SPE-175368-MS

Field Development and well planning in Tight Carbonate Reservoir using Fracture Characterization and in-situ Stress mapping from core reorientation studies: Kuwait Case Study

Chinmaya Pattnaik[1], Narhari Srinivasa Rao [1], Samar Al-Ashwak[1], Neema Hussain Al-Ajmi[1], Vijaya Kumar Kidambi[1],Abdullah Motar Al Anzi[1],Qasem Dashti[1],C.Staffelbach[2],Jean-françois Barbé[2]
INSTITUTIONS (ALL): 1. FDGS, Kuwait Oil Company 2.Corias

This paper was prepared for presentation at the SPE Kuwait Oil & Gas Show and Conference held in Mishref, Kuwait, 11–14 October 2015.

Abstract

Fracture characterization is vital for efficient field development of naturally fractured Carbonate reservoirs. Successful development of fracture reservoir in the study area was possible due to early recognition of fracture play right from the exploration phase and through careful execution of relevant data acquisition campaign in the initial stages of field development. Comprehensive and integrated studies have been carried out over the past few years to arrive at an understanding of the conceptual model in deciphering structural evolution of North Kuwait Jurassic.

Extensive core and image log data was acquired in the initial stages of field appraisal, which helped in comprehensive forward planning in design of deviated and horizontal wells. The data analysis steps included accurate and reliable reorientation of the cores. These data were calibrated with the image logs, along with available seismic attributes, which resulted in better understanding of structural evolution and sweet spotting of horizontal wells. This reorientation of the core data also helped in establishing a number of quantitative fractures attributes such as frequency, spacing, dip-azimuth and aperture along with mapping of in-situ stress directions. The detailed integration of these data also helped in accurately mapping the local and regional present day stress and its variations spatially across the fields. Stress direction across the field was helpful for deciding the azimuth of wells during well planning along with selection of completion strategy for current set of horizontal drilling Campaign.

Drilling and testing results have been encouraging through enhanced reservoir performance in these tight carbonate reservoirs, based on these integrated studies.

Introduction

Discovery of commercial hydrocarbon in the deep tight fractured carbonate reservoirs and resource plays of Oxfordian – Callovian age (over 14000ft depth, HPHT) in the northern part of Kuwait, embark new chapter in the history of Kuwait Oil Company. Currently Kuwait Oil Company is under taking an early phase of appraisal in these deep, sub-salt and tight unconventional reservoirs.

The primary driver for successful appraisal of these tight unconventional reservoirs is, optimal wellbore design (horizontal well) maximizing reservoir contact which intersects open fractures or facilitates effective hydraulic fracturing. The key factors that determine the success in achieving the objectives of these horizontal wells are well selection, well placement along with well testing and selection of proper completion method.

This study is focused on better sub-surface understanding, in particular with respect to fractures. Most of the wells drilled in all the fields have full suites of e-logs including image logs mostly oil based mud image. In absence of industry standard water based fracture image interpretation (FMI), extensive conventional cores were taken in majority of the wells and described in a consistent manner to understand the depositional setting as well as to study fractures occurrence in the wells. detail structural analysis of the fields for all potential reservoirs were carried out with the help of reorientation of cores focusing on better understanding of the geometrical and structural characteristics of each field. Iintegration of well data with the structural style, faults and seismic derived attributes helped in high grading potential areas of fracture corridors for well planning and placement of horizontal wells in this deep tight fractured carbonate play (Fig.1).

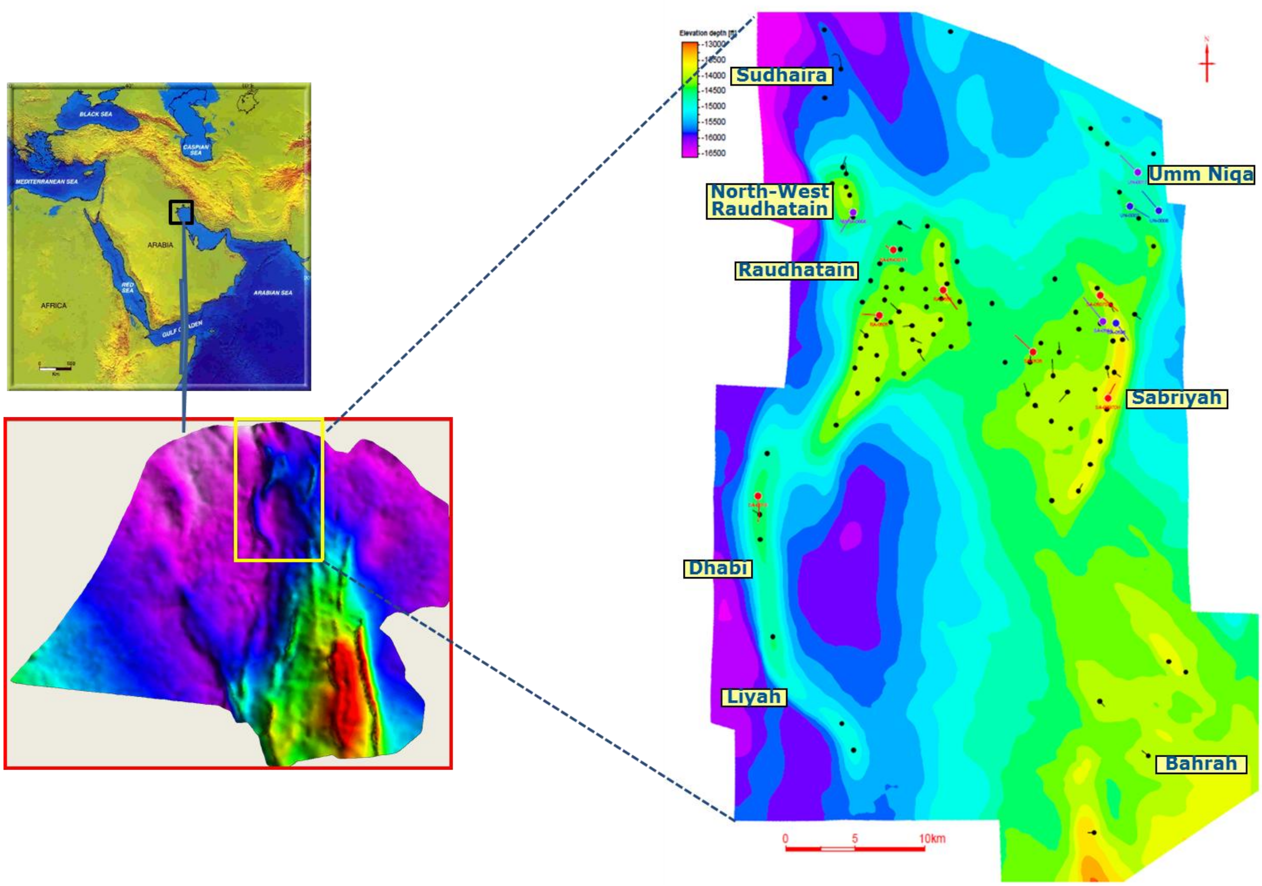


Fig:1.Location map of study area

The available seismic data in the study area is narrow azimuth, shot during late 90s with a maximum offset of about 10,000ft and low 48-fold. The seismic data was acquired with a surface geometry suited for shallower reservoirs and the data quality at Gotnia and deeper levels is sub-optimal. Study area geology is characterized by strong anhydrite -carbonate-clastics interfaces from the surface all the way down to the reservoirs. This provides an ideal environment for the generation of strong inter-bed multiples. Very often there is little or no move-out discrimination between multiples and primaries leading to sub-optimal multiple attenuation, in spite of the state of the art Demultiple signal processing techniques Fig: 2.

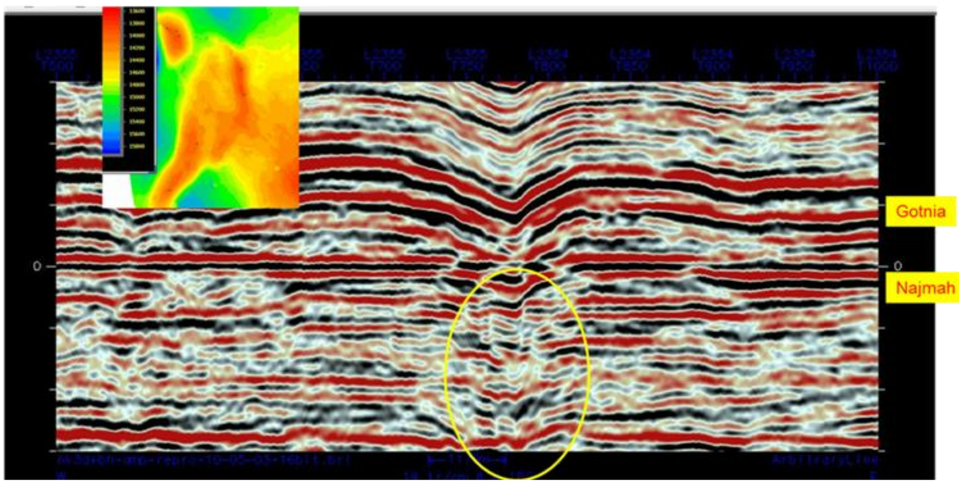


Fig: 2. Poor seismic resolution affected by multiples

Due to seismic data quality of limited resolution, the sophisticated fracture detection workflows such as study of azimuthal anisotropy could not be applied on this data. However, a dedicated PSDM was carried-out in the area of interest with high resolution velocity analysis along the crestal part of the structure to ensure integrity for structural mapping and to pick subtle faults and lineaments. The reflector corresponding to close to the top of the reservoir is very consistent and standard auto-tracking algorithms work good enough to map this event in the area. This provides high confidence in interpreting the anomalies seen in post stack attributes, extracted along the tracked horizon.

Geology Settings

This deep carbonate section is divided from bottom to top into the Marrat, Dharuma, Sargelu, Najmah, Gotnia and Hith formations. The Najmah-Sargelu formations represent the uppermost carbonate reservoirs in this area. The underlying Sargelu Formation consists of peloidal and coated grain mudstones and wackstones with a few oncoids deposited in a bathyal depth range. The upper portion of the Sargelu is marked by the first appearance of organic rich shales. The organic rich shale member of the Najmah Formation overlies Sargelu and was probably deposited in water depths representative of outer shelf or bathyal conditions. This Najmah Formation (Najmah Kerogen) is established source rock throughout the Middle-East. However, reservoir potential of this formation is severely limited by low porosity and permeability characteristics.

The limestone member of Najmah Formation, representing a shallowing upward succession overlies the shale member and appears to have been deposited in an outer shelf environment aggrading upward to shallower inner shelf. The top of the Najmah Formation is an unconformity at the base of Gotnia

Formation, which consists of alternations of crystalline salts and anhydrites with features of sabkha and subaqueous deposition and acts as excellent regional seal. Because of various episodes of the tectonic phases undergone by the basin and flowing nature of salt, considerable variability is seen in the architecture of these alternating salt-anhydrite layers, which are unconformable to the formations above and below.

Najmah-Sargelu section, in the study area, occurs at a depth range of 13000-14000 ft. with an average thickness of 230 ft., matrix porosity of less than 2% and permeability of 0.1mD. Geological and petro-physical data and production tests have shown that fractures play the primary role in attaining sustainable production from Najmah-Sargelu formations.

Methodology and Results

The basic methodology involves the study of cores recovered on many wells in Kuwait, in Najmah-Sargelu formation to derive insitu stress direction and fracture orientation, which resulted in better understanding of structural evolution and are used extensively for planning of recently drilled horizontal wells.

The core reorientation work is based on the use of the AS3D Goniometer which permits a totally hand free 3D digitization of all planar and linear features. The main result of this digitization is to provide data measurements that can be imported into dedicated software and combined with other existing information. In the studied wells, geometry of sedimentary and tectonic structures from the core was collected with AS3D.

The original data points obtained from the reference lines are computed and restored in their real spatial position by a reorientation process in two steps, depending on the deviation of wells. The data are first plotted on a stereonet with respect to each reference line. This is reprocessed to obtain the best reorientation corresponding to the most coherent geometry of sedimentary and tectonic structures in core. The sedimentary and tectonic trends for each scribeline are then superposed to obtain the general trends for the core. In case of deviated well, deviation data is used to reorient the data to true geographic position. A schematic view of core reorientation methodology is shown in figure-3.

With the AS3D goniometer, the orientations of the bedding and the fracture planes are measured relative to a fixed reference system with the axis parallel to the core axis. This reference system is then rotated within the general geographic system so that the core axis becomes parallel to the well trajectory. A step-by-step rotation is then applied around the core axis until the bedding match the known features (i.e., from seismic or image log data). The same rotations are then applied to the fractures to obtain their orientation with respect to North. This method allows sampling of large parts of the core at relatively low costs and is easily implemented.

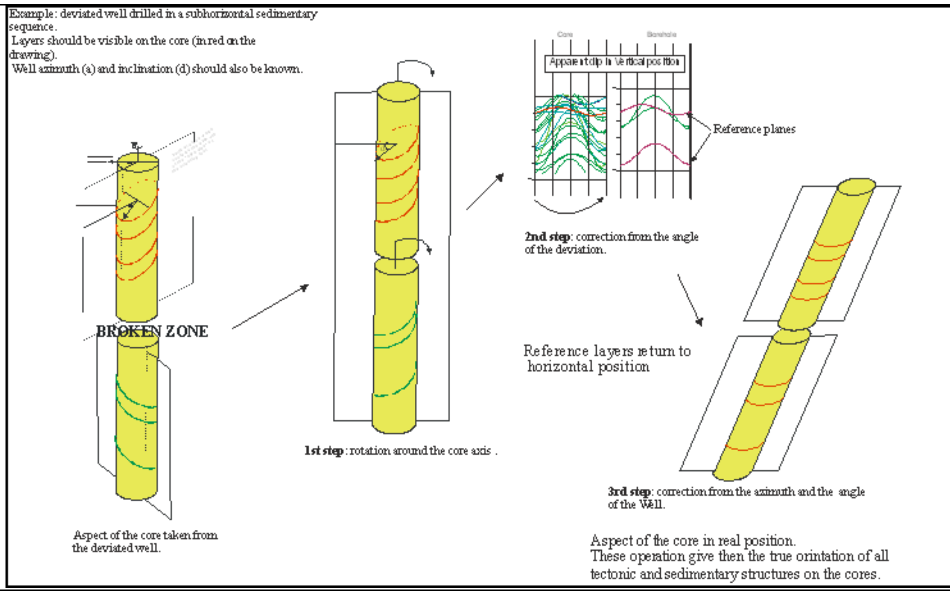


Fig: 3 A schematic view of core reorientation.

The details methodology of core reorientation principles is described by A.M.Alenzi etal (IPTC, 16661, 2013).

Drilling induced fractures form during drilling as a result of in situ crustal stresses surrounding the rock, as well as stress imbalances caused by removal of excess loading pressure (Kulander et. al., 1990). Because horizontal stresses strike parallel to the planes made by drilling induced fractures, these fractures can be used to measure modern day stress fields. Drilling induced fractures in the core are 'picked' in order to obtain their azimuth. Some Borehole images of the inside of the drill hole are then compared with the core images for matching features. Once same set of fractures (or breakouts) are found in the core and the borehole, then it is possible to rotate the core images data to match the orientation of the borehole image. This final orientation of drilling induced fractures in the core will thus provide the direction of maximum horizontal compressional stress in this area.

Drilling induced fractures in the rock indicate the forward direction of the drill bit, an element at the end of a drill pipe that actually does the cutting. Because these fractures may extend sidewise beyond the column to be drilled, they may also be present in the borehole walls, which ultimately provide the means to extract contemporary horizontal stresses and fault regimes at the regional scale.

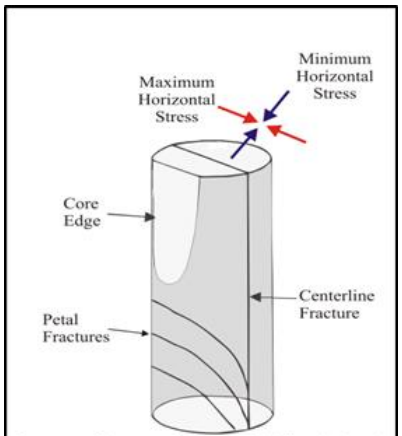
There are four types of induced fractures: petal, centerline, petal-centerline, and core edge fractures.

- ✓ Petal fractures are fractures that initiate at the edge of the borehole and curve smoothly downward toward the center of the core (Bell, 1996).
- ✓ Centerline fractures propagate ahead of the drill bit as a continuous fracture that vertically bisects the core.
- ✓ Petal-centerline fractures are petal fractures that grow to become a centerline fracture or that join with a centerline fracture.

- ✓ Core edge fractures are smooth curved fractures located along the edge of the core. (Fig.4)

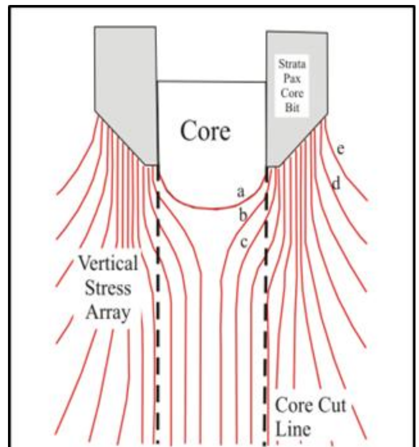
Generally, the induced fractures are stress-related petal coring-induced fractures, which initiate from near the core boundary and propagate downwards from a dip of 30° to 75°.

Some of these induced fractures form at the same depth on opposite sides of the cores and several of them propagate downward into the core but usually stop at about 1/3 to 1/4 of the core diameter. It is commonly thought that the petal fractures are tensile fractures that form beneath the core bit and propagate ahead of the core bit. The fractures form along the principal stress trajectories beneath the core bit, as illustrated in the fig. 5 below.



Cartoon of three major types of drilling induced fractures and the direction of minimum and maximum horizontal stresses (from Yatschenko, 2008)

Fig: 4. Types of drilling induced fracture



A schematic illustration of bit-induced stress stray array below core, modified from Jaeger & Cook, 1979 (After Lorenz and Finley, 1979)

Fig: 5. Bit induced stress below core

Petal fractures follow optimum lines of stress towards the bit centerline (see traces of lines a, b, c) and possibly outwards as well (lines d, e). These stress-related fractures are developed during or after coring. The development of induced fractures is under the control of pre-existing mechanical anisotropy (natural fractures, bedding planes, burrows). Their orientation is influenced by the in-situ stress.

The number of induced fractures observed in all the wells is variable and depending on the lithology.These fractures are generally observed in the fine-grained and competent rocks. The planes presented moderate dip values, generally around 72°.

In most of the studied wells, a large number of induced fractures (petal or centerline) have been observed and reoriented (Fig. 6&7).

Fig:6. Petal and centerline induced fractures

Fig:7.Core edge induced fracture

The directions of these fractures are showing the expected actual in situ maximum horizontal stress that is affecting the well area.

The figure below (fig:8) is extract from the World Stress map project and is showing some orientation of actual horizontal stress observed in the Gulf Area. The mean orientation of the stress is generally oriented NE-SW due to the Zagros fault activity. (Yatsenko, A., 2008)

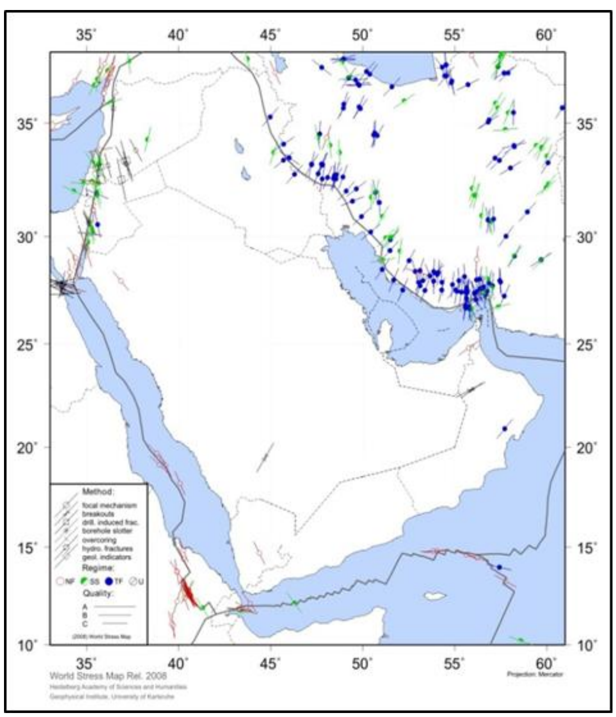


Fig: 8. Orientation of actual horizontal stress observed in the gulf area

If we plot the result of the induced fractures reorientation in the Najmah-Sargelu cores from Kuwait, we can find many wells showing similar orientation of the induced fractures (Fig: 9).By plotting on the same map (fig:9) the orientation of the main natural fractures and K3 minimum permeability vector, we can see that the permeability is influenced by the actual stress. The minimum permeability vector (blue arrays) is generally perpendicular to the actual maximum horizontal stress direction. This means that the drainage will be in the direction of the main stress and that probably the fractures that are perpendicular to the actual horizontal stress might be closed in well conditions.

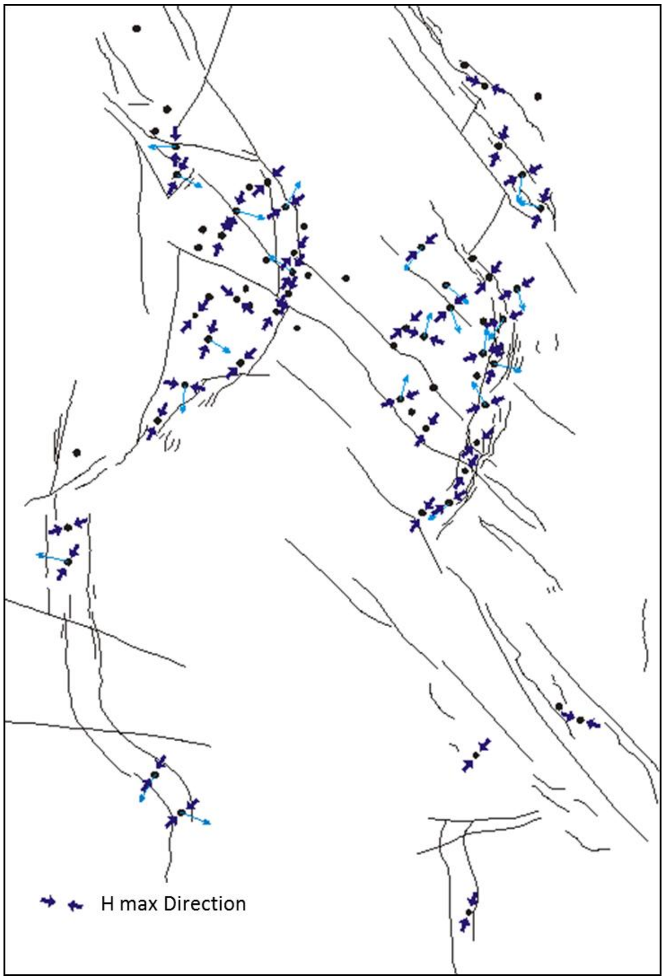


Fig:9.Maximum horizontal stress direction derived from core induced fracture

In fact, some recent studies (Z.Rahim & al 2012) have pointed out that wells drilled in the direction of minimum horizontal stress are potentially more favorable to flow from the perspective of reservoir development and optimal production. In such a situation, hydraulic fractures grow transverse to the wellbore axis allowing multiple fractures to be placed without the possibility of fracture overlapping. Consequently, a few wells that have been drilled in the minimum horizontal stress direction encountered several drilling-related problems, such as stuck pipe, breakouts, and breakdowns.

Well Planning Strategy

The key major challenges for the well design, from the sub-surface perspective, can broadly be classified under two major categories namely well planning and well placement. A major effort is necessary during the well planning phase, where the asset team needs to go through entire gamut of well selection process by carefully integrating sub-surface data, which results in suitable design of drain-hole profile based on the target reservoir.

The results of reoriented core data are used to extensively to derive local and regional present day stress and its variations spatially across the fields. The core fracture reorientation data with seismic interpretation has helped to understand kinematic evolution of each fields and its impact on expected fracture set. Richard etal. 2014 (Fig:10)

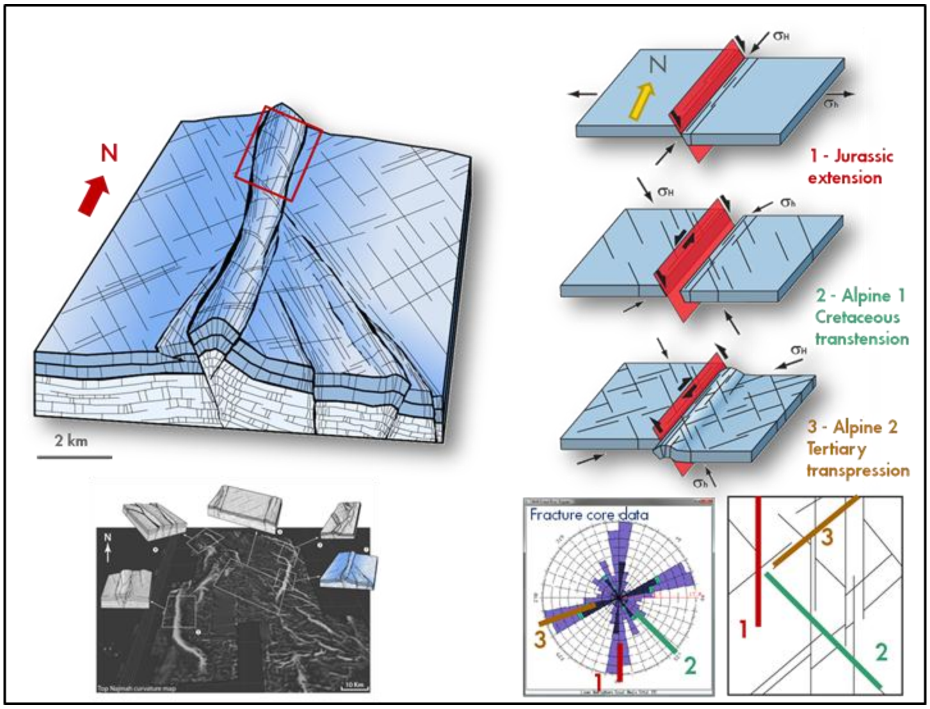


Fig: 10. Kinematic evolution and impact on expected fracture sets

These results in turns are helpful not only for deciding the well azimuth during well planning phase but also selection of completion strategy for current horizontal drilling campaign. As fractures play the primary role in attaining sustainable production from Najmah-Sargelu formations, the primary objective for the well planning phase is to target these fracture corridors. As per current understanding of kinematic evolution and its impact on the expected fracture sets, the azimuth of the planned horizontal wells are mostly perpendicular to the strike of open fractures of the offset wells. Core reorientation work has significant value addition in indicating areas of potential high fracture densities thus assisting the well placement process.

The well placement strategy varies spatially and vertically based on real time data as well as based on the geological, structural evolution and mechanical stratigraphic understanding of the reservoir. Crestal highs are the target for the intersection of fracture sweet spot natural fractures in Najmah limestone reservoir. The drain holes are planned to sample whole of limestone (40-45 ft. TSD), where the target is planned to intersect the through going fracture corridors. These efforts have resulted in very good initial successes in recently drilled Najmah limestone horizontal well in Sabriyah field. As a part of ongoing Najmah Limestone appraisal, dedicated wells are now under drilling to target matrix areas with low fracture intensity off the crestal area. Najmah MFS reservoir (37-39 ft. TSD), consists of thin limestone rich beds and intercalation of Kerogen rich layers. Based on the conceptual fracture model the thin limestone layers are fractured (bed bound) and the Kerogen rich layers are mostly devoid of fracture. The drain hole in Najmah MFS is to plan to target thin limestone rich beds, which are rich in bed bound fractures and avoid Kerogen rich layers.

In both the reservoirs the drain holes are planned to intersect maximum open fractures (planned perpendicular to the strike) and to avoid fault intersection.

Fracture analysis from the cores and borehole image analysis established strong correlation between open /partial open fractures along present-day maximum horizontal stress and the flowing zones. Detail analysis carried out on the well scale as well as field scale based on the subsurface integration of data and the horizontal wells targets are carefully selected to intersect fracture sweets spots. From the core reorientation analysis as well as integration with surveillance and well test/production the fractures those are parallel to maximum horizontal stress direction expected to remain open and contributes to flow. Good match was established between fracture porosity and permeability estimated from the core studies and Flow meter logs (Fig: 11).

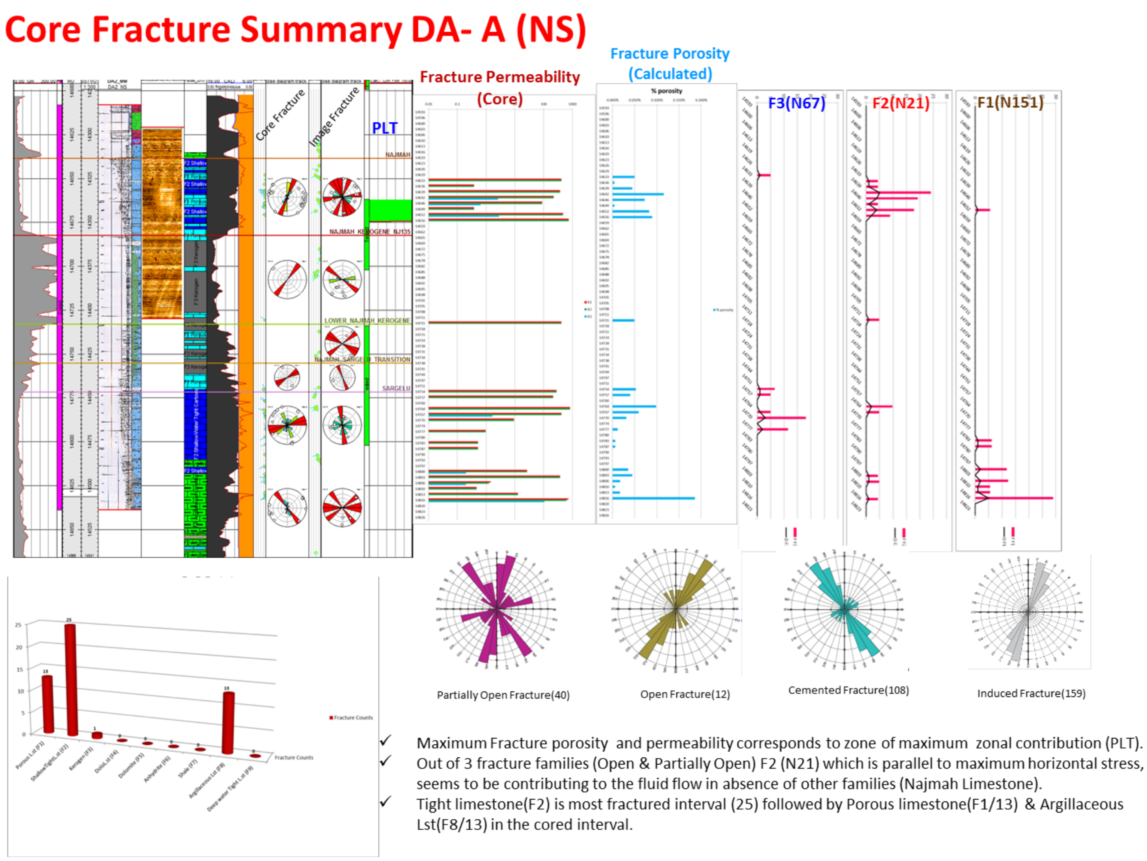


Fig: 11. Core Fracture Summary in DA-A well.

Conclusions

The integrated approach adopted in this study, where combining the well data from core reorientation with image log data, and seismic data provided critical insights into the fracture properties in the study area. The core reorientation work along with Fracture analysis assisted in optimizing well placement to penetrate the most heavily fractured corridors also establish strong correlation between open /partial open fractures along present-day maximum horizontal stress and the flowing zones Good match was established between fracture porosity and permeability estimated from the core studies and Flow meter logs. Drilling and testing results have been extremely encouraging through enhanced reservoir performance in these tight carbonate reservoirs based on the integrated studies.

Acknowledgements

The authors sincerely thank the Management of Kuwait Oil Company for granting permission to present this paper. Permission granted by the Ministry of Oil, the Sate of Kuwait for publishing this paper is also gratefully acknowledged. Special thanks are due to KOC-Technical Review Committee for critical review of the manuscript.

References

Priest, S.D. & Hudson, J.A., 1976. Discontinuity spacing in rocks. International Journal of Rock Mechanics, Mineral Science & Geomechics, Abstracts 13: 135-148.

Engelder,T. & Geiser, P., 1980. On the use of regional joint sets as trajectories of paleostress field during the development of the Appalachian Plateau, New York. Journal of Geophysical Research 85: 6319-6341.

Narr,W. & Lerche, I., 1984. A method of estimating of subsurface fracture density in core.American Association of Petroleum Geologists Bulletin 68: 637-648.

Hancock, P.L., 1985. Brittle microtectonics: principles and practice.Journal of Structural Geology 7: 437-457.

Huang, Q. & Angelier, J., 1989. Fracture spacing and its relation to bed thickness. Geological Magazine 104: 550-556.

Price, N.J. & Cosgrove, J.W., 1990. Analysis of geological structures. Cambridge University Press (Cambridge): 502 pp

Kulander, B.R., Dean, S.L. & Ward Jr.,W.J., 1990. Fractured core analysis – interpretation, logging and use of natural and induced fractures in core. *In:* American Association of Petroleum Geologists Methods in Exploration 8: 88 pp.

Loosveld, R.J.H. & Franssen, R.C.M.W., 1992. Extensional vs. shear fractures: implications for reservoir characterisation. European Petroleum Conference (Cannes, 16-18 November) Proceedings 2, Paper SPE 25017: 65-66.
Narr, W. & Suppe, J., 1991. Joint spacing in sedimentary rocks. Journal of Structural Geology 13: 1037-1048.

Bergerat, F., Bouroz-Weil, C. & Angelier, J., 1992. Paleostresses inferred from macrofractures, Colorado Plateau, Western USA.Tectonophysics 206: 219-243.

Fulljames, J.R., Zijerveld, L.J.J., Franssen, R.C.M.W., Ingram, G.M. & Richard, P.D., 1996. Fault seal processes: systematic analysis of fault seals over geological and production time scales. *In:* Hydrocarbon seals, importance for exploration and production – Proceedings of the Norwegian Petroleum Society Hydrocarbon Seals Conference (Trondheim), Petroleum Abstract: 641329.

Gauthier, B.D.M. Franssen, R.C.W.M. Drei, S., 2000 Fracture networks in Rotliegend gas reservoirs of the Dutch offshore: implications for reservoir behaviour Geologie en Mijnbouw / Netherlands Journal of Geosciences 79 (1): 45-57

Ameen Mohammed S, Ismail M Buhidma, and Zillur Rahim ; 2010. The function of fractures and in-situ stresses in the Khuff reservoir performance, onshore fields, Saudi Arabia. Am Assoc Pet Geol Bull 94(1):27-60

Rao, N.S etal. 2012. An integrated approach for overburden drilling hazard mapping: Kuwait case study, SEG 2012.

Rao, N.S etal. 2012. Seismic applications for better horizontal drain hole selection to successful well placement, SEG 2012.

Pattnaik.C&Rao, N.S., 2012.Best practice of data integration in developing naturally fracturedtight carbonate reservoirs: Kuwait case study (Abstract), AAPG, ICE, 2012

Al-enezi. A & Pattnaik.C, 2013. Reliable Fracture Characterisation and Value Addition through Special Core Reorientation: Kuwait Case Study, IPTC,175368.

Pascal Richard etal, 2014. Structural Evolution Model for the North Kuwait Carbonate Fields and its Implication for Fracture Characterisation and Modelling, IPTC,17260.