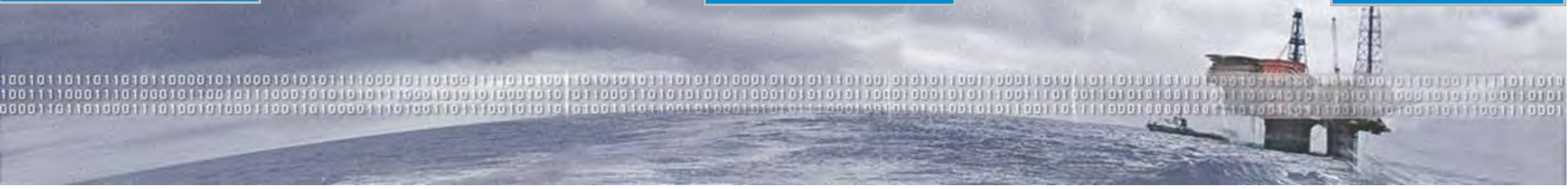
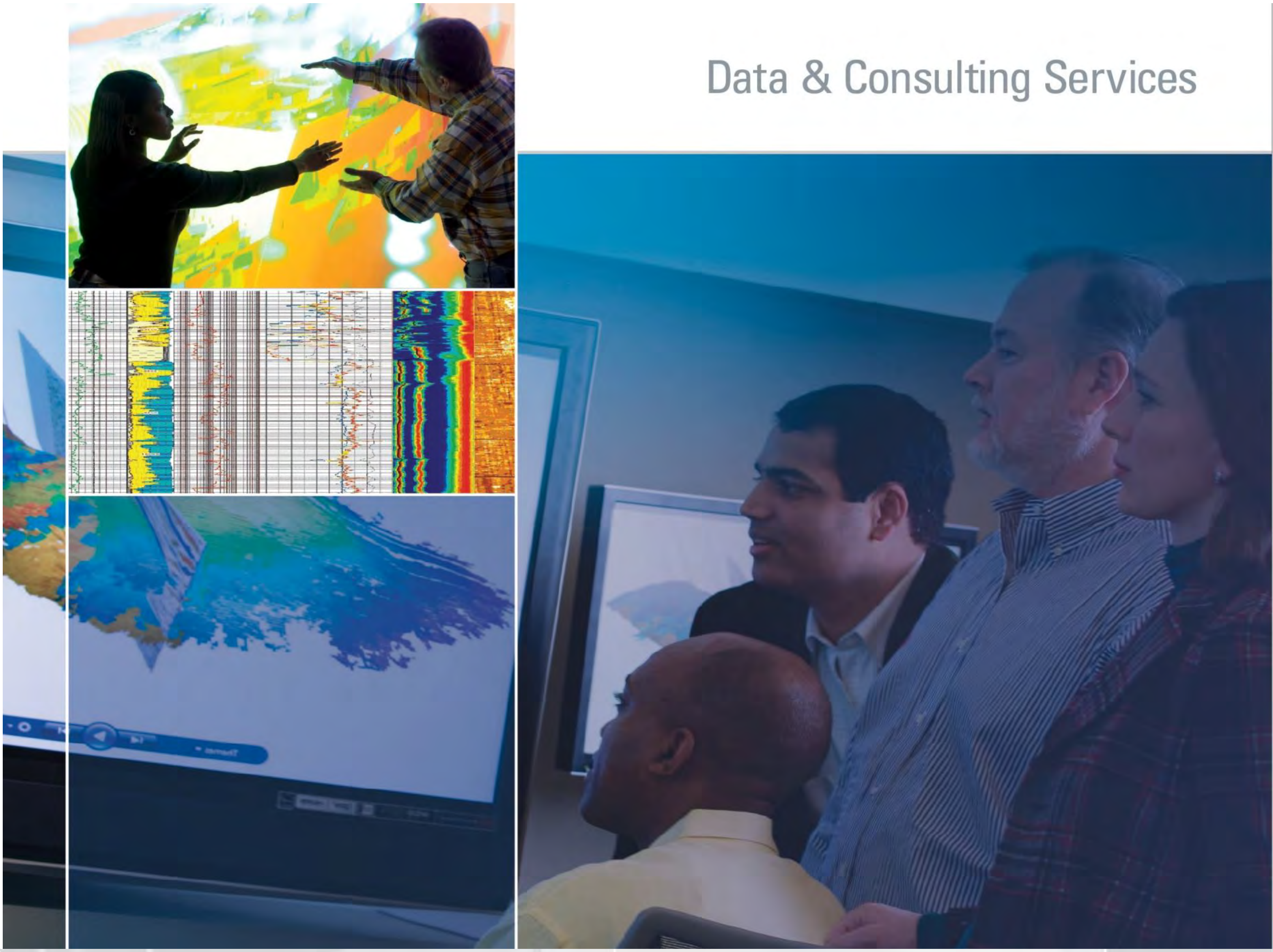
Imperial

Attachment 2

Cold Lake Expansion Project
Fracture Characterization





COLD LAKE EXPANSION PROJECT

FRACTURE CHARACTERIZATION

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Schlumberger

Executive Summary

Imperial Oil (IOL), have commissioned Schlumberger to perform a study for caprock fractures characterization on 16 wells in the development area of Cold Lake Expansion SA-SAGD (Solvent-assisted SAGD) project. The results of this analysis will be used in conjunction with other studies to determine the competency of the caprock for fluids injection in their planned SA-SAGD development project. Image data were used to identify and characterize the natural fractures in the Colorado Shale (caprock) and Grand Rapids (GR) Formations. The study has identified 42 natural fractures (12 resistive/healed) in the GR formation and 241 (38 resistive/healed) in the caprock. The Clearwater (CLW) Formation data were also analyzed and no fractures were identified.

The fracture study was performed as a two-step analysis. The first part of the report describes the features identified within each well, focusing on the feature type (i.e. open (conductive), healed (resistive), shear (minor displacement fault), drilling induced, breakout) and orientation.

The second part of the study involves a detailed analysis to determine if conductive and shear fractures have systematic trends in orientation: a. across stratigraphic boundaries; b. spatially within the same stratigraphic unit; and c. within the same well. In addition fracture densities for each stratigraphic unit for conductive and shear fractures were also determined and compared to the equivalent structure contour maps.

Study results:

- Interpretation of the fractures from the FMI logs show no correlation of strike orientation trends across the Grand Rapids/Colorado shale interface and no relationship between orientation of fractures in Grand Rapids and Colorado Shale Formation on the cumulative regional plots. The analysis has not identified any systematic trends within the same stratigraphic unit with the exceptions of the “NE/SW” - oriented healed fractures in the Grand Rapids formation and the “NW/SE” trend in the shear fracture population of Colorado Shale Formation. Several wells have similar strike trends in GR and caprock, but the number of fractures in the GR formation is too small to make any conclusive results; therefore, there is no evidence to relate any regional trends within these two units within a single well.
- Open fractures in the GR Formation are scarce and exhibit random orientation in the investigated area with no relationships between fracture orientation and structural grain; therefore it is concluded that these single fractures are related to local events.
- Spatial distribution of conductive fracture strikes in Colorado Shale Formation show three distinctive trends, “NW/SE”,“NE/SW” and “E/W”, in three separate areas. All three trends show close relationship to the structural grain indicating (un)loading events of neotectonic age as the primary mechanism of their origin.
- The average calibrated density of fractures is 0.028 fractures per meter in the GR and 0.11 fractures per meter in the caprock. 89.2% of the fractures in the Colorado Shale formation are occurring in the upper part of the formation. The majority of highly fractured wells in upper Colorado Shale Formation are located along steeper paleo-slopes as seen from the structure contour map.

- The average non calibrated number of conductive and shear fractures in the caprock unit where they were identified is 16.9 fractures per well, with the highest density of 46 conductive and shear fractures in IMP OV-GR57 COLD LK 11-35-65-3 well.

In summary, the natural fractures in the GR formation are scarce and show no evident trends to assess an obvious mechanism of fracture generation. There is also no relationship between the natural fractures in the Grand Rapids formation and the caprock.

The caprock portion of the FMI logs shows more fracturing in the upper part of Colorado Shale Formation. The highest fracture density in the caprock is related to the denser structural gradient, implying a neotectonic source of origin.

The average calibrated number of all open natural fractures per metre (0.11) in the caprock is not indicative of fracture connectivity in the caprock in the 16 FMI wells analyzed; the caprock appears intact from the standpoint of fluid transmissivity through natural fractures.

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1. Introduction

1.1 Objective

Imperial Oil (IOL), have commissioned Schlumberger to perform a study on the Cold Lake Expansion Project for natural fractures characterization of the caprock. The results of this analysis will be used in conjunction with other studies to determine the competency of the caprock for steam injection in their planned SAGD development project.

The main objective of the project was to:

1. Provide a detailed analysis of the fractures or possible brittle deformation within three stratigraphic units: a) Clastics of Clearwater formation which is below the reservoir, b) Clastics of Grand Rapids formation which contains the reservoir and c) predominantly shales of the Colorado Shale formation which is further subdivided into lower and upper Colorado Shale formation.
2. Identify fracture types as conductive (possibly open), resistive(healed) or shear (if associated with displacement or truncation)
3. Provide an interpretation on tectonic or structural relationships between the fractures in the caprock and fractures in the reservoir and underburden. Due to the fact that open fractures are major conduits for fluid flow, relationships between fractures in the three stratigraphic formations can indicate if fractures belong to a pervasive regional trend (consistent orientation, planarity, equal spacing, etc.) or they are nonsystematic fractures primarily related to syndepositional and/or neotectonic and reactivational events.

Image data from 16 wells in the Cold Lake Expansion Project area were used to identify and characterize fractures in the caprock. The presence of fractures or cracks degrades the sealing capacity of the caprock, so the identification of fractures sets is crucial in heavy oil operation to understand the caprock integrity.

The fracture study was performed as a two-step analysis. The first part of the report includes fractures and faults identification within each well. Besides distinguishing basic fracture categories (i.e. conductive, resistive fracture, shear/faulting), fractures trends and fractures densities were also described for caprock and underburden formations. The focus in this study was attributed to conductive and shear resistive types of fractures since "pure" resistive fractures are completely healed and therefore not a hazard to caprock integrity.

The second part of the study involves the detailed analysis of fractures to determine if fractures were closely spaced and have systematic trend or they exhibit random orientations and distribution. Special attention was paid to fracture style (attributes such as fracture dimension, spacing, termination). Other important elements that were observed are (a) fracture clustering (do fractures come in swarms or randomly spaced intervals); and (b) fracture inheritance (do fractures cross-cut or terminate at stratigraphic boundaries). Fracture connectivity (whether fractures are lithologically bound or crossing heterogeneous media) was also investigated. Upon obtaining these fracture attributes, the spatial distribution of fracture patterns within different stratigraphic horizons is analysed to assess the presence or absence of regional fracture sets. In addition, the analysis has addressed spatial extension of fractures in the caprock, and the influence of the structure contours of each structural horizon on fracture control of the overburden.

2. Data Acquisition and Quality

The present study comprises of image data recorded in sixteen (16) wells. All of them were acquired by Full Bore Formation MicroImager (FMI*) and image data were recorded using conventional wireline data acquisition techniques.

The physics of the FMI measurement makes it a highly versatile geological and reservoir characterization tool that produces complete and reliable answer products. The FMI* tool is a 4 arm tool, with each arm comprised of 1 pad and 1 flap, thus creating it a total of 8 pads. Each pad provide 24 electrode measurements which makes a total of 192 micro-resistivity measurements that generate the electrical image of borehole with 0.2in resolution (Figure 1). GPIT (General Purpose Inclinometer Tool) check, speed correction, depth alignment, electrode equalization and static and dynamic normalization using a histogram equalization technique were performed on FMI images as standard process before image interpretation (Figure 2).

Figure 1. FMI tool with 4 pad/4Flaps.*

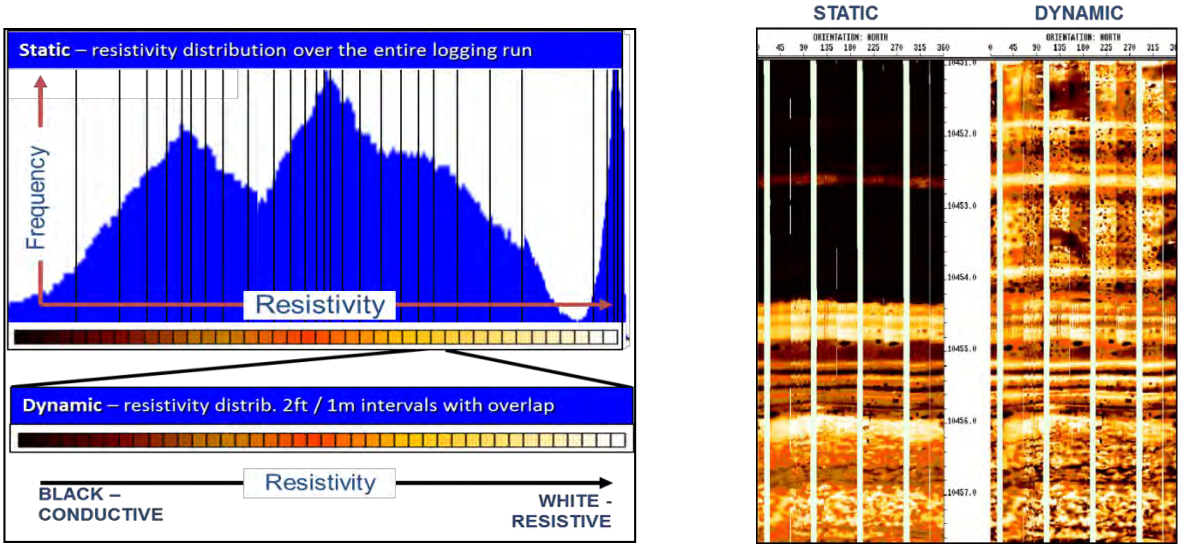


Figure 2. Micro resistivity values recorded by the FMI image tool converted into color images.

The log quality is evaluated based upon a combination of the type of acquisition defect and the proportion of the particular depth interval that is affected by that defect. FMI image data were reviewed by Schlumberger data processing center for further analysis to avoid any depth difference issues. Overall, the data quality from the 16 wells selected for this study is good and can be used for the analysis.

3. Data Sets and Methodology

The image log data from each well was analyzed interactively using Sclumberger's Techlog software (Version 2013.4), which includes the Geology modules for processing and detail interpretation of image data. Techlog geology modules utilities includes dip picking, dip classification in user defined dip sets, depth matching, stereonet displays, fractures density calculations etc. For this study the focus was on identifying and classifying fractures in the area. Structural features identified on the images were displayed and analyzed on a Schmidt net diagram by plotting the fracture strike and dip attitude on an upper hemisphere polar projection diagram. The calibrated fracture density was analyzed as a total number of fractures per meter (MD) for each stratigraphic unit in each well.

Appendix I comprises the list of the wells used for interpretation of brittle deformation (fractures and shear fractures/faults). The list was governed by the spatial distribution of wells to maintain equal spacing over the proposed development areas. Wherever possible, one well per grid section in the development area was selected.

4. Descriptive Fracture Classification on Image Logs

Fracture classifications are based on their physical appearance, geometrical distribution, and genetic development across a structure. Descriptive fracture classification is used to interpret fractures on images. A fracture is classified as conductive (open) or resistive (healed/closed) based on the response to electric current flow.

Structural features such as fractures are easily recognizable on digital images because of their steeper dip angle compared to bedding/cross bedding. A “3 pad rule” was applied for detecting fractures. That means that if a conductive or resistive trace is seen on three flap/pads continuously, a fracture would be identified.

A descriptive classification of fractures applicable to image logs is shown in Table 1. Fractures symbol and color are shown in Table 2. Image examples of all dip categories are shown in Figures 3-8.

It is important to note that all fractures from FMI images were documented and described in Chapter 6 – “Image Data Interpretation”. However, in the sections on statistical analysis (Chapters 7-10) healed fractures occurring in concretions or tight streaks and resistive fractures in a clastic lithology were excluded since they are related to solution events. Also, resistive fractures in clastics were not included in the natural fracture intensity calculation in Cold Lake Expansion Project area (Chapter 10) since they are healed and thus not a threat for a fluid flow.

	DIP CLASSIFICATION	DESCRIPTION
1	Continuous Conductive Fracture	Linear/Sinusoidal conductive feature with > 90% coverage that is visible on 6-8 flaps/pads of FMI as a dark trace. In the previous terminology this type of fracture would be called an “open fracture” (Figure 3).
2	Discontinuous Conductive Fractures	Linear/Sinusoidal conductive feature with < 90% coverage that is visible on 3-6 flaps/pads of FMI as a dark trace. In earlier terminology this type of fracture would be called a “partially open fracture” (Figure 3).
3	Resistive Fracture	Linear/Sinusoidal feature with coverage > 25% of a resistive trace; A fracture that is healed (usually calcite filled) and visible on images as white trace (Figure 4).
4	Conductive/Resistive/Partially Resistive Shear Fracture	Clear bedding truncation and/or displacement. Three categories of shear fractures are identified based on conductive, resistive (healed) or partially resistive trace (Figure 5).
5	Concretion Resistive/Conductive Fracture	Resistive (healed feature) and conductive fracture that is found in cemented or calcite concretion (Figure 6).
6	Drilling Induced Fracture	Conductive, discontinuous, subvertical to vertical thin dark traces, generally appear 180 degrees apart on the FMI/HMI images. Best indicator of stress regime in the area, usually parallel to “NE-SW” direction in Alberta (Figure 7).
7	Borehole Breakouts	Conductive, discontinuous, sub vertical to vertical features, generally appear 180 degrees apart from each other and 90 degrees apart from drilling induced fractures on the FMI images. These features are visible as dark diffuse patches that show the zones of failure of borehole wall which form symmetrically at the azimuth of the least principal horizontal stress which in case of Alberta is in “NW-SE” direction (Figure 8).

Table 1. Dip classification categories with description in Cold Lake Expansion Project.

FRACTURE TYPES, COLOR, SYMBOL
Concretion Conductive Fracture
Concretion Resistive Fracture
Cond. Continuous Fracture
Cond. Discontinuous Fractures
Drilling Induced Fracture
Partially Resistive Shear FRacture
Resistive Shear Fracture
Resistive-Fracture
Conductive Shear Fracture
Breakouts

Table 2. Fractures catgories with color and symbol used in Cold Lake Expansion Project.

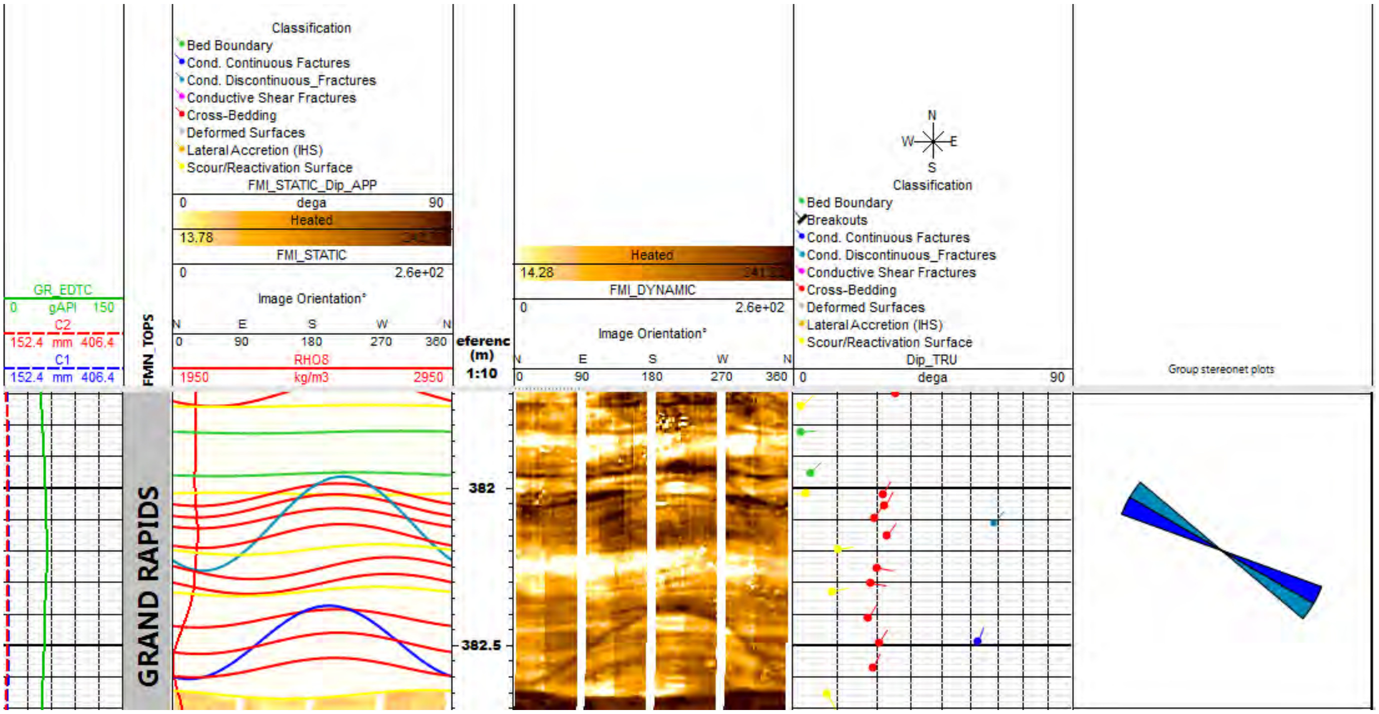


Figure 3 An image example of both types of conductive fractures. In dark blue is the "NW/SE" trending conductive continuous (open) fracture that is visible on the image as a dark band with at least 80-100% of the sinusoidal trace. Parallel to it is the "NW/SE" trending fracture displayed In light blue as an example of conductive discontinuous (partially open) fracture visible on less than 80% of the image. Both fractures are in the Grand Rapids formation of the IMP 12 OV COLD LK 12-4-66-3 well. [1]The header on the top of the figure is the legend and consists of: Track 1 - Open hole logs – gamma ray and calipers; Track 2 – Stratigraphic tops; Track 3 – Static image with sinusoids of dips classified; Track 4 - Depth in m (MD). Track 5 - Dynamic image with the resistive values from most conductive (dark brown – shales) to most resistive (light yellow and white – sands); Track 6 – Tadpole track with tadpoles of different dip category showing dip intensity – 0-90 degrees and with the small pointer showing azimuth of the dip; Track 7 – Fan plot showing strike orientation of fractures.

[1] The header used on Figure 3 is the same on all the subsequent figures showing an image examples of fractures

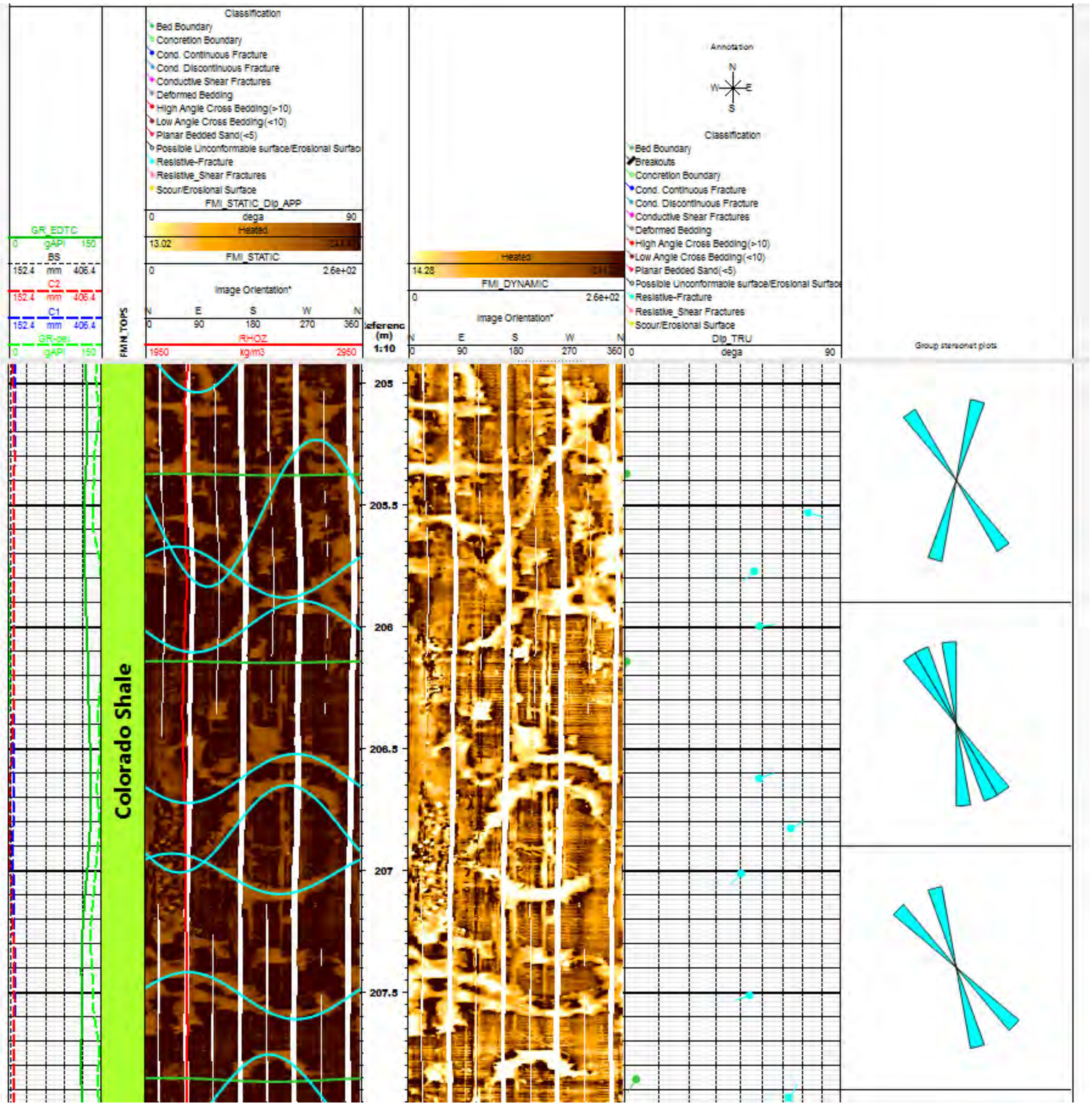


Figure 4 An image example of resistive (sealed/closed) fracture visible as light (white color) band on images in the Colorado Shale formation from IMP OV-GR7 COLD LK 12-16-66-3 well.

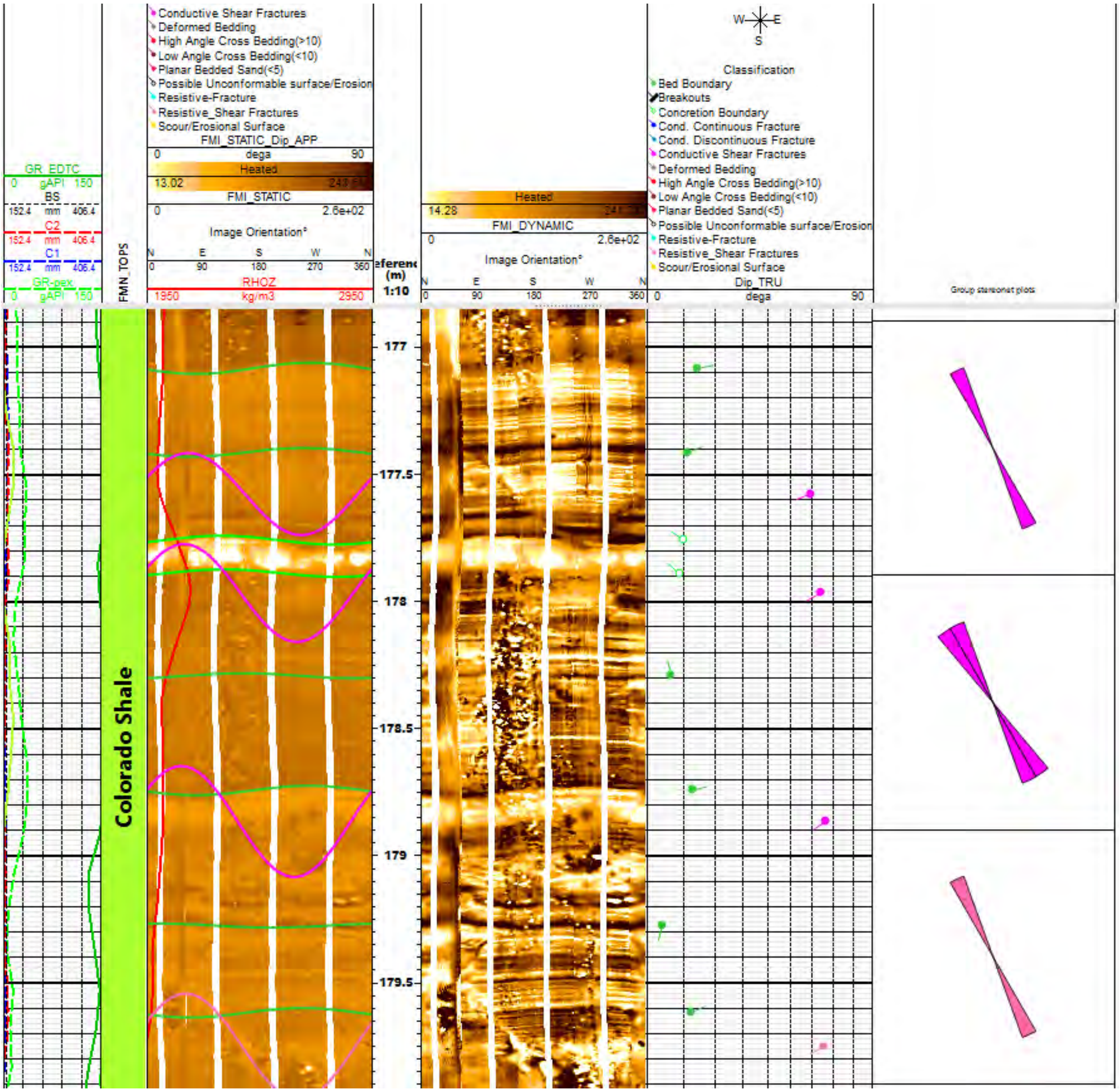


Figure 5 An image example of series of “NW/SE” striking conductive (upper 2 dips) and resistive shear (lower dip) fractures with visible bed displacements in Colorado Shale formation from IMP OV-GR7 COLD LK 12-16-66-3 well.

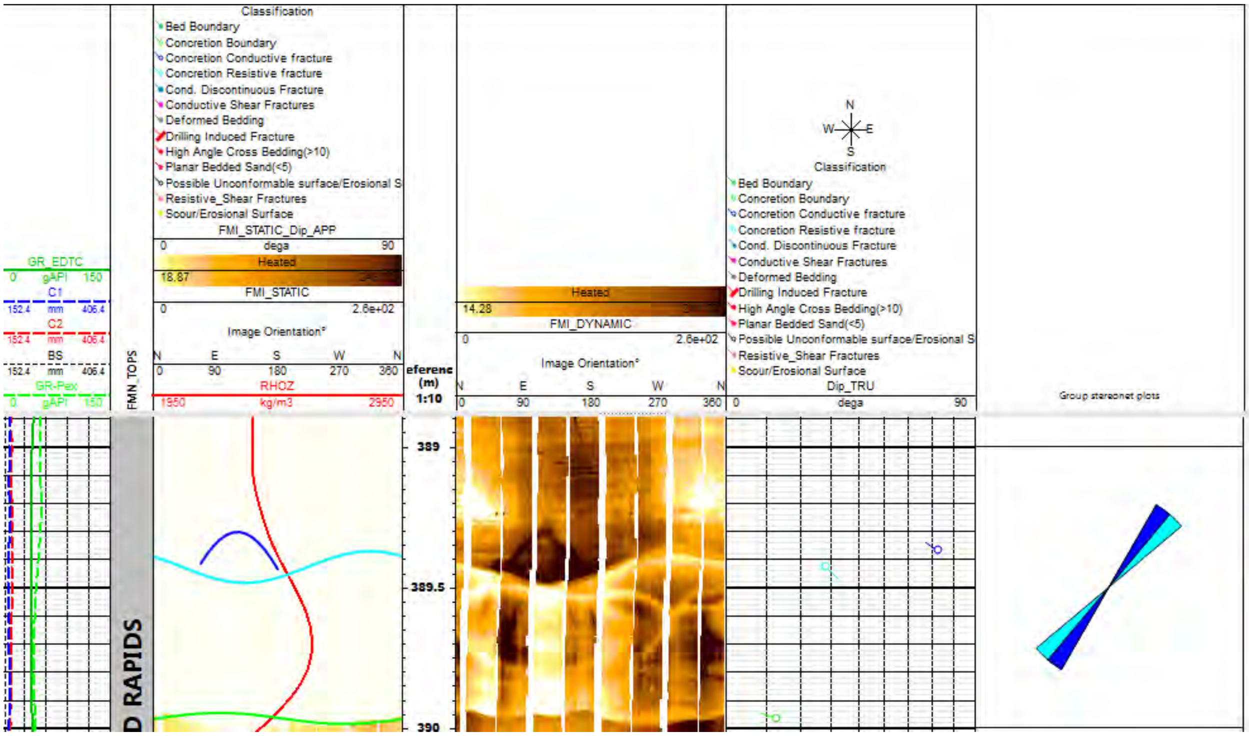


Figure 6 An image example of “NE/SW” trending concretion conductive and resistive fracture visible in high density cemented bed or calcite concretions in Grand Rapids formation from IMP OV-GR2 COLD LK 4-32-65-3 well.

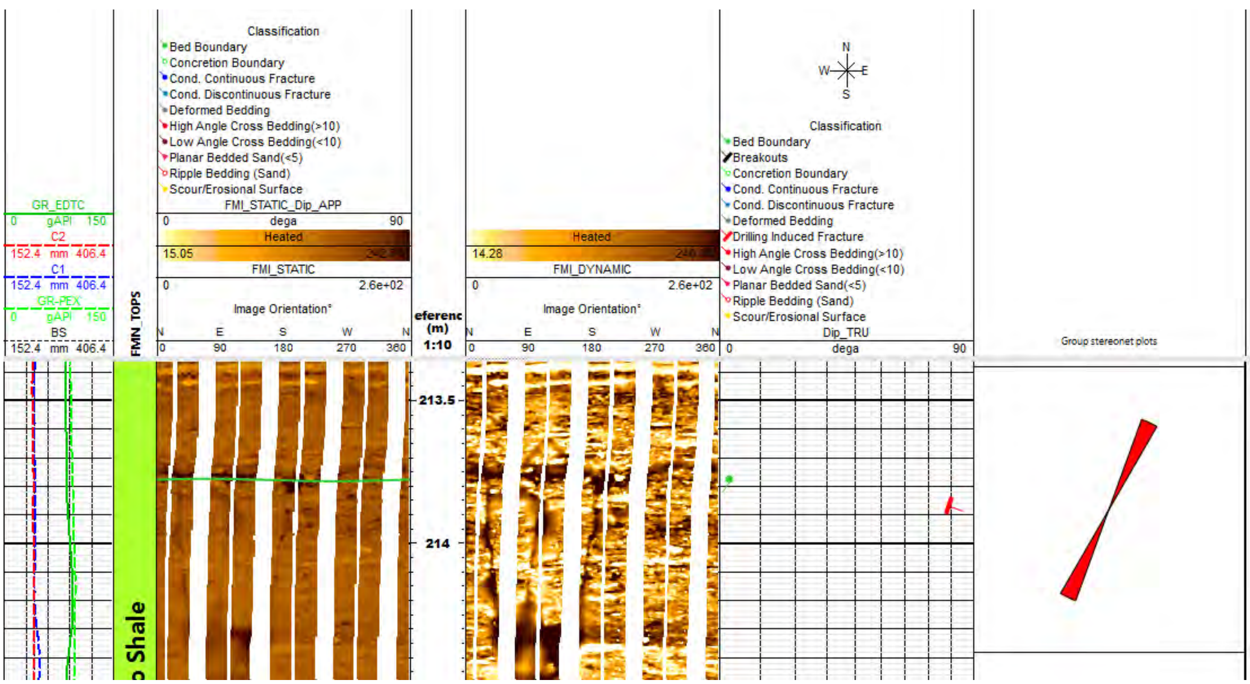


Figure 7 An image example of drilling induced fracture in the McMurray formation from well IMP OV-GR1 COLD LK 5-33-65-3. Thin dark vertical traces are 180 degrees apart. They have a characteristic image signature – displayed as “tracks” -two conductive bands with strike direction that is parallel to ”NE/SW” maximum compressive stress direction (SHmax).

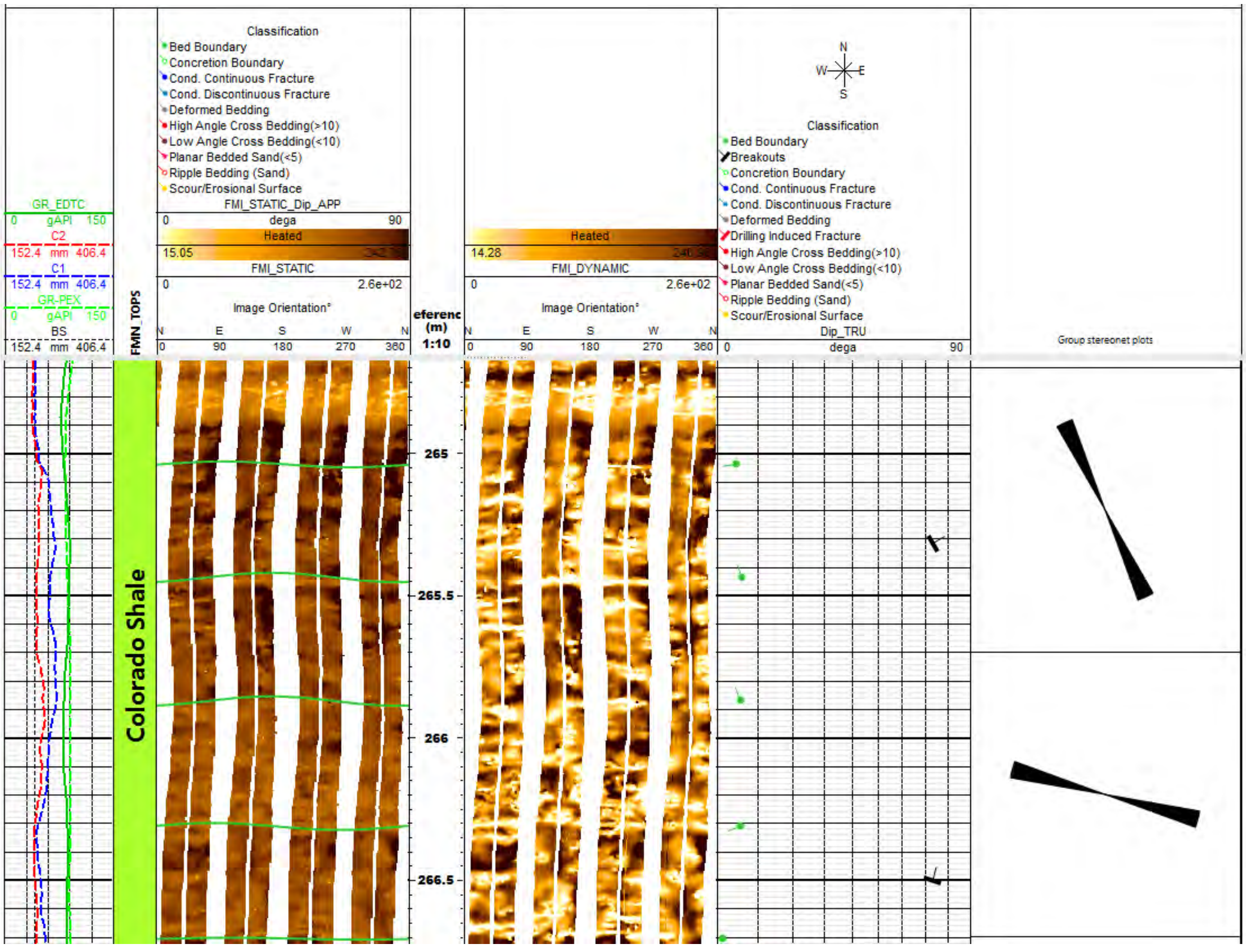


Figure 8 An image example of a borehole breakout in the Colorado Shale formation from the well IMP OV-GR1 COLD LK 5-33-65-3. Breakout features appear as dark parallel vertical patches on images. The "NW/SE" strike direction is perpendicular to the minimum compressive regional stress direction.

5. Cold Lake Field General Geology and Fracturing

5.1. General geology

The FMI logs in Cold Lake Expansion Project area covered three stratigraphic units: Clearwater, Grand Rapids and Colorado Shale formations. (Figure 9).

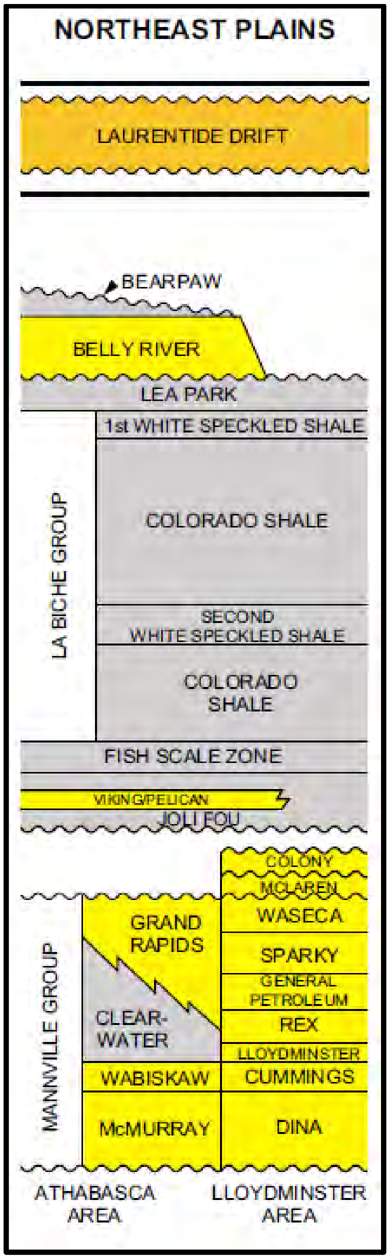
Clearwater formation is well exposed along the Athabasca River from Brule Rapids (Twp. 87, Rge. 16W4M) and along the Christina River, southeast of Fort McMurray, Alberta.
The lowermost Clearwater formation consists of soft black and greenish grey shales, with some interbedded grey and green sands, and ironstone concretions. At the base of the formation is a thin glauconitic sand called the Wabiskaw Member (in Lexicon of Canadian Stratigraphy - Badgley, 1952). To the southeast in the Cold Lake area the Clearwater formation consists of continuous, massive salt and pepper glauconitic sands and interbedded shales, with bitumen resources estimated at 6.4 x 109 cu m (40.3 x 109 bbl) (in Lexicon of Canadian Stratigraphy by Outtrim and Evans 1978).
In the lower Athabasca River area the Clearwater formation is approximately 85 m thick. In the project area the Clearwater formation has an average thickness of 45m.

The Grand Rapids formation comprises the upper part of the regressive Upper Mannville Group and consists dominantly of thick sandstones. Regional correlations to the south show that the sands were fed from a number of incised valleys cutting the Waseca, McLaren and Colony formations of the Lloydminster area (Douglas & Abrahamson 1997).

The Colorado Group, also called the Colorado Shale formation, is a stratigraphic unit of Cretaceous age in the Western Canadian Sedimentary Basin. The Colorado Shale formation consists of shale for the most part, and incorporates in addition conglomerate, sandstone and siltstone, and beds of chalk, chalky limestone, coquinas, phosphorite and concretionary beds including calcite, siderite and pyrite.

The Colorado Shale formation occurs in the sub-surface throughout southern and central Alberta, western and central Saskatchewan. It is found in outcrops along the south-western edge of the Canadian Shield, as well as in the front ranges of the Rocky Mountains of Colorado. The sediments of the Colorado group exceed 1,000 metres in thickness in central Alberta. In central Saskatchewan, it thins to 150 metres (Glass 1990). The Colorado Shale formation is divided into lower and upper unit separated by the Second White speckled shale.

The generalized and local stratigraphic columns of Cold Lake Expansion Project area are shown on Figure 9.



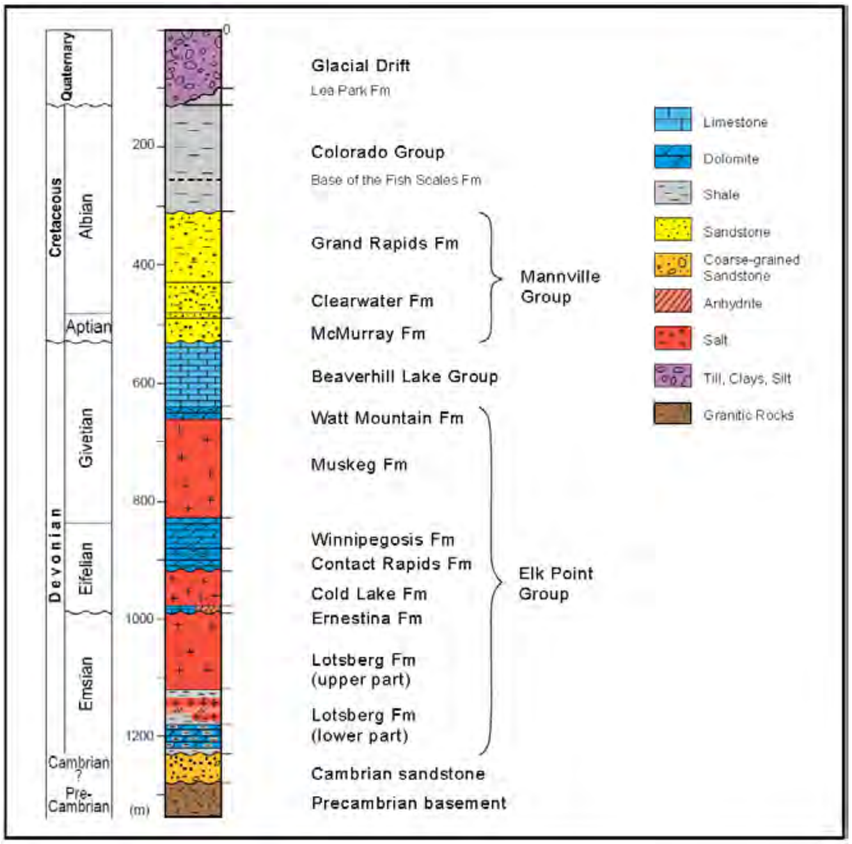


Figure 9 Generalized and local stratigraphic columns of the main stratigraphic units in Cold Lake Expansion Project area.(Energy and Utility Board Table of Formation 2002 and local stratigraphic section).

5.2. Fracture types and previous studies

Fracturing occurs due to external forces which have been active throughout geologic time. The general consensus among the structural community is that there are four types of regionally extensive joints (i.e. Dunne & Hancock. 1994, Cosgrove 1997):

1. Tectonic joints/fractures, formed at depth due to a combination of high pore fluid pressures and tectonic stresses (i.e. horizontal compression or tension due to plate boundary forces).

2. Hydraulic joints/fractures, related to high fluid pressures during sedimentary compaction.

3. Unloading joints/fractures, formed close to the surface during uplift, controlled by tectonic or residual stresses.

4. Release joints/fractures, formed after uplift and controlled by pre-existing structures.

Previous studies of fractures in Alberta based on field measurements of joints, aerial photo and satellite lineament analysis indicate the presence of several common fracture orientations in the region. However, the majority of fracture studies are done along the foothills front and satellite and aerial photo lineaments in the western sedimentary basin. These studies reveal the presence of two major fracture sets “NE-SW” and “NW-SE”. (Babcock 1973; Bell & Babcock 1986; Bell & Bachu 2003; Bell & Gough 1979: Mollard 1988. Rumsey 1971 and Scheidegger 1983)

Exfoliation fractures are special cases of unloading joints formed at, and parallel to, the current land surface in rocks of high compressive strength. These would be seen as low angle subhorizontal fractures parallel to bedding and as such horizontal. These fractures are hard to distinguish from bedding planes on FMI images because of their parallelism.

In addition, comparison of randomly oriented fractures identified with glacial paleotopographic maps would also show the difference between regional stresses and locally originated fractures due to glacial processes.

6. Image Data Interpretation

Image data interpretation of 16 wells from Cold Lake Expansion Project provides the insight about the number of fractures found in each of the stratigraphic formations (Clearwater, Grand Rapids and Colorado Shale). The image data interpretation also provides information on the type and orientation of the fractures. In some wells, FMI tool was not logged to the top of the Colorado Shale formation because of operational issues. The table below is showing the list of wells with FMI logged intervals.

	Well	Top (m)	TD (m)
1	IMP OV-GR2 COLD LK 4-32-65-3	144	425
2	IMP OV-GR1 COLD LK 5-33-65-3	207	452
3	IMP 12 OV COLD LK 12-33-65-3	40	440
4	IMP OV-GR57 COLD LK 11-35-65-3	30	444
5	IMP OV-CW4 COLD LK 7-2-66-3	180	498
6	IMP 12 OV COLD LK 3-4-66-3	34	443
7	IMP 12 OV COLD LK 12-4-66-3	35	446
8	IMP OV-GR7 COLD LK 12-16-66-3	30	431
9	IMP 13 OV COLD LK 6-17-66-3	30	447
10	IMP OV-GR10 COLD LK 4-21-66-3	30	438
11	IMP OV-GR39 COLD LK 13-1-66-4	190	400
12	IMP OV-GR45 COLD LK 7-2-66-4	171	483
13	IMP OV-GR36 COLD LK 14-14-66-4	191	448
14	IMP OV-GR40 COLD LK 14-23-66-4	179	445
15	IMP OV-GR28 COLD LK 13-12-66-4	61	443
16	IMP 12 OV COLD LK 14-2-66-3	40	503

Table 3. List of wells with FMI logged interval.

The FMI image interpretation from 16 wells studied in the Cold Lake Expansion Project are shown below.

6.1 Well name: IMP OV-GR2 COLD LK 4-32-65-3

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation, one (1) concretion conductive, one (1) concretion resistive, two (2) conductive shear and three (3) resistive shear fractures are observed. Conductive and resistive concretion fractures are found in calcite concretions with strike in "NE-SW" direction and dip magnitude of 72° and 30° respectively. Shear fractures are observed between 310m and 314m (MD) in upper part of the Grand Rapids formation. Conductive shear fractures show "N-S" and "E-W" strike directions with 58° and 65° dip magnitude while resistive shear fractures are trending in "E-W" and "ENE-WSW" direction with 30° -35° dip magnitude (Figure 10 and Figure 11).

The Colorado Shale formation displays 19 fractures including two (2) discontinuous conductive, 14 conductive shear and three (3) resistive shear fractures. Discontinuous conductive fractures are striking in "NW-SE" and "E-W" directions with dip magnitude of 46° and 51°. Shear fractures show random strike direction in "NW-SE", "NE-SW" and "WNW-ESE" and their dips vary from 24°-62° (Figure 12). Most of the shear fractures are present in upper part of the Colorado Shale formation (Figure 13).

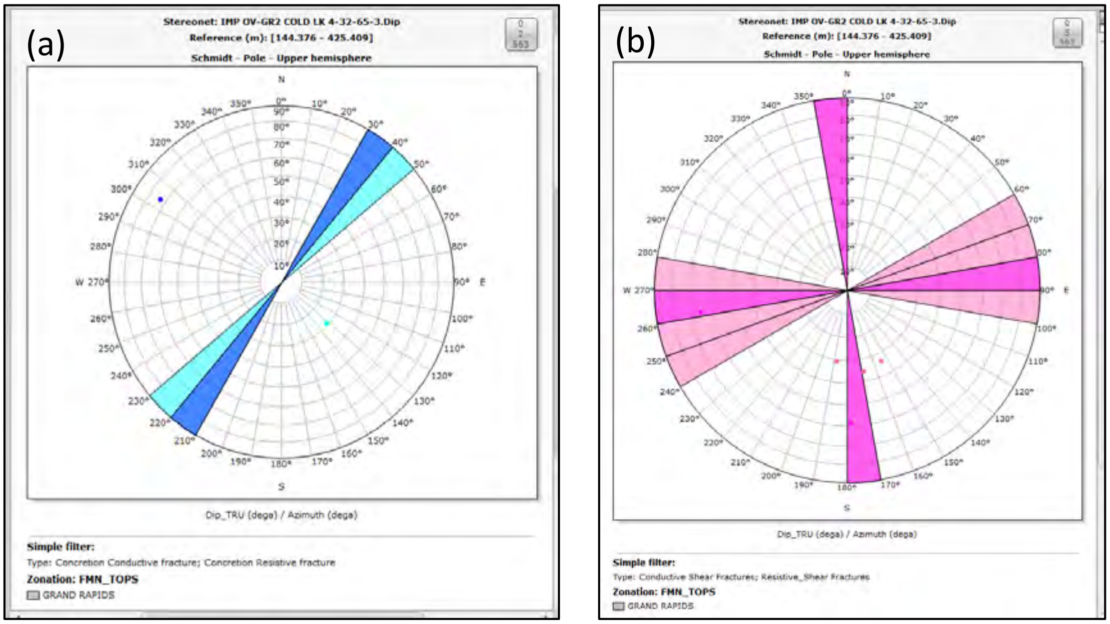


Figure 10 Schmidt diagram of concretion conductive (blue color) and concretion resistive fractures (cyan color) (a) and conductive shear (magenta color) and resistive shear (pink color) fractures (b) in the Grand Rapids formation for the well 4-32-65-3.

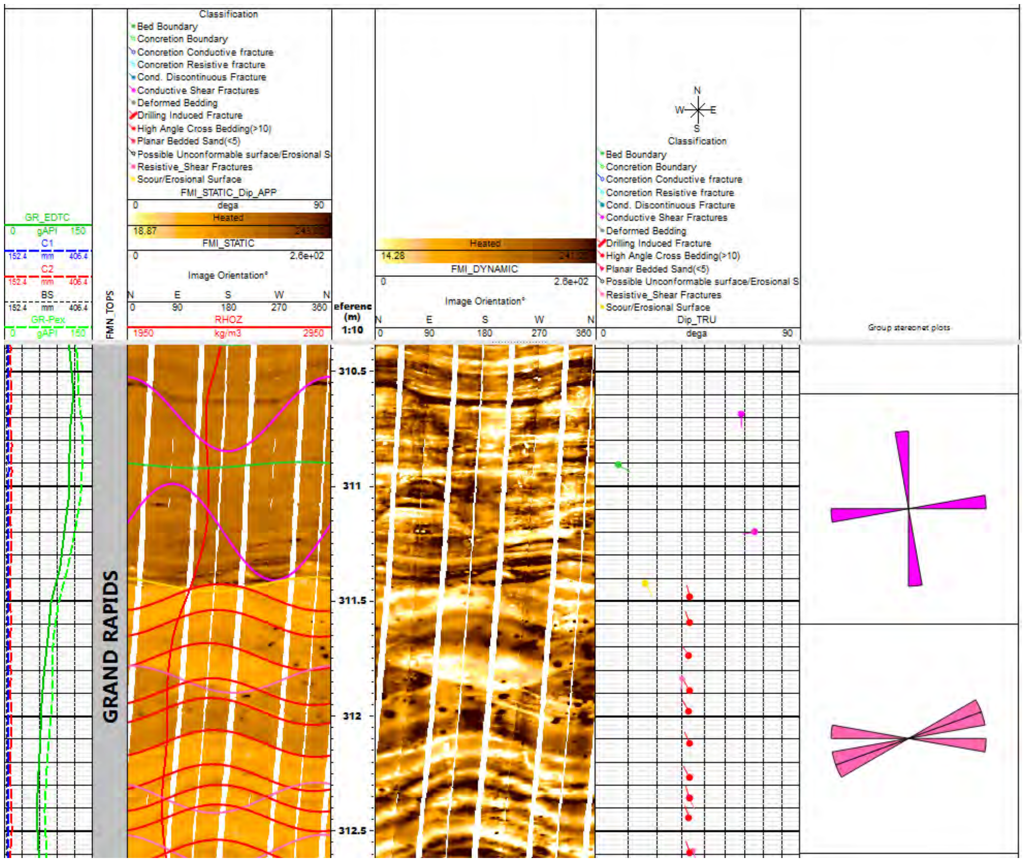


Figure 11 FMI image example of conductive shear (magenta color tadpole) and resistive shear fracture (pink color) in the Grand Rapids formation for the well 4-32-65-3.

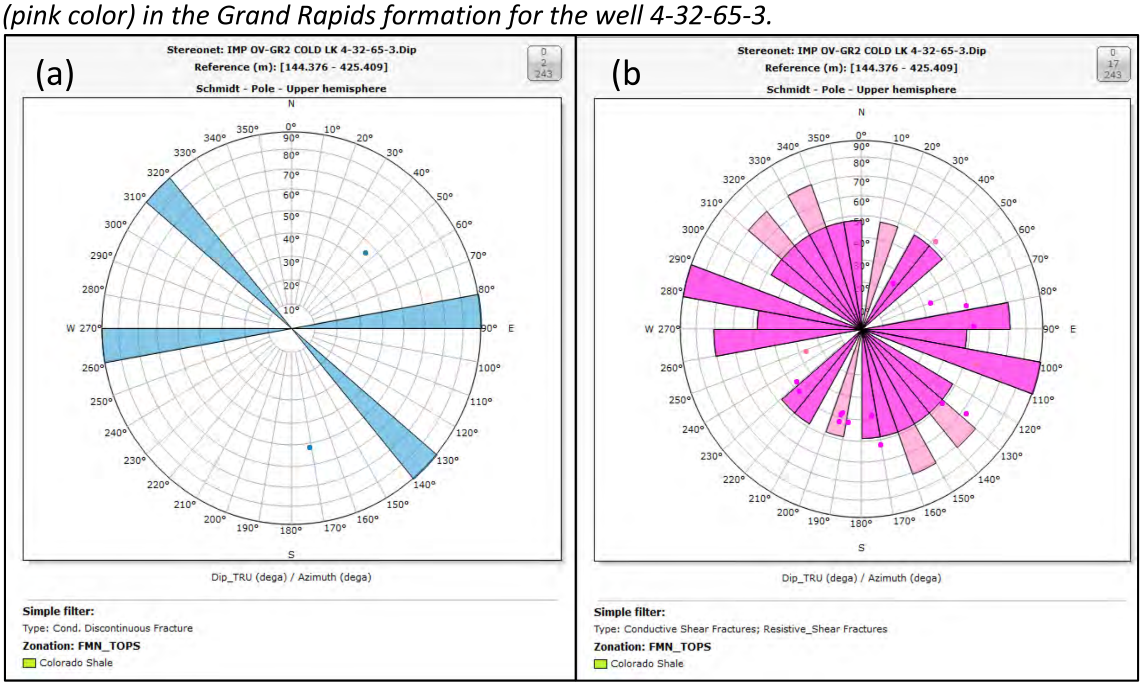


Figure 12 Schmidt diagram of discontinuous conductive (blue color) (a) and conductive shear (magenta color) and resistive shear (pink color) fractures (b) in the Colorado Shale formation for the well 4-32-65-3.

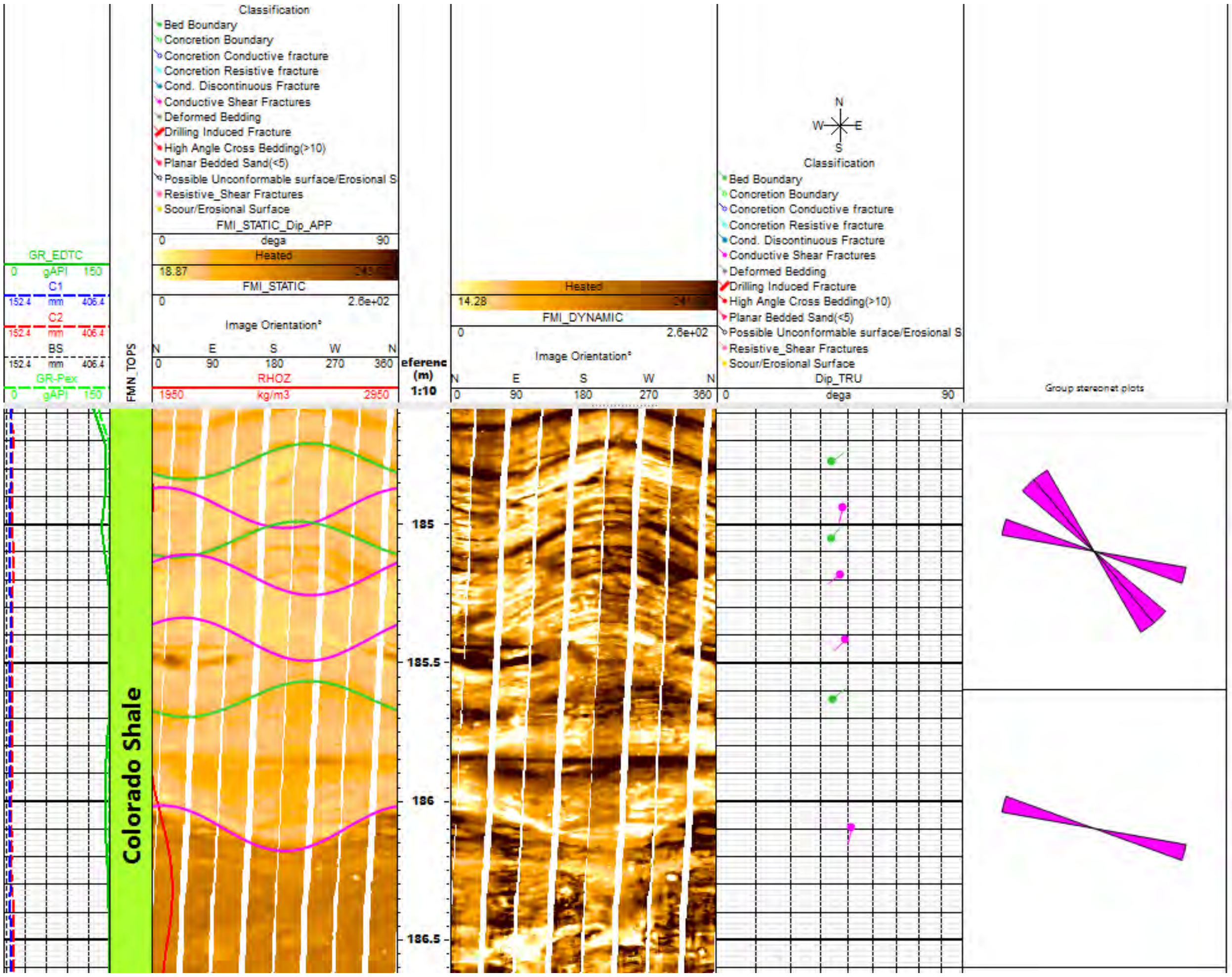


Figure 13 FMI image example of conductive shear (magenta color tadpoles) fractures in the Colorado Shale formation for the well 4-32-65-3.

6.2 Well name: IMP OV-GR1 COLD LK 5-33-65-3

Fractures are not observed in the Clearwater and Grand Rapids formation.

In Colorado Shale formation, two (2) discontinuous conductive and one (1) continuous conductive fracture are observed with strike in “NE-SW” and “E-W” directions and dip magnitude ranging from 59^{o} and 80^{o} (Figure 14). One (1) “NE-SW” striking drilling induced fracture and 18 breakout features with “NW-SE” strike are also observed in the formation. Both drilling induced and breakouts are high angle features with dip magnitude from 70^{o} -80^{o} (Figure 15).

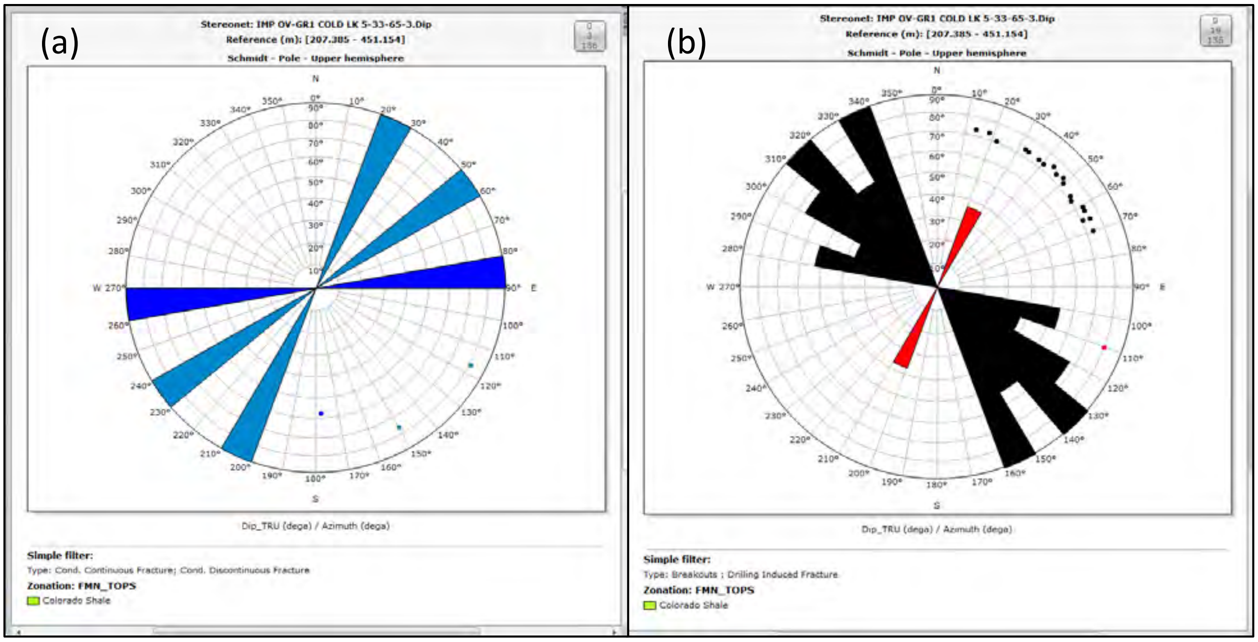


Figure 14 Schmidt diagram of discontinuous conductive (light blue color) and continuous conductive (dark blue color) fractures (a) and drilling induced (red color) and breakouts (black color) features (b) in the Colorado Shale formation for the well 5-33-65-3.

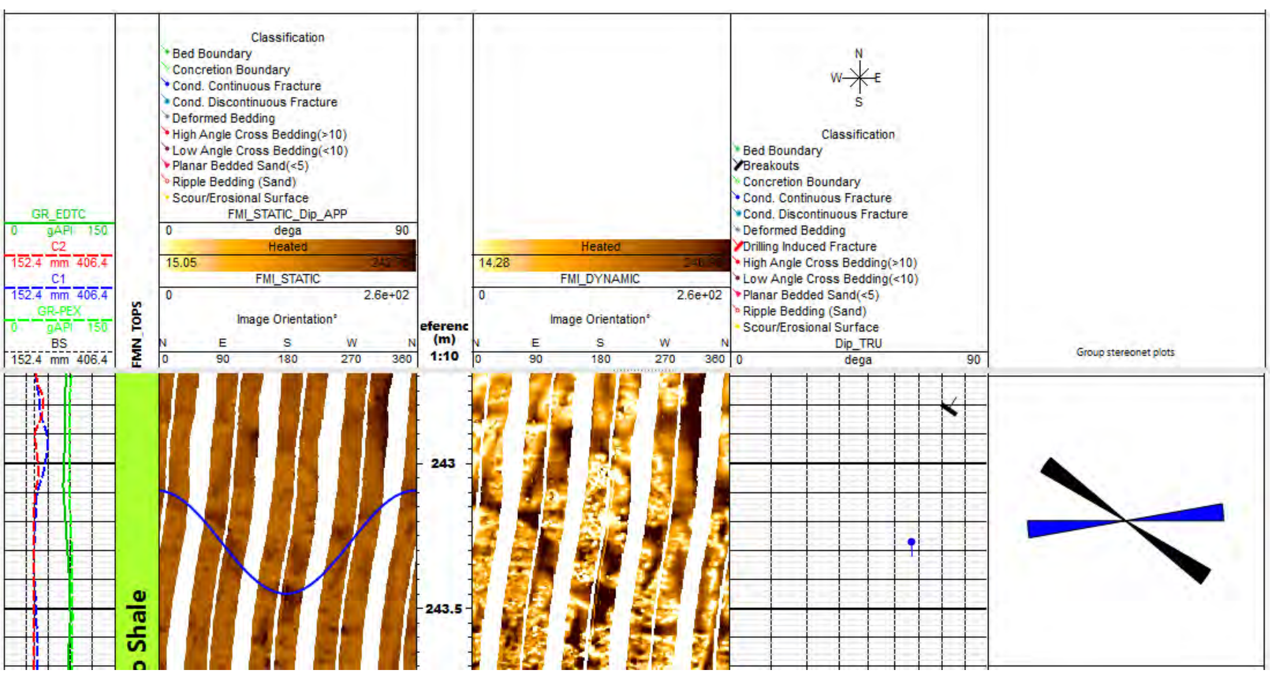


Figure 15 FMI image example of continuous conductive fracture (blue tadpole) and borehole breakout (black tadpole) in the Colorado Shale formation for the well 5-33-65-3.

6.3. Well name: IMP 12 OV COLD LK 12-33-65-3

Fractures are not observed on FMI images in any of three stratigraphic units (Clearwater, Grand Rapids and Colorado Shale formation).

6.4. Well name: IMP OV-GR57 COLD LK 11-35-65-**3**

Fractures are not observed in the Grand Rapids formation.

One (1) "NE-SW" striking resistive fracture is observed in the Grand Rapids formation at 412.5m (MD) with dip magnitude of 46° (Figure 16, Figure 17).

A total of 64 fractures are interpreted from FMI images in the Colorado Shale formation including 15 discontinuous conductive, 29 conductive shear, two (2) resistive shear and 16 resistive fractures. Conductive discontinuous and shear fractures (both resistive and conductive) show a random or dispersed strike direction with dip magnitude ranging from 21° to 80° (Figure 18). Most of these fractures appear to be concentrated at depth between 153m -166m (MD) and 172m-183m (MD) in upper part of the Colorado Shale formation (Figure 19). Resistive fractures show dominant strike in "WNW-ESE" direction with dip magnitude ranging from 46° to 80° (Figure 20). Resistive fractures are present at depth from 208m-226m (MD) (Figure 21). One (1) "NW-SE" trending breakout and one (1) "NE-SW" striking drilling induced fracture are also observed in the Colorado Shale formation.

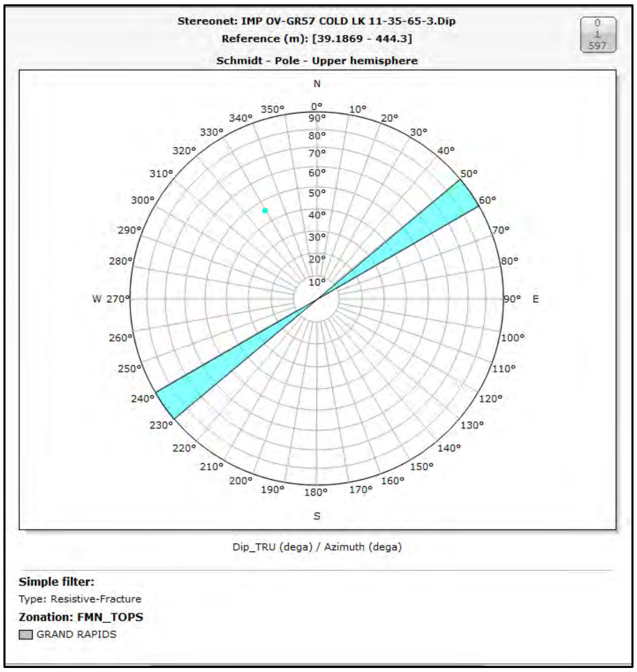


Figure 16 Schmidt diagram of a resistive fracture in the Grand Rapids formation for the well 11-35-65-3.

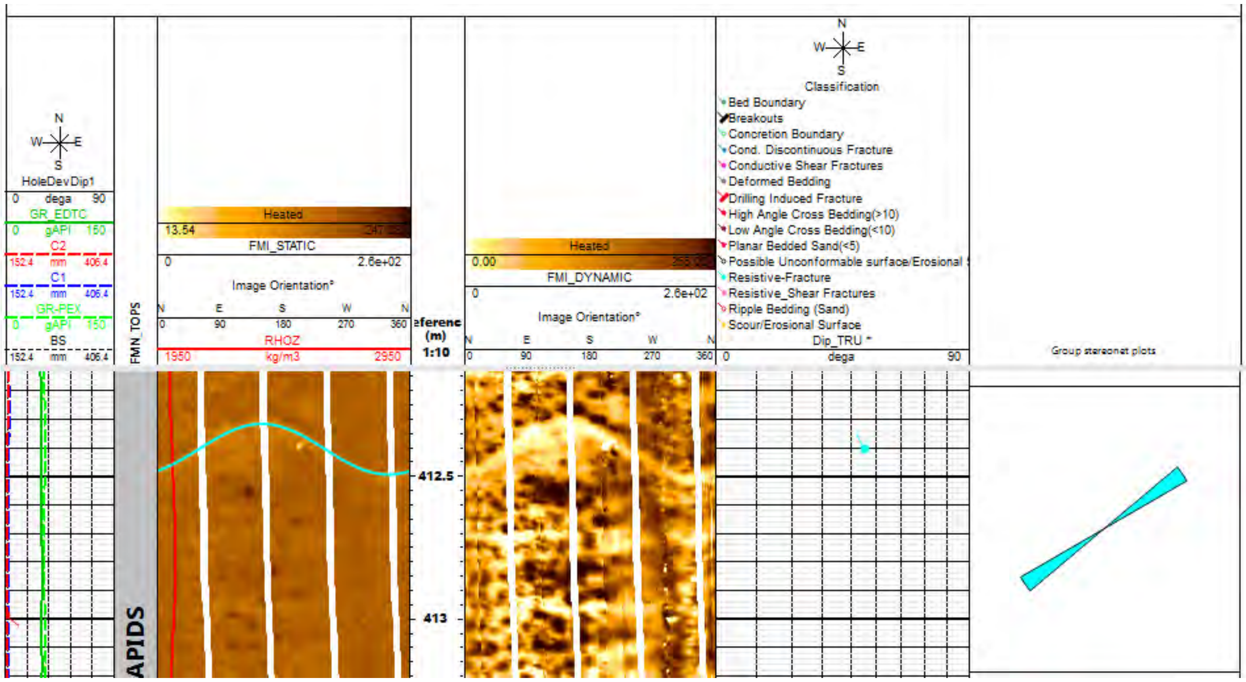


Figure 17 FMI images showing a resistive fracture (cyan color tadpole) in the Grand Rapids formation for the well 11-35-65-3. Fan plot is showing the fracture strike.

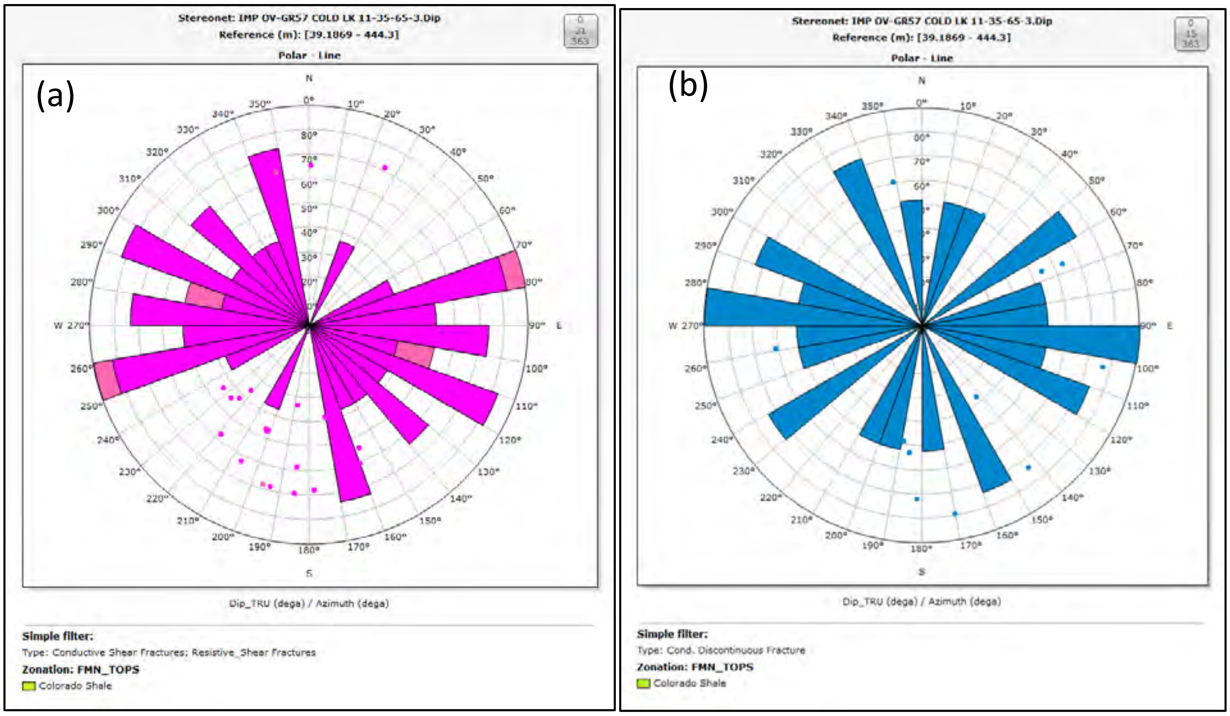


Figure 18 Schmidt diagram of discontinuous conductive in blue color (a), conductive shear and resistive shear (magenta and pink color) fractures (b) in the Colorado Shale formation for the well 11-35-65-3.

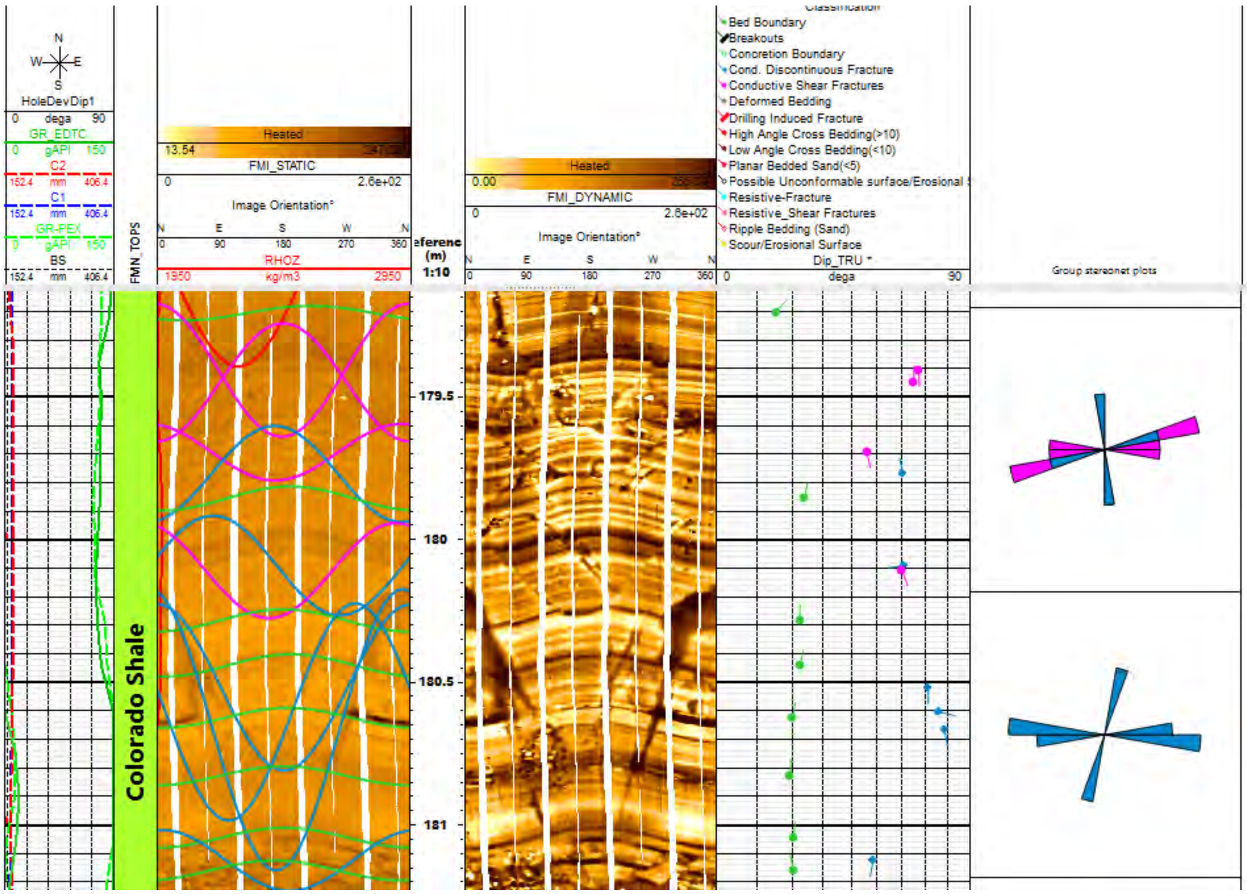


Figure 19 FMI images showing discontinuous conductive (blue color tadpoles) and conductive shear fractures (magenta color tadpoles) fractures in the Colorado Shale formation for the well 11-35-65-3. Fan plots are showing the fracture strike.

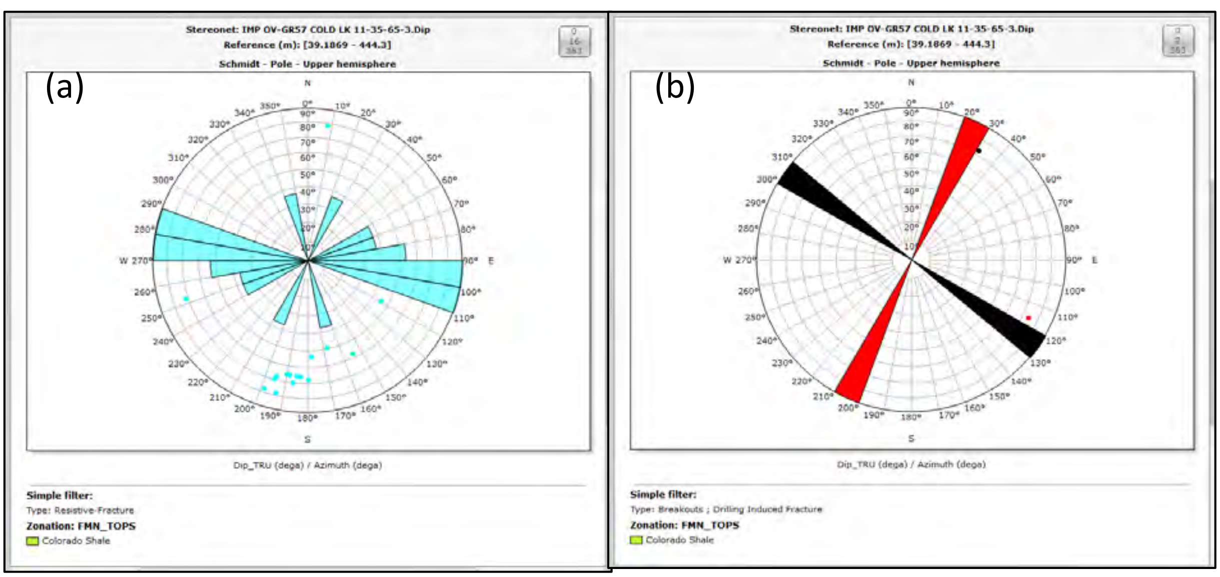


Figure 20 Schmidt diagram of resistive fractures (a), breakouts (black color) and drilling induced fracture (red color) (b) in the Colorado Shale formation for the well 11-35-65-3.

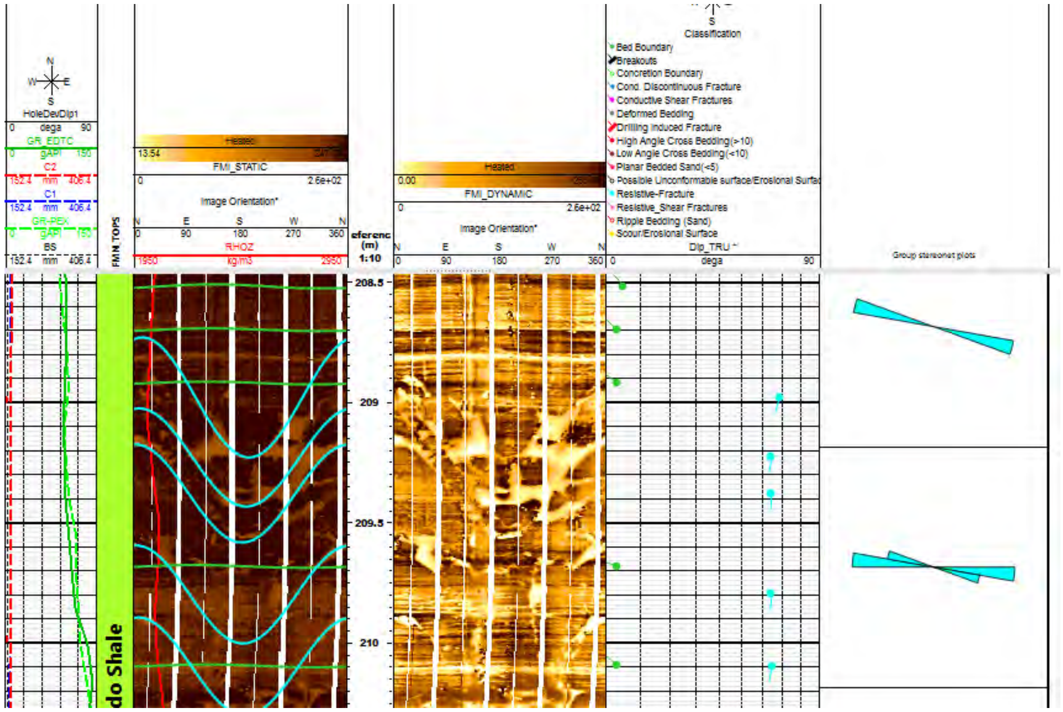


Figure 21 FMI images showing resistive fractures (cyan color tadpoles) in the Colorado Shale formation for the well 11-35-65-3. Fan plots are showing the fracture strike.

6.5 Well name: IMP OV-CW4 COLD LK 7-2-66-3

Fractures are not observed in the Clearwater and Grand Rapids formations.

In Colorado Shale formation, two (2) resistive fractures are observed at 213.4m (MD) and at 215.9m (MD) with strike in “NS” and “NE-SW” directions (Figure 22). Their dip magnitude is 43^{o} and 80^{o} respectively.   Image example of resistive fractures is shown in Figure 23.

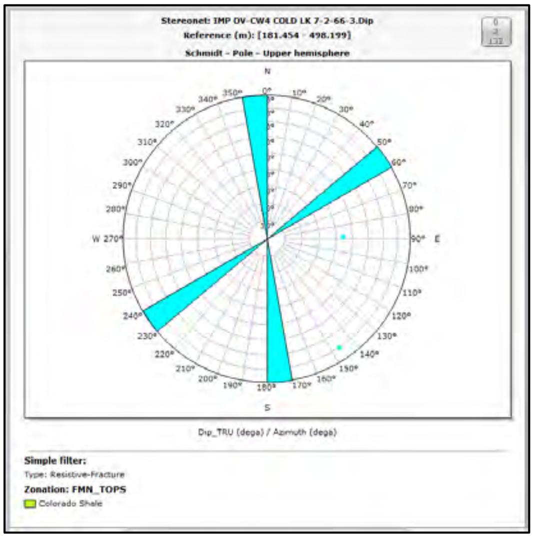


Figure 22 Schmidt diagram of resistive fractures in the Colorado Shale formation for the well 7-2-66-3.

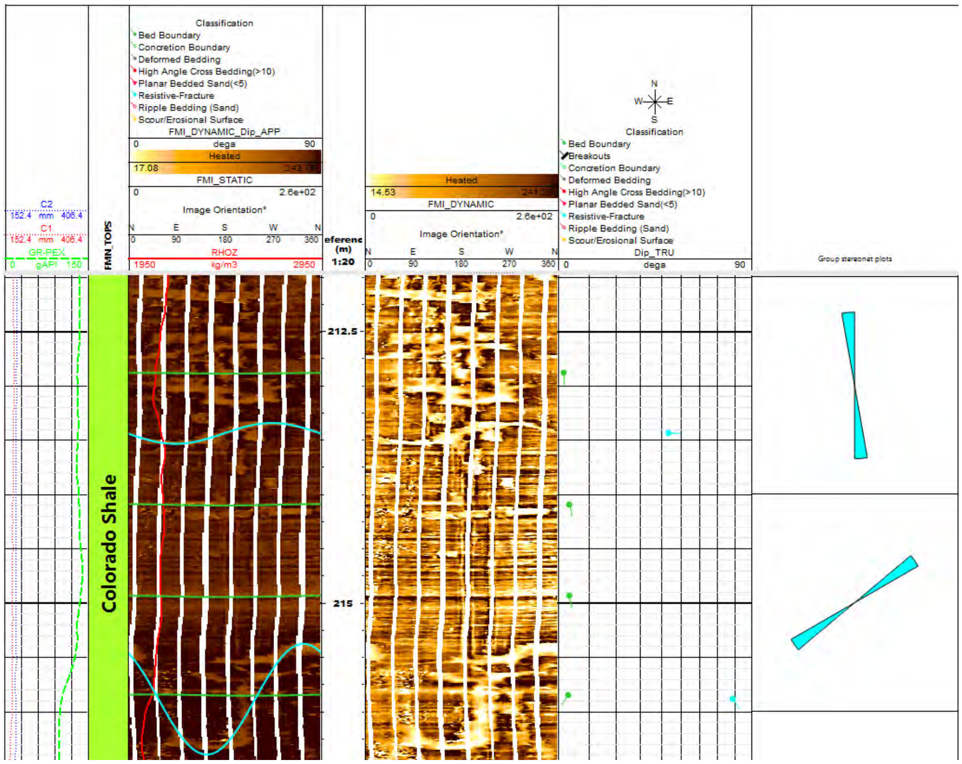


Figure 23 FMI images showing resistive fractures (cyan color tadpoles) in the Colorado Shale formation for the well 7-2-66-3.Fan plots are showing the fracture strike.

6.6. Well name: IMP 12 OV COLD LK 3-4-66-3

Fractures are not observed in the Clearwater and Colorado Shale formations.

In the Grand Rapid formation two (2) concretion resistive fractures are observed in a calcite concretion at 391.5 m (MD) with strike in "NW-SE" direction and dip magnitude of ~45° (Figure 24 and Figure 25).

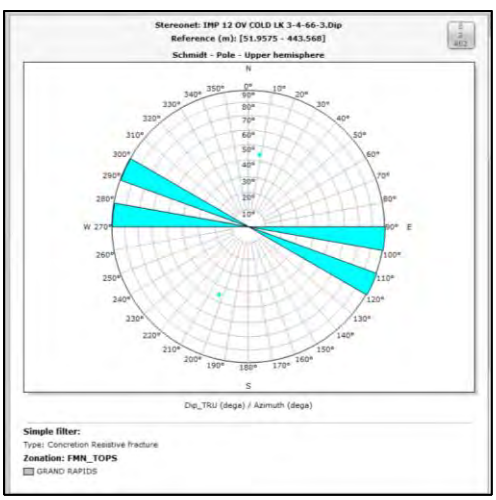


Figure 24 Schmidt diagram of concretion resistive fractures in the Grand Rapids formation for the well 3-4-66-3.

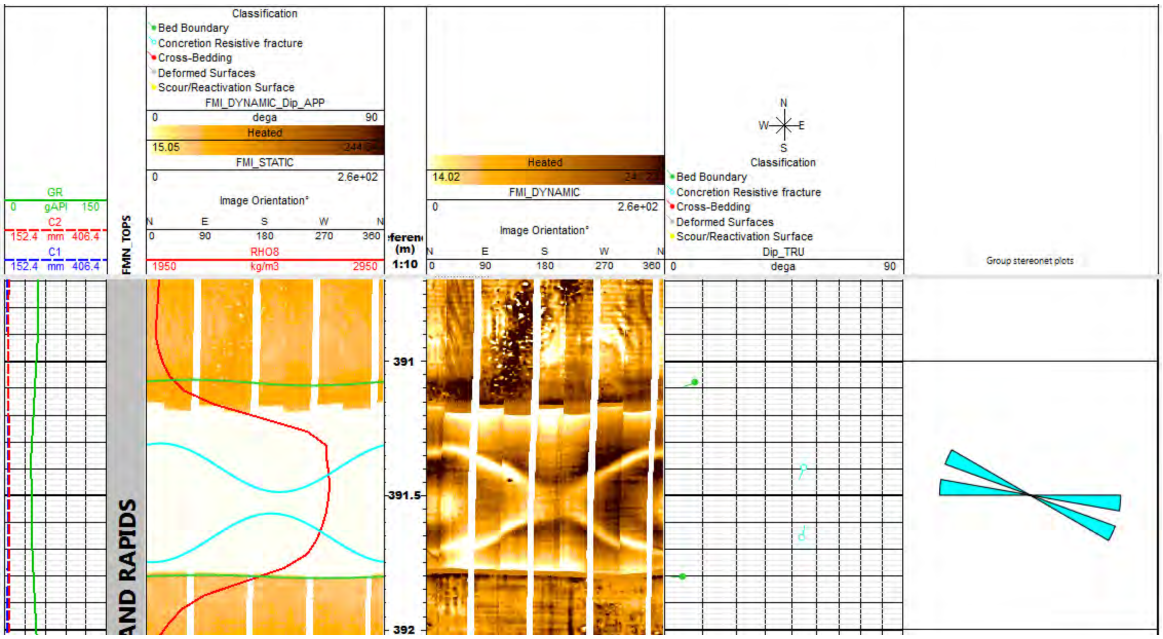


Figure 25 FMI images showing concretion resistive fractures (cyan color tadpoles) in the Grand Rapids formation for the well 3-4-66-3.Fan plots are showing the fracture strike.

6.7. Well name: IMP 12 OV COLD LK 12-4-66-3

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation, three (3) discontinuous conductive and one (1) continuous conductive fractures are observed. Fractures show primary strike in “NW-SE” direction with dip magnitude ranging from 42° -60° (Figure 26). Image example of conductive fractures is shown Figure 27. In the Colorado Shale formation, one (1) “N-S” striking conductive shear fracture is observed with dip magnitude of 70° at 248.3m (MD) (Figure 28). Image example of shear fracture is shown on Figure 29.

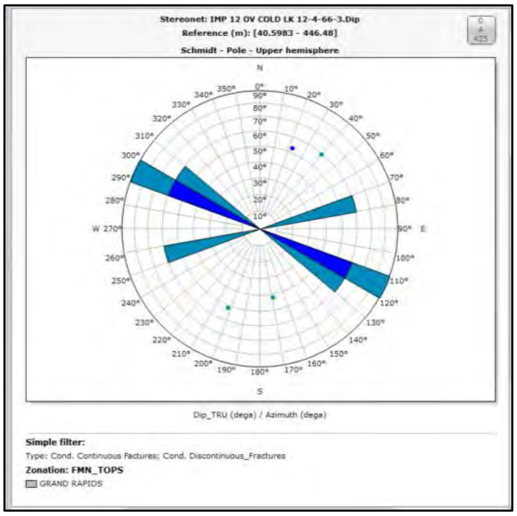


Figure 26 Schmidt diagram of continuous conductive fractures (dark blue color) and discontinuous conductive fractures (light blue color) in the Grand Rapids formation for the well 12-4-66-3.

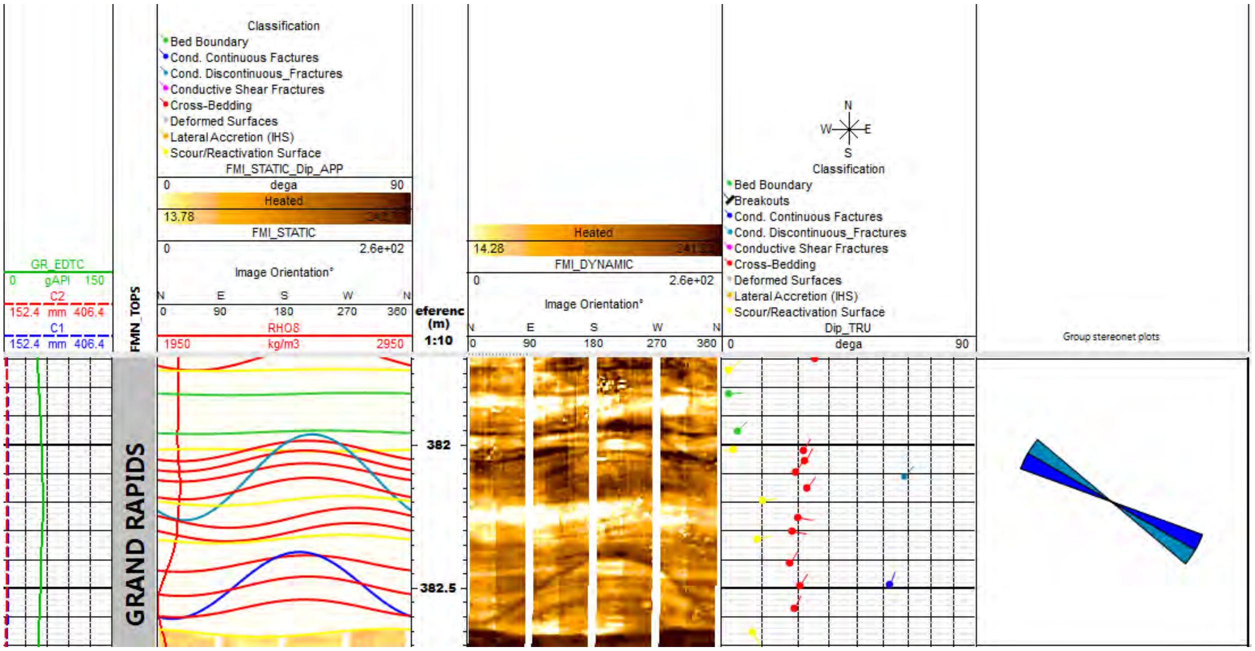


Figure 27 FMI images showing continuous conductive fracture (dark blue color tadpole) and discontinuous conductive (light blue color tadpole) fracture in the Grand Rapids formation for the well 12-4-66-3. Fan plot is showing the fracture strike.

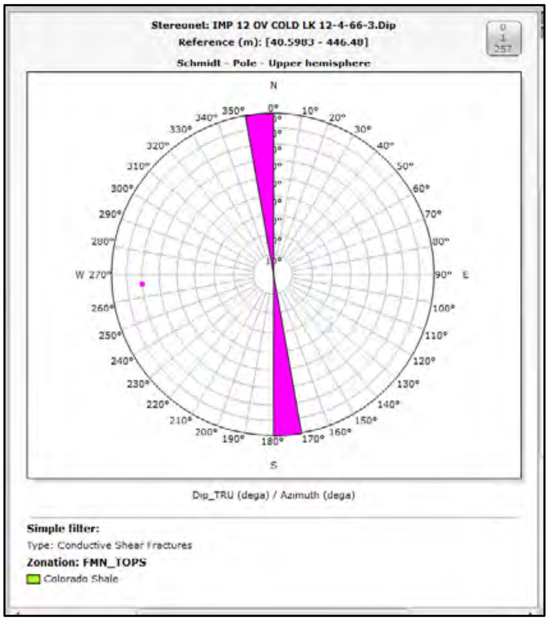


Figure 28 Schmidt diagram of conductive shear fracture (magenta color) in the Colorado Shale formation for the well 12-4-66-3.

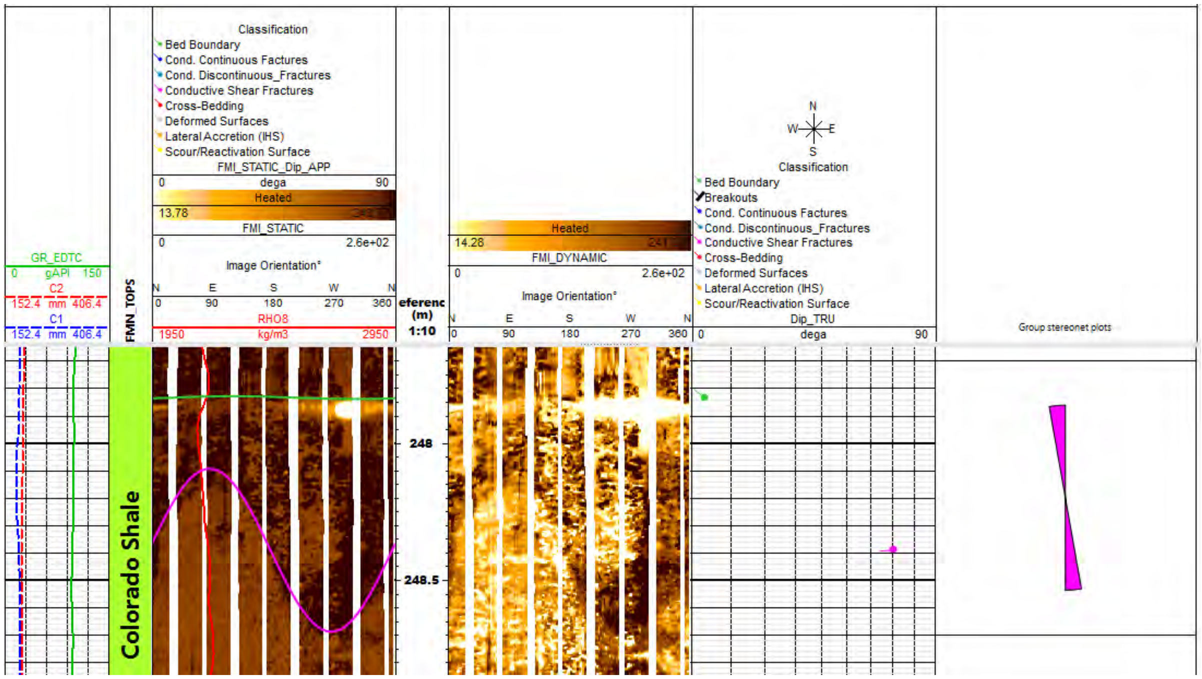


Figure 29 FMI images showing conductive shear fracture (magenta color tadpole) in the Colorado Shale formation for the well 12-4-66-3. Fan plot is showing the fracture strike.

6.8. Well name: IMP OV-GR7 COLD LK 12-16-66-3

Fractures are not observed in the Clearwater formation.

One (1) continuous conductive fracture is identified at 386.6m (MD). The conductive fracture is striking in "NW-SE" direction with dip magnitude of ~51^{o} (Figure 30). Image example of continuous conductive fracture is shown on Figure 31.

In the Colorado Shale formation, 46 fractures are interpreted including two (2) discontinuous conductive, 27 conductive shear, two (2) resistive shear and 15 resistive fractures. All fracture types are primarily striking in "NW-SE" direction with dip magnitude ranging from 22^{o} -80^{o} (Figure 32). Discontinuous conductive and shear fractures are present at depth between 150m-161m (MD) and 177m-183m (MD). Resistive fractures are mainly concentrated at depth between 202m-209m (MD). Image example of shear fractures is shown in Figure 33.

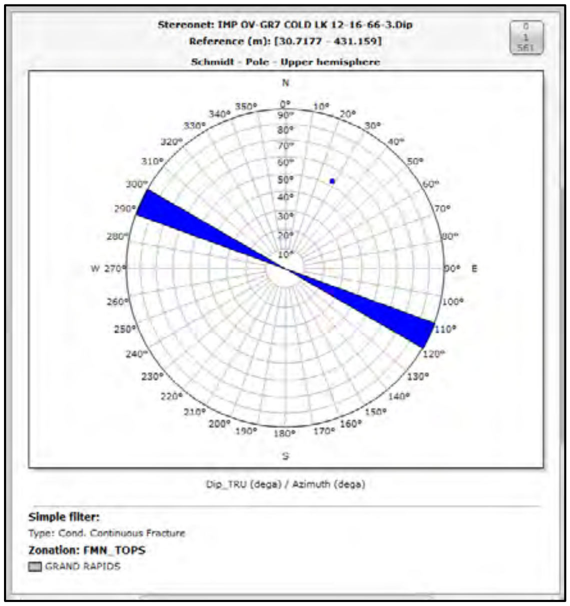


Figure 30 Schmidt diagram of continuous conductive fracture (blue color) in the Grand Rapids formation for the well 12-16-66-3.

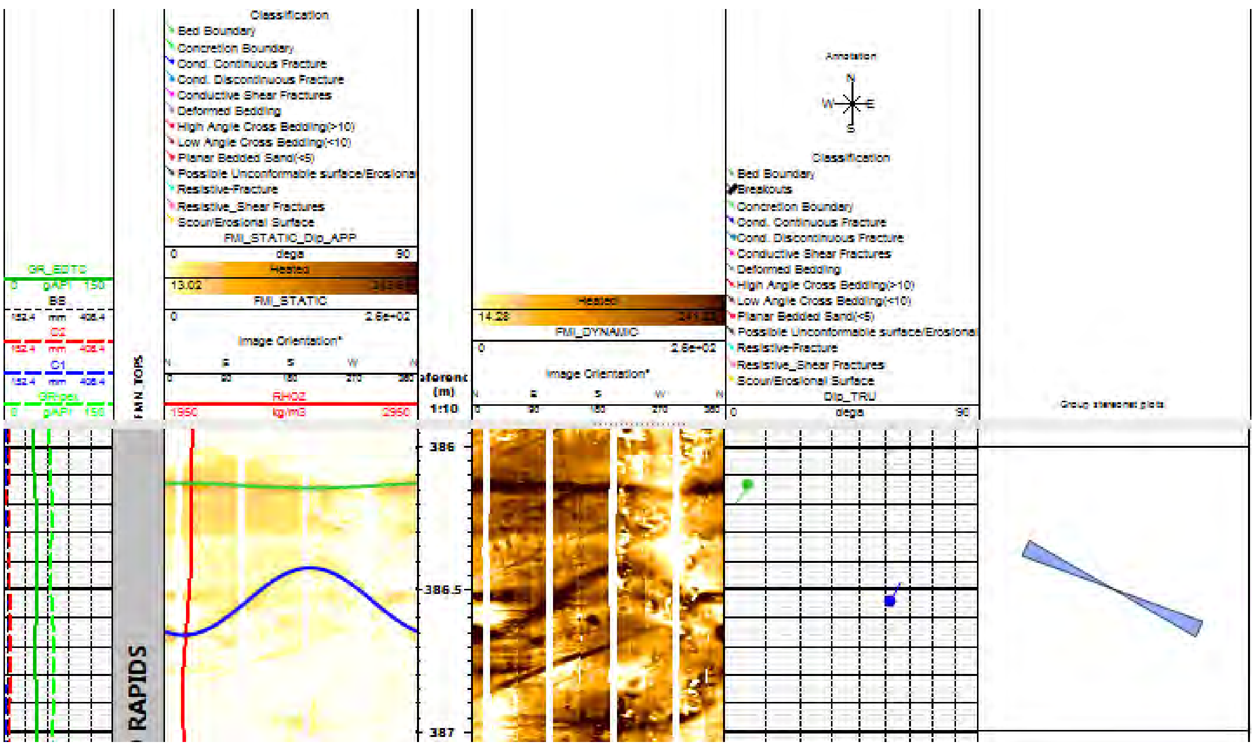


Figure 31 FMI images showing continuous conductive fracture (blue color tadpole) in the Grand Rapids formation for the well 12-16-66-3. Fan plot is showing the fracture strike.

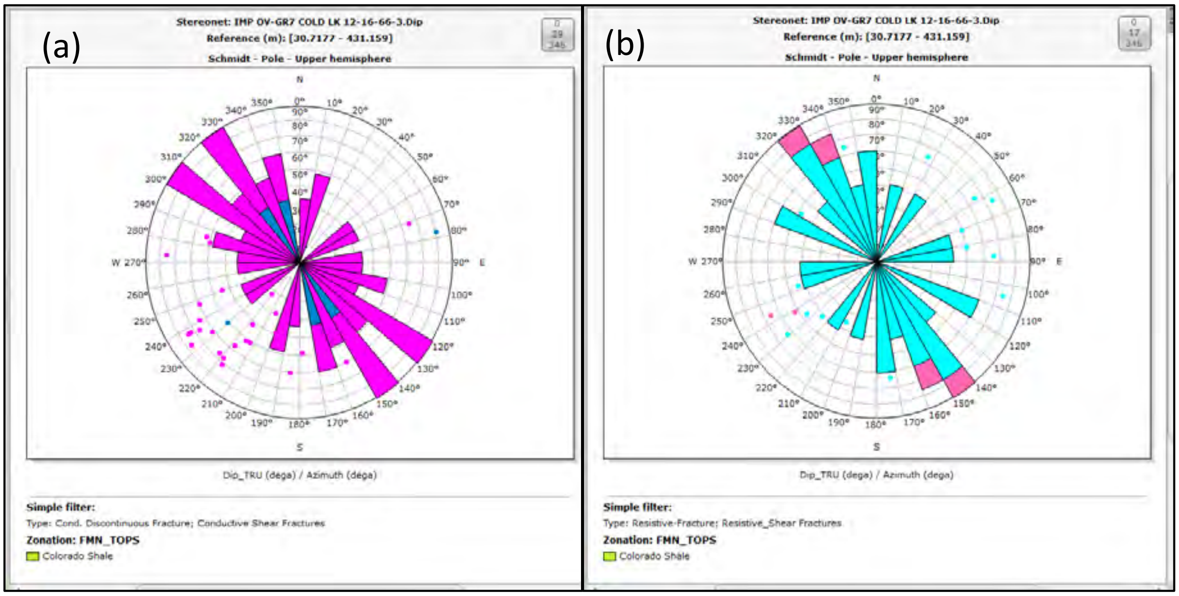


Figure 32 Schmidt diagram of discontinuous conductive fractures (blue color) and conductive shear fractures (magenta color) (a), resistive fracture (cyan color) and resistive shear fracture (pink color) (b) in the Colorado Shale formation for the well 12-16-66-3.

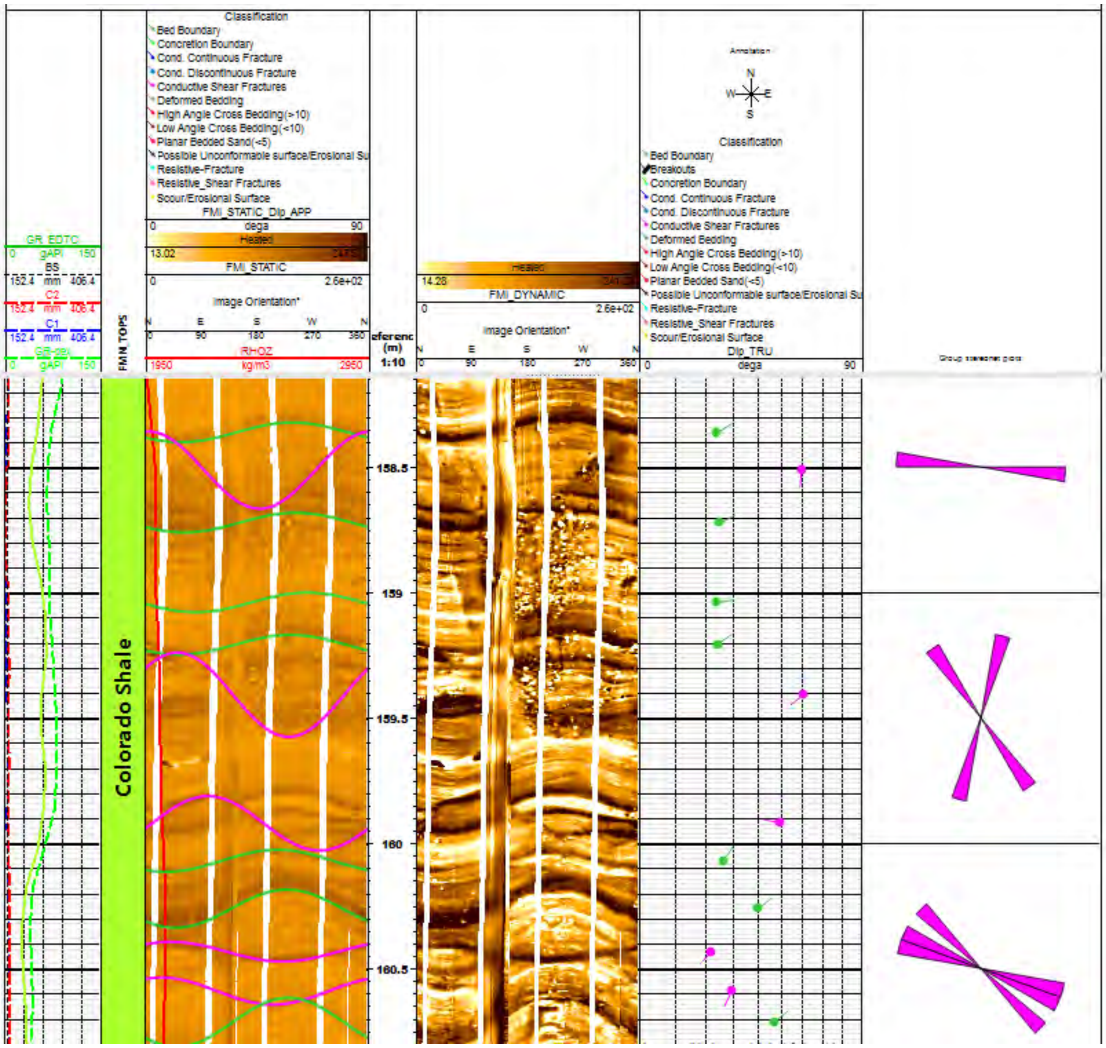


Figure 33 FMI images showing conductive shear fractures (magenta color tadpoles) in the Colorado Shale formation for the well 12-16-66-3.

6.9. Well name: IMP 13 OV COLD LK 6-17-66-3

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation, three (3) discontinuous conductive fractures are observed between 373.5m-374.5m (MD). Fractures are striking in “NW-SE” and “N-S” directions with dip magnitude of 45^{o}-70^{o} (Figure 34). Image example of discontinuous conductive fractures are shown on Figure 35.

A total of 16 fractures are identified in the Colorado Shale formation including one (1) discontinuous conductive, 12 conductive shear, one (1) resistive shear and one (1) resistive fracture. Discontinuous conductive fracture shows strike direction in “NNW-SSE” with dip magnitude of 51^{o}. Conductive shear fractures show two dominant strike directions in “NNE-SSW” and “NW-SE” with some dispersion in strike and dip magnitude from 50^{o} -79^{o}. Resistive and resistive shear fractures are trending in “NNW-

SSE" and "NW-SE" directions with dip magnitude of 46° and 70° respectively. Schmidt diagram of fractures in the Colorado Shale formation is shown on Figure 36. Most of the shear fractures and discontinuous conductive fracture are present between 148m- 166m (MD) and 183m-195m (MD). Image example of conductive shear fractures in the Colorado Shale formation is shown in Figure 37.

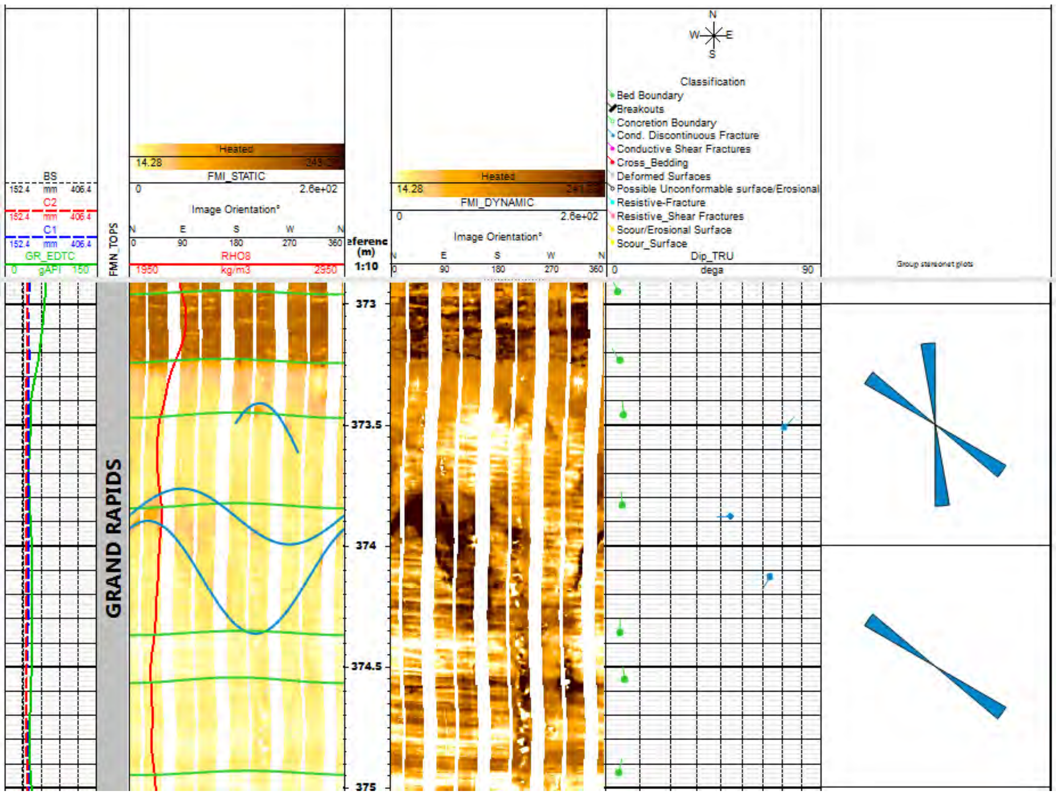


Figure 34 FMI images showing discontinuous conductive fractures (blue color tadpole) in the Grand Rapids formation for the well 6-17-66-3. Fan plots are showing the fracture strike.

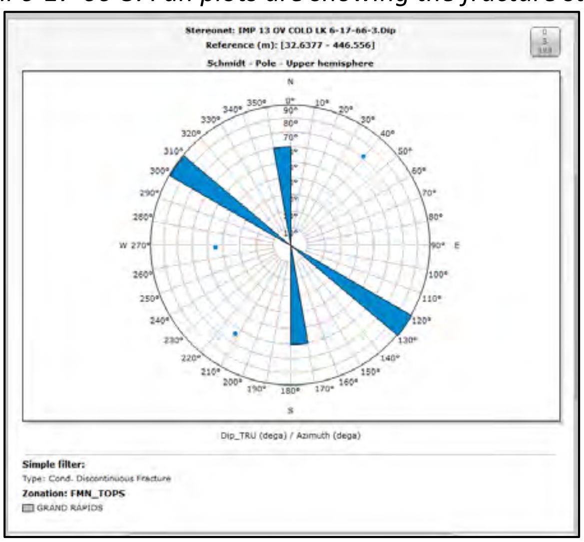


Figure 35 Schmidt diagram of discontinuous conductive fracture (blue color) in the Grand Rapids formation for the well 6-17-66-3.

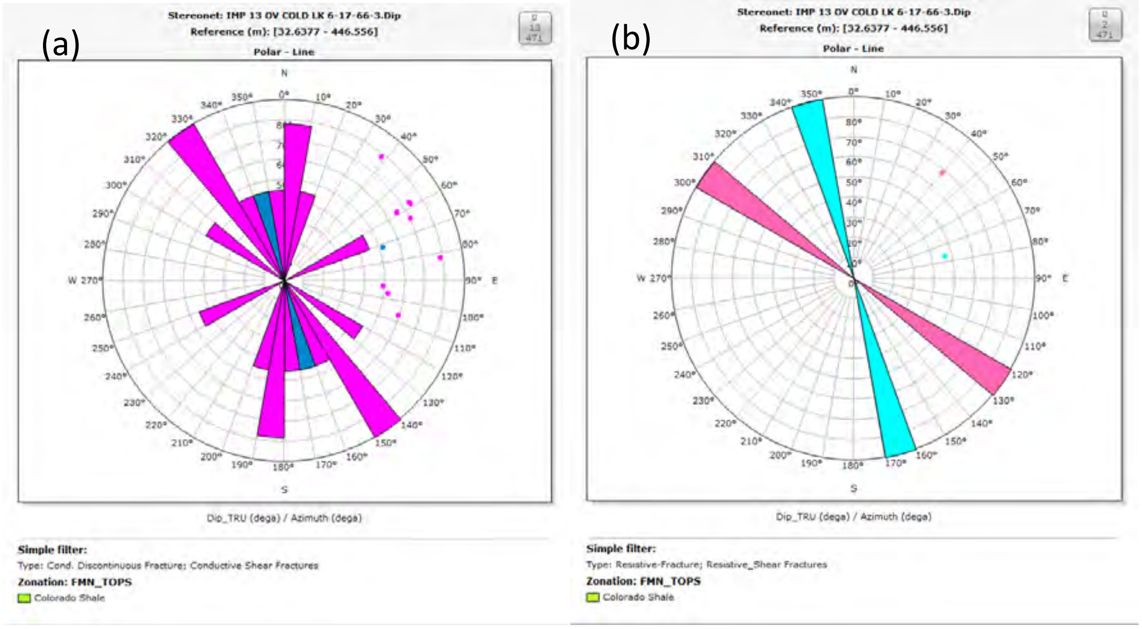


Figure 36 Schmidt diagram of discontinuous conductive fractures (blue color) and conductive shear fractures (magenta color) (a), resistive fracture (cyan color) and resistive shear fracture (pink color) (b) in the Colorado Shale formation for the well 6-17-66-3.

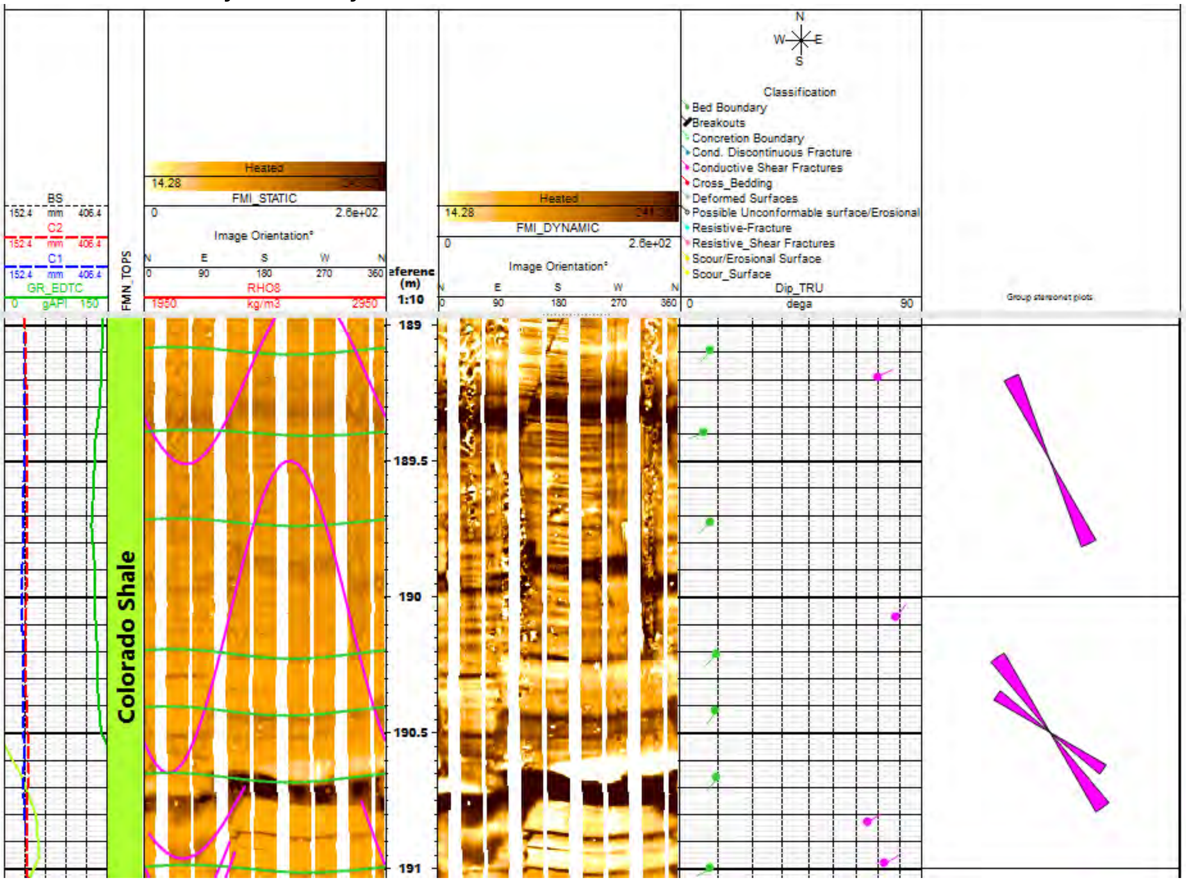


Figure 37 FMI images showing conductive shear fractures (magenta color tadpoles) in the Colorado Shale formation for the well 6-17-66-3. Fan plots are showing fracture strike.

6.10. Well name: IMP OV-GR10 COLD LK 4-21-66-3

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation, one (1) conductive shear, one (1) resistive and three (3) concretion resistive fractures are interpreted. Conductive shear and resistive fractures show “N-S” and “NE-SW” directions with dip magnitude of 31^{o} and 39^{o} respectively (Figure 38). Concretion fractures show random strike direction in “NS”, “NE-SW” and “NW-SE” with dip magnitude from 34^{o} -46^{o} (Figure 38). Concretion fractures are present in high density calcite concretion at 408.5m (MD). Image example of conductive shear fracture is shown in Figure 39.

A total of 38 fractures are observed in the Colorado Shale formation including three (3) continuous conductive, 28 discontinuous conductive and seven (7) conductive shear fractures. Continuous conductive fractures show random strike direction in “NNE-SSW”, “NE-SW” and “WNW-ESE” directions with dip magnitude from 41^{o} -79^{o} (Figure 40). Discontinuous conductive and conductive shear fractures show a dominant strike in “NNW-SSE” direction with dip magnitude from 40^{o} -80^{o} (Figure 40). Most of the fractures are present between 153m-164m (MD) and 186m-191m (MD) (Figure 41). Breakouts are also observed in the Colorado Shale formation with strike direction in “NW-SE” (Figure 42).

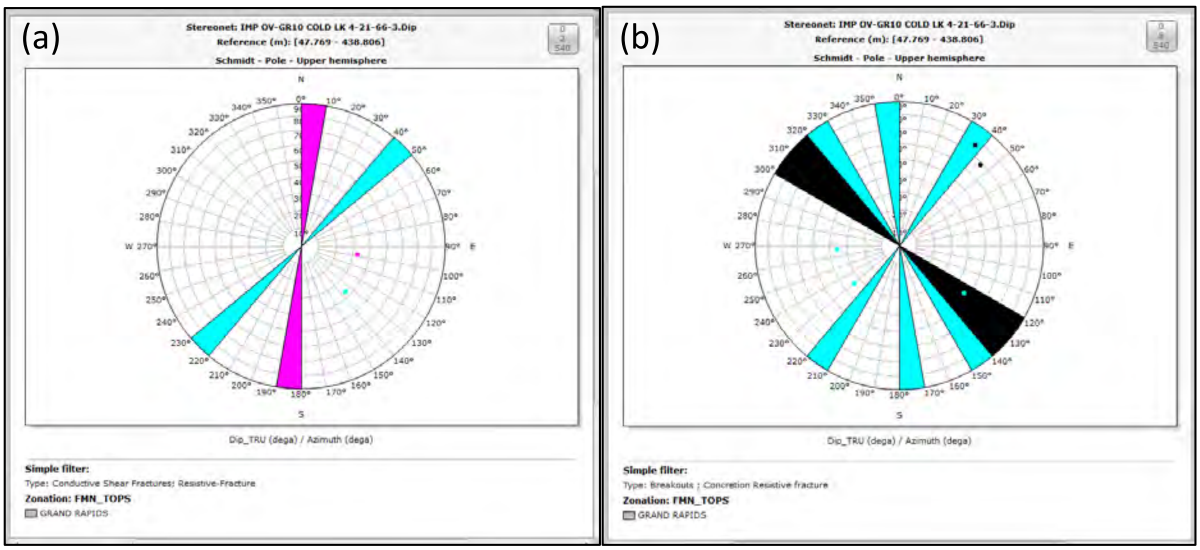


Figure 38 Schmidt diagram of conductive shear fracture (magenta color) and resistive fracture (cyan color) (a), concretion resistive fracture (cyan color) and breakouts (black color) (b) in the Grand Rapids formation for the well 4-21-66-3.

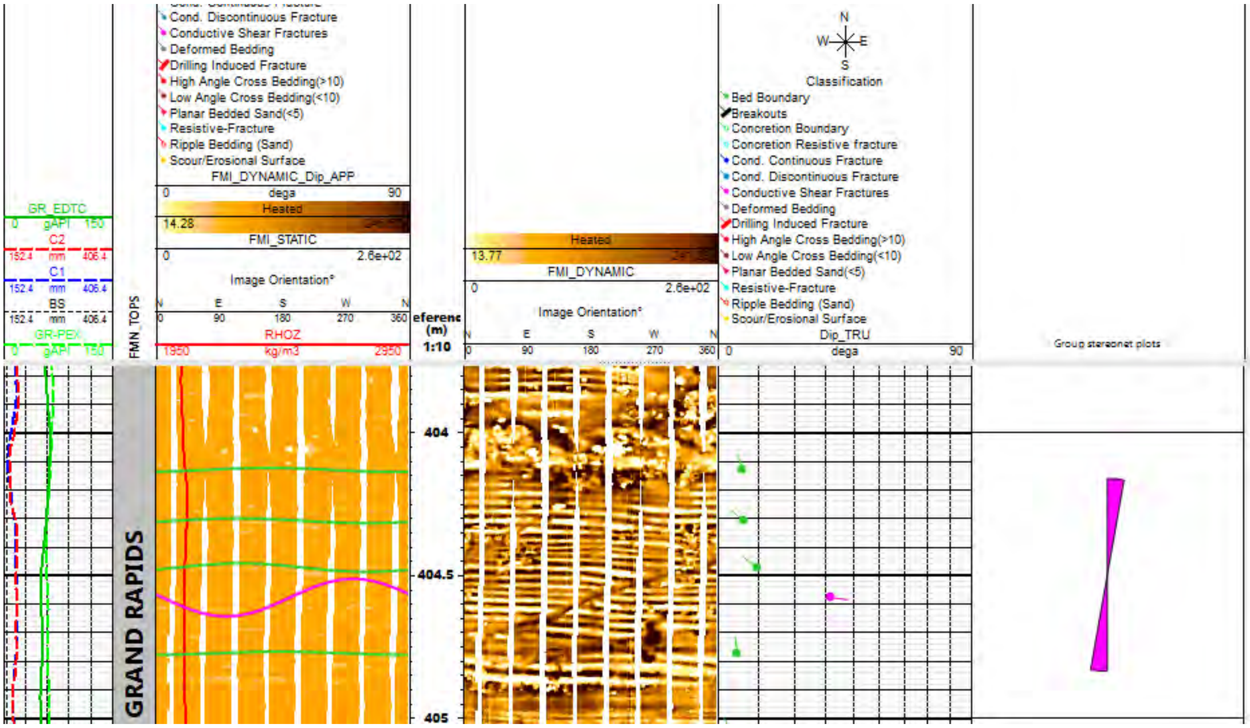


Figure 39 FMI images showing conductive shear fracture (magenta color tadpole) in the Grand Rapids formation for the well 4-21-66-3. Fan plot is showing fracture strike.

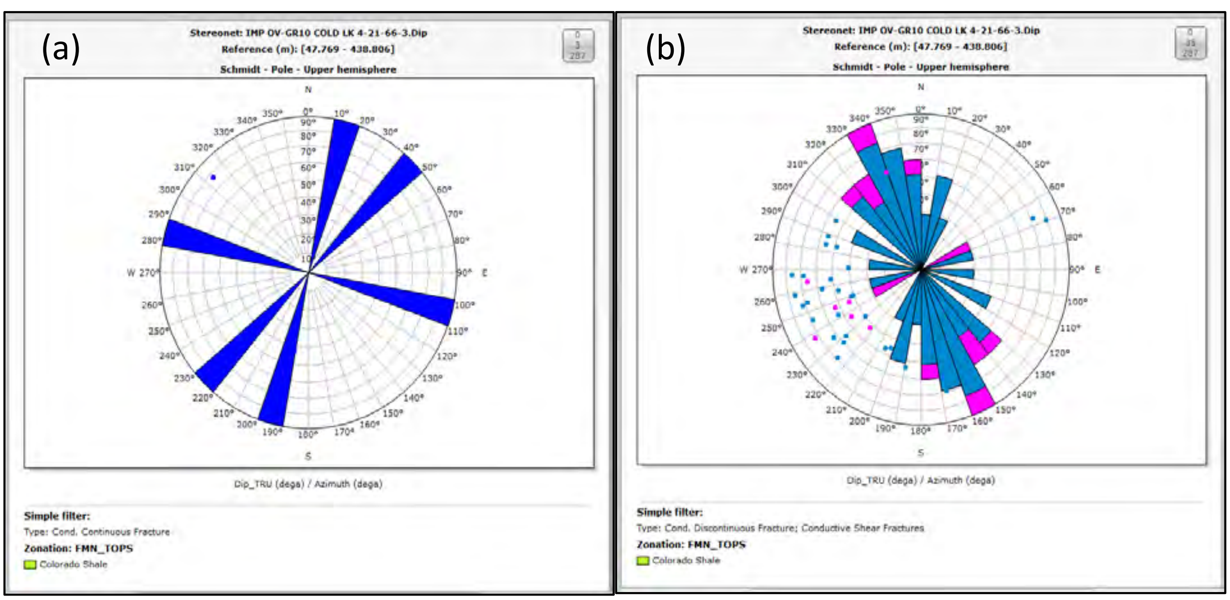


Figure 40 Schmidt diagram of continuous conductive fractures (a), discontinuous conductive (blue color) and conductive shear fracture (magenta color) (b) in the Colorado Shale formation for the well 4-21-66-3.

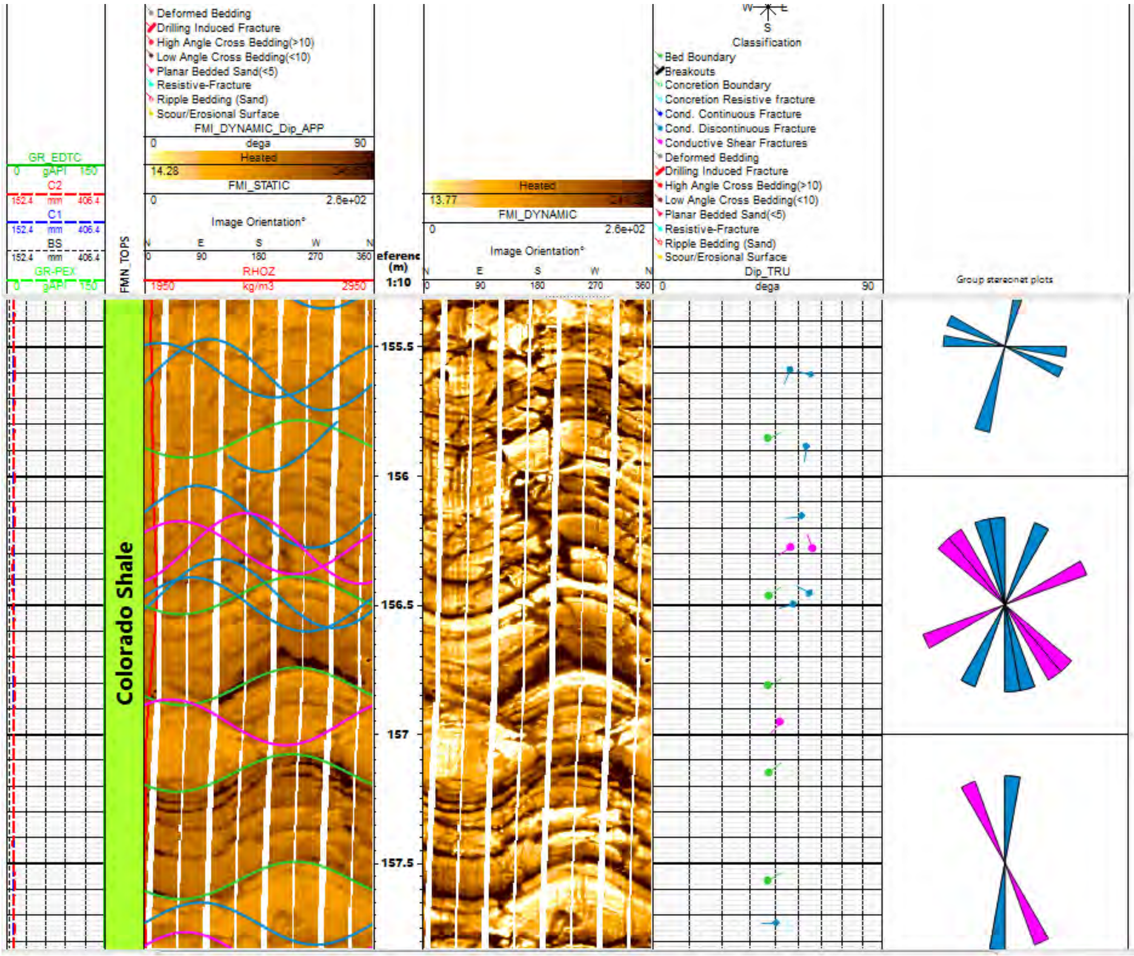


Figure 41 FMI images showing discontinuous conductive fractures (blue color tadpoles) and conductive shear fracture (magenta color tadpole) in the Colorado Shale formation for the well 4-21-66-3. Fan plots are showing fracture strike.

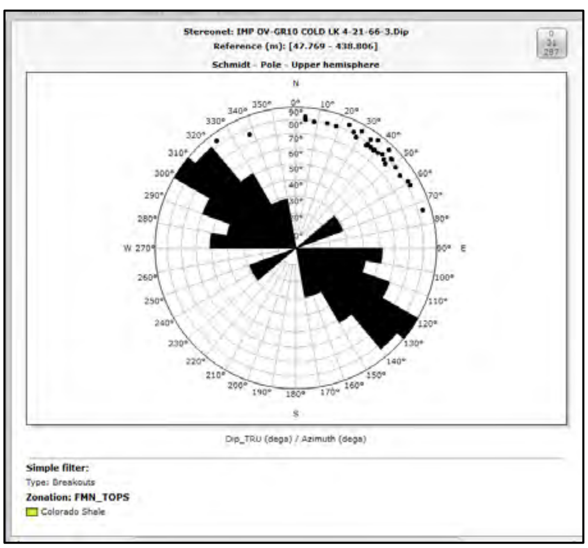


Figure 42 Schmidt diagram of breakouts in the Colorado Shale formation for the well 4-21-66-3.

6.11. Well name: IMP OV-GR39 COLD LK 13-1-66-4

FMI image is not logged in the Clearwater formation for the well 13-1-66-4.

Fractures are not observed in the Grand Rapids formation.

In the Colorado Shale formation, four (4) continuous conductive fractures are observed with primary strike direction in "NE-SW" and dip magnitude varies from 40°-56° (Figure 43). High angle breakout features are also observed with strike in "NW-SE" direction and dip magnitude of ~80° (Figure 43). Image example of fractures is shown in Figure 44.

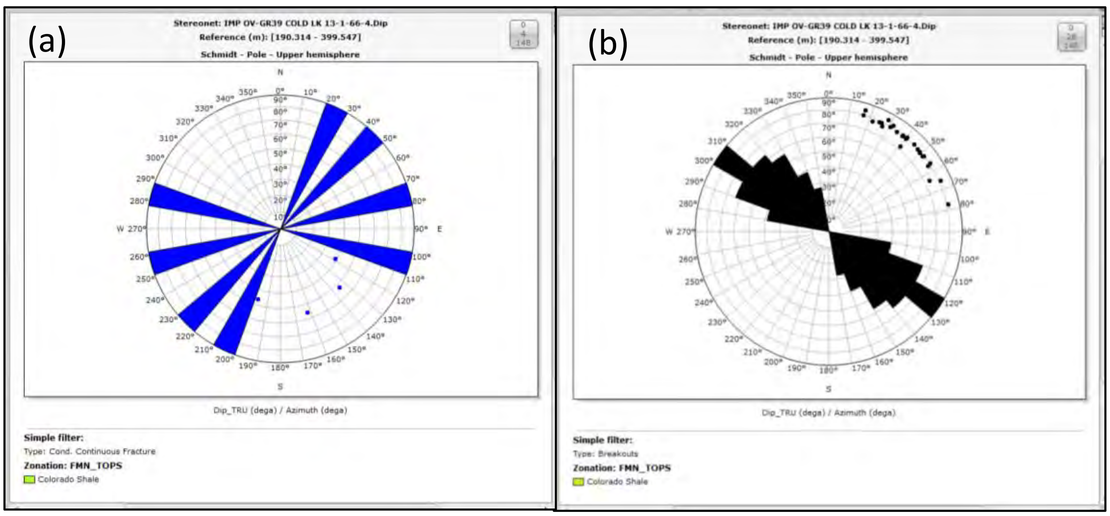


Figure 43 Schmidt diagram of continuous conductive fractures (a) and breakout features (b) in the Colorado Shale formation for the well 13-1-66-4.

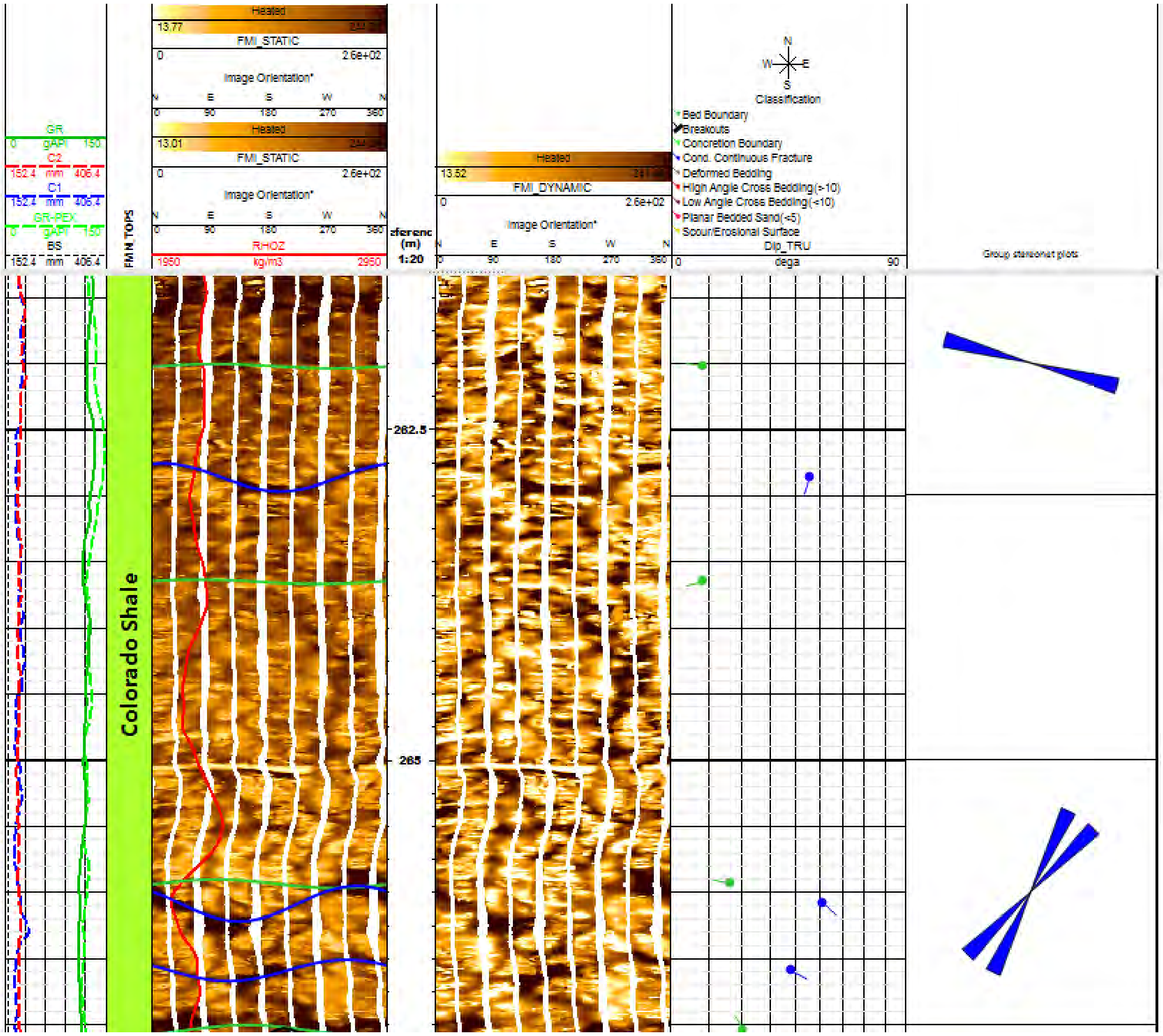


Figure 44 FMI images showing continuous conductive fractures (blue color tadpoles) in the Colorado Shale formation for the well 13-1-66-4. Fan plots are showing fracture strike.

6.12. Well name: IMP OV-GR45 COLD LK 7-2-66-4

Fractures are not observed in the Clearwater formation.

Five (5) fractures are observed from FMI images in the Grand Rapids formation including three (3) discontinuous conductive and two (2) resistive fractures. Both fracture types are showing strike direction in “NE-SW” with dip magnitude from 34° to 64° (Figure 45). Image example of discontinuous conductive fractures in the Grand Rapids formation is shown in Figure 46.

A total of 14 fractures are interpreted in the Colorado Shale formation including two (2) continuous conductive, nine (9) discontinuous conductive, two (2) conductive shear and one (1) resistive fractures. Conductive fractures show primary trend in “NE-SW” direction with dispersion in strike direction and dip magnitude from 36° -82° (Figure 47). Conductive shear fractures show strike in “NNW-SSE” and “NW-SE” directions with dip magnitude of ~52° and resistive fracture is striking in “WNW-ESE” direction with dip magnitude of 59° (Figure 47). Fractures are mainly present at depth from 190m-195m (MD) and from 241m-245m (MD) (Figure 48). 44 breakout features are also observed in the Colorado Shale formation with high angle dip ~80° and "NW-SE" strike direction (Figure 49).

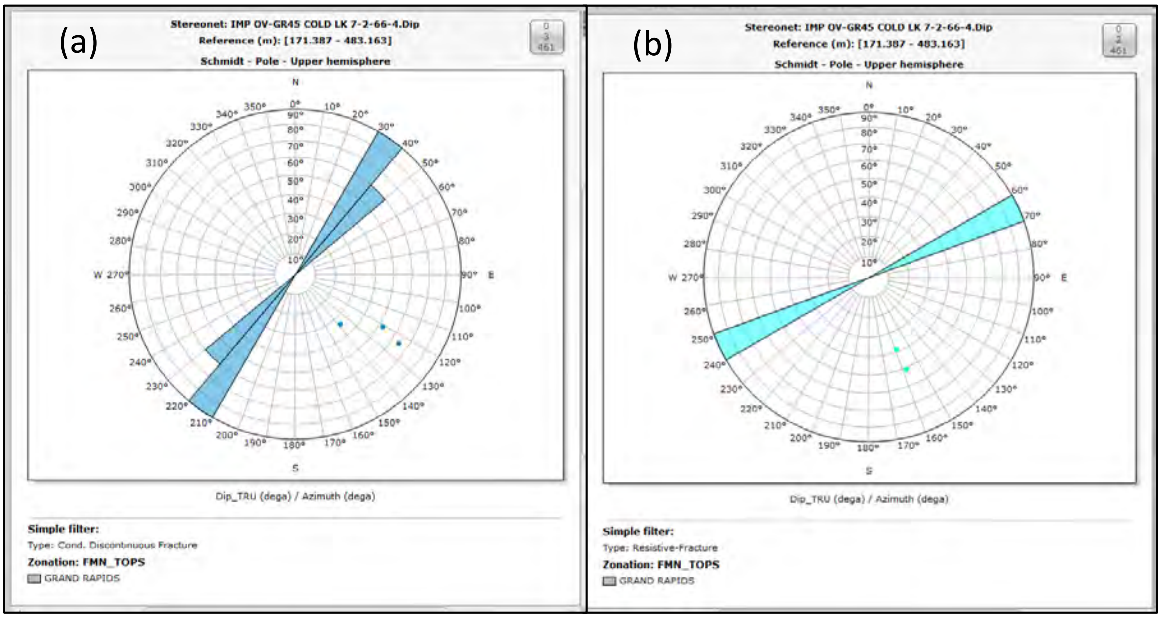


Figure 45 Schmidt diagram conductive discontinuous (blue color) fracture (a) and resistive fracture (cyan color) (b) in the Grand Rapids formation for the well 7-2-66-4.

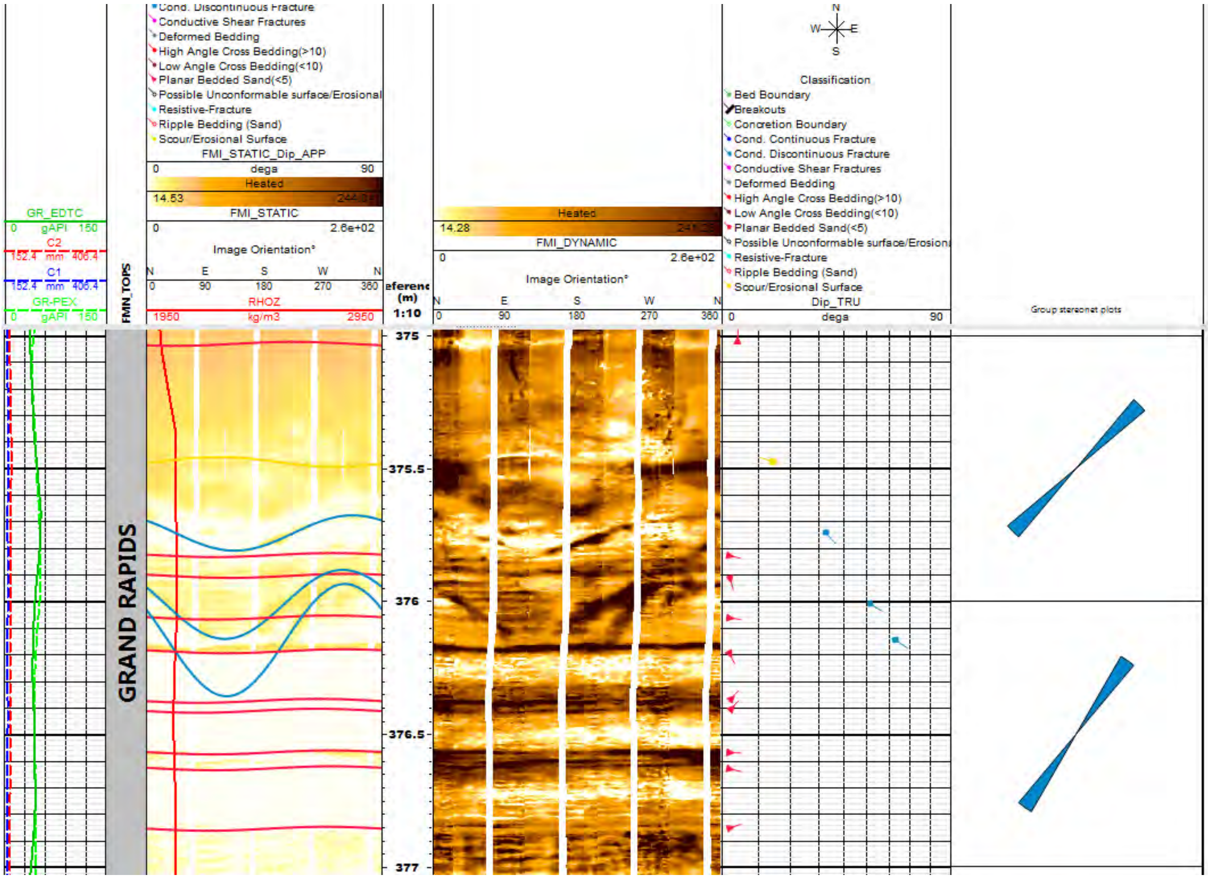


Figure 46 FMI images showing discontinuous conductive (blue color tadpoles) fracture in the Grand Rapids formation for the well 7-2-66-4.

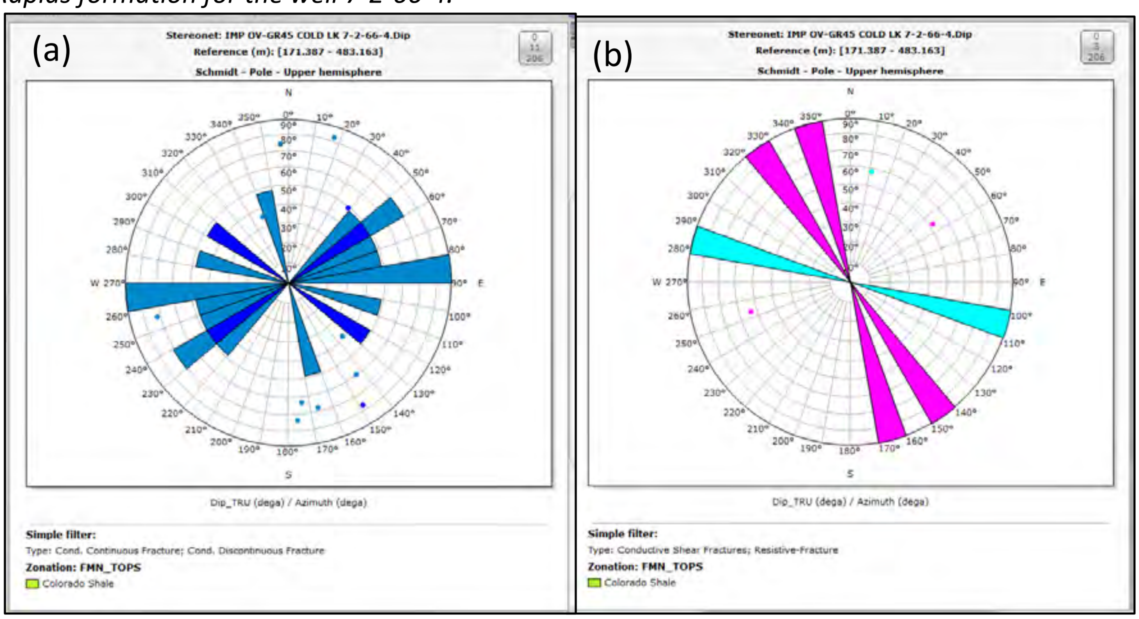


Figure 47 Schmidt diagram of continuous conductive (dark blue color) and discontinuous conductive (light blue color) fractures (a), conductive shear (magenta color) and resistive (cyan color) fractures (b) in the Colorado Shale formation for the well 7-2-66-4.

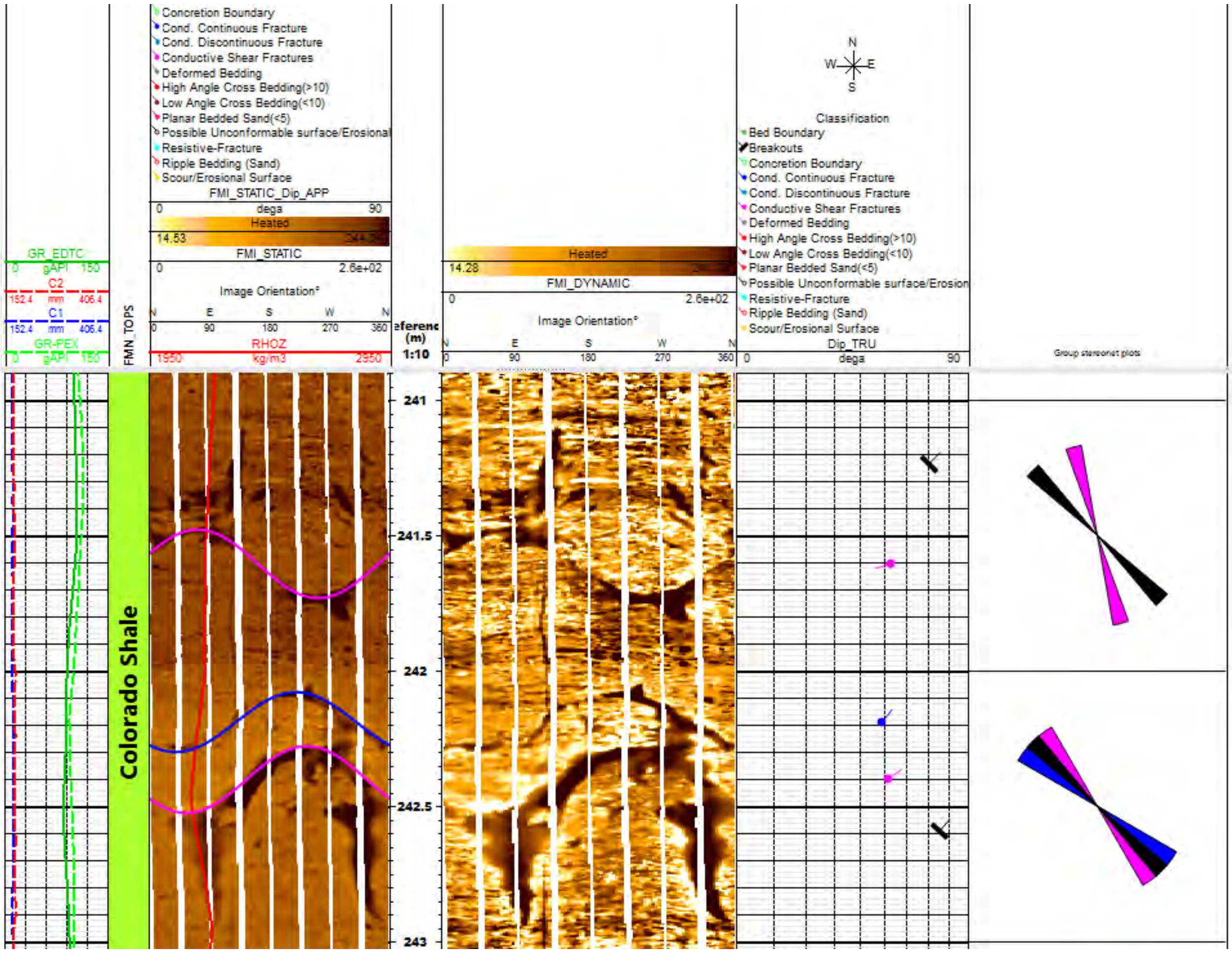


Figure 48 FMI images showing continuous conductive (blue color tadpoles), conductive shear (magenta color tadpoles) fractures and breakouts (black color) in the Colorado Shale formation for the well 7-2-66-4. Fan plots are showing the strike direction.

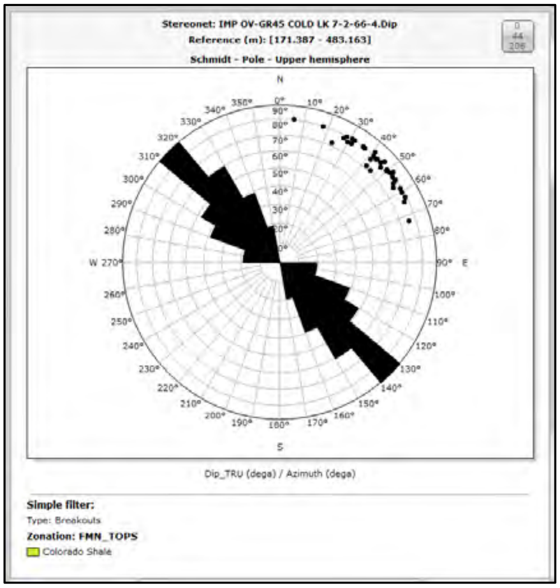


Figure 49 Schmidt diagram of breakouts in the Colorado Shale formation for the well 7-2-66-4.

6.13. Well name: IMP OV-GR36 COLD LK 14-14-66-4

Fractures are not observed in the Clearwater formation.

Three (3) resistive fractures are observed in the Grand Rapids formation. Resistive fractures are striking in “NE-SW” direction with dip magnitude of 42°-50° (Figure 50). Image example of resistive fractures is shown on Figure 51.

In the Colorado Shale formation, one (1) conductive shear fracture, two (2) continuous conductive fractures and three (3) resistive fractures are identified. Conductive fractures are showing the trend in “NE-SW” direction with dip magnitude of 51° -55° whereas conductive shear fracture and resistive fractures are trending “NNE-SSW” (Figure 52). Image examples of conductive fractures are shown in Figure 53 and conductive shear and resistive fractures on Figure 54.

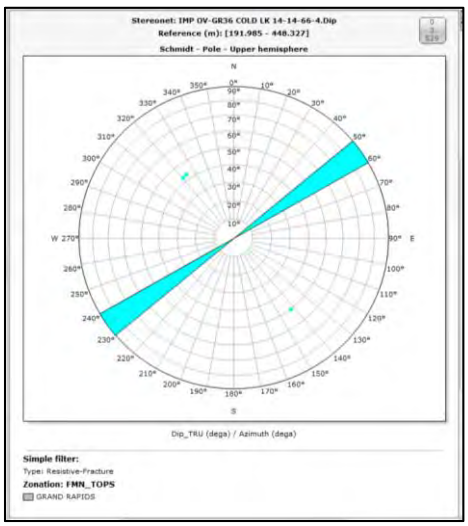


Figure 50 Schmidt diagram of resistive fractures in the Grand Rapids formation for the well 14-14-66-4.

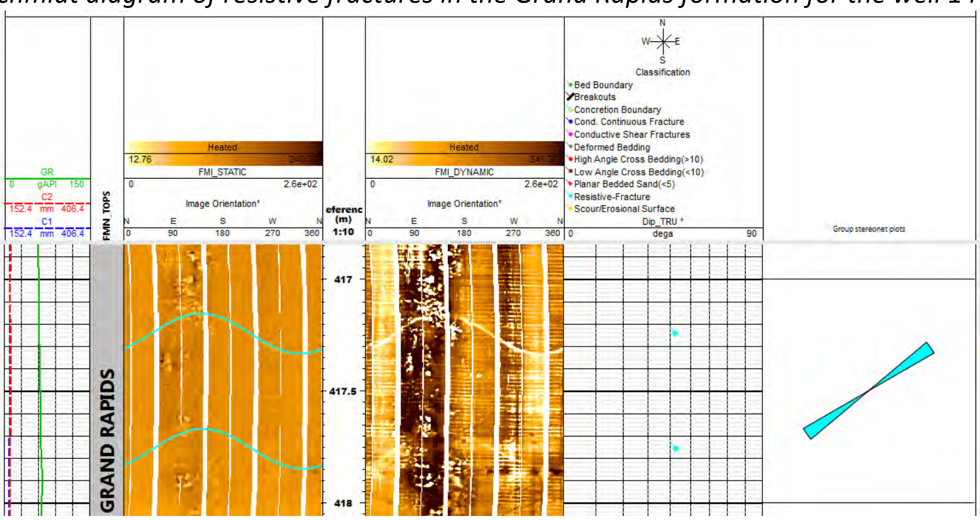


Figure 51 FMI images showing resistive fractures (cyan color tadpoles) in the Grand Rapids formation for the well 14-14-66-4.Fan plot is showing fractures strike.

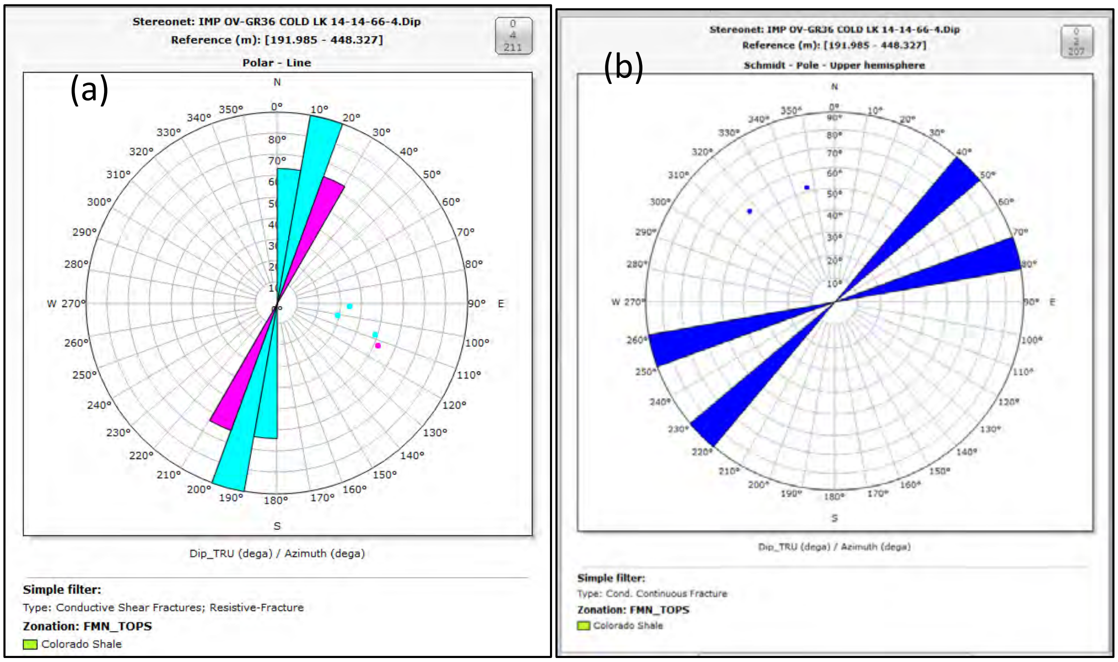


Figure 52 Schmidt diagram of continuous conductive fractures (a) conductive shear (magenta color) and resistive (cyan color) fractures (b) in the Colorado Shale formation for the well 14-14-66-4.

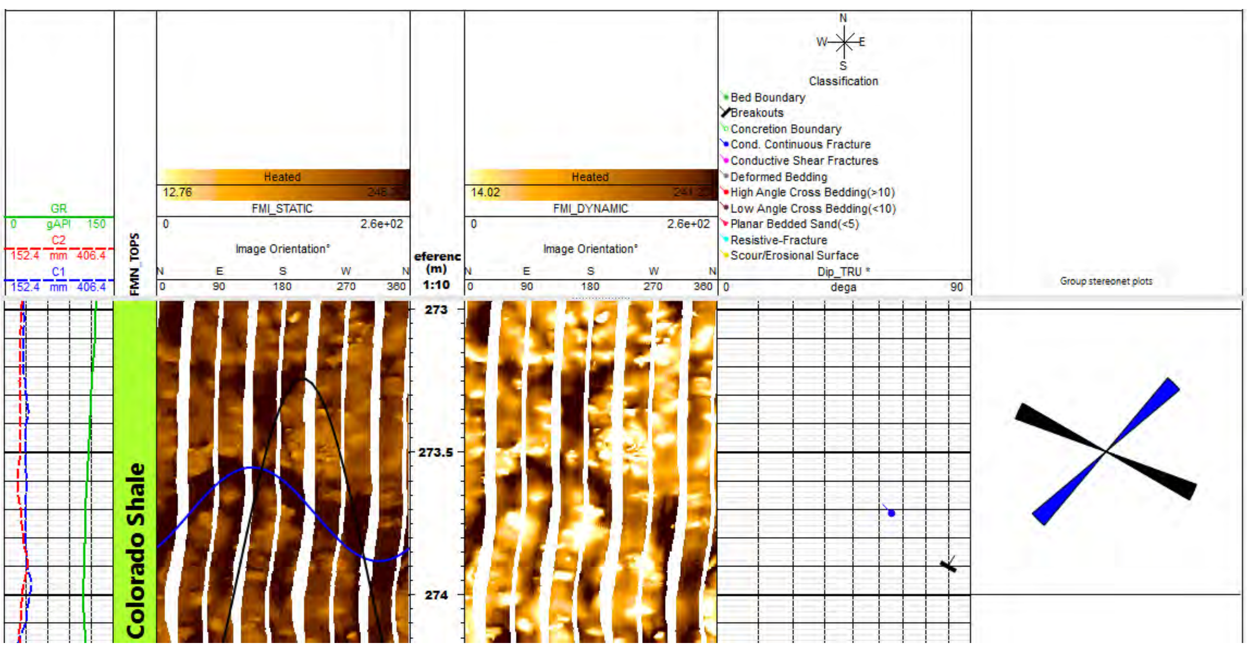


Figure 53 FMI images showing continuous conductive fracture (blue color tadpole) in the Colorado Shale formation for the well 14-14-66-4.Fan plots are showing fractures strike.

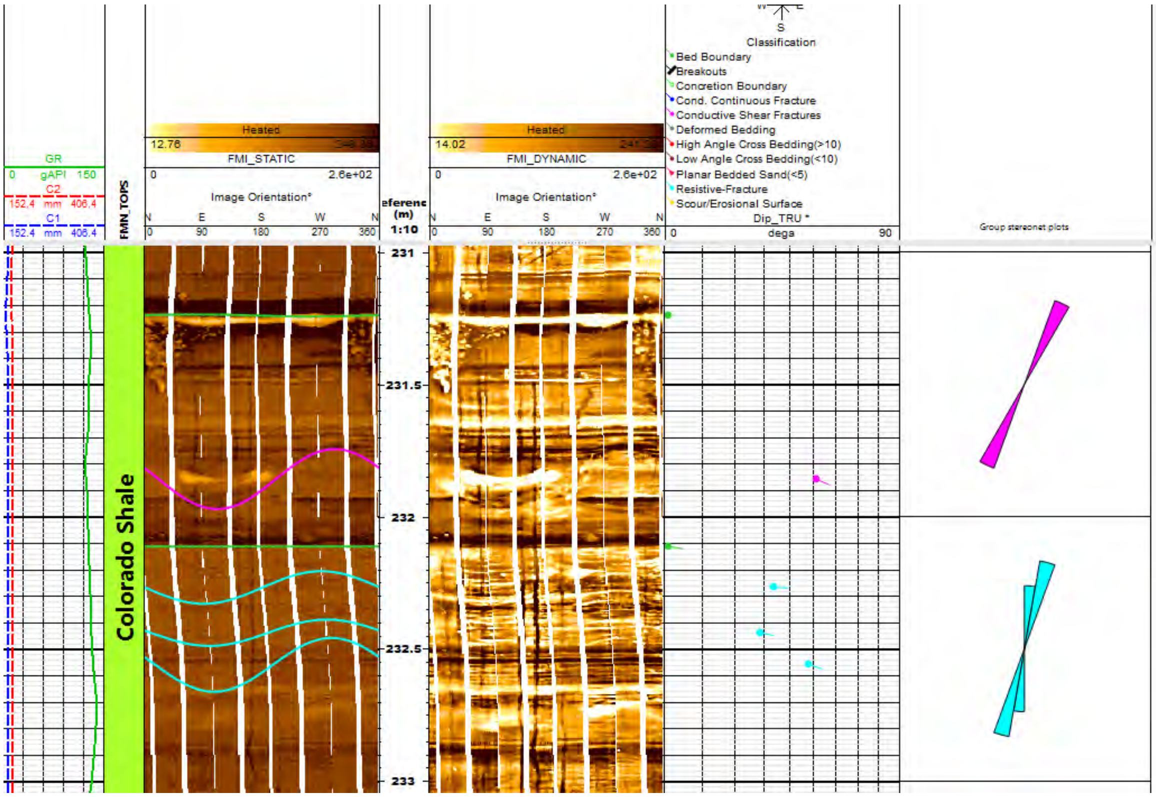


Figure 54 FMI images showing "NNE-SSW" conductive shear and resistive fractures in the Colorado Shale formation for the well 14-14-66-4.

6.14. Well name: IMP OV-GR40 COLD LK 14-23-66-4

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation one (1) conductive shear, two (2) resistive shear and three (3) resistive fractures are observed. Conductive and resistive shear fractures are trending in “ENE-WSW” and “NW-SE” directions with dip magnitude of 34°-40° (Figure 55). Resistive fractures are striking in “NE-SW” direction with dip magnitude of 42° -49° (Figure 55). Image example of conductive shear fracture is shown on Figure 56.

In the Colorado Shale formation, one (1) discontinuous conductive fracture is interpreted at 202.28m (MD) with strike in “NE-SW” direction and dip magnitude of 72° (Figure 57). Breakouts are also observed with “NW-SE” strike and dip magnitude of ~80°. Image example of conductive fracture is shown on Figure 58.

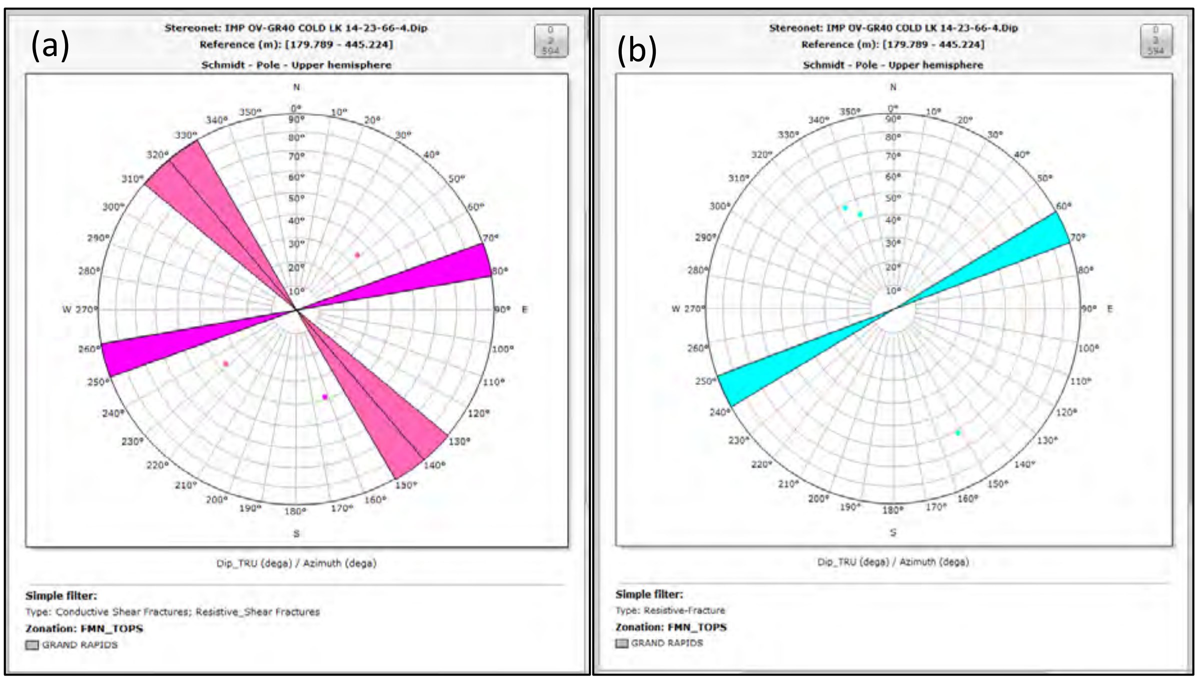


Figure 55 Schmidt diagram of conductive shear (magenta color) and resistive shear fractures (pink color) (a) and resistive fractures (b) in the Grand Rapids formation for the well 14-23-66-4.

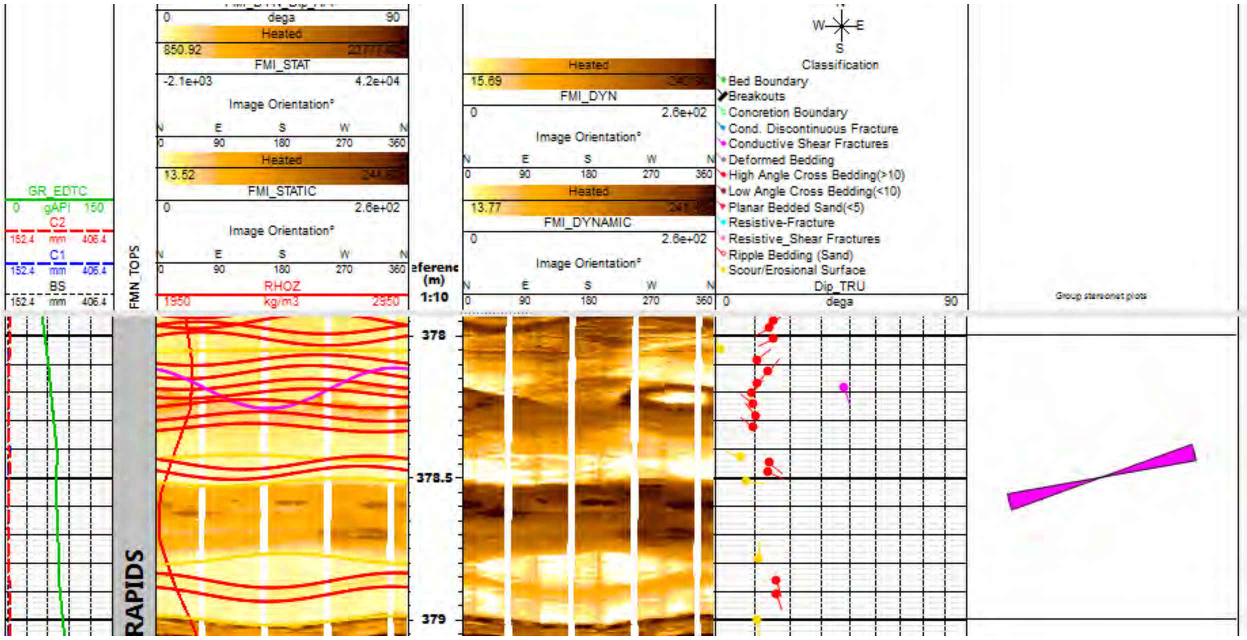


Figure 56 FMI Images showing conductive shear (magenta color tadpole) in the Grand Rapids formation for the well 14-23-66-4. Fan plot is showing the fracture strike.

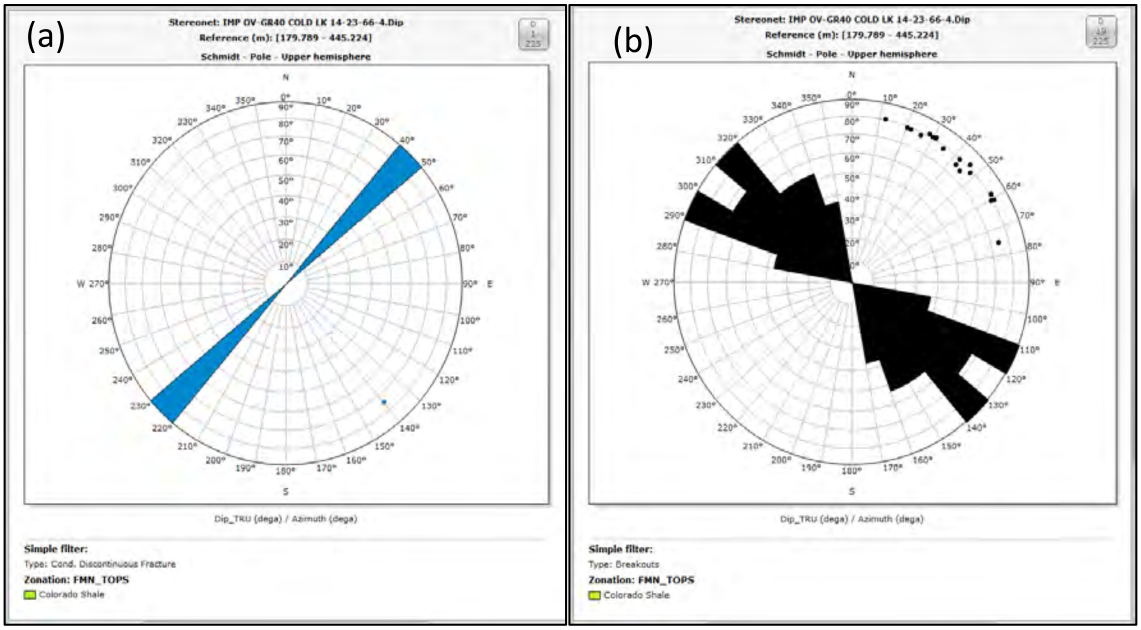


Figure 57 Schmidt diagram of discontinuous conductive fracture (a) and breakouts features (b) in the Colorado Shale formation for the well 14-23-66-4.

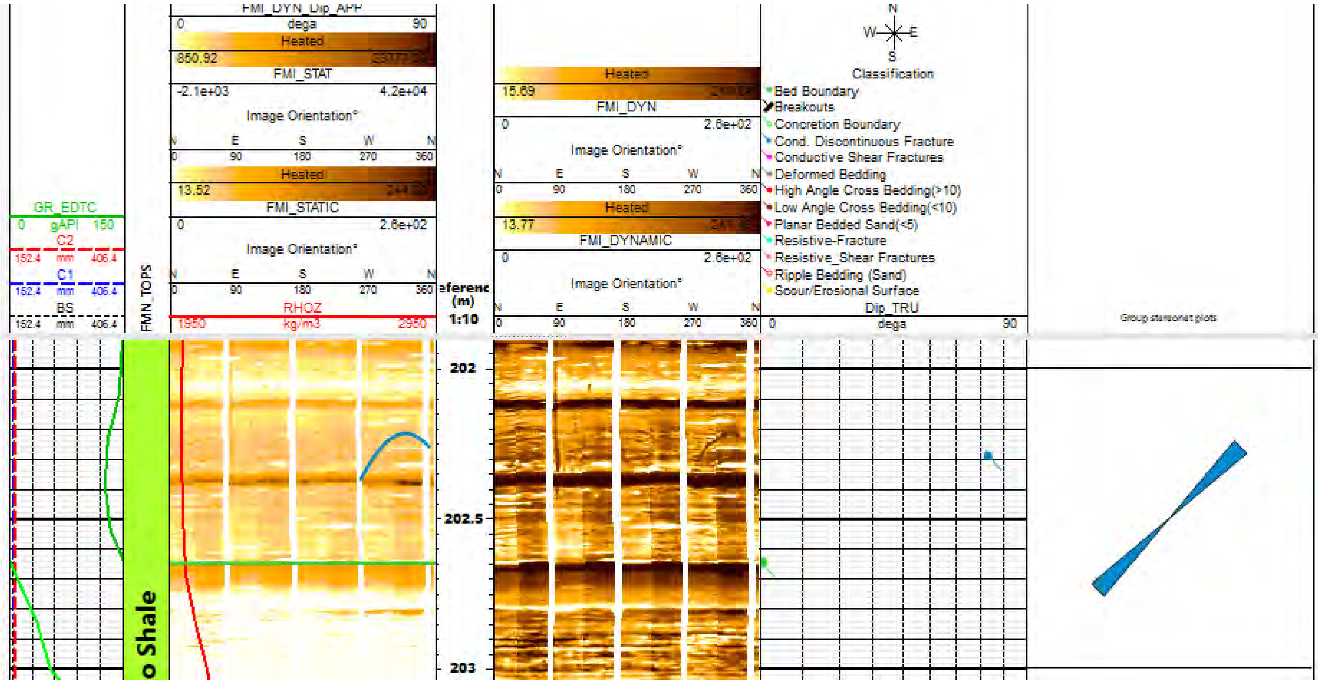


Figure 58 FMI Images showing discontinuous conductive fracture (blue color tadpole) in the Colorado Shale formation for the well 14-23-66-4. Fan plot is showing the fracture strike.

6.15. Well name: IMP OV-GR28 COLD LK 13-12-66-4

Fractures are not observed in the Clearwater formation.

In the Grand Rapids formation, one (1) discontinuous conductive fracture, two (2) resistive fractures and five (5) concretion resistive fractures are identified. Discontinuous conductive and resistive fractures are striking in “WNW-ESE” and “NE-SW” directions with dip magnitude of 49° -72° (Figure 59). Concretion resistive fractures are striking primarily in “NE-SW” direction with dip magnitude 70° -81° (Figure 59). Image example of conductive fracture is shown in Figure 60.

A total of 30 fractures are observed in the Colorado Shale formation, including four (4) continuous conductive, 22 discontinuous conductive and four (4) conductive shear fractures. Conductive fractures are striking mainly in “NE-SW” direction with dip magnitude ranging from 41° -84° (Figure 61). Conductive shear fractures are showing two main trends in “NE-SW” and “NW-SE” directions with dip magnitude ranging from 38°-78° (Figure 61). Image example of fractures is shown on Figure 62.

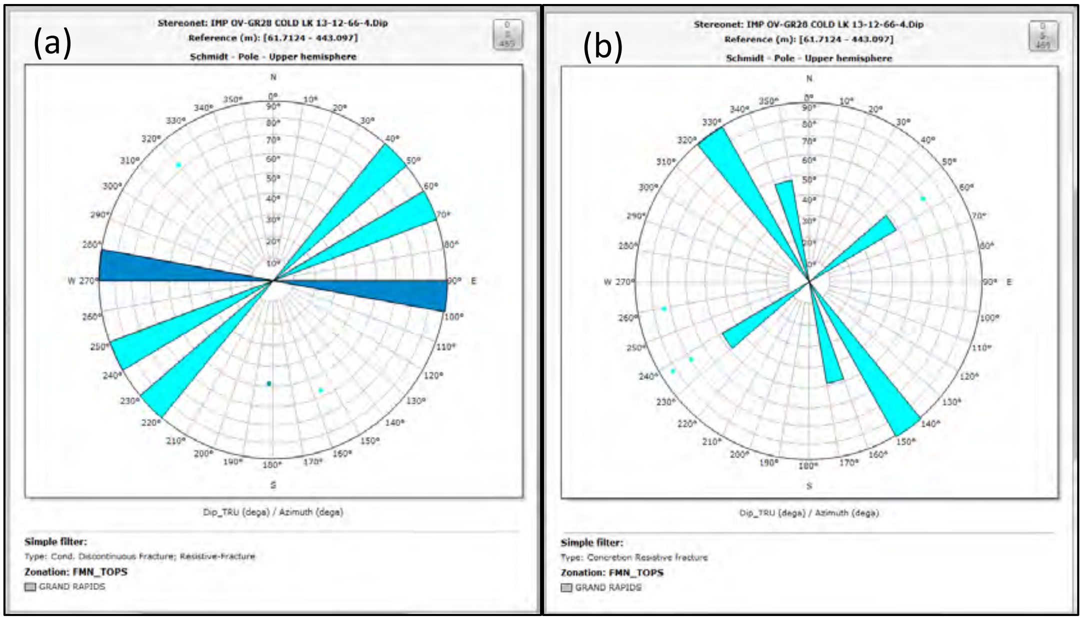


Figure 59 Schmidt diagram of discontinuous conductive (blue color) and resistive fractures (cyan color) (a), concretion resistive fracture (b) in the Grand Rapids formation for the well 13-12-66-4.

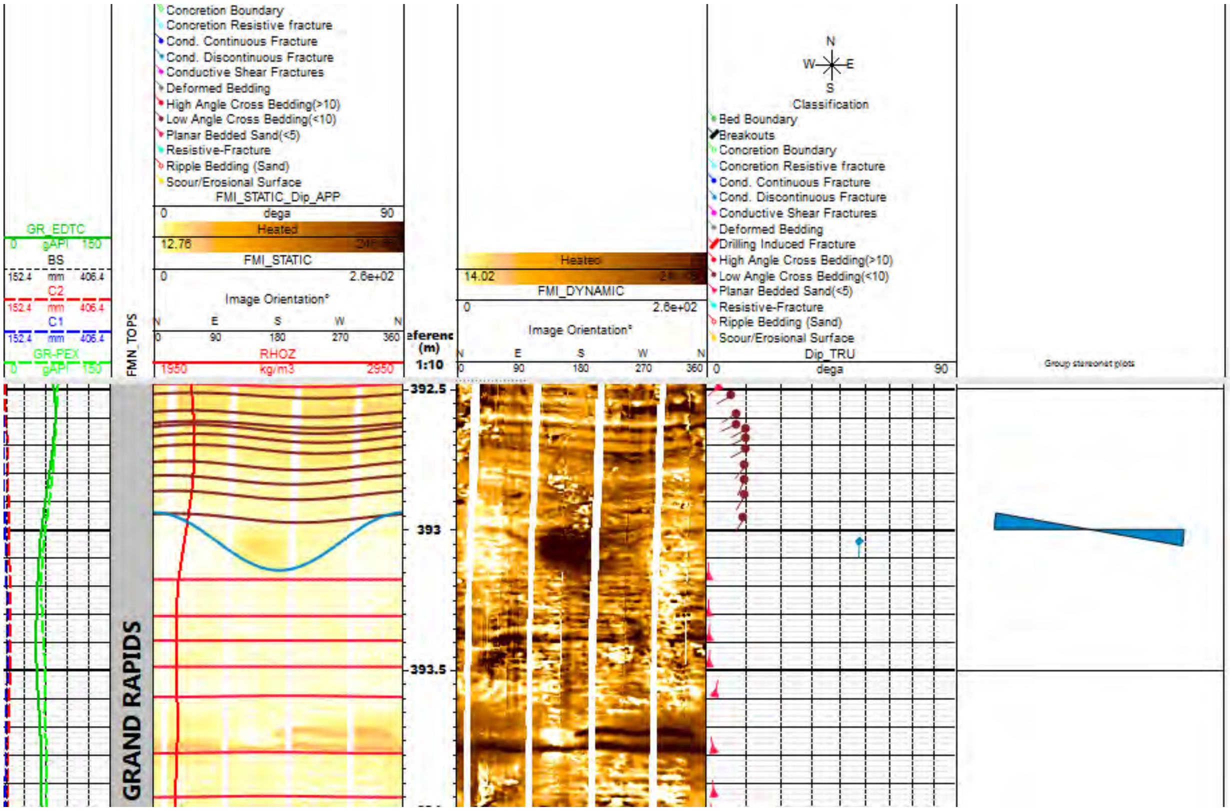


Figure 60 FMI images showing discontinuous conductive fracture in the Grand Rapids formation for the well 13-12-66-4.

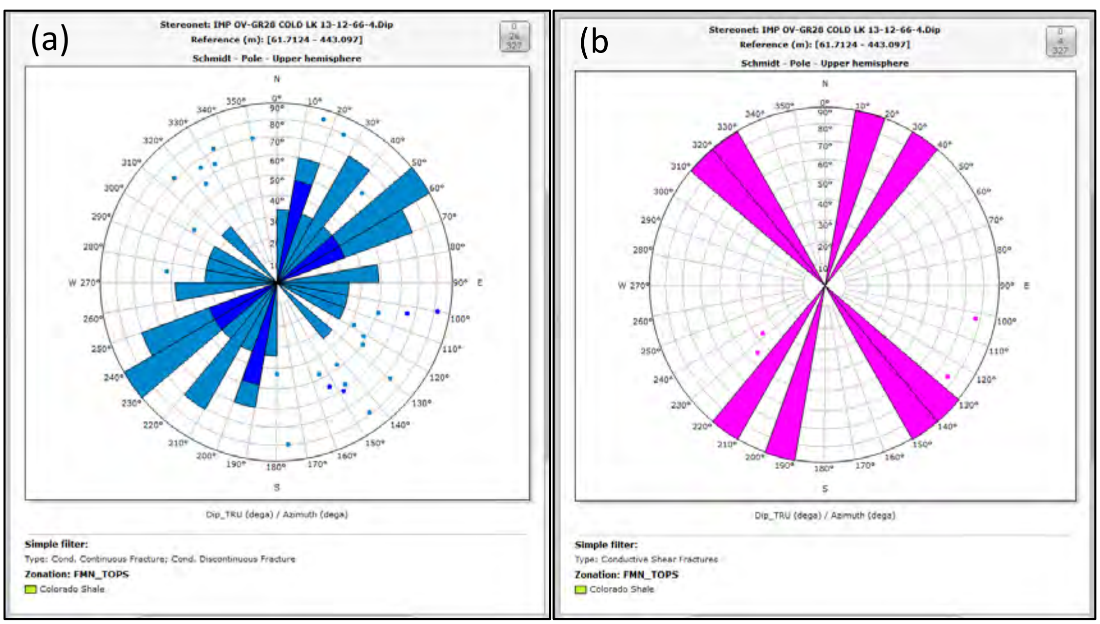


Figure 61 Schmidt diagram of continuous conductive (dark blue color) and discontinuous conductive (light blue color) fractures (a), conductive shear (magenta color) fractures (b) in the Colorado Shale formation for the well 13-12-66-4.

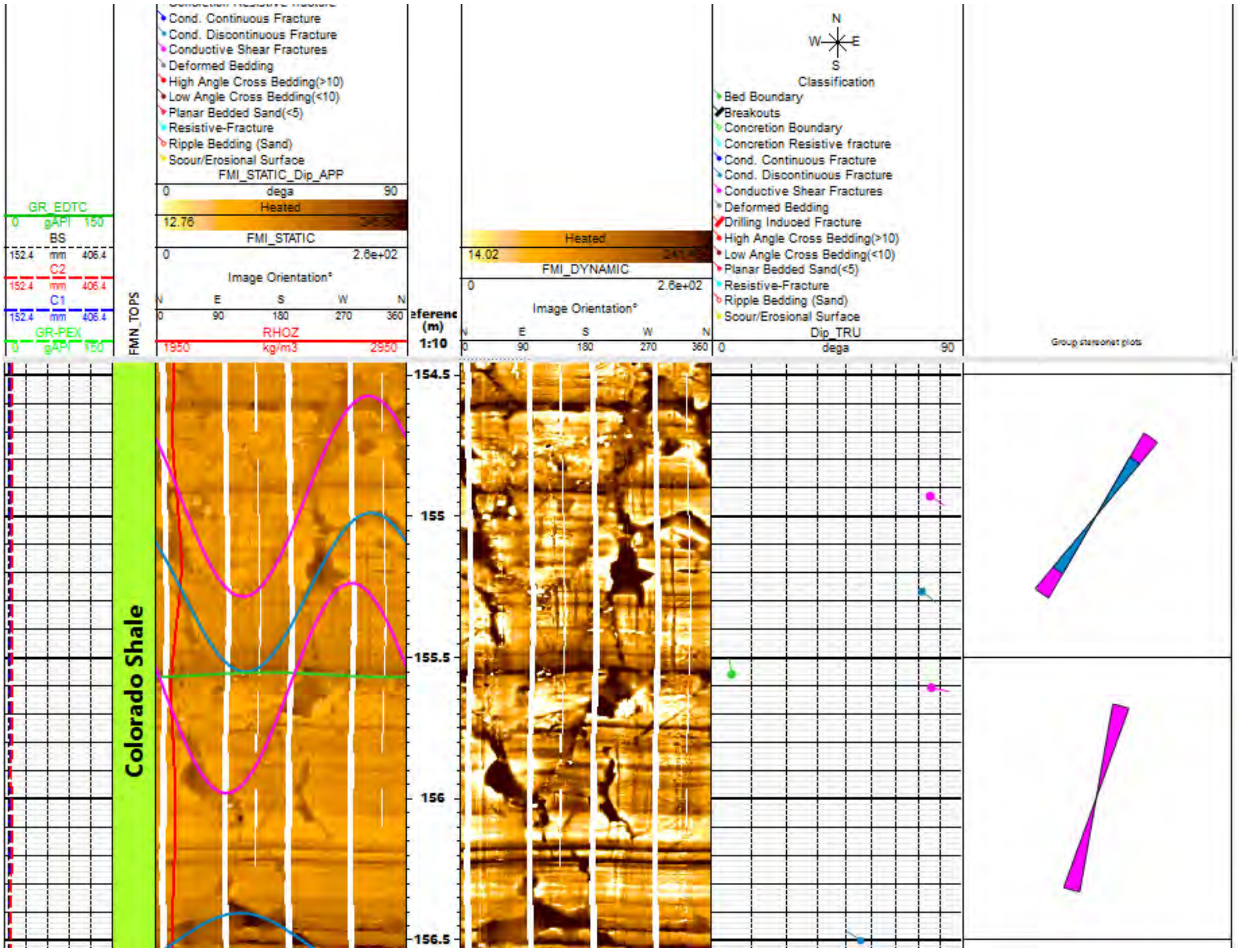


Figure 62 FMI images showing discontinuous conductive (blue color tadpoles) and conductive shear (magenta color tadpoles) fractures in the Colorado Shale formation for the well 13-12-66-4. Fan plots are showing fracture strike.

6.16. Well name: IMP 12 OV COLD LK 14-2-66-3

Data quality of FMI images appear to be affected by the hole condition or tool noise in well 14-2-66-3, however images were interpretable over most of the section.

Fractures are not observed in the Clearwater formation and in the Colorado Shale formation.

In the Grand Rapids formation, nine (9) discontinuous conductive fractures and two (2) concretion resistive fractures are observed. Conductive fractures show variation in strike direction with dip magnitude ranging from 38°-74° (Figure 63). Concretion resistive fractures show strike in “NE-SW” and “NW-SE” with dip magnitude 76° -80 ° (Figure 63). Image example of conductive fractures is shown on Figure 64.

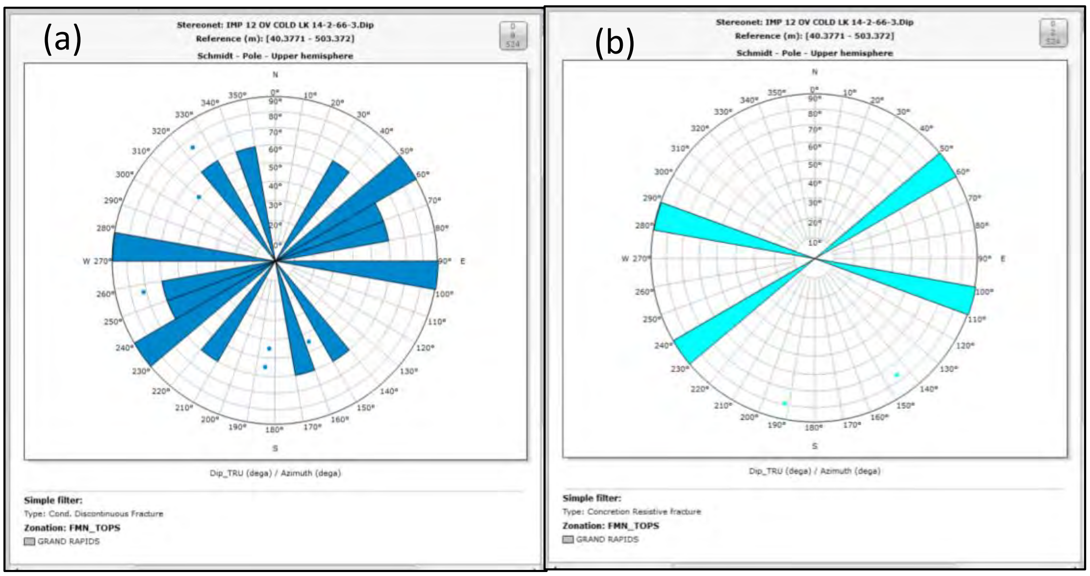


Figure 63 Schmidt diagram of discontinuous conductive fractures (a) and concretion resistive fractures (b) in the Grand Rapids formation for the well 14-2-66-3.

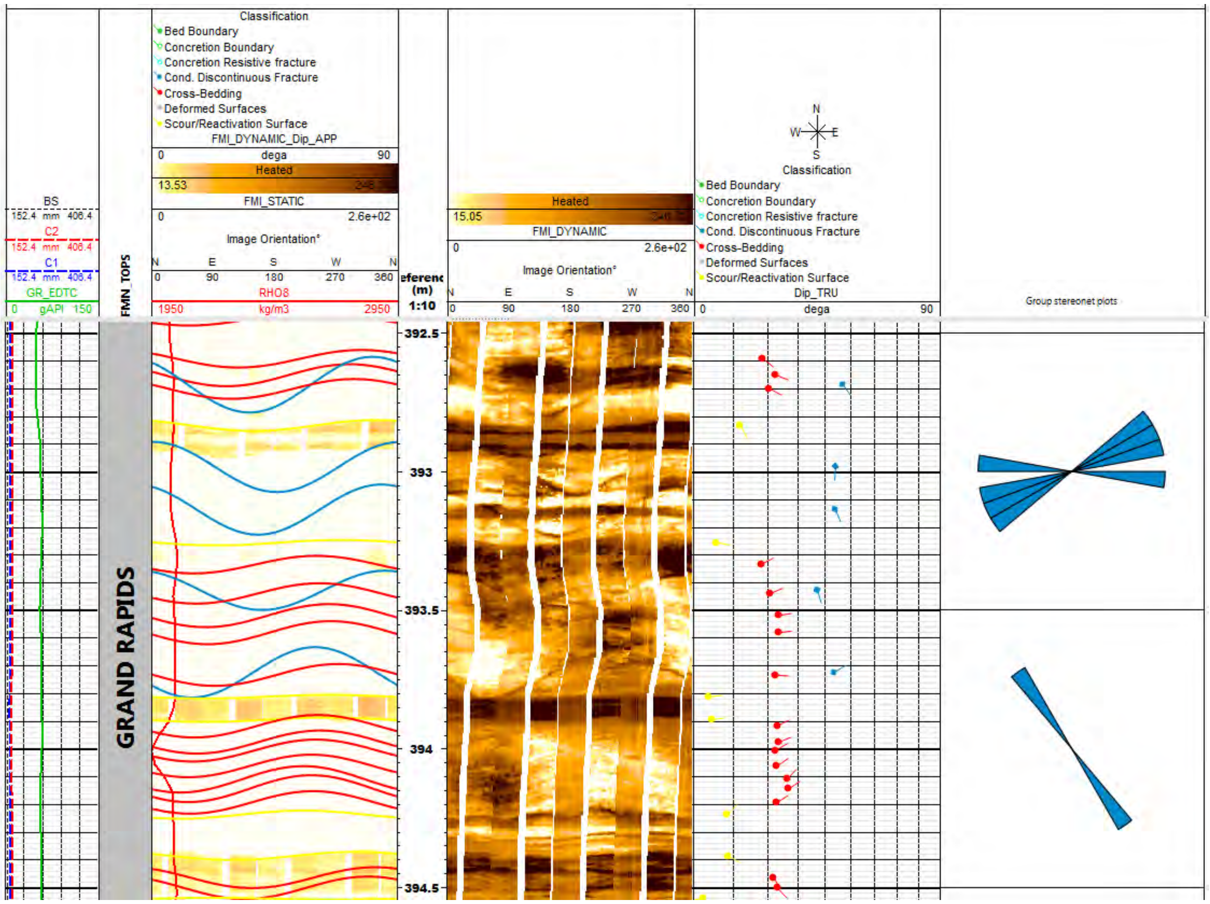


Figure 64 FMI images showing discontinuous conductive (blue color tadpoles) fractures in the Grand Rapids formation for the well 14-2-66-3. Fan plots are showing fracture strike.

7. Fracture Analysis and Discussion

This part of the report provides an interpretation of the overall fracture distribution and trends in all three stratigraphic formations: Clearwater, Grand Rapids and Colorado Shale. The cumulative diagram results are divided into three groups – continuous and discontinuous fractures that genetically belong to the same open and partially open fractures, shear fractures whether they are healed or open and finally healed (resistive) fractures with no obvious displacement.

The orientation of fractures is also examined in Chapter 8 on stratigraphic zonation of fractures. In addition, fracture spatial distribution and their orientation is analyzed in Chapter 9 with discussion on fracture intensities in Chapter 10.

7.1. Cumulative diagram of conductive fractures

A total of 119 continuous and discontinuous conductive fractures were identified in the study area over Grand Rapids and Colorado Shale formations, as seen on Figure 65. Out of 119 features, 18 were identified as continuous fractures (Figure 65a) and 101 were identified as discontinuous fractures (Figure 65b). Out of 16 investigated wells, three wells did not display any fractures on FMI logs: IMP 12 OV COLD LK 12-33-65-3; IMP 12 OV COLD LK 3-4-66-3; and IMP OV-CW4 COLD LK 7-2-66-3.

The cumulative diagram of conductive fracture orientations show a general scattering of fracture poles, with some slightly discernible trends. The primary set is “NE/SW” (peaks at 055°/235°). The secondary trend is within highly uniform distribution of strike poles of “NW/SE” quadrant and is “NNW/SSE” (peaks at 345°/165°). These trends are the result of a sub-set of discontinuous fracture strikes that overweights the relatively small sub-set of continuous trends. However the maximum trend in continuous orientation are subparallel to the primary set having offset of only 10 degrees (peak at 045°/225°) – see Figure 65.

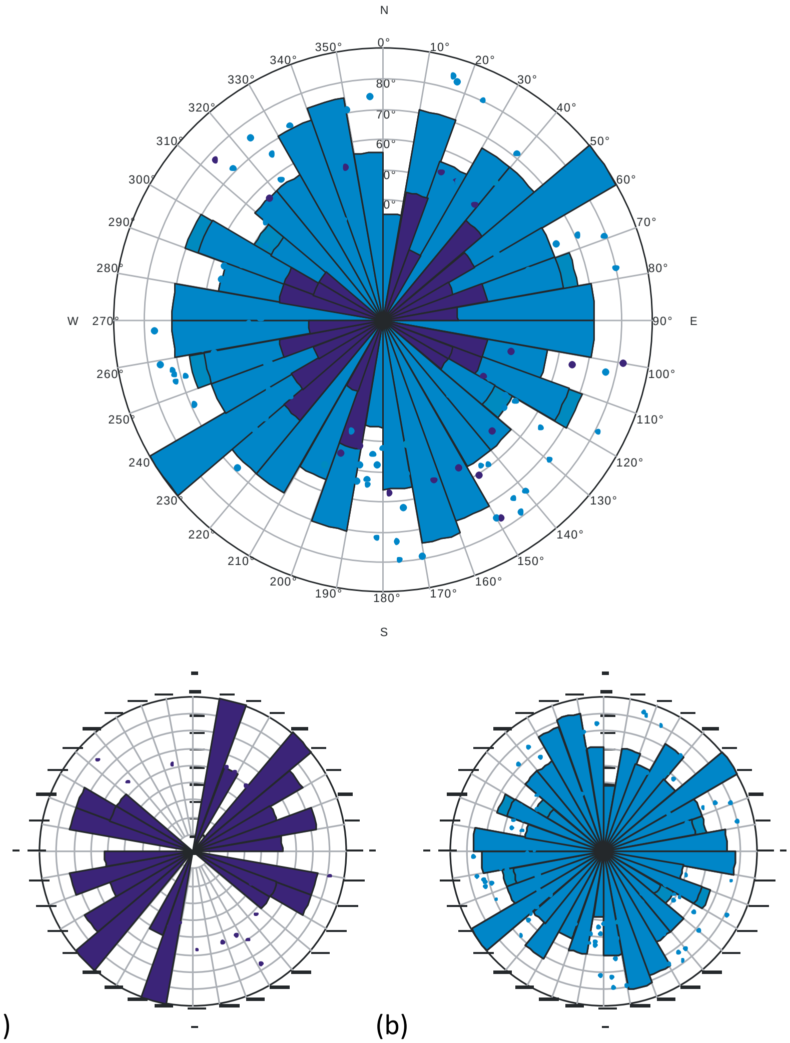


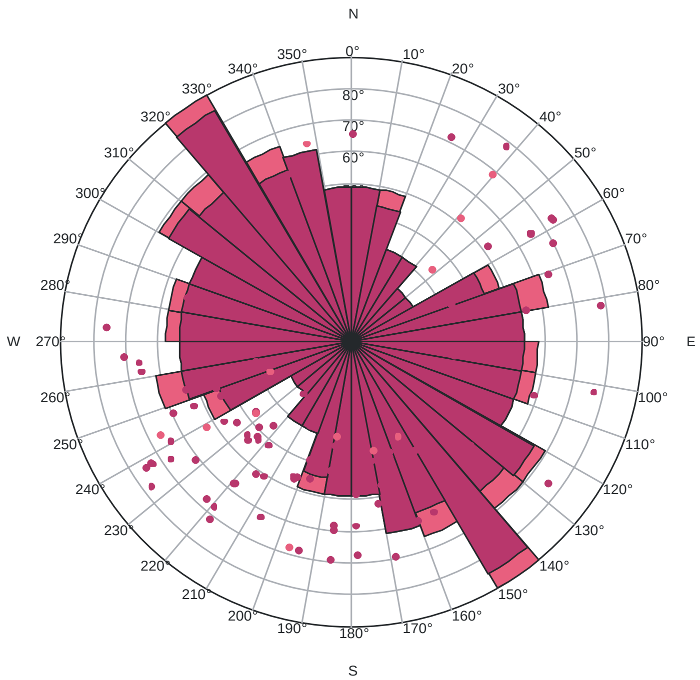
Figure 65 Cumulative fan plot of strike orientation of conductive fractures (upper central figure) , further divided into continuous (a) and discontinuous conductive fracture (b).

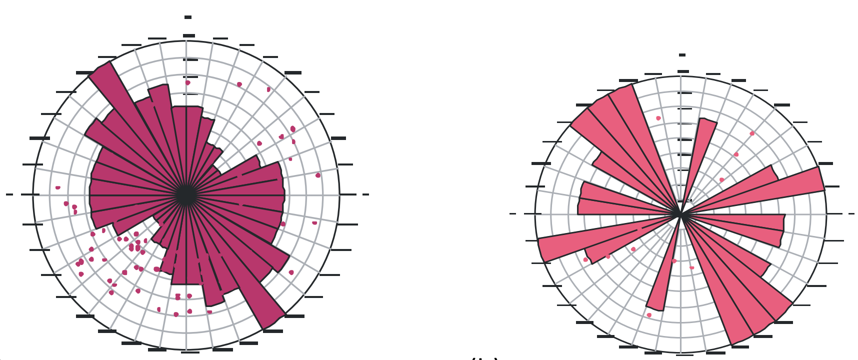
7.2. Cumulative diagram of shear fractures

A total of 114 shear fractures were identified in the study area over Grand Rapids and Colorado Shale formations as seen on Figure 66. This category of fractures comprises both open (conductive trace) or healed (resistive) trace fractures which display obvious shear displacement an thus possibly indicating the same origin of shearing.

Out of 114 shear fractures, 101 were identified as shear conductive fractures (Figure 66a) and 13 were identified as shear resistive fractures (Figure 66b). Out of 16 investigated wells, in six wells there were no shear fractures identified: IMP OV-GR39 COLD LK 13-1-66-4; IMP OV-GR1 COLD LK 5-33-65-3; IMP OV-GR45 COLD LK 7-2-66-4; IMP 12 OV COLD LK 3-4-66-3; IMP 12 OV COLD LK 14-2-66-3; IMP 12 OV COLD LK 12-33-65-3.

The cumulative diagram of trends of all groups of shear fractures indicates clustering of fracture orientation poles with “NW/SE” striking orientation being the most dominant (peaks at 325°/145°). The secondary weaker trend is “ENE/WSW” and has more scattered distribution of strike poles (peaks at 075°/255°). This secondary trend is mostly seen in healed shear fracture strikes as seen on Figure 66b. The resistive shear group has more scatter as a result of smaller data set (trends at “NW/SE”, “ENE/WSW” and “NNE/SSW”) . However, in both data sets the maximum orientation is predominantly the “NW/SE” implying the same episode of shearing– Figure 66a and Figure 66b.





(a) (b)

Figure 66. Cumulative fan plot of strike orientation of shear fractures (upper central figure), further divided into conductive (open) shear (a) and resistive (healed) shear fractures (b).

7.3. Cumulative diagram of healed (resistive) fractures

A total of 50 resistive fractures were identified in the study area in Grand Rapids and Colorado Shale formations, as seen on Figure 67. As stated before this group of fractures does not include the healed fractures that occur in concretion beds and do not have the same origin. Out of 16 investigated wells, seven wells did not display any healed fractures on the FMI logs: IMP 12 OV COLD LK 12-33-65-3; IMP 12 OV COLD LK 12-4-66-3; IMP 12 OV COLD LK 14-2-66-3; IMP 12 OV COLD LK 3-4-66-3; IMP OV-GR1 COLD LK 5-33-65-3; IMP OV-GR2 COLD LK 4-32-65-3; IMP OV-GR39 COLD LK 13-1-66-4;

The cumulative diagram of healed fractures strikes indicate a general scattering of fracture orientation poles with some slightly visible trends. The primary set is "NE/SW" (peaks at 065°/245°). The secondary trend has more diffuse distribution of poles and "WNW/ESE" trend (peaks at 285°/105°).

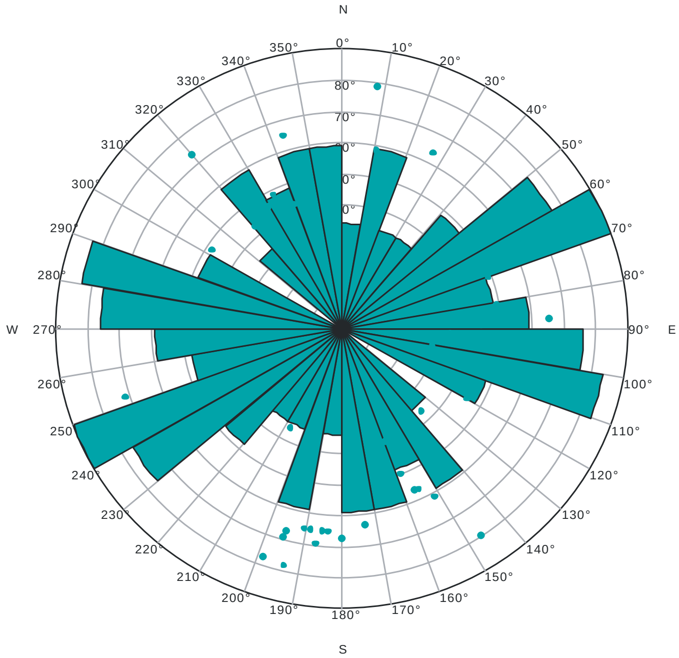


Figure 67 Cumulative fan plot of strike orientation of resistive (healed) fractures.

7.4. General conclusion

The cumulative diagrams of the three groups of brittle deformation shown in this section, did not display any directional similarities, as seen on Figures 65-67. Rather, their primary sets are in opposing directions indicating probably different mechanical and/or tectonic origin.

8. Stratigraphic Zonation of Fractures

Another analysis to further examine the presence/absence of regional fracture sets is grouping fractures according to their stratigraphic intervals. The concept behind this is to examine which fracture sets as seen on cumulative diagram of all fractures are confined only to certain stratigraphic units and also to examine if some of the fracture sets are repeated over one or several stratigraphic horizons. Figure 68 represents stratigraphic subdivision of the three major categories in the study area – open, shear and healed fractures.

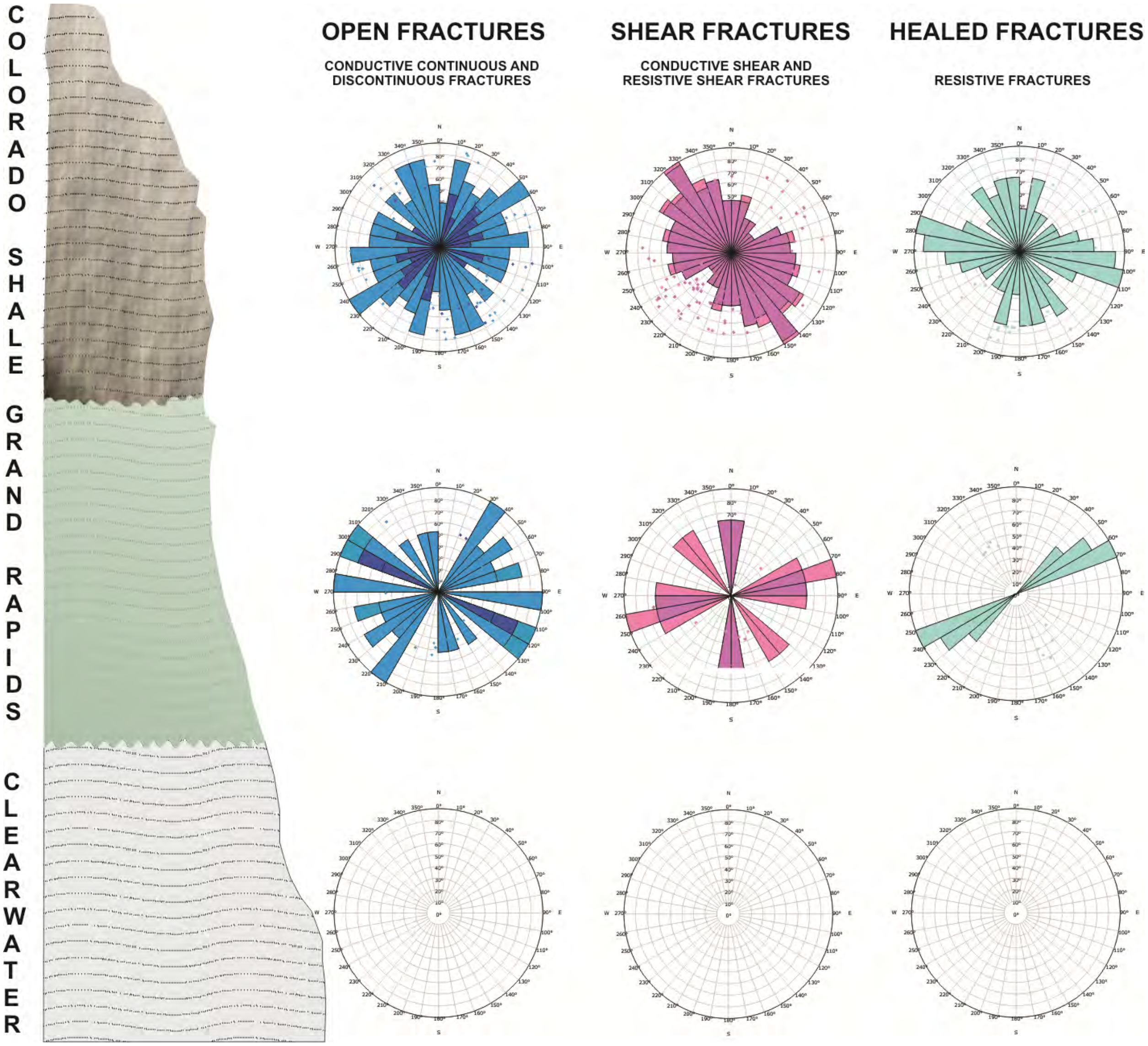


Figure 68 Stratigraphic distribution and orientation of fractures in the study area within each geological formation. Continuous conductive (open) fractures are in dark blue color, discontinuous conductive (partially open) fractures are in blue color, conductive shear fractures are displayed as magenta color, resistive shear fractures are displayed as lighter magenta color and resistive (healed) fracture are displayed in cyan color.

8.1. Fractures in Clearwater formation

No fractures of any category were identified in the Clearwater formation. In the majority of wells (80%) the logged FMI interval was ~25 meters and in a couple of them the logged interval was sufficiently large (i.e. >80m), to identify any kind of brittle deformation. Therefore, the Clearwater formation is interpreted as an intact formation in the studied wells.

8.2. Fractures in Grand Rapids formation

A total of 42 fractures out of which 21 continuous and discontinuous conductive fractures, 9 conductive and resistive shear fractures and 12 resistive fractures were identified in Grand Rapids formation in the investigated wells (Figure 68).

The distribution of the relatively small population of conductive fractures (21) shows generally scattered orientations and three trends of the same intensities – "NE/SW", "E/W" and "NW/SE". Conductive fractures in Grand Rapids formation are present in five out of 16 imaged wells. Similarly the shear fractures are represented in three out of 16 imaged wells. Their orientation indicates one major ENE/ESE trend and two secondary sets of the same intensity - "N/S" and "NW/SE". The population of resistive fractures shows distinctive "ENE/WSW" trend which is present in six out of 16 investigated wells.

All three groups of fractures do not show any directional similarities with the possible exception of resistive shears being subparallel to resistive fractures with 10^{o} difference of orientation of "ENE/WSW" trending sets. Dip magnitude of the open fractures in Grand Rapid formation varies, with the majority of them having a median dip angle (~49^{o}) as seen on the histogram of dip intensities (Figure 69).

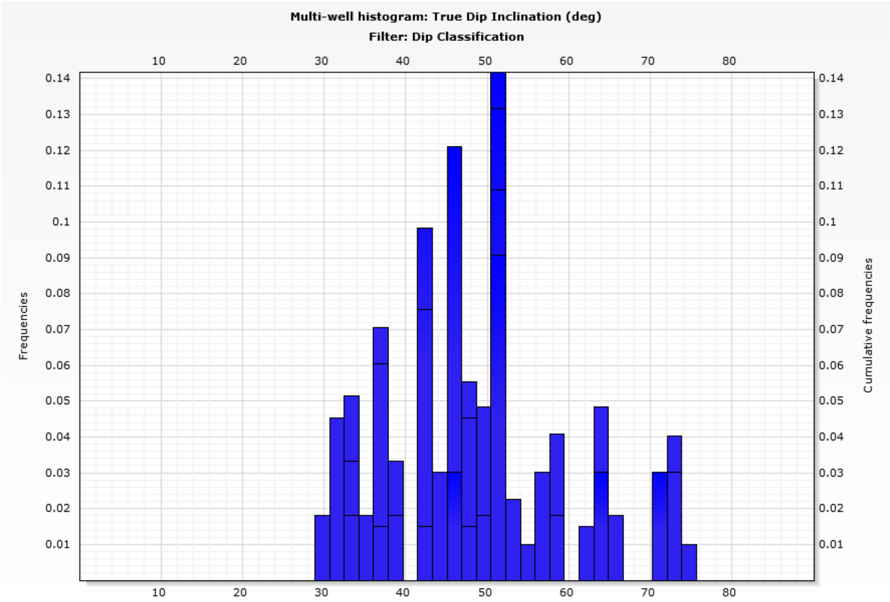


Figure 69 Histogram of the dip magnitudes of all open fractures for Grand Rapid formation.

8.3. Fractures in Colorado Shale formation

A total of 241 fractures were detected in Colorado Shale formation in the investigated wells which include: 98 continuous and discontinuous conductive fractures, 105 shear fractures (open and healed) and 38 resistive(healed) fractures (Figure 68).

Conductive fractures in Colorado Shale formation are present in 12 out of 16 imaged wells. The most dominant trend within conductive continuous and discontinuous types of fractures is "NE/SW" (peaks at 055°/235°). The orientation of the rest of population shows scattering and several trends of approximately same intensity – "ENE/WSW", "NNE/SSW" and "NNNW/SSE".

The shear fractures are represented in 9 out of 16 imaged wells. The orientation of both conductive and resistive shear fractures indicate a definite "NW/SE".

The resistive fractures are represented in 6 out of 16 imaged wells. The population of resistive fractures show "ESE/WNW" trend and some scattering in "N/S" direction.

As noted in the distribution of fractures in Grand Rapids formation, there are no similar trends between the three major groups (conductive/shear/resistive) fractures in Colorado Shale formation. Rather, their major sets have opposing directions – "NE/SW" in conductive population, "NW/SE" in shear population and "ESE/WNW" in resistive population (Figure 68).

The majority of the fractures have median to steep dip as seen on the histogram of dip intensities (Figure 70) with varying dip directions.

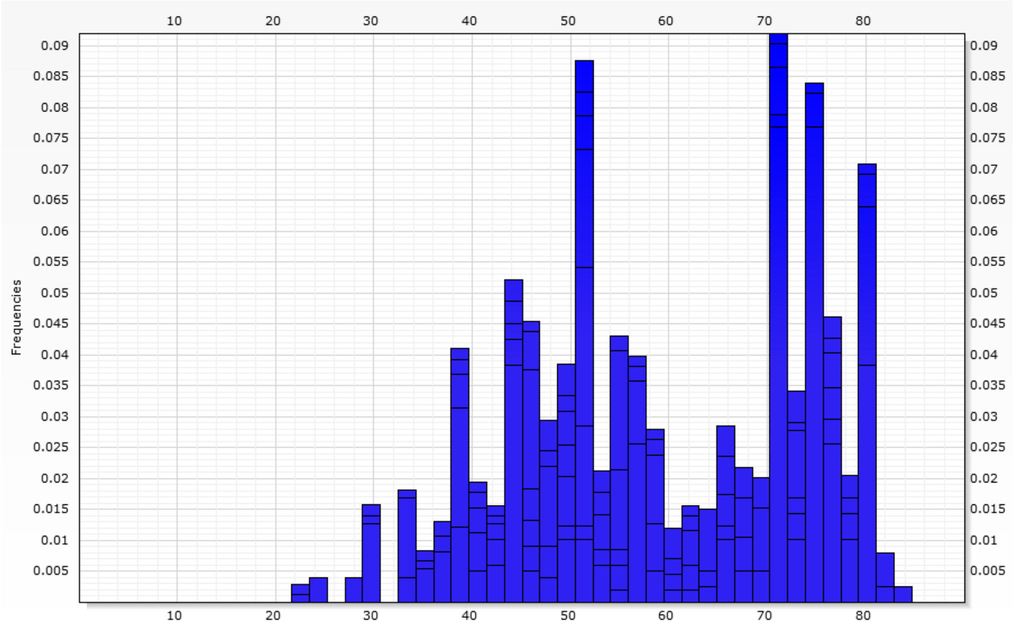


Figure 70 Histogram of the dip magnitudes of all open fractures for Colorado shale formation.

8.4. General Conclusion

The analysis in this chapter has established little or no similarities in strike orientation within the three types of fractures in both of the investigated units (Grand Rapids and Colorado Shale formations). In addition, as seen from the Figure 68 which represents all cumulative diagrams of the features identified on the images there is little or no correlation of trends along and across the Grand Rapids/Colorado shale interface. The only persistent trends established are the “NE/SW” oriented resistive population in Grand Rapids formation, and the “NW/SE” trend in the shear population of Colorado Shale formation. However, this statement only relies on the investigated wells and further testing is required to prove these trends.

9. Spatial Distribution of Fracture Orientation in the Study Area

9.1. Fracture orientation in Grand Rapids formation

In order to further examine systematics of fracturing in the area, the strike orientation of conductive continuous and discontinuous (light and dark blue) and shear conductive fractures (magenta) in the Grand Rapids formation are displayed on various Cold Lake Expansion Project maps. As discussed in previous chapters on cumulative fracture orientation, conductive fractures in the Grand Rapids formation are scarce and they exhibit random orientation in the investigated area as can be seen from Figure 71. Only two of the 8 wells that have conductive fractures have 3 or more fractures (IMP OV-GR40 COLD LK 14-23-66-4 and IMP 12 OV COLD LK 12-4-66-3) and their trend is generally “NE/SW” and “NW/SE”.

Once fractures in the Grand Rapids formation are displayed on top of Grand Rapids structure contour map it can be further inferred that there are no relationships between fracture orientation and structural grain as seen on Fig. 72. Therefore it is interpreted that the majority of these single fractures are related to some local events that are beyond the scope of the regional observation. The only exception is the highest fracture occurrence in IMP 12 OV COLD LK 12-4-66-3 that may be related to the steep gradient observed from both salt dissolution map and structure contour map. Schlumberger reviewed the maps reflecting the salt dissolution over Cold Lake area and concluded that the higher fracture intensity in Grand Rapids in well IMP 12 OV COLD LK 12-4-66-3 may be partly due to proximity to salt dissolution edge. However, the strike orientation of these fractures is not obviously related to the salt dissolution edge since fractures are cutting the roughly “N/S” striking edge of salt dissolution at high angles implying some other mechanism of formation (Figure 72).

Within the small population of resistive fractures in Grand Rapids formation an obvious “NE/SW” trend appears. Again, no obvious relationship to the structural grain can be established. The only exception is the single ‘NW/SE” striking resistive shear fracture within IMP OV-GR40 COLD LK 14-23-66-4 well (Figure 73).

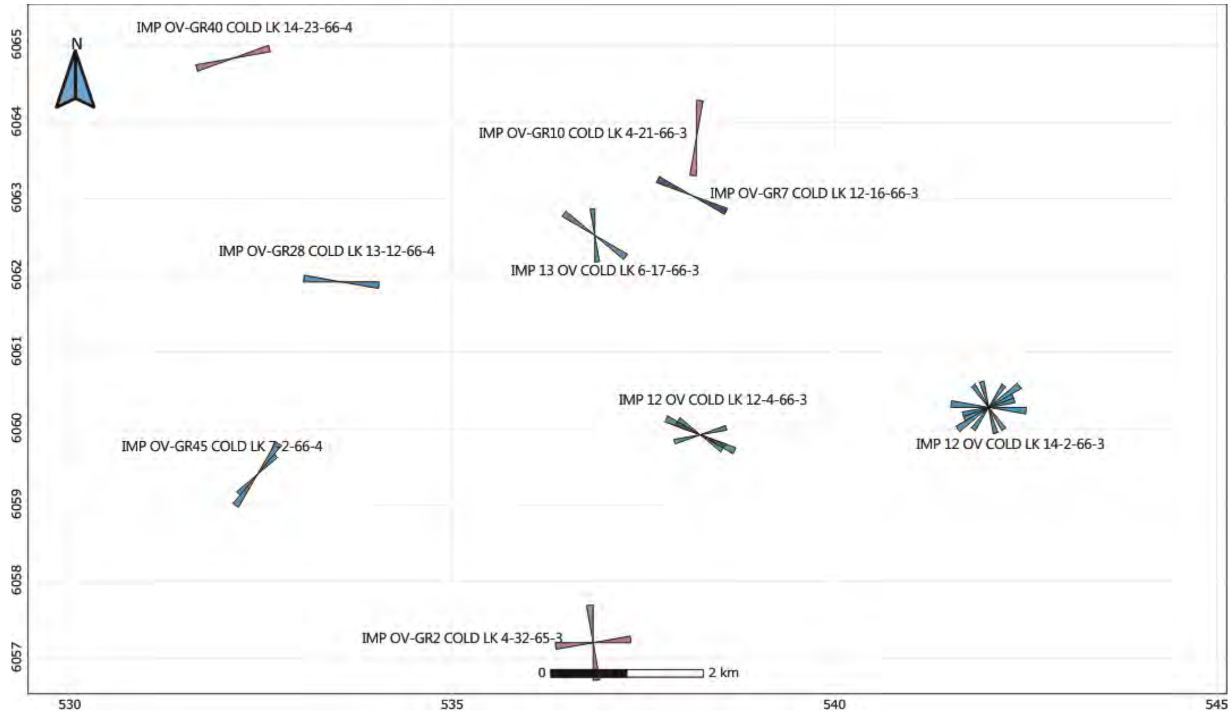


Figure 71 Fracture strike orientation of conductive continuous and discontinuous (light and dark blue) and shear conductive fractures (magenta) in Grand Rapids formation. The "x" and "y" axis are expressed in "km" units of UTM zone 12.

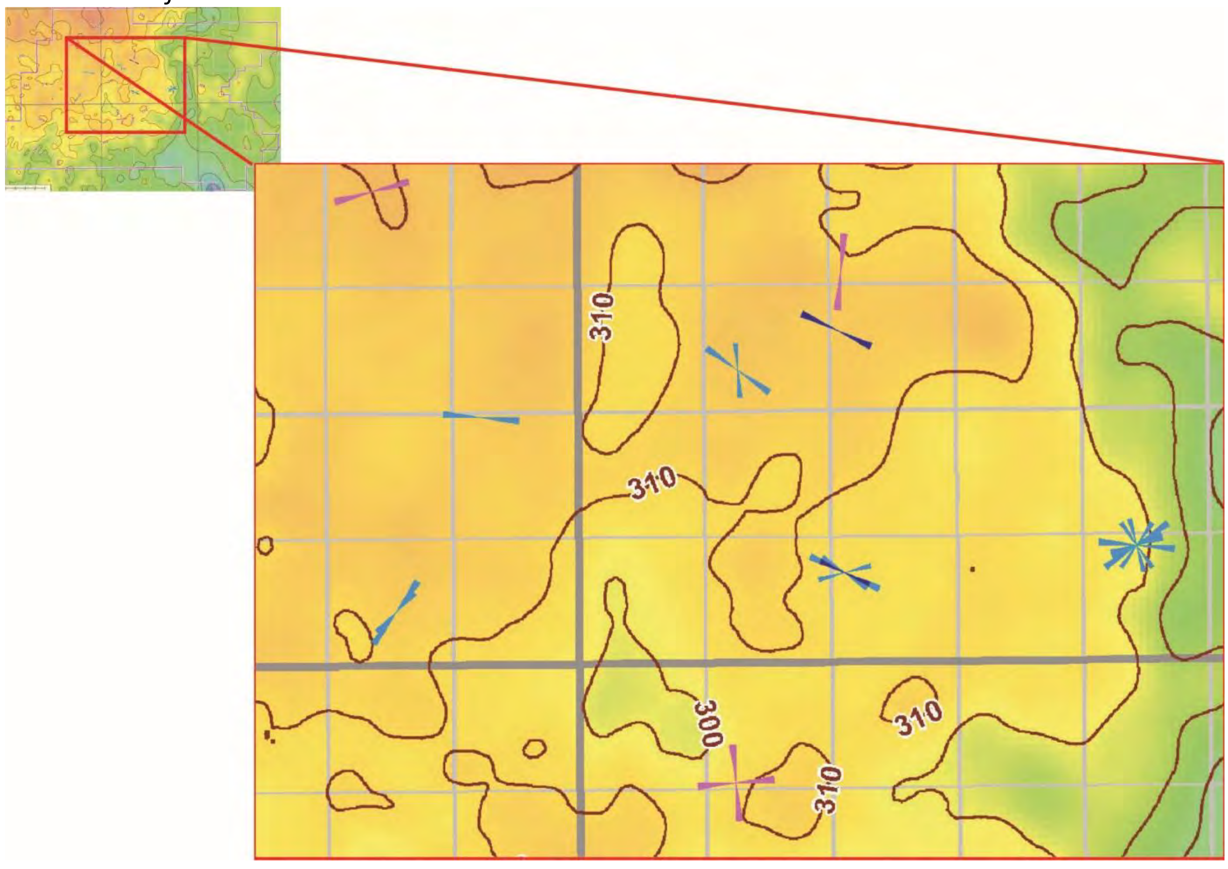


Figure 72 Same fracture orientation map as on Fig71 overlaid on structure contour map of the top of the Grand Rapids formation (contours are in m TVD).

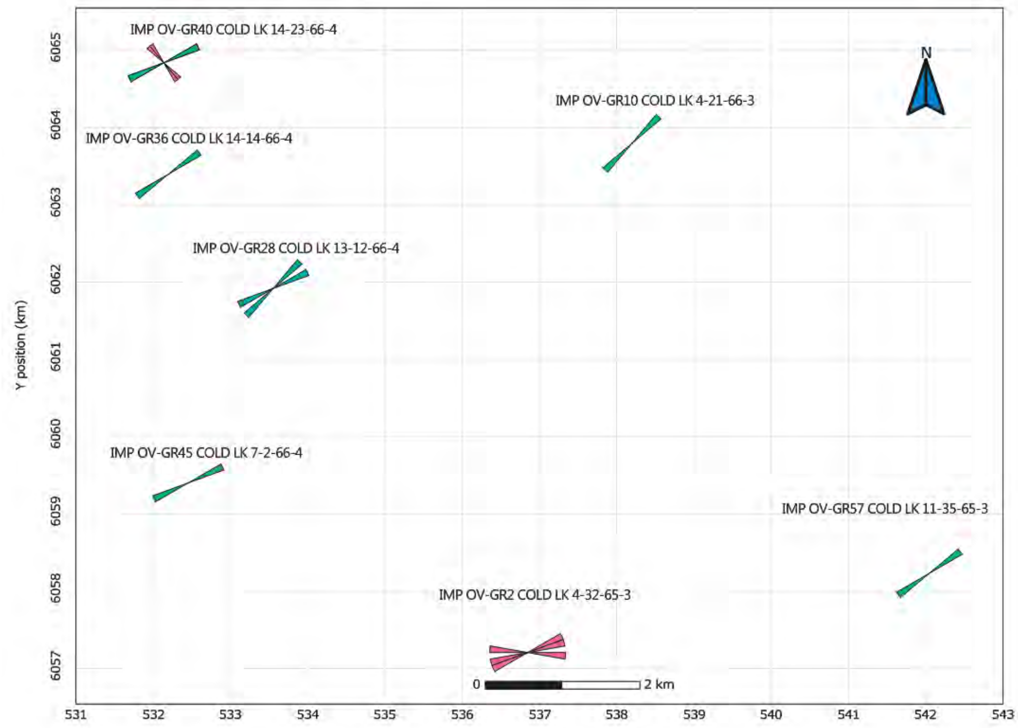


Figure 73 Fracture strike orientation of resistive shear fractures(magenta) and resistive fractures (cyan) in Grand Rapids formation. The “x” and “y” axis are expressed in “km” units of UTM zone 12.

9.2. Fracture orientation in Colorado Shale formation

Spatial distribution of conductive fracture strikes in Colorado Shale formation shows a different fracture arrangement with a couple of exceptions. The most distinguished feature is a very strong "NW/SE" trend in three neighboring wells: IMP OV-GR10 COLD LK 4-21-66-3; IMP OV-GR7 COLD LK 12-16-66-3 and IMP 13 OV COLD LK 6-17-66-3 (Figure 74). All three groups of conductive fractures (continuous , discontinuous and shear) are contributing to that trend. In contrast, the most western wells (IMP OV-GR40 COLD LK 14-23-66-4, IMP OV-GR36 COLD LK 14-14-66-4, IMP OV-GR28 COLD LK 13-12-66-4, IMP OV-GR39 COLD LK 13-1-66-4 and to a certain degree IMP OV-GR45 COLD LK 7-2-66-4) have predominantly 'NE/SW" trending fractures. In addition, the wells located to the south of the study area such as IMP OV-GR57 COLD LK 11-35-65-3, IMP OV-GR1 COLD LK 5-33-65-3 and IMP OV-GR2 COLD LK 4-32-65-3 have scattering orientations with roughly "E/W" dominant trends. Hence, it can be seen that the orientation of the fractures varies significantly with three opposing directions in three areas (Figure 74).

Once these fracture sets are overlain on the top of the structure contour map of the base of Quaternary unit the results show very close correlation with the structure grain. In almost all of the wells with more then a single fracture interpreted there is a close alignment of their orientation with the structural grain. Therefore these fractures are a reflection of the paleotopography and given the fact that they are in the upper Colorado Shale formation, they are probably the result of loading/unloading events of neotectonic age (glacial load and/or glacial isostatic rebound).

This is further supported by the orientation of resistive shear fractures and resistive fractures in Colorado Shale formation as seen on the Figure 76. These fractures have less frequency of occurrence and more scattered orientation but do follow the trend of conductive (open) group of fractures. This is especially true for "NW/SE" trending fractures in IMP OV-GR7 COLD LK 12-16-66-3 and IMP 13 OV COLD LK 6-17-66-3, and ~"E/W" of the IMP OV-GR57 COLD LK 11-35-65-3. The parallelism of the two categories: shear open and shear healed fractures, indicate the same geological episodes of the shearing.

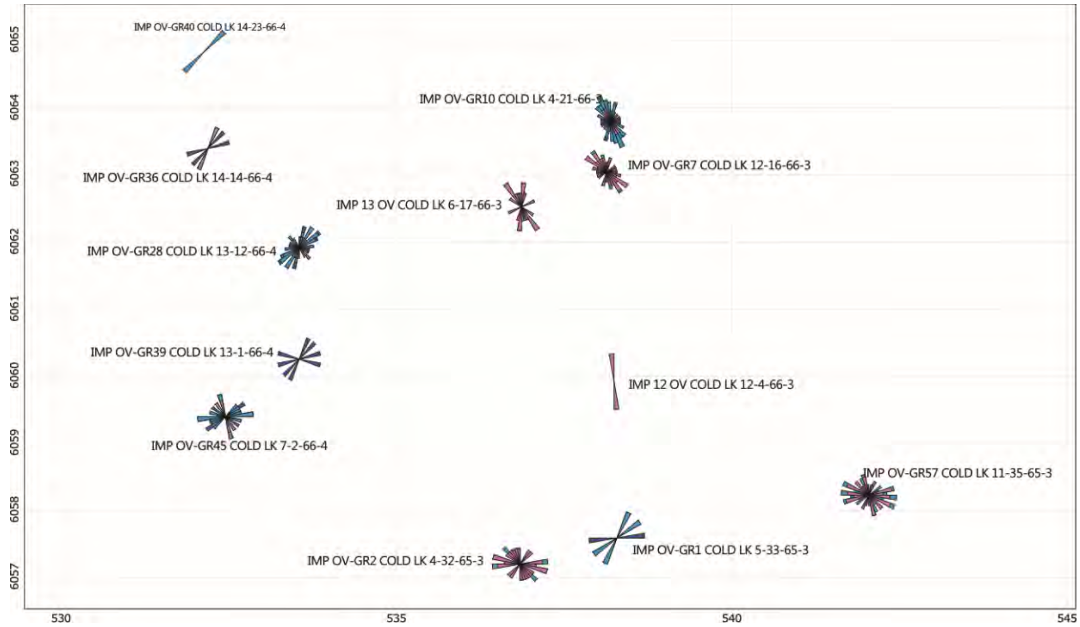


Figure 74 Fracture strike orientation of conductive continuous and discontinuous (light and dark blue) and shear conductive fractures (magenta) in Colorado Shale formation. The "x" and "y" axis are expressed in "km" units of UTM zone 12.

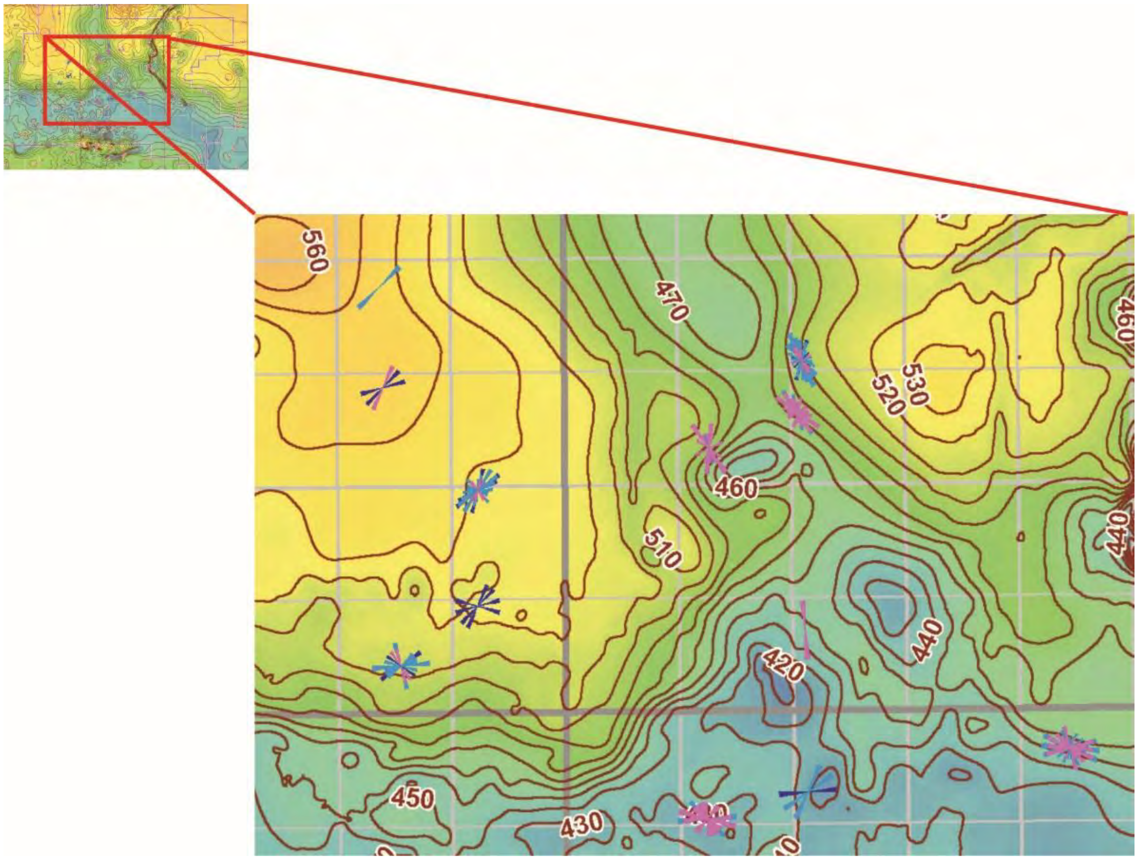


Figure 75 Same fracture orientation map as on Fig74 overlaid on the structure contour map of the top of Colorado Shale formation (contours are in m TVDSS)

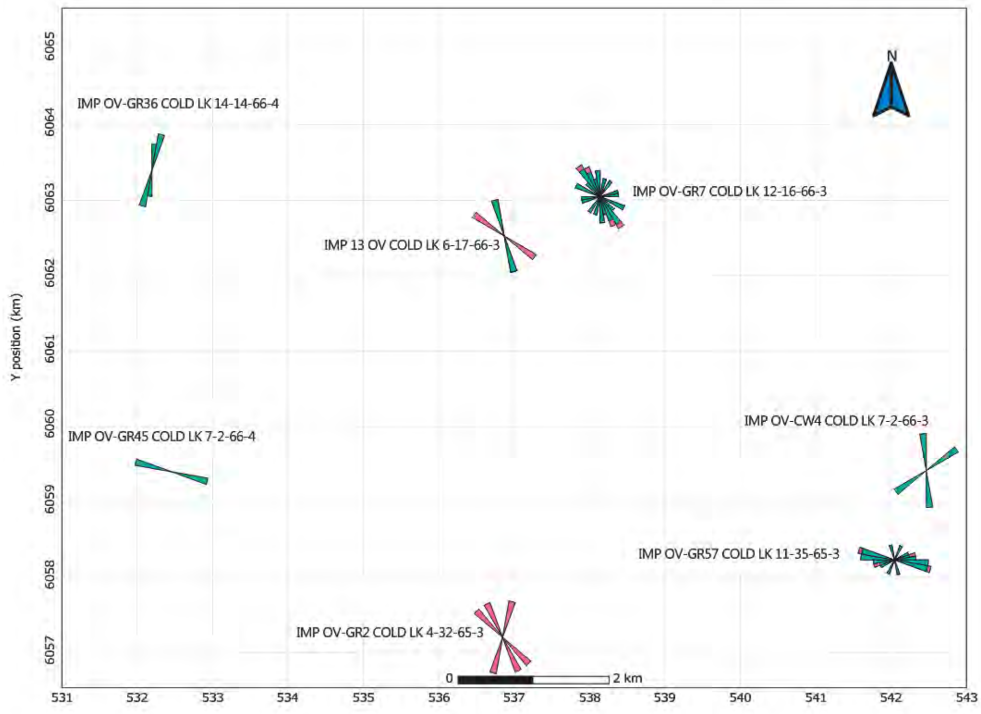


Figure 76 Fracture strike orientation of resistive shear fractures (magenta) and resistive fractures (cyan) in Colorado Shale formation. The “x” and “y” axis are expressed in “km” units of UTM zone 12.

9.3. General conclusion

Conductive fractures in the Grand Rapids formation are scarce and they exhibit random orientation in the investigated area with no relationships between fracture orientation and structural grain as seen from Figure 71 and Figure 72. Therefore the majority of these single fractures are related to local events that are beyond the scope of the regional observation. However, within the relative small population of resistive fractures in Grand Rapids formation, an obvious “NE/SW” trend appears but with no obvious relationship to the structural grain.

Spatial distribution of conductive fracture strikes in Colorado Shale formation show three distinctive trends in the investigated area: “NW/SE” trend in the north and north-east area, “NE/SW” in the west and northwest area, and scattered roughly “E/W” trend in central and southern areas. All three distinctive trends show close relationship to the structural grain possibly indicating (un)loading events of neotectonic age as the primary mechanism of their origin.

There is no relationship between orientation of fractures in Grand Rapids and Colorado Shale formations on the cumulative regional plots. Several wells have fractures that have similar trends (i.e. IMP OV-GR7 COLD LK 12-16-66-3 and IMP 13 OV COLD LK 6-17-66-3) but the number of fractures in lower Grand Rapids formation is too small to obtain any conclusive results. Therefore, there is no evidence to relate any regional trends within these two units within a single well.

10. Natural Fracture Intensity in Cold Lake Expansion Project Area

Another way of looking into fracture distribution is by plotting the average fracture density (number of fractures per stratigraphic unit thickness –f/m) on the 2D map to examine if some areas are more fractured than the others. In the following chapter the non-calibrated fracture density refers to the total number of fractures of the stratigraphic unit of the given well, whereas the calibrated fracture density was calculated as the number of fractures per measured depth (f/m) for each stratigraphic formation. As mentioned in Section 1.1., the analysis of fracture densities below didn't include resistive fractures since these are completely healed and therefore not a hazard to caprock integrity.

10.1. Fracture density in Grand Rapids formation

In the Grand Rapids formation, in seven (7) out of 16 wells there were no fractures identified. There are very few fractures in Grand Rapids formation (a total of 30). The average non calibrated number of fractures in wells where they were identified is 3.33 fractures per well for wells where fracture were observed. The calibrated average number of fractures in the Grand Rapids formation for the average thickness of ~113 meters is 0.028 fracture per meter, which translates to 1 fracture for every 34 meters. The highest fracture density is seen in: IMP 12 OV COLD LK 14-2-66-3 with 0.074 f/m, and IMP 12 OV COLD LK 12-4-66-3with 0.035 f/m.

Detailed fracture per well break down is listed in Chapter 14 -Appendix II.

The number of fractures per well map (Figures 77-78), reflects the lack of fractures in the Cold Lake area with fracture densities ranging from 0 to 9 fractures per well. This map also shows high variability in fracture densities in the neighbouring wells from the ones with no fractures like IMP OV-CW4 COLD LK 7-2-66-3 and IMP OV-GR57 COLD LK 11-35-65-3 to the most fractured well IMP 12 OV COLD LK 14-2-66-3 (Figure 77). The values of fracture number per well were then contoured using standard krigging procedure using 0.005 incremental contour gradient. The results are displayed in pseudo colour from the wells having most of the fractures in red to the ones with no fractures in blue and overlain on the top of structure contour map of Grand Rapids formation. This fracture intensity map shows very little correlation between the number of fractures and the steeper topographical gradients. The only exception is the highest density in IMP 12 OV COLD LK 12-4-66 which could be related to the drop in the elevation values as seen from structure contour map (from 300m to 280m). Generally speaking, the low number of fractures reflects peneplain structural relief.

10.2. Fracture density in Colorado Shale formation

For the Colorado Shale formation, in four (4) out of 16 wells there were no fractures identified. A total of 203 fractures were identified in Colorado Shale formation, significantly higher than the number of fractures seen in Grand Rapids formation. The average non calibrated number of fractures in wells where they were identified is 16.9 fractures/well, The calibrated average number of fractures for the average thickness of Colorado Shale formation (148.94m) is 0.11 fracture per meter or 1 fracture for every 8.8 meters. The most fractured wells are: IMP OV-GR57 COLD LK 11-35-65-3 with 0.284 f/m, and IMP OV-GR10 COLD LK 4-21-66-3 with 0.210 f/m.

In several wells the number of fractures exceeds 30 (i.e. IMP OV-GR10 COLD LK 4-21-66-3 -38 -38 fractures; IMP OV-GR57 COLD LK 11-35-65-3 -46; IMP OV-GR7 COLD LK 12-16-66-3 -31 fractures). The majority of the fractures in Colorado Shale formation are located in the upper part of the logged interval. Out of 203 fractures 22 fractures (10.83%) are within lower part of the Colorado Shale and 181 (89.17%) are in the upper part of the Colorado Shale formation. Detailed fracture per well break down is listed in Appendix II.

The map of the total number of fractures per well (Figure 79) reflects the distribution of the fractures in the Cold Lake Expansion Project area with fracture occurrences ranging from 0 to 46 fractures/well. Similarly to Grand Rapids formation fracture occurrence map, the number of fractures also varies significantly from well to well. The total number of fractures was contoured using standard krigging procedure using 0.01 incremental contour gradient. The results are displayed in pseudo colour from the wells having most of the fractures in red to the ones with no fractures in blue and overlain on the top of structure contour map of Colorado Shale formation. Here, the fracture intensity map shows higher degree of correlation between the number of fractures and topographical (slope) gradients (Figure 80). This especially applies to steeper “NW/SE” trending slope with IMP OV-GR10 COLD LK 4-21-66-3, IMP OV-GR7 COLD LK 12-16-66-3 and IMP 13 OV COLD LK 6-17-66-3 having 38,31 and 14 fractures respectively. However, in some other wells (i.e. IMP OV-GR28 COLD LK 13-12-66-4) the higher number of fractures is not consistent with any structural relief exhibited. In general, there is a good correlation between steeper slopes of the top of Colorado Shale structure and the increased number of fractures.

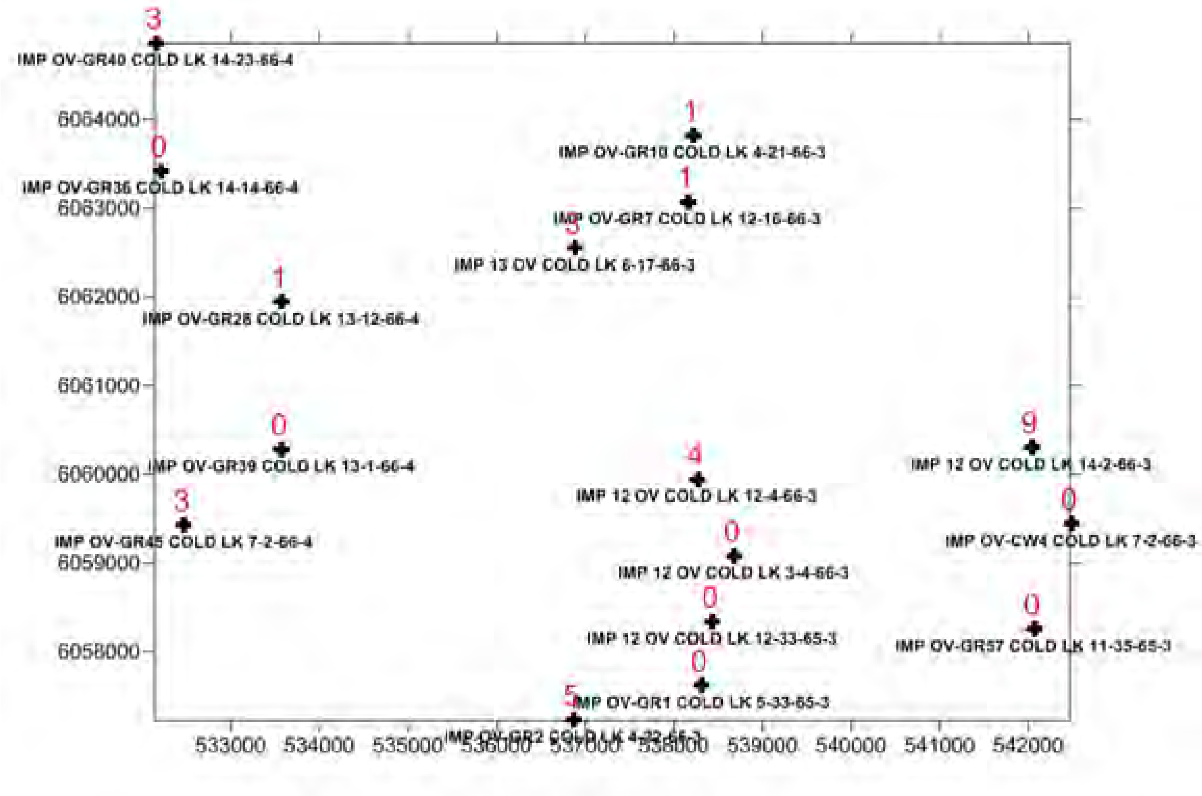


Figure 77 Grand Rapids total number of conductive fractures per well. The “x” and “y” axis are expressed in “m” units of UTM zone 12.

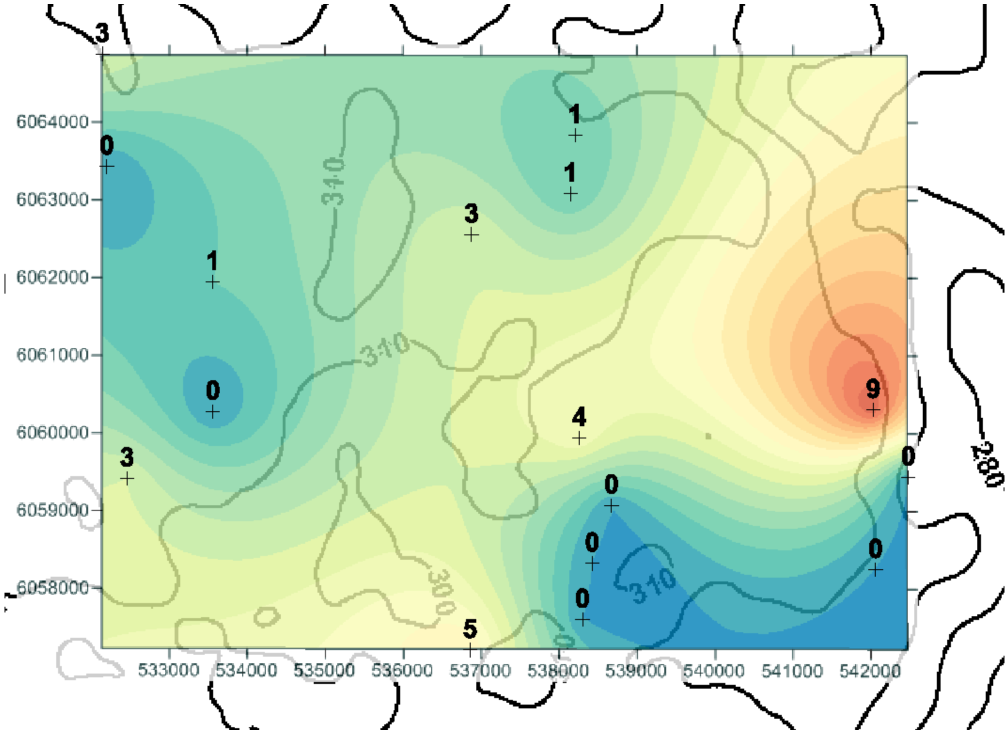


Figure 78 Grand Rapids fracture density map (color scale – higher fracture number displayed in shades of red; lower fracture number displayed in shades of green and blue) on the top of Grand Rapids structure contour map (contours are in m TVD).

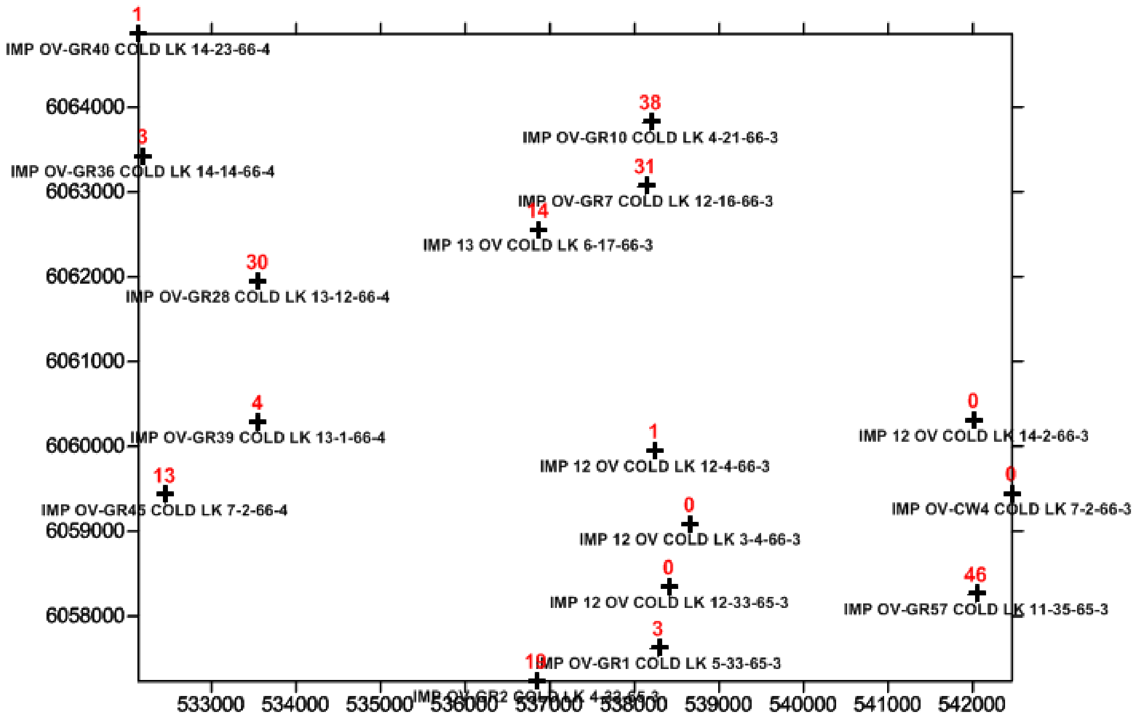


Figure 79 Colorado Shale total number of conductive fractures per well. The “x” and “y” axis are expressed in “m” units of UTM zone 12.

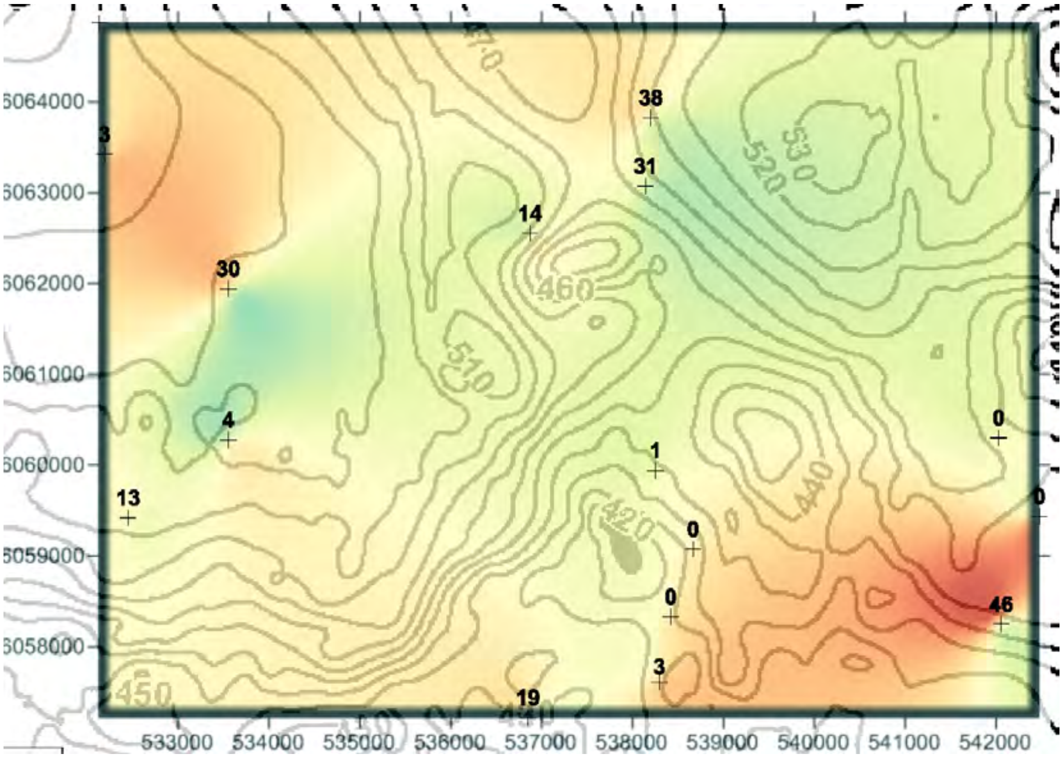


Figure 80 Colorado Shale fracture density map (color scale – higher fracture number displayed in shades of red; lower fracture number displayed in shades of green and blue) on the top of Colorado Shale structure contour map (contours are in m TVDSS).

10.3. General conclusion

The results of fracture density analysis show very different distribution and intensity of fractures as seen from Figures 77-80. Fracture density maps of Grand Rapids and Colorado Shale formations have a different distribution of intensities with fractures in Grand Rapids formation being very few to fractured upper Colorado Shale formation. In Colorado Shale formation the majority of highly fractured wells are located along the steeper paleoslopes which control the strikes of the major fracture set within the well.

11. Conclusion

Imperial Oil (IOL), have commissioned Schlumberger to perform a study for caprock fractures characterization on 16 wells in the development area of Cold Lake Expansion project. The results of this analysis will be used in conjunction with other studies to determine the competency of the caprock for fluids injection in their planned SA-SAGD development project. Image data were used to identify and characterize the natural fractures in the Colorado Shale (caprock), Grand Rapids (GR) and Clearwater (CLW) formations.

The fracture study was performed as a two-step analysis. The first part of the report describes the type of features identified on within each well, focusing mainly on brittle deformation i.e. open –conductive fracture, healed - resistive fracture, shear -minor displacement faulting, drilling induced fracture and borehole breakout. In addition the orientation of these features were part of the analysis. The second part of the study involves quantitative analysis to determine if fractures have systematic trends in orientation: a. across stratigraphic boundaries; b. spatially within the same stratigraphic unit; and c. within the same well. In addition fracture densities for each stratigraphic unit were also determined and compared to the equivalent structure contour maps.

Study results:

- The study has identified 42 natural fractures (12 resistive) in the GR formation and 241 (38 resistive) in the caprock. There were no fractures identified in the CLW formation. The average calibrated density of all open fractures is 0.028 in the GR and 0.11 In the caprock. 89.17% of the fractures in the Colorado Shale formation are occurring in the upper part of the formation. The majority of highly fractured wells in upper Colorado Shale formation are located along steeper paleo-slopes as seen from the structure contour map.
- Interpretation of the fractures from the FMI logs show no correlation of strike orientation trends across the Grand Rapids/Colorado shale interface and no relationship between orientation of fractures in Grand Rapids and Colorado Shale formation on the cumulative regional plots. The analysis has not identified any systematic trends within the same stratigraphic unit with the exceptions of the “NE/SW” - oriented healed fractures in the Grand Rapids formation and the “NW/SE” trend in the shear fracture population of Colorado Shale formation. Several wells have similar strike trends in GR and caprock, but the number of

fractures in the GR formation is too small to make any conclusive results; therefore, there is no evidence to relate any regional trends within these two units within a single well.

- Open fractures in the GR Formation are scarce and exhibit random orientation in the investigated area with no relationships between fracture orientation and structural grain; therefore it is concluded that these single fractures are related to local events.
- Spatial distribution of conductive fracture strikes in Colorado Shale formation show three distinctive trends, “NW/SE”,“NE/SW” and “E/W”, in three separate areas. All three trends show close relationship to the structural grain indicating (un)loading events of neotectonic age as the primary mechanism of their origin.

In summary, the natural fractures in the GR formation are scarce and show no evident trends to assess an obvious mechanism of fracture generation. There is also no relationship between the natural fractures in the Grand Rapids formation and the caprock.

The caprock portion of the FMI logs shows more fracturing in the upper part of Colorado Shale formation. The highest fracture density in the caprock is related to the denser structural gradient, implying a neotectonic source of origin. The average non calibrated number of fractures in the caprock unit where they were identified is 16.9 fractures per meter, with the highest density of 46 fractures in IMP OV-GR57 COLD LK 11-35-65-3 well.

The average calibrated number of natural all open fractures per metre (0.11) in the caprock is not indicative of fracture connectivity in the caprock in the 16 FMI wells analyzed; the caprock appears intact from the standpoint of fluid transmissivity through natural fractures.

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13. Appendix I List of Wells

WELL NAME	UTME	UTMN
IMP 12 OV COLD LK 12-33-65-3	538413.82	6058338.08
IMP 12 OV COLD LK 12-4-66-3	538246.55	6059945.2
IMP 12 OV COLD LK 14-2-66-3	542016.13	6060303.56
IMP 12 OV COLD LK 3-4-66-3	538660.04	6059081.07
IMP 13 OV COLD LK 6-17-66-3	536866.52	6062550.26
IMP OV-CW4 COLD LK 7-2-66-3	542464.35	6059440.98
IMP OV-GR1 COLD LK 5-33-65-3	538288.34	6057618.16
IMP OV-GR10 COLD LK 4-21-66-3	538195.37	6063821.19
IMP OV-GR2 COLD LK 4-32-65-3	536844.79	6057230.29
IMP OV-GR28 COLD LK 13-12-66-4	533552.25	6061942.47
IMP OV-GR36 COLD LK 14-14-66-4	532193.36	6063420.16
IMP OV-GR39 COLD LK 13-1-66-4	533552.51	6060281.76
IMP OV-GR40 COLD LK 14-23-66-4	532136.84	6064862.81
IMP OV-GR45 COLD LK 7-2-66-4	532451.85	6059425.24
IMP OV-GR57 COLD LK 11-35-65-3	542043.98	6058256.04
IMP OV-GR7 COLD LK 12-16-66-3	538137.1	6063070.36

14. Appendix II Total and average fracture distribution in the Grand Rapids formation

Well name	Logged interval (m)	[2]ALL CONDUCTIVE FRACTURES	ALL FRACTURES BUT PURE RESISTIVE	ALL HEALED RESISTIVE FRACTURES	# shear conductive and conductive fractures average density (f/m)
		# shear (open) conductive and conductive (open continuous and discontinuous) fractures	# shear (open) conductive/ shear (healed) resistive and conductive fractures	# resistive (healed) fractures and shear (healed) resistive	
IMP 12 OV COLD LK 12-33-65-3	112.8899	0	0	0	0.000
IMP 12 OV COLD LK 12-4-66-3	113.3995	4	4	0	0.035
IMP 12 OV COLD LK 14-2-66-3	121.6904	9	9	0	0.074
IMP 12 OV COLD LK 3-4-66-3	109.9247	0	0	0	0.000
IMP 13 OV COLD LK 6-17-66-3	108.9407	3	3	0	0.028
IMP OV-CW4 COLD LK 7-2-66-3	127.7987	0	0	0	0.023
IMP OV-GR1 COLD LK 5-33-65-3	112.6823	0	0	0	0.000
IMP OV-GR10 COLD LK 4-21-66-3	120.0666	1	1	1	0.008
IMP OV-GR2 COLD) LK 4-32-65-3	111.0413	2	5	3	0.018
IMP OV-GR28 COLD LK 13-12-66-4	113.9315	1	1	2	0.009
IMP OV-GR36 COLD LK 14-14-66-4	114.5069	0	0	3	0.000
IMP OV-GR39 COLD LK 13-1-66-4	84.7569	0	0	0	0.000
IMP OV-GR40 COLD LK 14-23-66-4	113.3317	1	3	5	0.009
IMP OV-GR45 COLD LK 7-2-66-4	112.7725	3	3	2	0.027
IMP OV-GR57 COLD LK 11-35-65-3	129.7101	0	0	1	0.000
IMP OV-GR7 COLD LK 12-16-66-3	113.9881	1	1	0	0.009

[2] All values from Conductive fractures column (shaded in green) was used for fracture density map calculation column (shaded in red)

15. Appendix III Total and average fracture distribution in the Colorado Shale formation

WELL NAME	Logged interval (m)	ALL CONDUCTIVE FRACTURES[3]	ALL FRACTURES BUT PURE RESISTIVE	# of fractures in Lower Colorado	# of fractures in Upper Colorado	ALL HEALED RESISTIVE FRACTURES	# shear conductive and conductive fractures average density (f/m)
		# shear (open) conductive and conductive (open continuous and discontinuous) fractures	# shear (open) conductive/ shear (healed) resistive and conductive fractures			# resistive (healed) fractures and shear (healed) resistive	
IMP 12 OV COLD LK 12-33-65-3	122.9792	0	0	0	0	0	0.000
IMP 12 OV COLD LK 12-4-66-3	140.6533	1	1	1	0	0	0.007
IMP 12 OV COLD LK 14-2-66-3	174.4772	0	0	0	0	0	0.000
IMP 12 OV COLD LK 3-4-66-3	126.3207	0	0	0	0	0	0.000
IMP 13 OV COLD LK 6-17-66-3	165.4499	13	14	1	13	2	0.079
IMP OV-CW4 COLD LK 7-2-66-3	133.876	0	0	0	0	2	0.000
IMP OV-GR1 COLD LK 5-33-65-3	95.313	3	3	0	3	0	0.031
IMP OV-GR10 COLD LK 4-21-66-3	180.5245	38	38	1	37	0	0.210
IMP OV-GR2 COLD LK 4-32-65-3	118.9005	16	19	4	15	3	0.135
IMP OV-GR28 COLD LK 13-12-66-4	216.1406	30	30	3	27	0	0.139
IMP OV-GR36 COLD LK 14-14-66-4	129.9541	3	3	2	1	3	0.023
IMP OV-GR39 COLD LK 13-1-66-4	126.2336	4	4	3	1	0	0.032
IMP OV-GR40 COLD LK 14-23-66-4	142.5319	1	1	0	1	0	0.007
IMP OV-GR45 COLD LK 7-2-66-4	146.2588	13	13	4	9	1	0.089
IMP OV-GR57 COLD LK 11-35-65-3	155.1494	44	46	0	46	18	0.284
IMP OV-GR7 COLD LK 12-16-66-3	170.172	29	31	3	28	17	0.170

[3] All values from Conductive fractures column (shaded in green) was used for fracture density map calculation column (shaded in red)

16. Appendix IV Map of FMI wells used in this report