[PS]Characterizing Fracture Corridors for a Large Carbonate Field of Kuwait by Integrating Borehole Data with the 3-D Surface Seismic*

Sunil K. Singh[1], Mahmood Akbar[2], Badruzzaman Khan[1], Hanan Abu-Habbiel[1], Bernard Montaron[2], Lars Sonneland[2] and Robert Godfrey[2]

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[1]Exploration Group, Kuwait Oil Company, Kuwait, Kuwait. (singh@kockw.com)
[2]Geology & Rock Physics, Schlumberger Dahran Carbonate Research Center, Al Khobar, Saudi Arabia.

Abstract

Developing fractured carbonate reservoirs has always been demanding for the geoscientists of the oil industry. Fracture corridors are thought to be the main features controlling fluid movements in these reservoirs. Locating these corridors and determining their vertical and lateral extents are the main requirements by those involved in planning locations for new producer and injector wells in any field of interest. Information on fracture corridors can further be used to construct comprehensive DFN (Discrete Fracture Network) models for reservoirs with a higher degree of certainty.

This paper discusses an innovative workflow to locate fracture corridors and estimate their dimensions. The workflow is centered around the Fracture Cluster Mapping (FCM) technique, which facilitates integration of borehole scale data, geomechanics, and tectonics with the 3D surface seismic. Surface-seismic data processing is optimized for it to be used for fracture clusters / corridors detection. Having a good understanding of fractures' pattern in the field and optimally processed 3D seismic data, Ant Tracker (essential part of FCM for automatic extraction of discontinuities) is run on the seismic cube and parameters are conditioned to highlight fracture clusters / corridors of certain orientations related to tectonic history.

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The workflow was tested on the exploration area for the Jurassic carbonates of low porosity, low permeability and about 3000 ft thickness in Kuwait. The FCM technique highlighted on the seismic cube fracture corridors of varying density, orientation, vertical and horizontal extents across the study area. At the well locations (existing ones and newly drilled ones), the predicted fracture corridors matched reasonably well with the fracture orientation and density interpreted for each well from cores and borehole images.

The approach has a great value in deciding locations for new wells, planning well trajectories (to avoid or intersect a certain type of fracture network), and production predictions. It is important to use this approach in preparing comprehensive DFN models. It is more important in the areas where deeper depths and sparse well data have added more uncertainty in fracture prediction. The approach was developed and tested first time ever for few fields in Kuwait..

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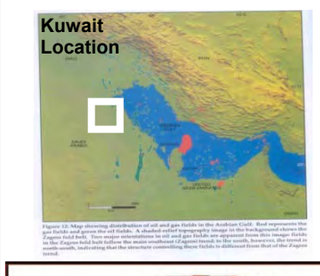
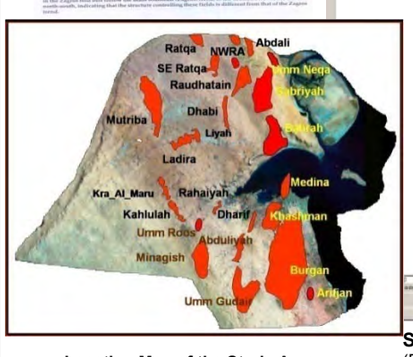
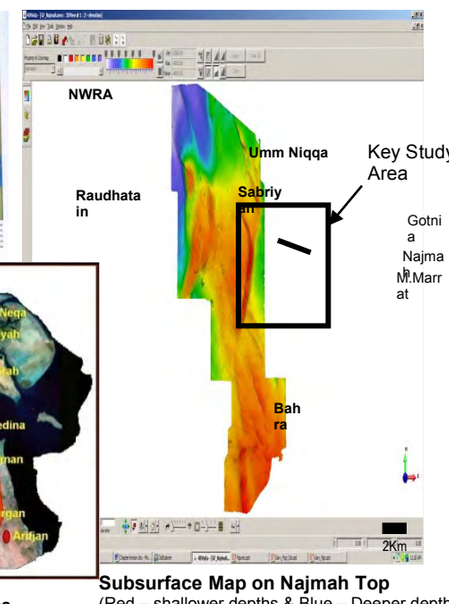
Study Area & General Characteristics

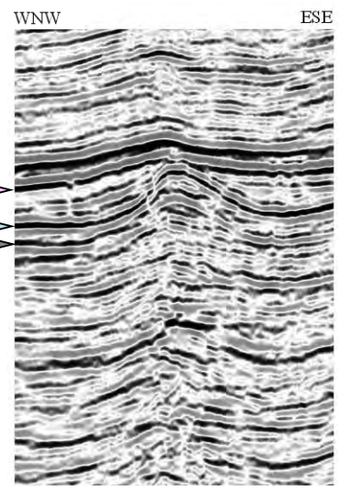




Location Map of the Study Area



Subsurface Map on Najmah Top
(Red – shallower depths & Blue – Deeper depths)



A Seismic Cross-section from Sabriyah Field

.NW-SE trending strike-slip faults are common. NNE-SSW trending strike slip faults are present.

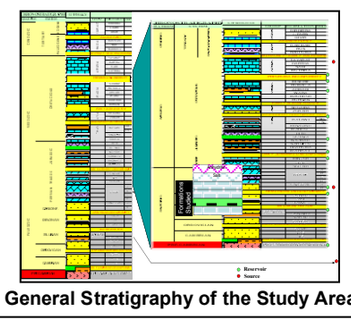
.Flower structures are present.

.NWRA field is a domal structure due to salt movement.

.Sabriyah structure is a popped up anticline caused by transpression along the two steep faults (striking NNE-SSW) flanking its eastern and western sides.

.Najmah, Sargelu and Marrat are the main carbonate reservoirs in the Jurassic section.

.Hith anhydrite & Gotnia salt are the cap rocks.

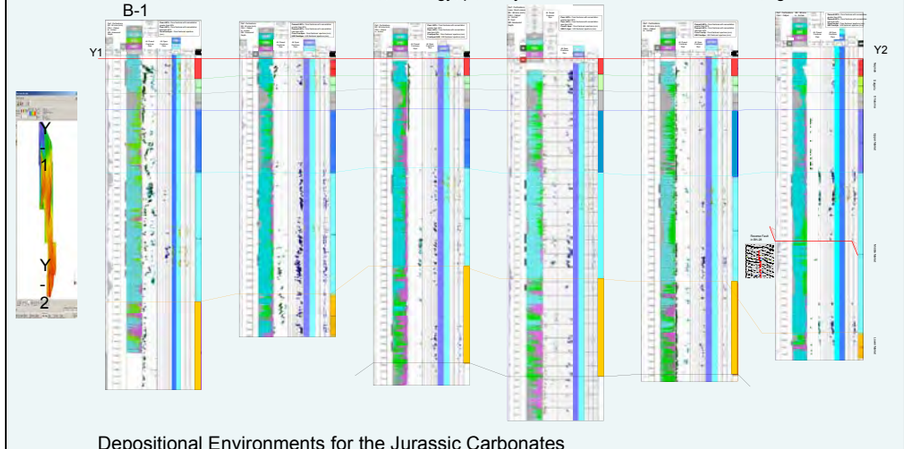


General Stratigraphy of the Study Area

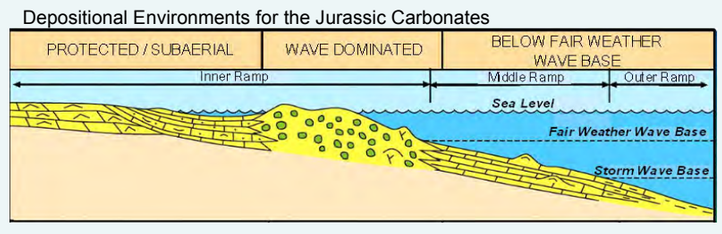
Petrophysical Properties

- ***Matrix Porosity***
  - *Range 0 -22%*
  - *Najmah/Sargelu 3% (mean)*
  - *Upper Marrat 3%(mean)*
  - *Middle Marrat 2.5%(mean)*
  - *Lower Marrat 1.8%(mean)*
- **Matrix Permeability**
  - *Range 0 -119 md (mean 2 md)*
  - *Najmah/Sargelu 1 md (mean)*
  - *Upper Marrat 2 md (mean)*
  - *Middle Marrat 2 md (mean)*
  - *Lower Marrat 2 md (mean)*

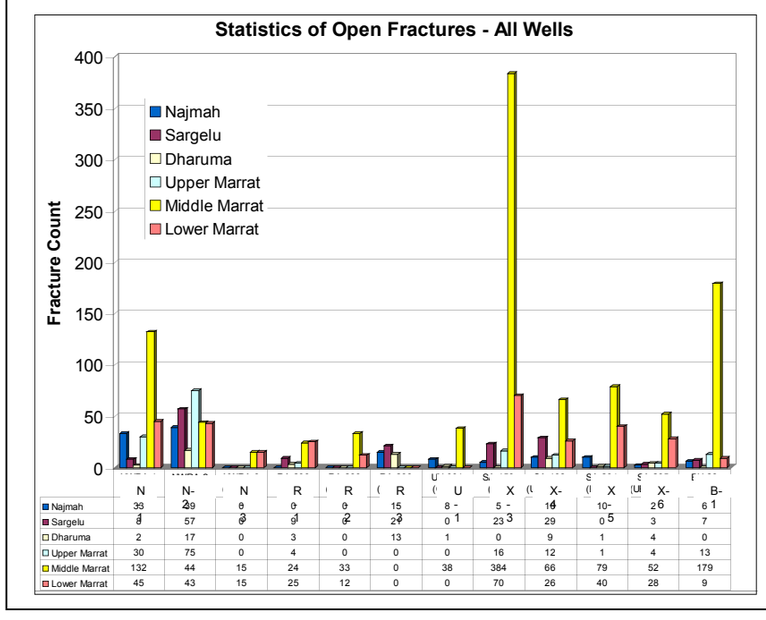
Correlation of formations' thickness, lithology, porosity & fractures for the wells U-1 through B-1

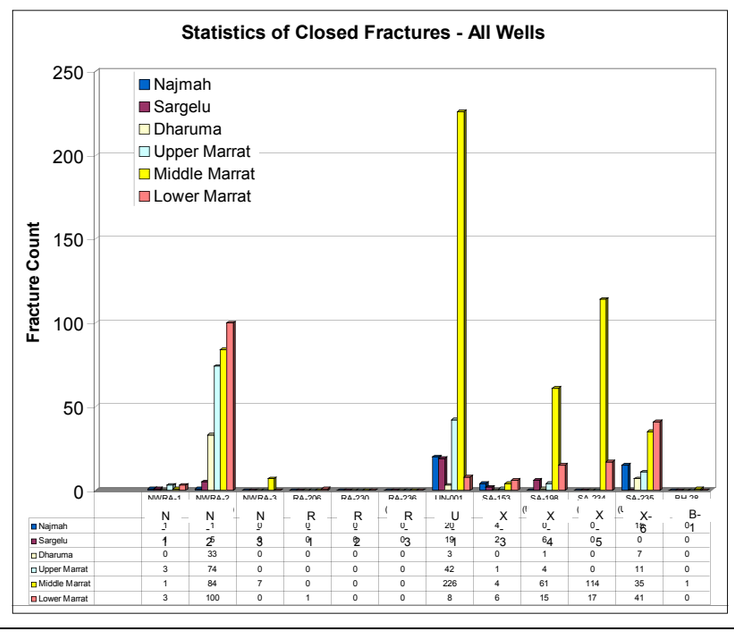


Depositional Environments for the Jurassic Carbonates



Borehole Fracture Data



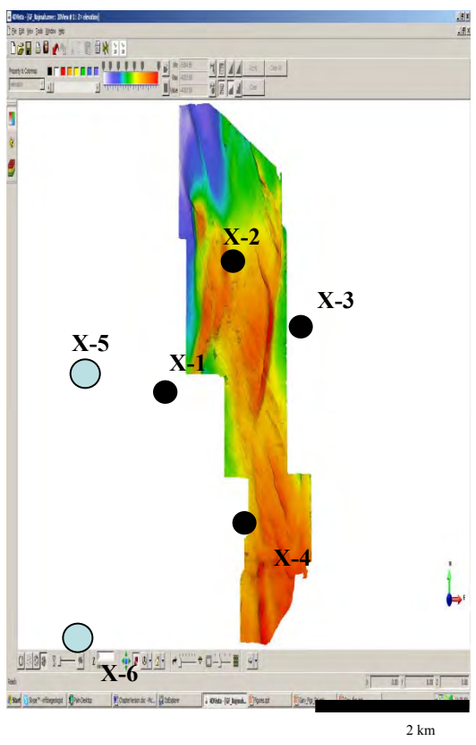


Well Data Observations

- Out of 14 wells, 12 wells were logged with oil-base mud imaging tools. With the exception of one deviated well (N-3), all wells were drilled vertically across the Jurassic Section.
- Data for open and closed/filled fractures from borehole image analysis indicated uneven distribution of fractures. Cores indicated a similar behaviour.
- In addition to diffuse occurrences, fractures in some wells appeared to exist as clusters of different widths, 1-5 m to 25-30m.
- Drilling & production well data supported erratic behaviour of fractures occurrence.

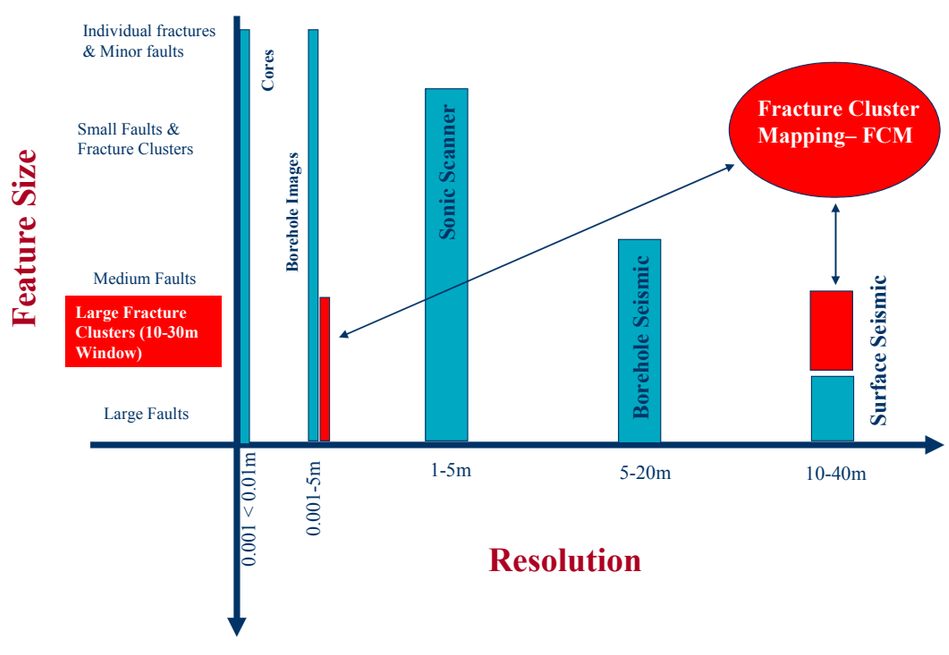
Fracture Interpolation & Extrapolation

Well Locations in the Sabriyah Field, used as a Key Area because of new drilling

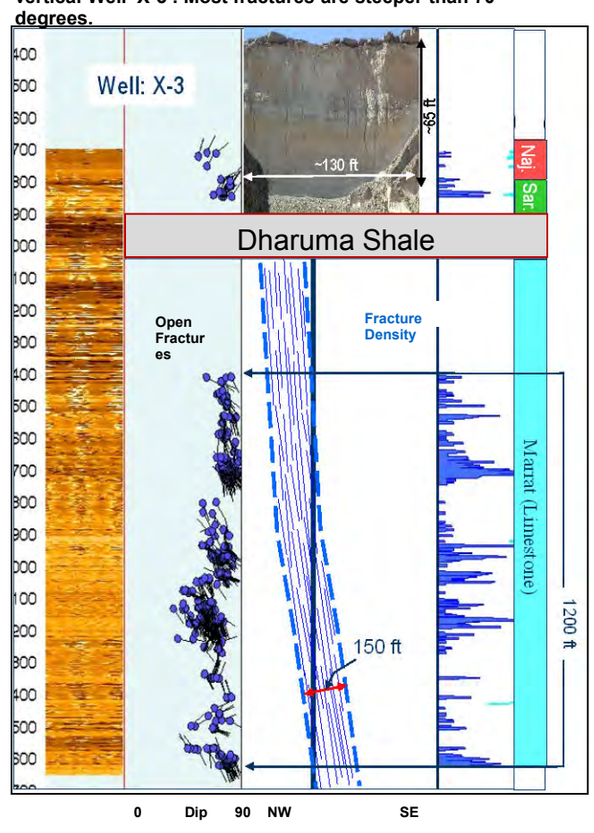


- **Generally individual fractures are difficult or largely impossible to be detected with the 3D surface seismic.**
- **Fracture clusters of width 10-30m & larger height (~ 10-30m) should have certain signatures on the 3D Surface Seismic of good quality and resolution.**
- **Fracture Cluster Mapping (hereafter called FCM*) workflow helped to identify fracture clusters of varying width, height, dip and orientation in the study area.**
- **Sabriyah Field was taken as the Key Area for developing, testing and validating theFCM workflow.**
- **Locations X-1 through X-4 are for existing wells. Locations X-5 and X-6 are for the new wells, which were used for blind testing the FCM results at their locations using cores, borehole image logs and production data.**
- **The technique was applied to all Five Fields comprising the study area.**

Cross plot showing resolution and size of structural features (faults & fractures) that are detectable with different measurements used for their detection in the subsurface.

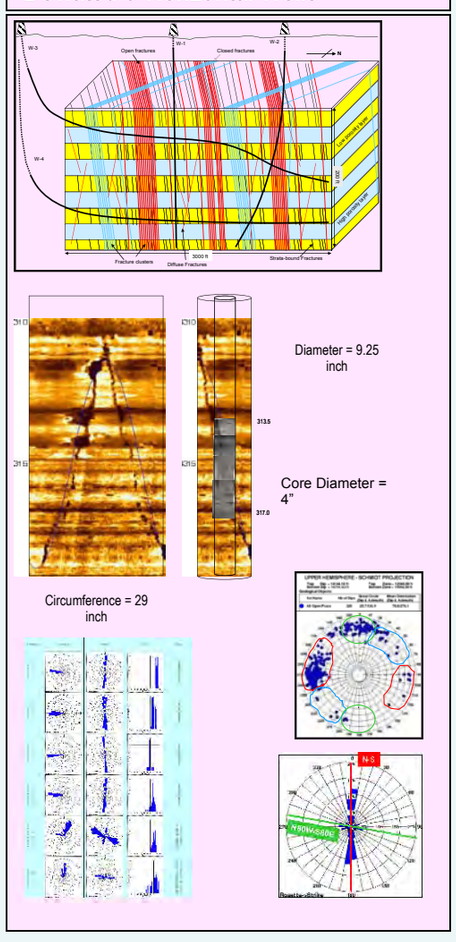


A large fracture cluster(150 ft wide) intersected by the vertical Well 'X-3'. Most fractures are steeper than 70 degrees.



FCM : An Integrated Approach / Workflow for Fracture Cluster Mapping

Core, Borehole Images, Petrophysical logs, drilling record.. From Vertical, Deviated & Horizontal Wells



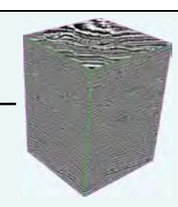
Borehole Data Analysis

Fracture Data: Dip Attributes, Morphology & Occurrence Mode

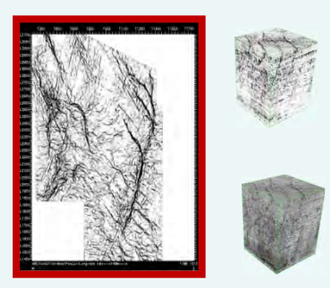
Statistical distribution of fracture attributes for single & multiwells, e.g., histograms, azimuth rosettes, etc.

Regional & Local Tectonic Setups & Stress Fields, Outcrop Observations

3D Seismic Cube from Objective Driven Processing



Fracture Sensitive Seismic Attributes – Dip Deviation, Curvature Volume found to be the Best Attributes for fractures



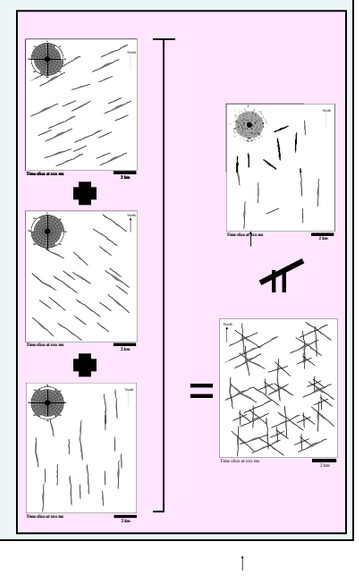
Define Optimal Set of Directional (A0, A1, A2, ….., An) & Inclination (P0, P1, P2, ….., Pn) Filters for Ant Track Processing to Delineate Fractures Fitting the Criteria

Run Ant Track application with A1 & P1 Filter Parameters | **Run Ant Track application with A2 & P2 Filter Parameters** | ..... | **Run Ant Track application with An & Pn Filter Parameters**

Save Output as 3D Cube – C1 | **Save Output as 3D Cube – C2** | ..... | **Save Output as 3D Cube – Cn**

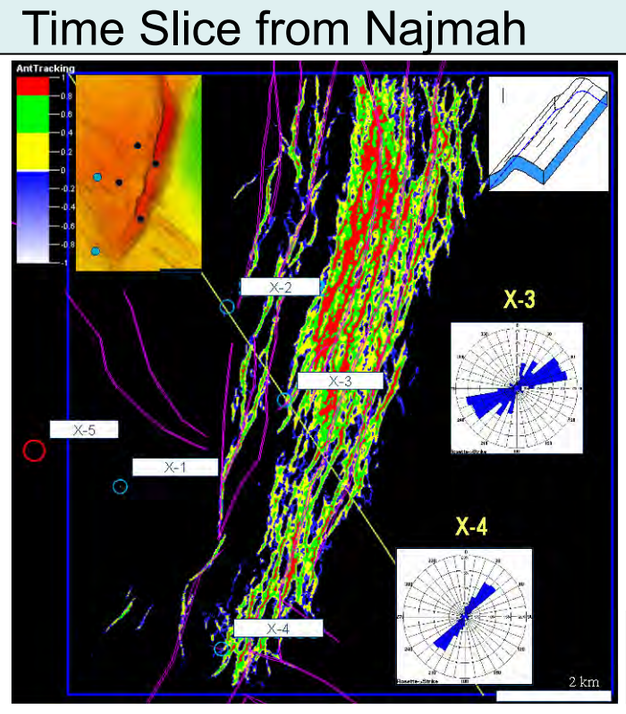
Combine All 3D Cubes: C1 + C2 + …..+ Cn into a Single 3D Cube representing a Fracture Cluster Cube

Validation: Correlation of FCM Results with Fractures at Already Drilled Input Wells & also with Newly Drilled Wells



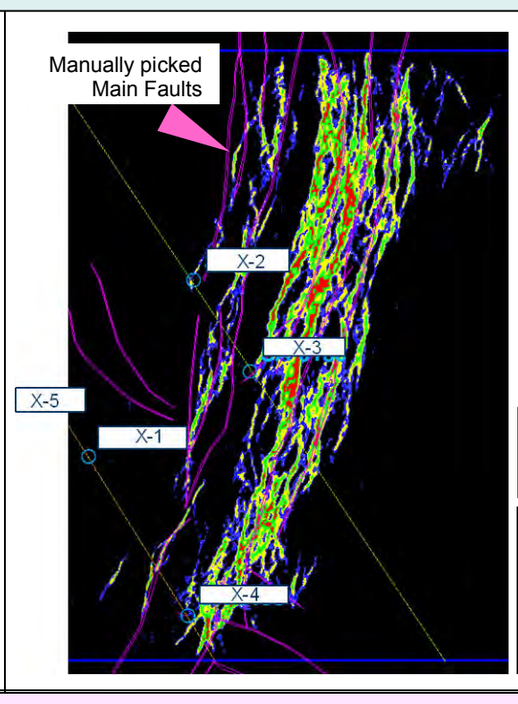
FCM Results & Validation

Time Slice from Najmah



Largely NNE-SSW striking fracture clusters got detected by Ant Tracker from the 3D seismic when the Azimuth Filter was opened to 360 degrees search. It did not match with the ENE-WSW strike of large number (more than 400) of open fractures seen by the borehole images at Well X-3 and largely NE-SW striking open fractures at Well X-4 in the interval Najmah through Lower Marrat.

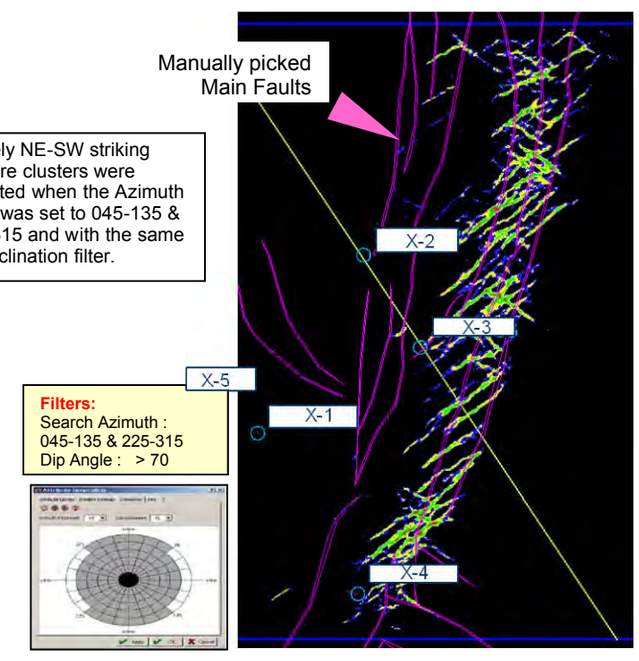
Filters:
Search Azimuth : All 360 deg. Features' Dip Angle : > 70



Largely NNE-SSW striking fracture clusters were detected when the Azimuth Filter was set to 315-045 & 135-225 and with the same dip inclination filter.

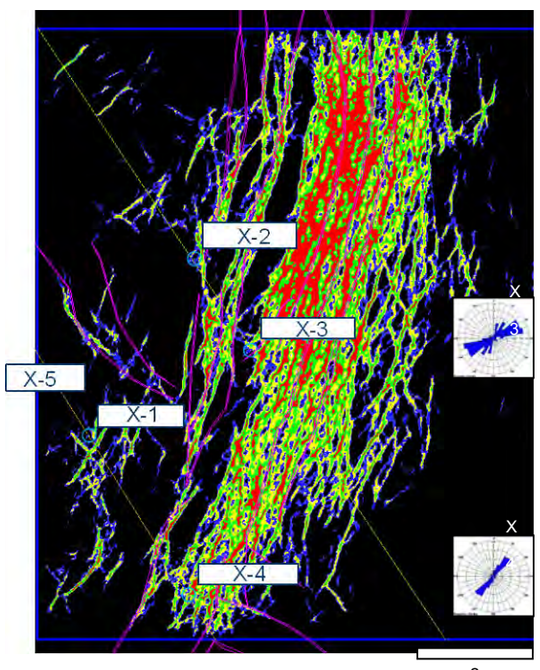
Filters:
Search Azimuth : 315-045 & 135-225
Dip Angle : > 70

Largely NE-SW striking fracture clusters were detected when the Azimuth Filter was set to 045-135 & 225-315 and with the same dip inclination filter.



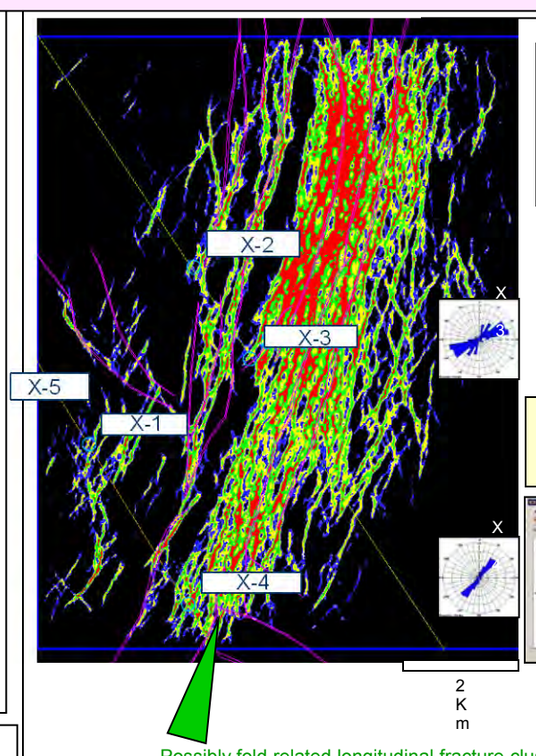
Filters:
Search Azimuth : 045-135 & 225-315
Dip Angle : > 70

Time Slice from Middle Marrat



A time slice from Middle Marrat showing largely NNE-SSW and some NW-SE striking fracture clusters detected by Ant Tracker from the 3D seismic when the azimuth filter was set to 360 degree. Very few NE-SW or ENE-WSW striking fracture clusters were extracted.

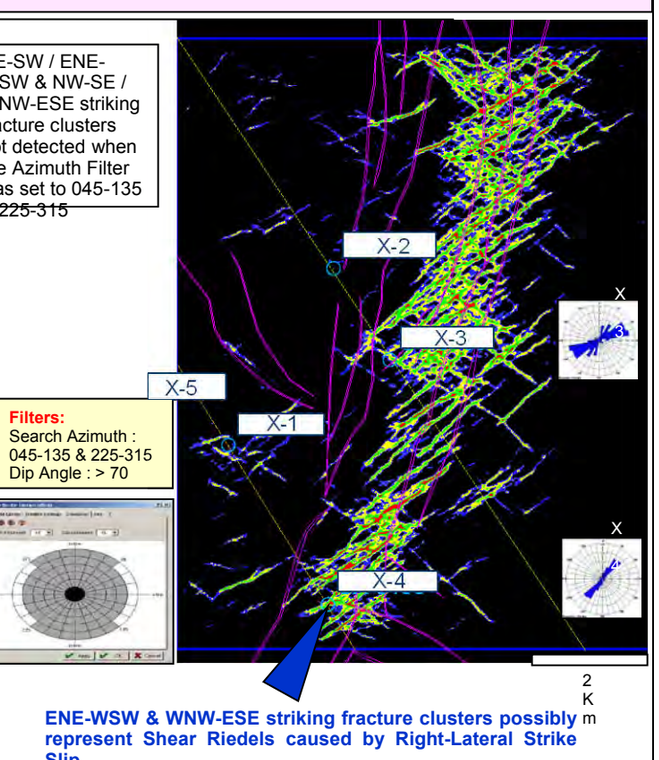
Filters:
Search Azimuth : All 360 deg.
Features' Dip Angle : > 70



Largely NNE-SSW striking fracture clusters got detected by Ant Tracker when the Azimuth Filter was set to 315-045 & 135-225

Filters:
Search Azimuth : 315-045 & 135-225
Dip Angle : > 70

NE-SW / ENE-WSW & NW-SE / WNW-ESE striking fracture clusters got detected when the Azimuth Filter was set to 045-135 & 225-315

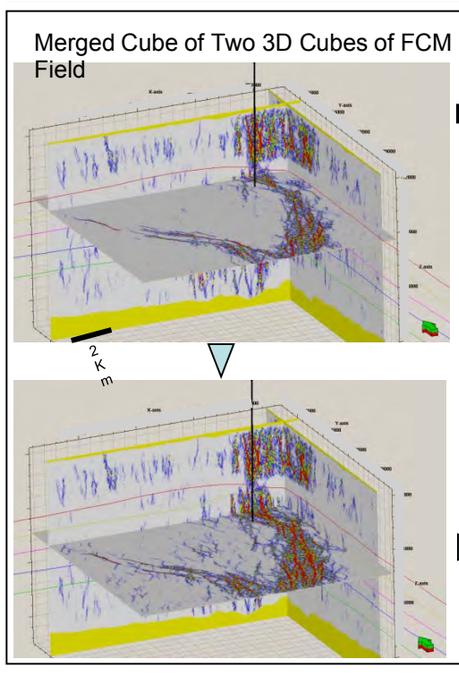


Filters:
Search Azimuth : 045-135 & 225-315
Dip Angle : > 70

Possibly fold related longitudinal fracture clusters following the NNE-SSW trending fold axis of Sabriyah Anticline

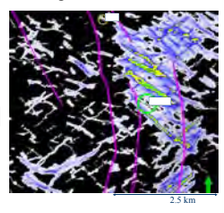
ENE-WSW & WNW-ESE striking fracture clusters possibly represent Shear Riedels caused by Right-Lateral Strike Slip

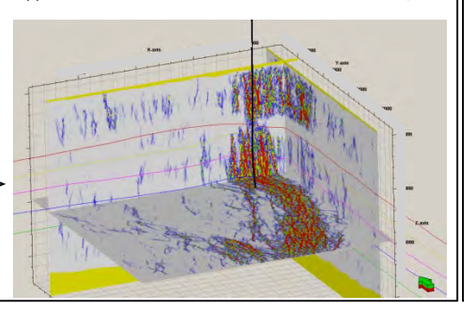
Merged Cube of Two 3D Cubes of FCM Results at Umm Niqqa Field



- Two 3D Cubes of FCM Results merged into one 3D Cube show Fracture Clusters of varying Vertical and Horizontal Extents at different time slices through Jurassic carbonates.

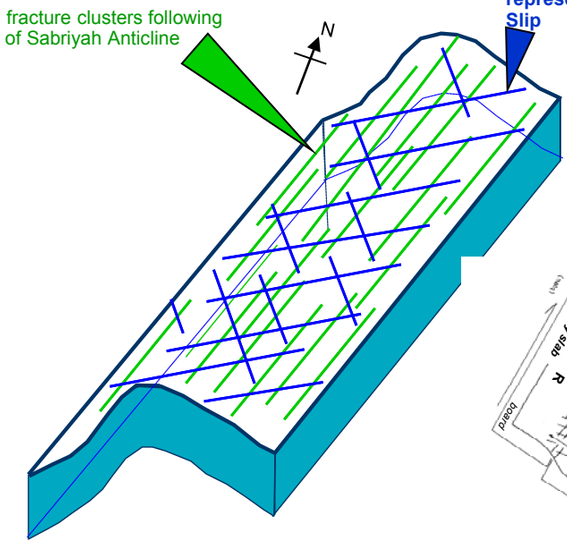
A time slice from the merged 3D Cube of fracture clusters at the Middle Marrat level, showing nearly orthogonal sets of fracture clusters in Umm Niqqa Field.



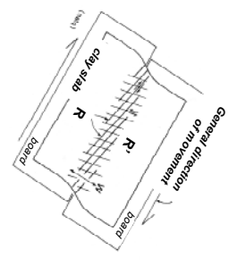


FCM Technique Identified Three Main Fracture Cluster Sets within the Sabriyah Anticline:

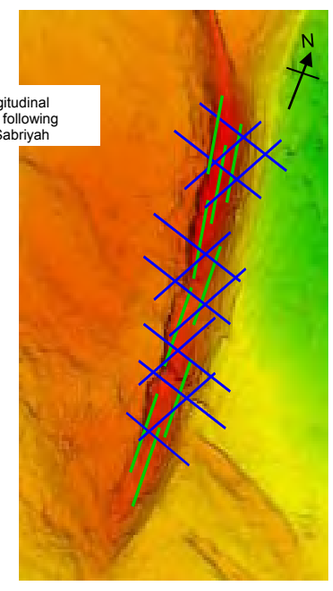
- NNE-SSW Longitudinal set of fracture clusters striking parallel to the NNE-SSW trending fold axis.
- NE-SW & NW-SE sets of fracture clusters striking oblique to the fold axis. These fracture clusters exist within and outside the Sabriyah anticline. They are more of regional type set of fractures.
- ENE-WSW & WNW-ESE sets of fracture clusters striking oblique to the fold axis. These oblique sets of fracture clusters appear to be Riedel Shears. This is why they are so much concentrated within the Sabriyah anticline.



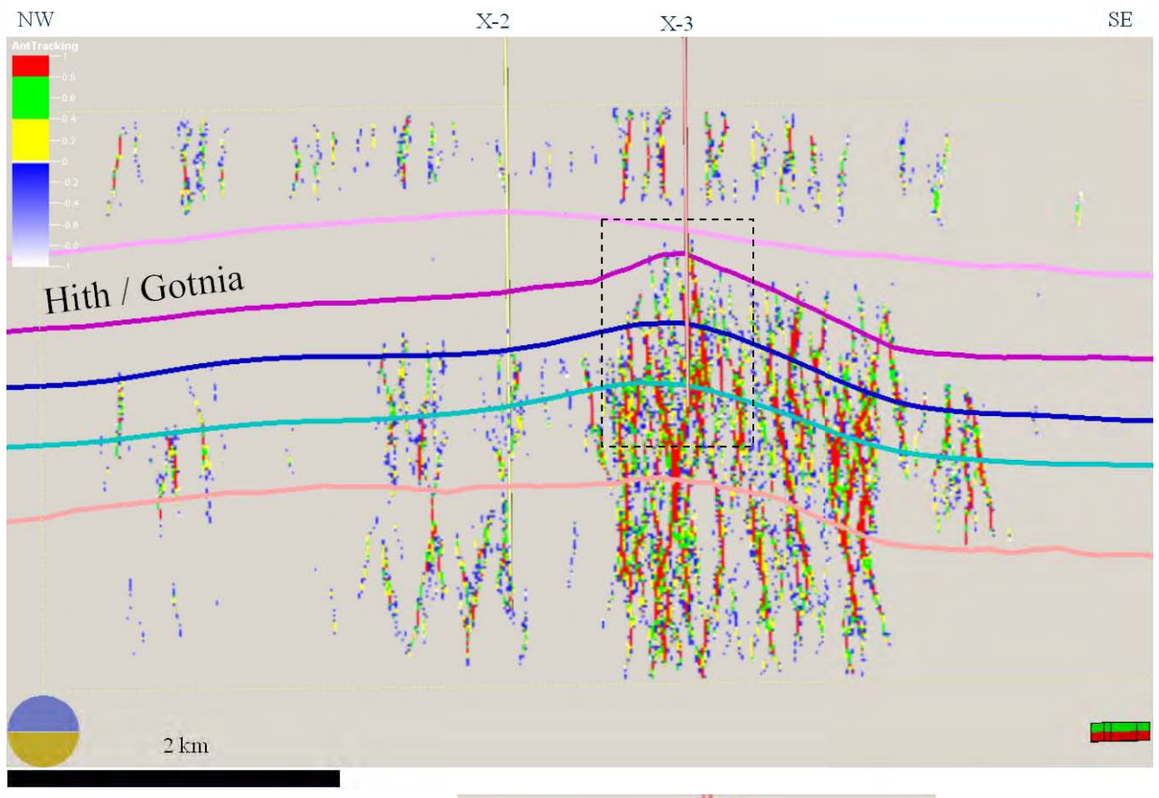
Schematic showing popped up Sabriyah anticline with different types of fracture clusters



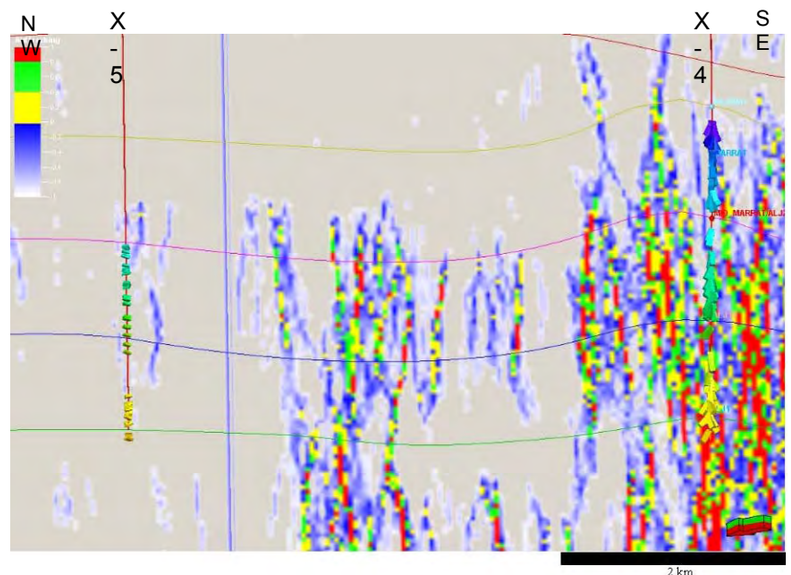
Modified from Tchalenko (1970)

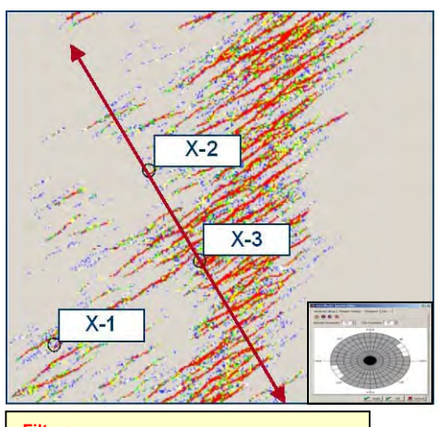


FCM Validation: Predicted Fracture Clusters' Correlation with the Borehole Fracture Data at Existing / Input Wells & New Wells



Hith/Gotnia
Najmah
Middle Marrat
Lower Marrat
Minjur





Filters:
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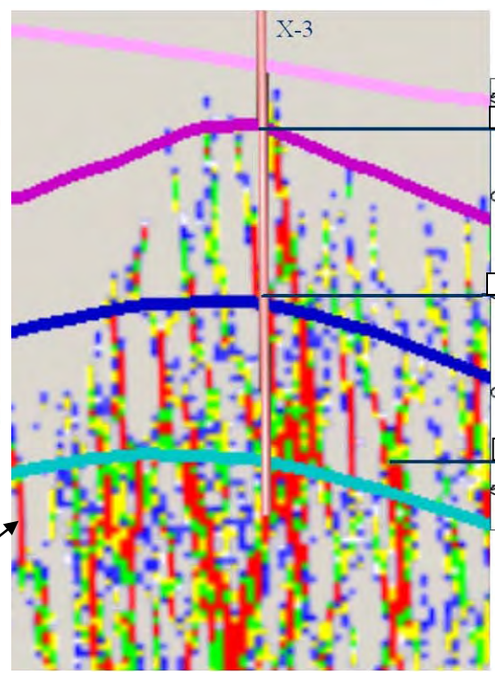
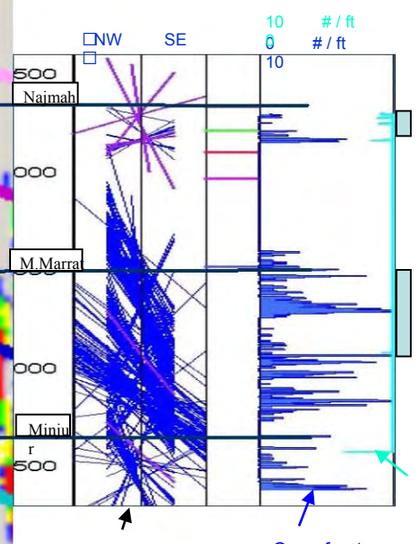
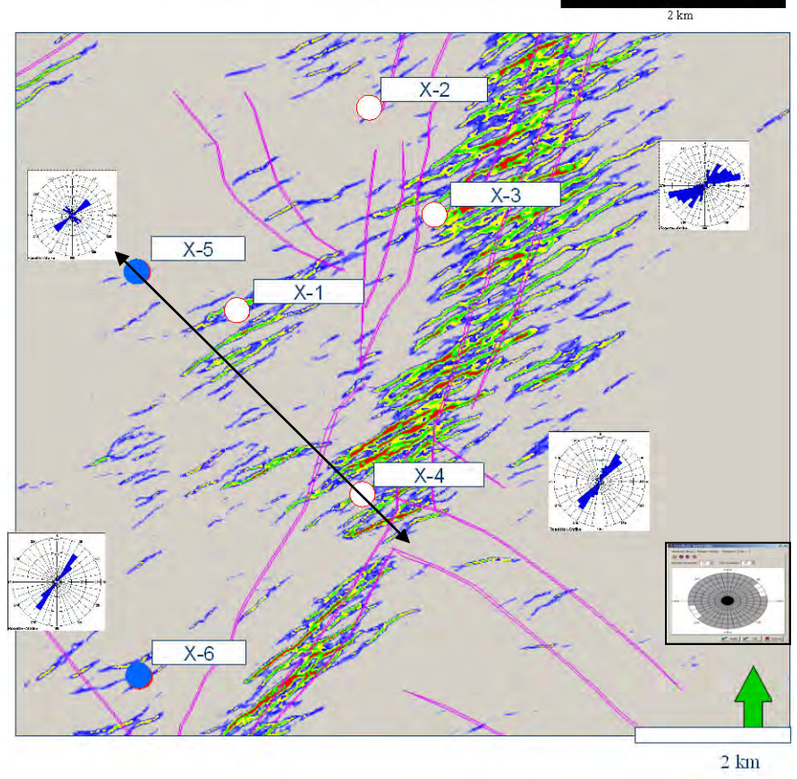
Features' Dip Angle : > 70



Larger fracture cluster





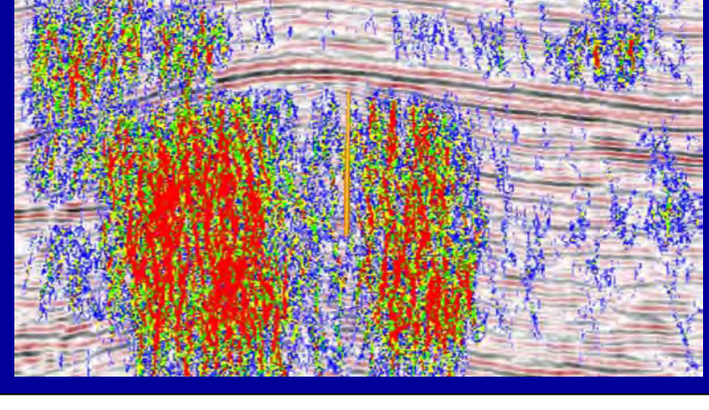
Section through wells X-2 and X-3 showing fracture clusters extracted by FCM using 050-080 & 230-260 azimuth filter to enhance ENE-WSW trending lineaments (i.e., fracture clusters). The well X-3 does not intersect any fracture cluster over the interval from top Najmah to top Middle Marrat. It interesects a major fracture cluster in the interval from Middle Marrat top Minjur. A similar observation was made in the wellbore from cores and borehole images as shown by the stick plot and fracture density curves for open and closed / filled fractures.

Section through wells X-5 and X-4 showing fracture clusters extracted by FCM using 050-080 & 230-260 azimuth filter to enhance ENE-WSW and NE-SW trending lineaments (i.e., fracture clusters). The well X-4 intersects medium to large fracture clusters at Najmah-Sargelu and also Marrat levels. Hence has a higher production of oil and gas. On the other hand, well X-5 (which was logged and completed after the completion of FCM results for the Sabriyah Field) intersects a very small cluster of fractures. Cores and borehole images indicated that large majority of the fractures are tension gashes associated with stylolites. The production of well X-5 is nearly 10 times less than the production of well X-4.

Conclusion

- **Integration of image log data and FCM technique helped in locating major to minor fracture clusters across the area**
- **The predicted fracture clusters matched reasonably well with the fracture data observed at the input wells and new wells over at least two fields**
- **Fracture clusters identification can be much improved by having higher resolution 3D Surface Seismic, for instance higher resolution 3D Seismic obtained with 'Q' (see the comparison between FCM results acquired with the higher resolution Q-Seismic & Conventional 3D seismic)**

Section of Q-Land Seismic with Fracture Clusters – NWRA Field



Section of Conventional 3D Seismic with Fracture Clusters – NWRA Field