and a standard deviation of 0.80 m. Most mechanical layers have a thickness less than 1.5 m (Fig. 4).

Spacing and fracture intensity (FI)

An approximately 30 m long scan-line A was logged on a bedding surface (Fig. 7a). The texture of this layer is dominantly mud-supported as it consists of wackestone to mudstone. The fracture population of this scan-line contains both background diffuse fracturing and fractures in the damage zone of two extensional faults. The fracture spacing of the T3 set is characterized by a log-normal distribution (Fig. 7b) with a mean ln of fracture spacing of 1.92 and a standard deviation of 1.37

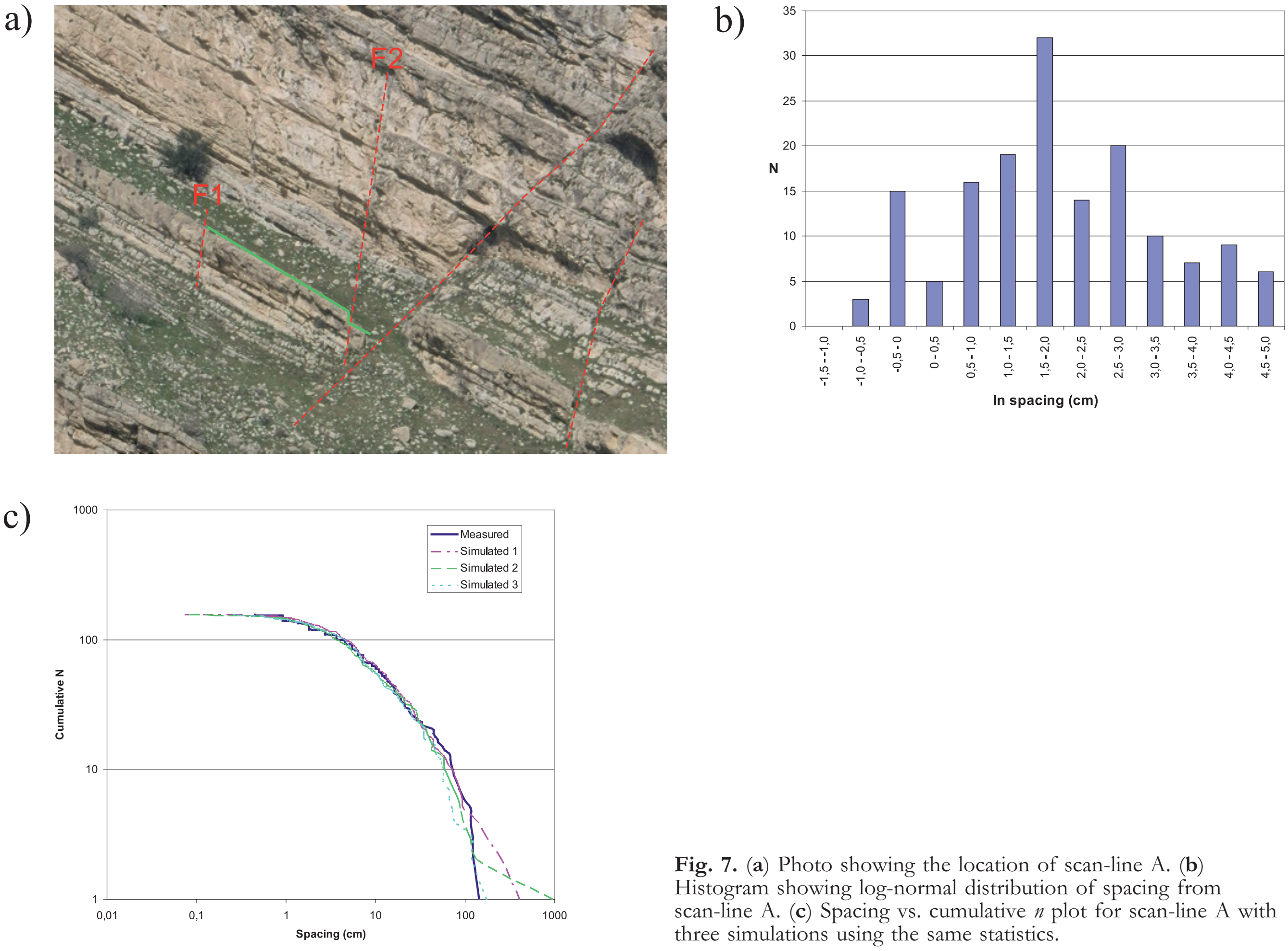

Fig. 7. (**a**) Photo showing the location of scan-line A. (**b**) Histogram showing log-normal distribution of spacing from scan-line A. (**c**) Spacing vs. cumulative *n* plot for scan-line A with three simulations using the same statistics.

corresponding to 6.9 cm (geometric mean) and 3.9 cm respectively. A log-normal fracture spacing with the same statistical parameters was simulated and plotted against cumulative number on a log-log plot together with the measured data (Fig. 7c). This shows a good match with the measured data. Discrepancies between the measured and simulated fracture spacing were found only for the largest values, a feature which is attributed to truncation effects.

Fracture intensity (FI) or 1D fracture density is the number of fracture intersections (*n*) per unit length (m) along a line. This has also been referred to as the P10 (m^{-1}) (Dershowitz & Herda 1992; Aliverti *et al.* 2003). FI may be determined for a total population of fractures or for a single set. For a total population the FI is affected by a directional bias since the number of fracture intersections is dependent on the orientation of the observation line. This sampling bias can be corrected on an individual fracture basis (Terzaghi 1965). FI of one particular set is defined in this study as the fracture intensity determined along a line perpendicular to this set, and is the inverse of mean fracture spacing (FI=1/mean spacing).

FI (like the fracture spacing) is not constant for one fracture set in one mechanical layer. This lateral variability in FI for set T3 is demonstrated in Figure 8, which shows the FI along scan-line A for binned intervals of 4 m. In particular the FI is anomalously high close to the faults. Consequently, when comparing FI or fracture spacing vs. mechanical stratigraphy or MLT, fault damage zones must be avoided. Between the fault damage zones the mean FI is 4.0 m^{-1} with a standard deviation of 1.2 m^{-1} (32% of mean value), which illustrates the variability of FI within one layer. Figure 8 also shows a moderately increasing trend from Fault#1 towards Fault#2.

Fracture intensity/fracture spacing vs. mechanical bed thickness

The scan-line data were taken mainly from matrix-supported textures (i.e. mudstone/wackestone), with only one data point taken from a grain-supported fabric (i.e. packstone/grainstone; Fig. 9). These data show that the thinnest mechanical layers have the smallest median spacing values for set T3 (Fig. 10), whereas the thicker mechanical beds have a very large spread in median spacing. The relationship between MLT and the median of fracture spacing shows a poor correlation. This is in contrast to Narr & Suppe (1991), who reported a linear relationship and a good correlation between the two parameters.

The fracture log data for set T3 (Fig. 11) show that the thickest mechanical layers have low FI, while the thinner mechanical layers (*c.* <1.5 m) have a very large spread in FI. A linear regression line through this dataset indicates that FI decreases with increasing MLT. However, the correlation between FI and MLT is poor, with the correlation coefficient R^2=0.10. Rather, the general trend is that the dispersion in FI increases with decreasing MLT.

The scan-line data have a higher precision than the fracture log data and there is a better correlation between the MLT and FI. There is still a large spread in FI for mechanical layers thinner than 1.5 m, and the best fit was for a negative

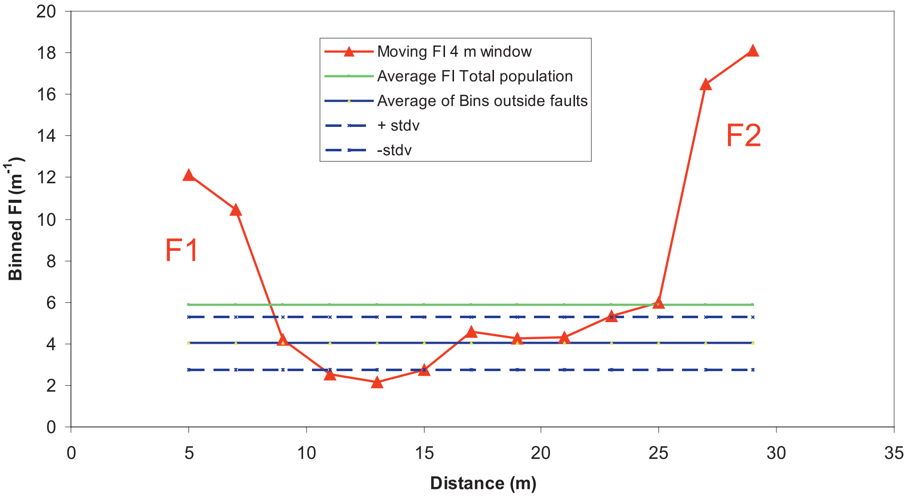

Fig. 8. Binned fracture intensity (FI) along scan-line A, 4 m binning interval.

logarithmic function (Fig. 9). The T3 set did show the best correlation with R^2=0.59, whereas the bias corrected FI including all fracture sets gave a R^2 of 0.52.

Fracture intensity vs. Dunham texture

A major effect on FI was seen when the dataset was divided into mud-supported textures (mudstone and wackestone) and grain-supported texture (packstone and grainstone) using the classification of Dunham (1962) (Fig. 11). For MLT <1.5 m and for mud-supported texture the average FI is 8.1, with a standard deviation of 3.7, whereas the corresponding values for grain-supported texture are 4.7 and 3.2, respectively.

For MLT >1.5 m no significant difference between mud- and grain-supported textures was observed. However, the number of layers measured is too low to be conclusive whether the texture has an effect on FI for this range of MLT.

Consequently, the linear regression line for mud-supported textures is above and has a steeper gradient than the linear regression for the grain-supported texture. The correlation is still rather poor, with the R^2 of 0.17 and 0.09 for the mud- and grain-supported textures, respectively.

FI vs. dolomite content

Most FI vs. MLT data taken in lithologies with grain-supported textures have low dolomite contents, 0–20% for fracture set T3 (Fig. 12a). Therefore, the current data cannot be used to evaluate the effect of dolomitization for grain-supported textures.

However, the mud-supported textures have a larger range in degree of dolomitization than the grain-supported ones (Fig. 12b). For this texture class the dolomite content is low (0–10%), in the thicker beds MLT >2 m (Fig. 12b). High dolomite content is generally found in the thinner beds <2 m, and complete dolomitization is reached for beds less than 1.5 m thick. The layers which have the lowest dolomite content (0–20%) show an increase in FI with decreasing MLT and a relatively good correlation between the two parameters (Fig. 12b). However, there are only five data points and no firm conclusions can be drawn from this number of data. The highly dolomitized layers (80–100%) cover the total range in FI. For MLTs <1.5 m there is a large degree of overlap between highly dolomitized and less dolomitized layers. Therefore, degree of dolomitization does not appear to have any significant effect on FI within the mud-supported texture class.

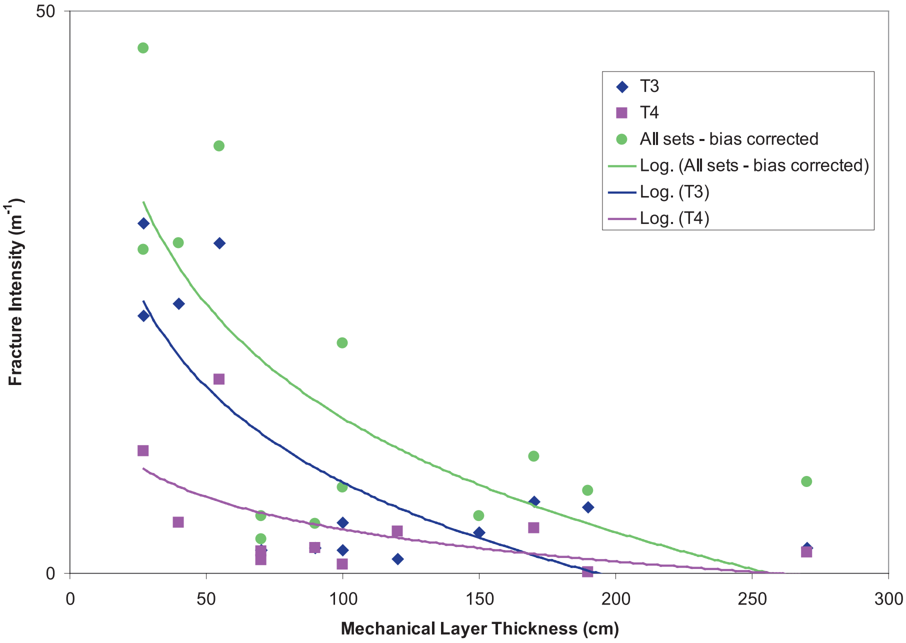

Fig. 9. Mechanical layer thickness vs. fracture intensity. Scan-line data.

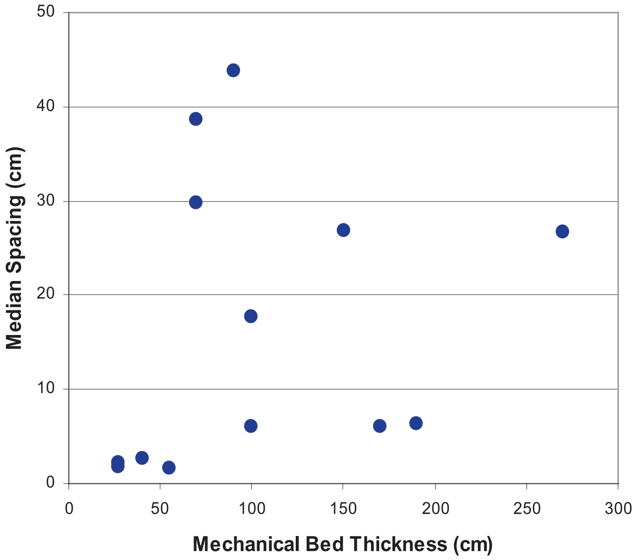

Fig. 10. Mechanical bed thickness vs. median spacing. Scan-line data.

DISCUSSION

Fracture distribution in layered platform top carbonates

Fracture density of the diffuse fracturing in layered sedimentary successions has been related to MLT in the Asmari Formation (e.g. McQuillan 1973), as well as in a general (e.g. Hobbs 1967; Rives *et al.* 1992). Good correlation between MLT and the median fracture spacing appears to be found in sequences with high competence contrasts, i.e. these which contain low friction shale layers between more brittle and competent fractured layers (e.g. Narr 1991; Gross *et al.* 1995; Ruf *et al.* 1998).

Models relating fracture spacing to mechanical bed thickness have been developed for well-layered sequences with high competence contrast between fractured brittle layers, e.g. sandstone or limestone interbedded with ductile shale or marl layers (e.g. Hobbs 1967; Gross *et al.* 1995; Ji *et al.* 1998). These authors relate the fracture spacing dependency on MLT to the reduction of tensile stress in the vicinity of tensile fractures, and that the lateral extent of this stress reduction shadow is related to the fracture height, which is limited to the bed thickness. These models represent cases where the bedding contacts can be considered to be weak. Furthermore, the models are derived for a simple case where one Mode I fracture set is generated during one phase of extension. This is not the case for the Khaviz Anticline case, where multiple fracture sets are formed coevally in a highly fluctuating stress field during the folding of the Asmari Formation (Wennberg *et al.* 2006).

A good correlation between MLT and FI/median fracture spacing was not found for the platform top carbonates of the Aquitanian Sequence of the Asmari Formation. This sequence is also characterized by lower contrasts in rock competence between adjacent beds than the above studies, i.e. there is a lack of low friction ductile layers between the fractured brittle carbonate rocks. Instead, the texture is shown to be important for the FI, since mud-supported textures have higher FI than grain-supported textures (Fig. 11). A similar relationship between texture class and FI was reported from Cretaceous platform carbonates in the Central Apennines of Italy by Di Cuia et al. (2004) and in the Carboniferous Lisbourne Group carbonates of Alaska by Hanks *et al.* (1997).

The relationship between texture and FI can be explained by the observation that grain size is the rock property that has the highest impact on ultimate strength in low-porosity carbonate rocks. Hugman & Friedman (1979) reported a linear relationship between ultimate strength and grain size, where the lowest grain size was reported to have the highest ultimate strength. Fracture intensity is related generally to rock strength or brittleness, and the stronger and more brittle rocks have higher fracture intensities (Nelson 2001).

Layered rocks with weak bedding interfaces are characterized by the termination of fractures at the bed contacts, whereas stronger bedding interfaces have higher probabilities for fractures to cut across the interfaces (Cooke & Underwood 2001). In the Aquitanian strata in the Khaviz Anticline the amount of fractures cutting across mechanical layer boundaries is 0–20%. In addition, the succession lacks incompetent shales separating the competent carbonate layers. This indicates moderate to strong bedding interfaces in the studied case. A similar situation with poor correlation between MLT and FI/fracture spacing and lack of incompetent interbeds was indicated by Hanks *et al.* (1997).

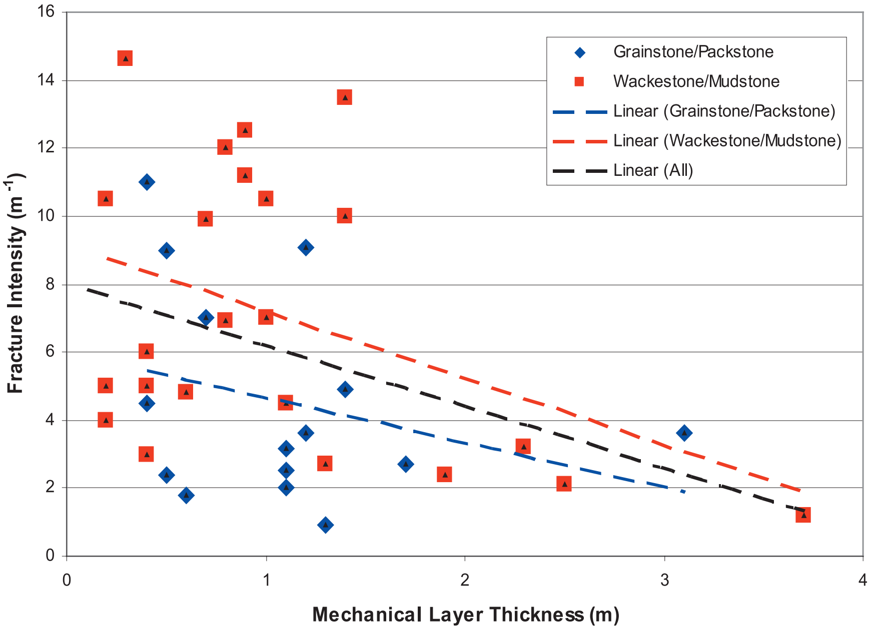

Fig. 11. Mechanical layer thickness vs. fracture intensity. Fracture log data.

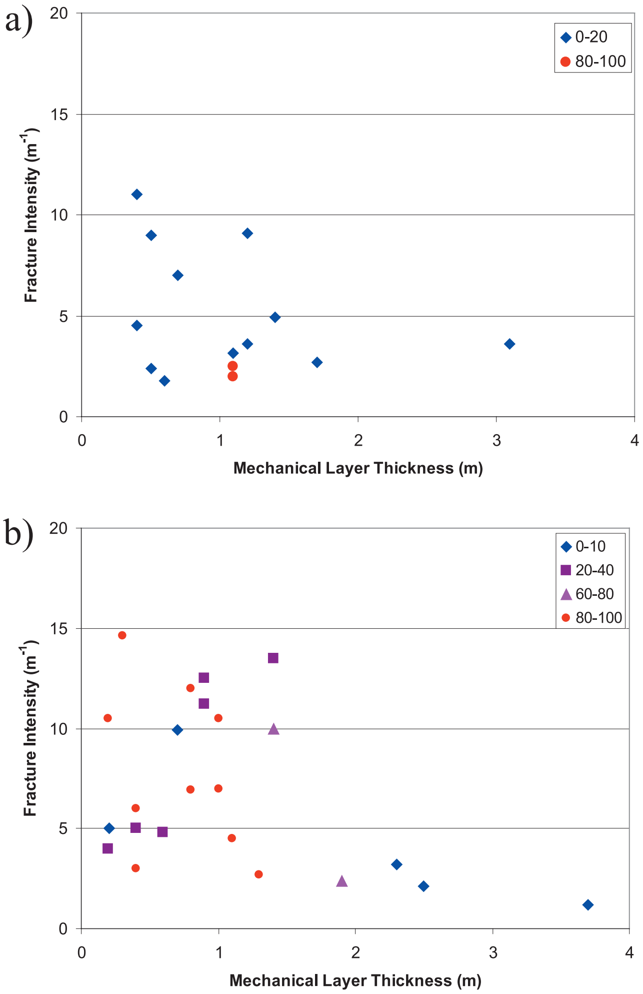

Fig. 12. Mechanical layer thickness vs. fracture intensity for various degrees of dolomitization in (**a**) grain-supported and (**b**) mud-supported textures. Fracture log data.

Based on the data presented and the above discussion it is suggested that in cases of moderate to strong bedding interfaces typical for platform top carbonates the MLT is of minor importance for the fracture spacing and FI, especially for layers thinner than 1.5 m (Fig. 11). In such cases the texture of the individual beds is more important. It may also be speculated that the strength of the interfaces between the brittle layers is an additional control on the fracture spacing.

A relationship between layer thickness and fracture spacing has been shown by McQuillan (1973) for the Asmari, Pahn and Pabdeh-Gurpi anticlines within the Zagros foothills of Iran. Lack of agreement between these examples and the current study area may relate to different parts of the Asmari Formation being studied or due to lateral facies variations.

In general, the degree of dolomitization is suggested to have an impact on FI, and that dolomite has higher FI than dolostone and limestone (e.g. Sinclair 1980; Nelson 2001). The ultimate strength also increases with increasing dolomite content in rocks of similar texture (Hugman & Friedman 1979). However, Hugman & Friedman (1979) also showed that the most dominant factor was the effect of the texture or grain size. Furthermore, Sinclair (1980) demonstrated the large impact of grain size (texture); fine-grained rocks were reported to have higher FI than coarse-grained rocks. The degree of dolomitization does not appear to have any significant effect on FI within the mud-supported texture class in the studied sequence (Fig. 12b). In the present case the texture appears to be more important than the effect of dolomite content, and any potential impact of dolomitization is interpreted to be masked by the dominating impact of texture.

Implications for drainage

The observations of fracture spacing and fracture intensity have some important implications for understanding hydrocarbon drainage in similar settings. The highest degree of fracturing, i.e. the most effective transport system for hydrocarbons, is found in the mud-dominated facies, those layers with lowest matrix porosity and permeability (Fig. 13a). Hence, the most effective transport system is in the layers with the smallest storage capacity and poorest ability to exchange fluids from the matrix system to the fracture system. In the studied succession up to 20% of the fractures continue into the neighbouring layers. Therefore, the fractures in the mud-supported matrix connect through fractures to the grain-dominated layers, which have higher porosities and represent the best hydrocarbon storage media. Communication between the layers in the reservoir is also facilitated through the more intense fracture network in fault damage zones. In a single well this implies that layers with the poorest matrix porosity and permeability are likely to have more fracture intersections and may therefore give a higher production rate than the layers with better matrix properties (Fig. 13b).

Application in fracture modelling

The results from the outcrop study indicate a close relationship between sediment deposition and fracture pattern. A complete understanding of fluid flow in a fractured reservoir is therefore dependent on an integrated approach, using sedimentological

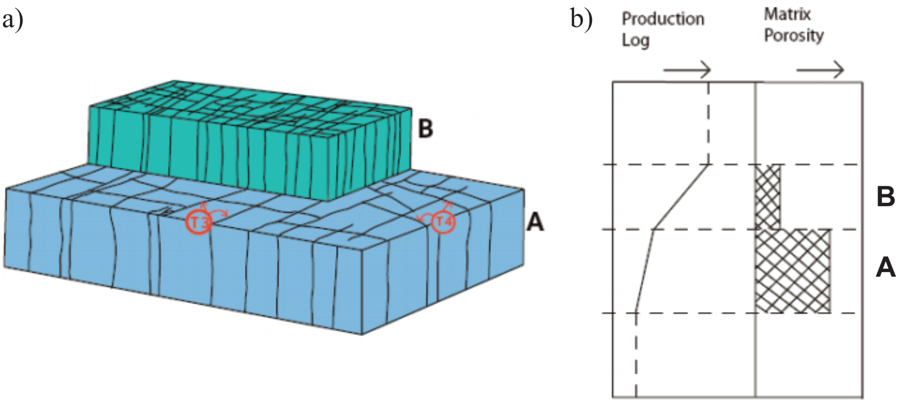

Fig. 13. (**a**) Block diagram of fractures in (A) grain-supported and (B) mud-supported textures. (**b**) Expected production log and porosities for the simplified stratigraphy in (a).

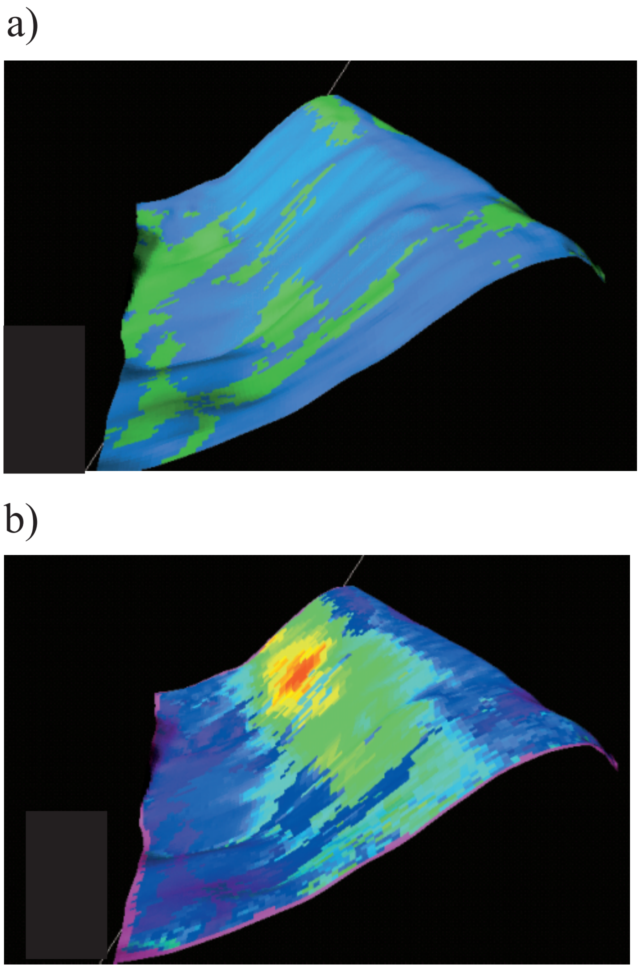

Fig. 14. Three-dimensional view of one layer from a geocellular model: (**a**) fracture facies distribution (green, grain-supported texture; blue, mud-supported texture); (**b**) fracture permeability in grid x-direction (red, highest permeability; pink/purple, lowest permeability).

and structural geological methods in the analysis and modelling of such reservoirs. The modelling of depositional facies in a reservoir model should aim to predict mechanical stratigraphy, which can be used further in populating fracture properties to be included in dynamic reservoir models.

One case where the results from the Khaviz Anticline were used to guide a 3D fracture model will be presented briefly. This subsurface case was in a similar depositional and structural setting on the backlimb of a major anticline. A fracture facies model was generated with a close link to the matrix model, and was based on detailed sedimentological and petrophysical well-log analysis. Since borehole image data were sparse in this field, the different fracture facies defined in the 3D geocellular model were controlled by the outcrop fracture study. Basically two fracture facies were identified, which were characterized by distinct geometrical fracture parameters (Fig. 14a). Following the study of the outcrop, the mud-supported textures were attributed with lower fracture spacing than the grain-supported textures. A Discrete Fracture Network was simulated and upscaled to equivalent fracture parameters for dual porosity simulation using Fraca$^{\text{TM}}$ (e.g. Bourbiaux *et al.* 1997; Cacas *et al.* 2001). In this case structural dip and curvature were also used to control the lateral variation in fracture intensity of different sets. Therefore, the final permeability field is influenced by both structural parameters and the distribution of fracture facies (Fig. 14b).

This paper has focused on the fracture distribution on the backlimb of one major anticline, where one fracture set is strongly dominating. A more complicated relationship between texture, mechanical bed thickness and fracture attributes is to be expected on the forelimb. This structural position has experienced higher strain, shows a larger spread in fracture orientation and the R fracture sets are better developed. This will result in an even more complicated relationship between fractures and stratigraphic elements. Further detailed, integrated micro textural and rock mechanical studies are necessary to improve understanding of the relationships between mechanical stratigraphy and fracture parameters.

CONCLUSIONS

The Aquitanian platform top sediments of the Asmari Formation in the NE backlimb of the Khaviz Anticline have a number of fracture characteristics.

- The succession is characterized by well-defined bedding planes and relatively thin layers (<4 m) with rapid changes in textures from laminated peritidal mudstones to bioclast and ooid grainstones, deposited in a platform top setting.
- The dominant fracture set in this structural position is the T3 fracture set, according to Price's (1966) classification, which strikes parallel to the anticline axis and is orientated sub-perpendicular to the structural dip.
- Fractures are, in general, stratabound with 80–100% of the fractures terminating within one layer or at the boundary to the next layer.
- Fracture spacing shows a log-normal distribution.
- Median fracture spacing and the fracture intensities show a poor correlation with mechanical bed thickness. This is suggested to relate to a lack of incompetent layers between competent and brittle carbonate layers in the studied section.
- Mud-supported textures, mudstone and wackestone, according to the Dunham (1962) classification, have higher fracture intensity than grain-supported textures, packstone and grainstone. It is suggested that this is typical for bedding interfaces of moderate strength.
- The most effective fluid transport system may be in the layers with the poorest matrix properties.
- A complete understanding of impact of fractures in a hydrocarbon reservoir requires an integrated approach, including sedimentological and structural geological studies.

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REFERENCES

Aliverti, E., Biron, M., Francesconi, A., Mattiello, D., Nardon, S. & Peduzzi, C. 2003. Data Anlaysis, processing and 3D fracture network simulation at wellbore scale for fractured reservoir description. *In:* Ameen, M.S. (ed.) *Fracture and In-Situ Stress Characterization of Hydrocarbon Reservoirs.* Geological Society, London, Special Publications, **209**, 27–37.

Angerer, E., Lanfranchi, P. & Rogers, S.F. 2003. Fractured reservoir modeling from seismic to simulator: a reality?. *The Leading Edge,* **22**, 684–689.

Aqrawi, A.A.M., Ehrenberg, S.N., Keramati, M. *et al.* 2006. Origin of dolomite in the Asmari Formation (Oligocene–Lower Miocene), Dezful Embayment, Southwest Iran. *Journal of Petroleum Geology,* (in press).

Blanc, E.J.P., Allen, M.B., Inger, S. & Hassani, H. 2003. Structural styles in the Zagros simple folded zone, Iran. *Journal of the Geological Society of London,* **160**, 401–412.

Bourbiaux, B., Cacas, M.C., Sarda, S. & Sabathier, J.C. 1997. A fast and efficient methodology to convert fractured Reservoir images into a dual-porosity model. Paper SPE 38907.

Cacas, M.C., Daniel, J.M. & Letouzey, J. 2001. Nested geological modelling of naturally fractured reservoirs. *Petroleum Geoscience,* **7**, S43–S52.

Cooke, M.L. & Underwood, C.A. 2001. Fracture termination and step-over at bedding interfaces due to frictional slip and interface opening. *Journal of Structural Geology,* **23**, 223–238.

Corbett, K., Friedman, M. & Spang, J. 1987. Fracture development and mechanical stratigraphy of Austin chalk, Texas. *AAPG Bulletin,* **71**, 17–28.

Dershowitz, W. & Herda, H.H. 1992. Interpretation of fracture spacing & intensity. *Proceedings of the 33rd US Symposium on Rock Mechanics, Santa Fe, NM*, 757.

Di Cuia, R., Gout, C., Bazalgette, L. & Masse, P. 2004. Are fractures, in a carbonate sequence, facies controlled?: the Mailla Mountain (Southern Italy), a key for complex reservoir modelling. Abstract presented at the EAGE 66th Conference & Exibition, Paris, France, 7–10 June.

Dunham, R.J. 1962. Classification of carbonate rocks according to their depositional texture. *In:* Ham, W.E. (ed.) *Classification of Carbonate Rocks.* American Association of Petroleum Geologists, Memoir, **1**, 108–121.

Ehrenberg, S.N., McArthur, J.M., Pickard, N.A.H. *et al.* 2004. Strontium isotope dating of the Asmari Formation (Oligocene–Miocene) in Ahwaz, Bibi Hakimeh and Marun oilfields, southwestern Iran (Abstract). *GeoArabia,* **9**, 61.

Gross, M.R., Fisher, M.P., Engelder, T. & Greenfield, R.J. 1995. Factors controlling joint spacing in interbedded sedimentary rocks: integrating numerical models with field observations from the Monterey Formation, USA. *In:* Ameen, M.S. (ed.) *Fractography, fracture topography as a tool in fracture mechanics and stress analysis.* Geological Society, London, Special Publications, **92**, 215–233.

Hanks, C.L., Lorenz, J., Teufel, L. & Krumhardt, A.P. 1997. Lithological and structural controls on natural fracture distribution and behaviour within the Lisburn Group, Northeastern Brooks Range and North Slope Subsurface, Alaska. *AAPG Bulletin,* **81**, 1700–1720.

Hessami, K., Koyi, H.A. & Talbot, C.J. 2001. The significance of strike-slip faulting in the basement of the Zagros fold and thrust belt. *Journal of Petroleum Geology,* **24**, 5–28.

Hobbs, D.W. 1967. The formation of tension joints in sedimentary rocks: an explanation. *Geological Magazine,* **104**, 550–556.

Huang, Q. & Angelier, J. 1989. Fracture spacing and its relation to bed thickness. *Geological Magazine,* **126**, 355–362.

Hugman, R.H.H. & Friedman, M. 1979. Effects of texture and composition on mechanical behaviour of experimentally deformed carbonate rocks. *AAPG Bulletin,* **63**, 1478–1489.

Ji, S., Zhu, Z. & Wang, Z. 1998. Relationship between joint spacing and bed thickness in sedimentary rocks: effects of interbed slip. *Geological Magazine,* **135**, 637–635.

Ladeira, F.L. & Price, N.J. 1981. Relationship between fracture spacing and bed thickness. *Journal of Structural Geology,* **3**, 179–183.

Lynn, H.B. 2004*a*. The winds of change, anisotropic rocks – their preferred direction of fluid flow and their associated seismic signatures – Part 1. *The Leading Edge,* **23**, 1156–1162.

Lynn, H.B. 2004*b*. The winds of change, anisotropic rocks – their preferred direction of fluid flow and their associated seismic signatures – Part 2. *The Leading Edge,* **23**, 1258–1268.

McQuillan, H. 1973. Small-scale fracture density in Asmari Formation of Southwest Iran and its relation to bed thickness and Structural setting. *AAPG Bulletin,* **57**, 2367–2385.

Narr, W. & Suppe, J. 1991. Joint spacing in sedimentary rocks. *Journal of Structural Geology,* **13**, 1037–1048.

Narr, W. 1991. Fracture density in the deep subsurface: techniques with application to Point Arguello Oil Field. *AAPG Bulletin,* **75**, 1300–1323.

Nelson, R.A. 2001. *Geological analysis of naturally fractured reservoirs* 2nd edn. Gulf Professional Publishing, Houston.

Price, N.J. 1966. *Fault and joint development in brittle and semi-brittle rocks.* Pergamon, Oxford.

Priest, S.D. 1993. *Discontinuity analysis for rock engineering.* Chapman & Hall, London.

Renshaw, C.E. & Pollard, D.D. 1995. An experimentally verified criterion for propagation across unbounded frictional interfaces in brittle, linear elastic materials. *International Journal of Rock Mechanical and Mineral Sciences and Geomechanics Abstracts,* **32**, 237–249.

Rives, T., Razak, M., Petit, J.P. & Rawnsley, K. 1992. Joint Spacing periodicity: field data, analogue and numerical modelling. *Journal of Structural Geology,* **14**, 925–938.

Ruf, J.C., Rust, K.A. & Engelder, T. 1998. Investigating the effect of mechanical discontinuities on joint spacing. *Tectonophysics,* **295**, 245–257.

Sepehr, M. & Cosgrove, J.W. 2004. Structural framework of the Zagros fold-thrust belt, Iran. *Marine and Petroleum Geology,* **21**, 829–843.

Sherkati, S. & Letouzey, J. 2004. Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. *Marine and Petroleum Geology,* **21**, 535–554.

Silliphant, L.J., Engelder, T. & Gross, M.R. 2002. The state of stress in the limb of the Split Mountain anticline, Utah: constraints placed by transacted joints. *Journal of Structural Geology,* **24**, 155–172.

Sinclair, S.W. 1980. *Analysis of macroscopic fractures on Teton Anticline, Northwestern Montana.* MS thesis. Department of Geology, Texas A&M University, Texas.

Svånå, T.A., Aqrawi, A.A.M., Azzizadeh, M. *et al.* 2005. The Asmari Formation in the Khaviz Anticline: sedimentology and diagenesis in an outcrop analogue to giant carbonate reservoirs in Iran. Abstract presented at the Norsk Geologisk Vintermøte, Røros, 10–12 January.

Terzaghi, R. 1965. Sources of errors in joint surveys. *Geotechnique,* **15**, 287–304.

Underwood, C.A., Cooke, M.L., Simo, J.A. & Muldoon, M.A. 2003. Stratigraphic controls on vertical fracture pattern I Silurian dolomite, northeasten Wisconsin. *AAPG Bulletin,* **87**, 121–141.

Wennberg, O.P., Azizzadeh, M., Aqrawi, A.A.M. *et al.* 2007. The Khaviz Anticline – an outcrop analogue to giant fractured Asmari Formation reservoirs in SW Iran. *In:* Lonergan, L., Jolly, R.J.H., Sanderson, D.J. & Rawnsley, K. (eds) *Fractured Reservoirs.* Geological Society, London, Special Publications, **270**.

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