[PS]Borehole Image-Based Aperture Characterization to Identify Primary Versus Secondary Fracture Opening*

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Abstract

In this article we discuss a unique method of evaluating fracture aperture from borehole image logs and its impact in reservoir characterization. Aperture calculation from image logs relies on the resistivity contrast between the fracture trace and surrounding rock. Traditionally, fracture aperture is represented by a single value which works well for idealized "parallel plate" fractures. This falls short in nature, as fracture surfaces are characteristically rough and fracture aperture varies continuously along the surface of the fracture. Fracture aperture is the key parameter for evaluating porosity and/or permeability in type 1 or type 2 fractured reservoir. It is therefore critical to get a thorough characterization of this property along the entire surface.
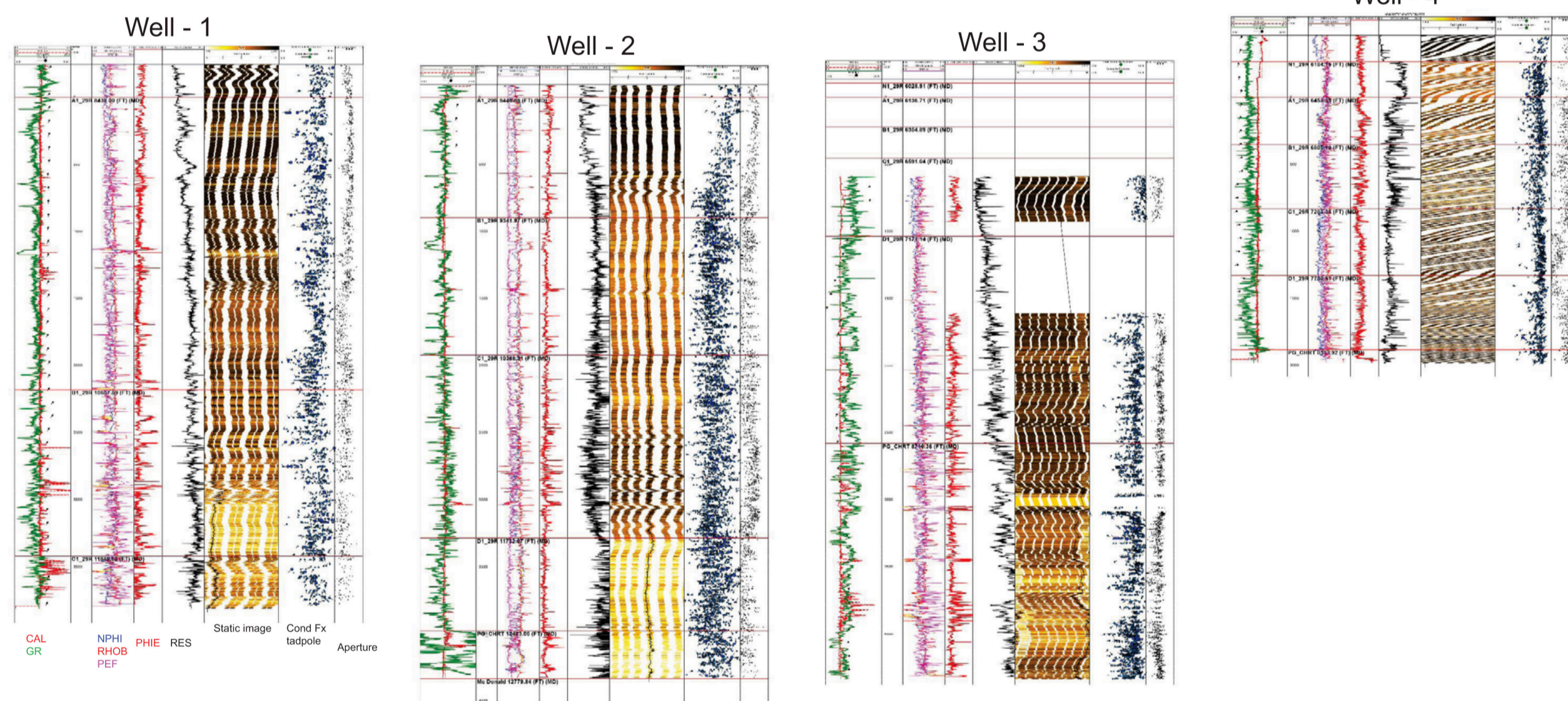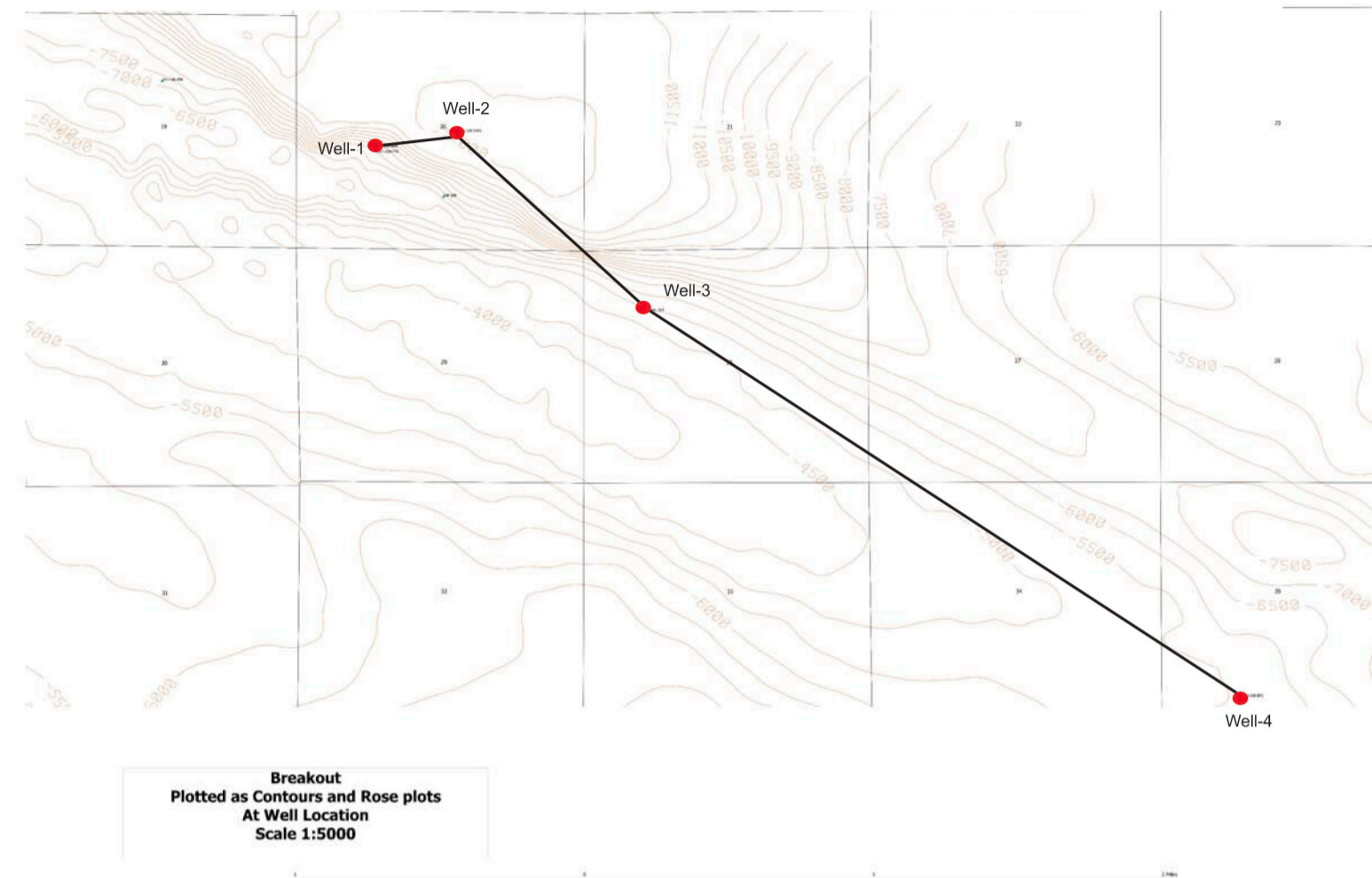
To address this issue, we have developed an algorithm that determines a continuous measurement of aperture along the trace of the fracture to capture the surface roughness (pinch and swell as opposed to parallel plate) of the fracture. The continuous data is then analyzed to identify the outliers in fracture aperture population. The outliers may be due to breakouts or some secondary processes. Based on the genetics of a fracture, the aperture variation along the trace can have a wide range with high standard deviation or a narrow range with a low standard deviation. Using this method on example reservoirs we show that typically the aperture variation can be related to the process of formation, where primary aperture will have a low standard deviation, whereas aperture created by secondary processes (like dissolution) or apertures impacted by breakouts have a high standard deviation. Based on the character of aperture the fractures, they can be classified in various groups that can in turn be related to facies hosting the fractures, thus providing a more robust means to distribute fracture porosity/permeability by facies in a static model. This method is especially beneficial in a carbonate or mixed carbonate system where facies are more likely to be altered by later diagenetic processes causing destruction or enhancement of aperture due to dissolution, recrystallization or filling. Characterizing and classifying the aperture will enhance the ability to better evaluate fracture porosity/permeability over the field. This will in turn lead to improved reservoir simulation reliability, robust history matching and optimized infill development in fractured reservoir fields.

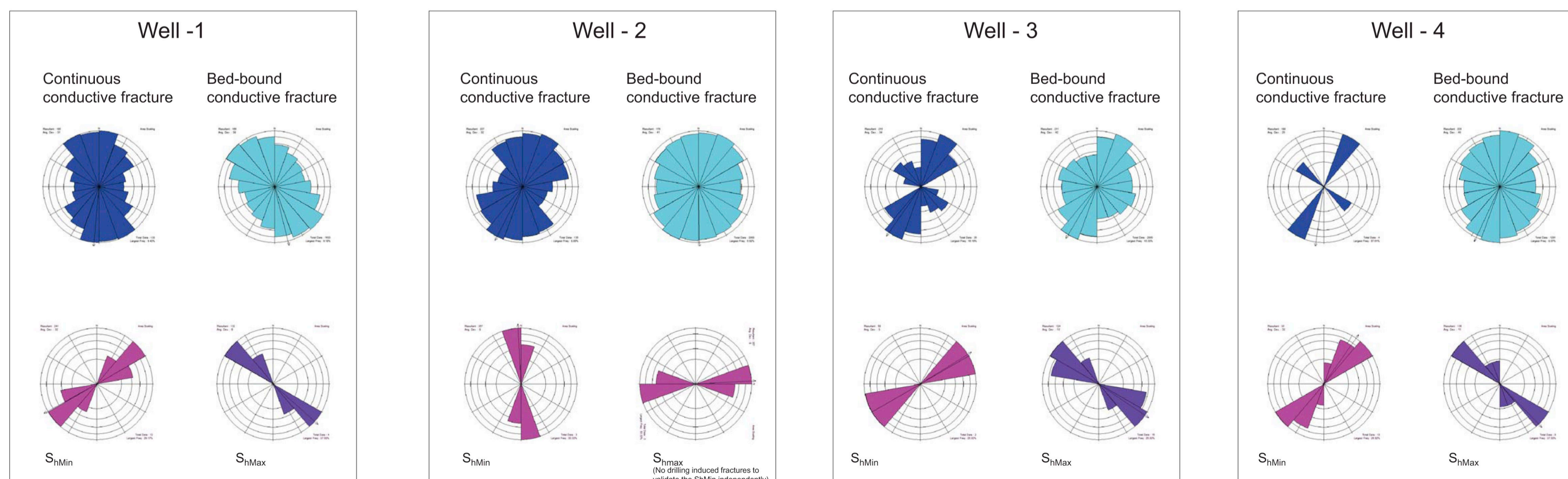# Borehole Image-Based Aperture Characterization to Identify Primary Versus Secondary Fracture Opening

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In this paper we discuss a unique method of evaluating fracture aperture from borehole image log and its impact in reservoir characterization. Aperture calculation from image log relies on the resistivity contrast between fracture trace and the surrounding rock. Traditionally fracture aperture is represented by a single value which works well for "parallel plate" fractures but falls apart in the real world where aperture varies continuously along the trace of the fracture. Fracture aperture being the key parameter for evaluating porosity and/or permeability in type 1 or type 2 fractured reservoir it is critical to get a thorough measurement of this property along the entire trace. To address this issue, we have developed an algorithm that delivers a continuous measurement of aperture along the trace of the fracture to capture the pinch and swell (or parallel plate) nature of the fracture.

The continuous data is then analyzed to identify the outliers in aperture population. The outliers may be due to breakouts or some secondary processes. Based on the genetics of fracture the aperture variation along the trace can have a wide range with high standard deviation or a narrow range with a low standard deviation. Using this method on a few reservoirs we worked on shows that typically the aperture variation can be related to the process of formation, where primary aperture will have a low standard deviation whereas aperture created by secondary processes (like dissolution) or apertures impacted by breakouts have a high standard deviation. Based on the character of aperture the fractures can be classified in various groups that can in turn be related to facies hosting the fractures thus providing a more robust means to distribute fracture porosity/permeability by facies in static model. This method is especially beneficial in carbonate or mixed carbonate system where facies are more likely to be altered by later diagenetic processes causing destruction or enhancement of aperture due to dissolution, recrystallization or filling. Characterizing and classifying the aperture will add to a predictive tool for evaluating fracture porosity/permeability over the field.


Breakout
Plotted as Contours and Rose plots
At Well Location
Scale 1:5000

Well - 1 Well - 2 Well - 3 Well - 4

CAL GR NPHI RHOB PEF PHIE RES Static image Cond Fx tadpole Aperture

Orientations

Well -1 — Continuous conductive fracture / Bed-bound conductive fracture / S_{hMin} / S_{hMax}

Well - 2 — Continuous conductive fracture / Bed-bound conductive fracture / S_{hMin} / S_{hmax} (No drilling induced fractures to validate the ShMin independently)

Well - 3 — Continuous conductive fracture / Bed-bound conductive fracture / S_{hMin} / S_{hMax}

Well - 4 — Continuous conductive fracture / Bed-bound conductive fracture / S_{hMin} / S_{hMax}

Summary

- The maximum horizontal stress as derived from the breakouts and drilling induced fractures is NW-SE (except in well 2 where it is ~ N-S)
- The conductive fractures (both continuous and bed bound) show a wide variation of strike with the dominant orientation being NS to NE-SW.
  - Wide dispersion in orientation of fracture strike indicates there are multiple sets of fracture.
  - The strike of fractures (especially for bed-bound fractures) shows some rotation from unit to unit likely indicating one set more dominant in some units than others (plots present in the 3rd section of the poster)
  - The most dominant set of conductive fractures is generally at high angle to maximum horizontal stress

Aperture algorithm

Figure - 1
Picked sinusoid

- Sinusoid
- Vertical inflexion
- True width

Figure - 2
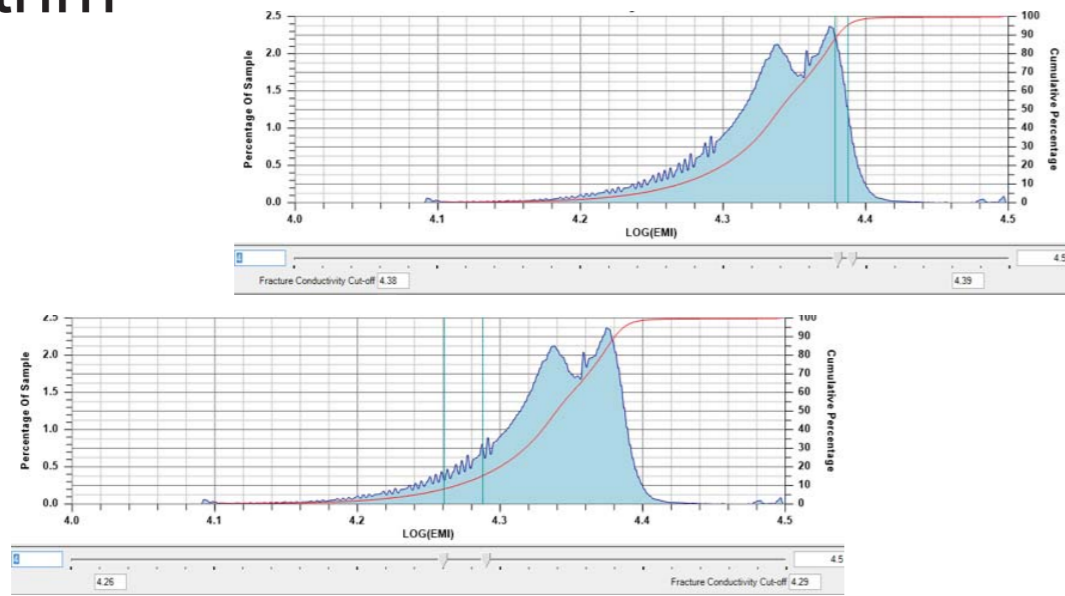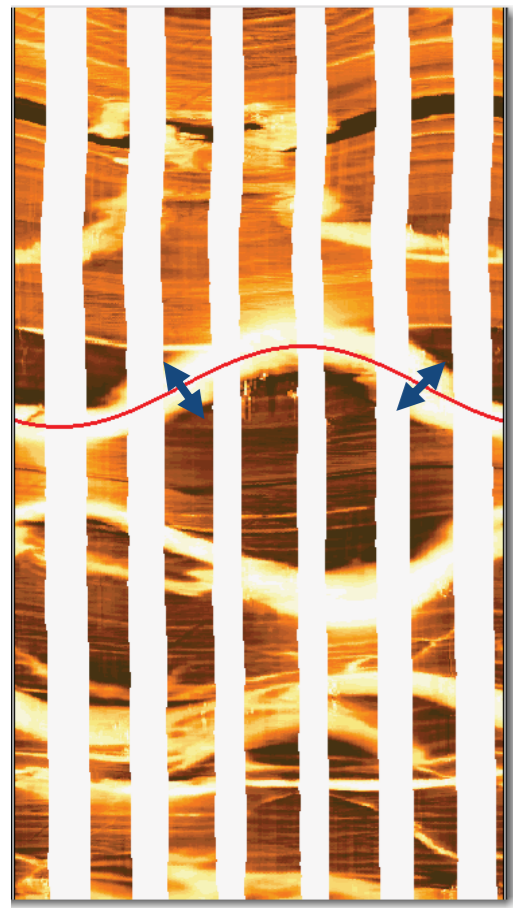
Resistivity cut-off

- Aperture is defined by using anomaly (either conductive or resistive) along the interpreted fracture
- Adjacent plot shows distribution of conductivity along the fracture
- A percentage of the distribution is used to define the aperture
  - *Using a percentage (instead of specific value) allows to use a standardized process that can be applied on data from different tools (XRMI, FMI, etc.)*
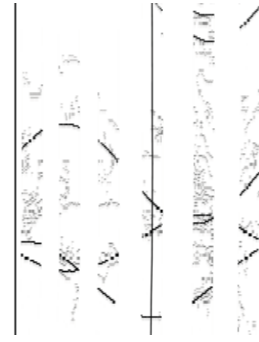- The percentage cut-off is determined by sampling several wells
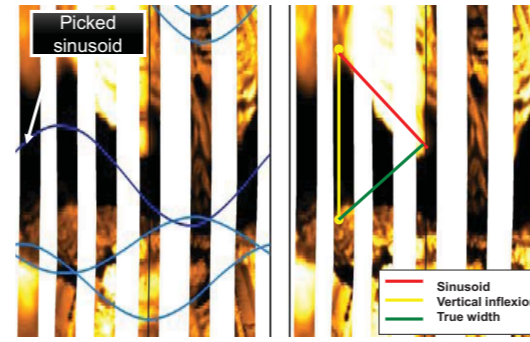
Geometry of the process

- In figure -1 The yellow dots are the minimum/maximum inflections found within the window. The yellow line is the distance between the inflection point which is at an angle to the sinusoid at a button location.
- The yellow line is projected perpendicular to the sinusoid (red) to get the fracture aperture at right angle to the fracture wall
  - This modification avoids overestimating the aperture when calculated along the sinusoid
- The trace at each button is captured for both cumulative fracture length and width. Figure-2 shows the trace of the sinusoid (of fracture) where the aperture was identified.
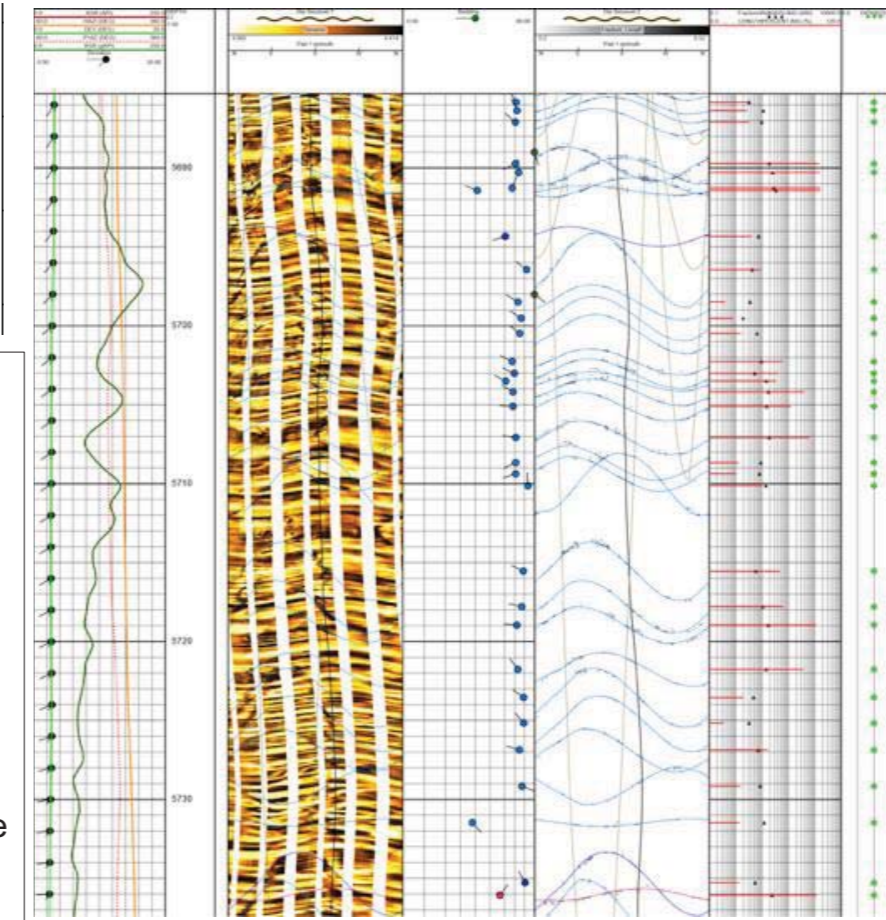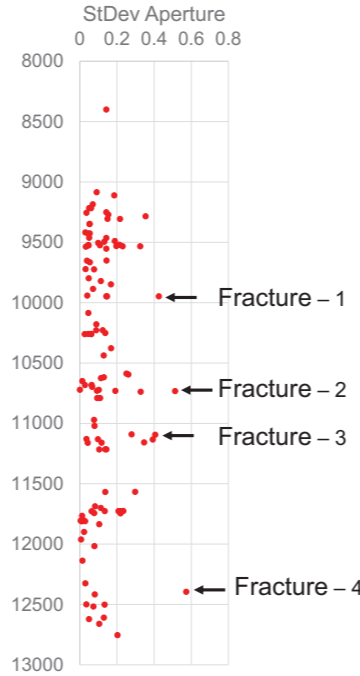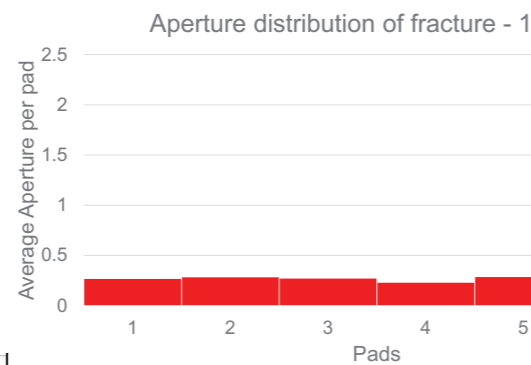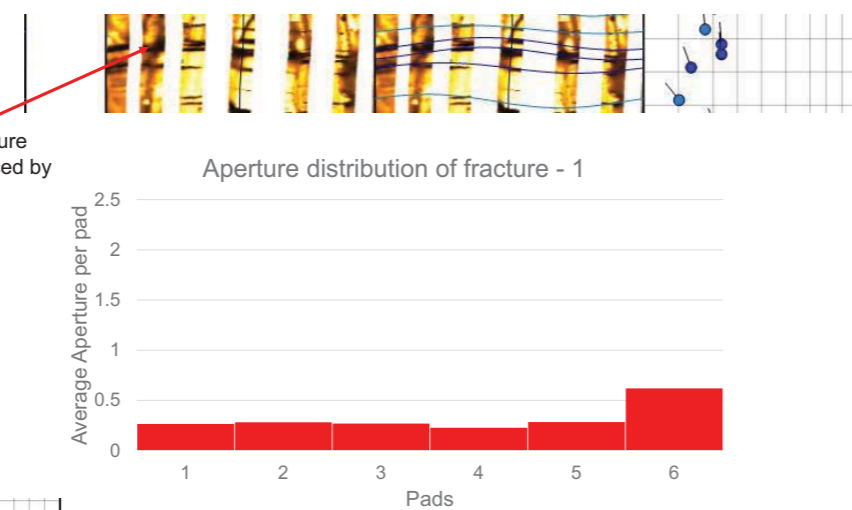
- The process provides a calculated value of aperture at each button on the pad where the fracture is recorded
  - For example: XRMI data with 6 pads up to 25 buttons in each pad will have (6 * 25 =) 150 readings of aperture for 1 fracture.
  - Thus providing an aperture profile
- The calculated aperture values at multiple points can be used for further statistical analysis to classify the aperture based on its characteristic feature
- Ideally the result is vetted against core data to get the precise cut off reasonable for the field
- Based on the stratigraphic architecture of the field the cut-off may vary for each sequence or lithologic column
  - Especially important to consider for carbonate or unconventionals
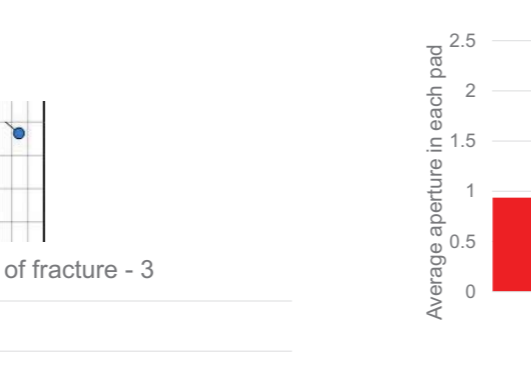
Fracture aperture influenced by dissolution

- The aperture distribution in histogram is the average aperture of all buttons calculated at each pad
- Variation of aperture across the pads highlights the profile of the aperture along the fracture
- Adjacent Plot-1 shows the standard deviation of apertures as calculated from the (average) apertures in each pad
- Standard deviation is used as an indicator to highlight the variability in fracture surface texture
  - Which might be due to the influence of secondary geological process or drilling damage
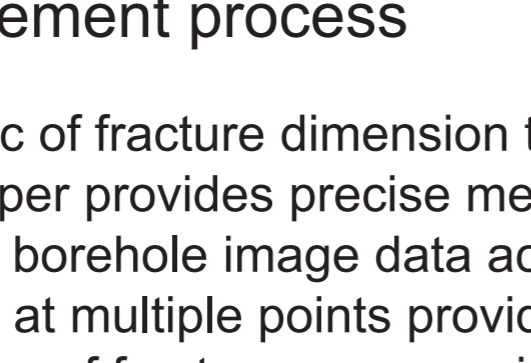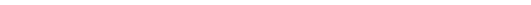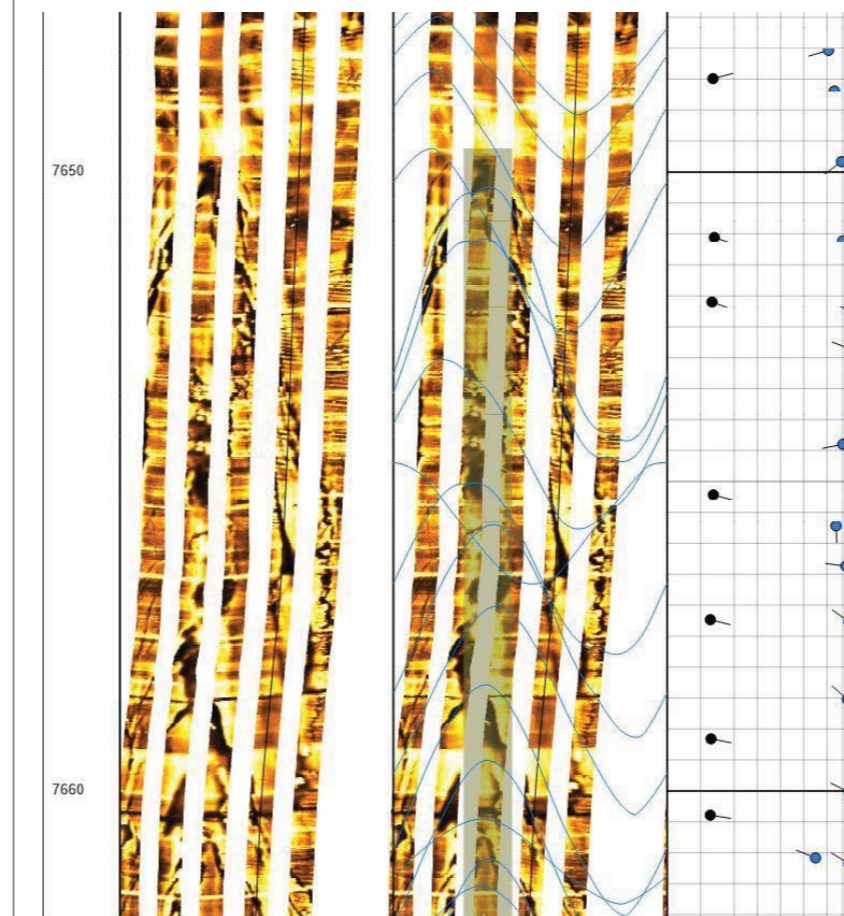
Fracture – 1

Fracture aperture (likely) enhanced by dissolution

Aperture distribution of fracture - 1

Fracture – 2

Aperture distribution of fracture - 2

Fracture – 3

Aperture distribution of fracture - 3

Fracture aperture (likely) enhanced by dissolution

Fracture – 4

Aperture distribution of fracture - 4
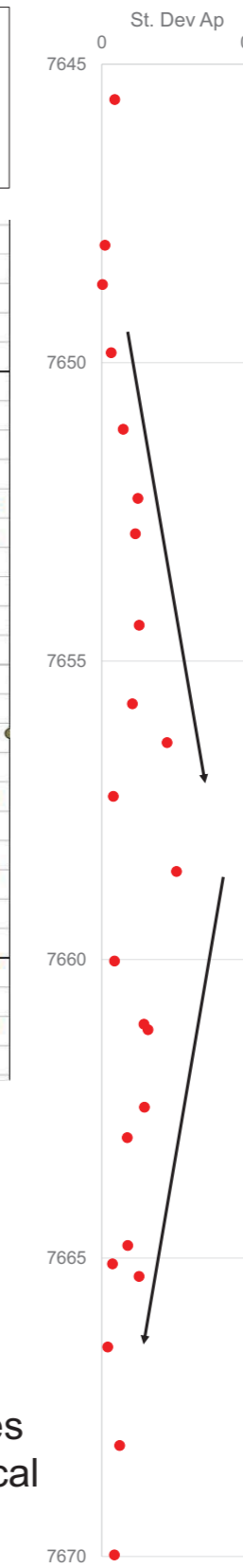
StDev Aperture
→ Fracture – 1
→ Fracture – 2
→ Fracture – 3
→ Fracture – 4

Fracture aperture influenced by breakouts

St. Dev Ap

Aperture distribution of some of the fractures within the breakout zone

Aperture distribution of fractures
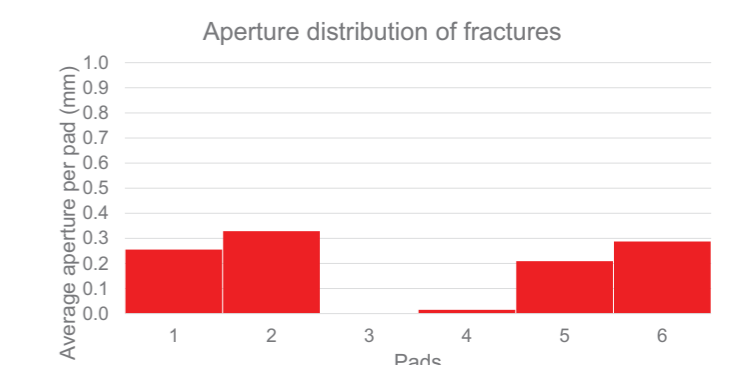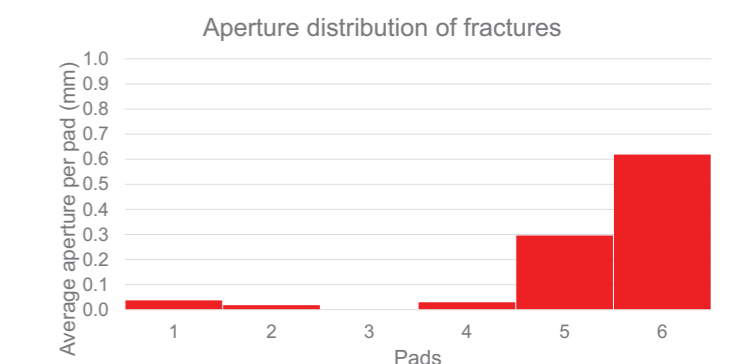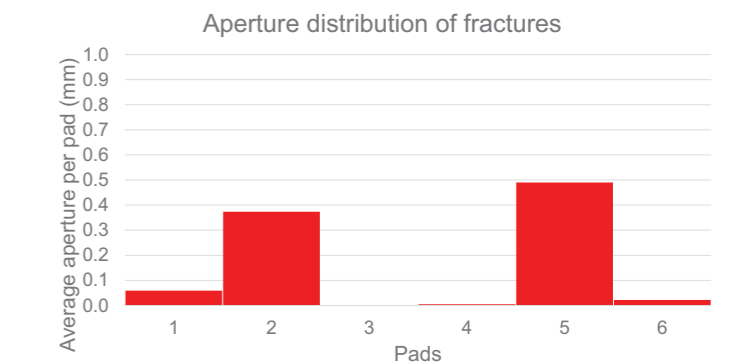
Aperture distribution of fractures

Aperture distribution of fractures

- Adjacent plot shows standard deviation of bed-bound fractures affected by breakout
- The plot shows a broad zone where the aperture values pick and then drop off
- Any such pattern in the plot is a flag for further QC
- The aperture profile of some of the fractures within the breakout zone shows a non-typical profile of fracture aperture pointing to widening of primary aperture by secondary factors (like breakouts in this case)

Summary of aperture measurement process

- Aperture is a critical characteristic of fracture dimension that can be estimated from borehole image log.
- The process described in this paper provides precise measurement of geometrically valid aperture along the fractures
  - This method can be applied on borehole image data acquired by any tool
- Capability of measuring aperture at multiple points provides an essential tool for evaluating aperture profile
- Simple analysis using the aperture of fractures can provide significant insight about the character and diagenesis of fracture that can impact field development

Logs derived from image log

Fracture density and porosity curves for **Continuous Conductive Fractures**

Rose diagram of continuous conductive fractures in each unit

Well - 1 | Well - 2 | Well - 3 | Well - 4 | Well - 4
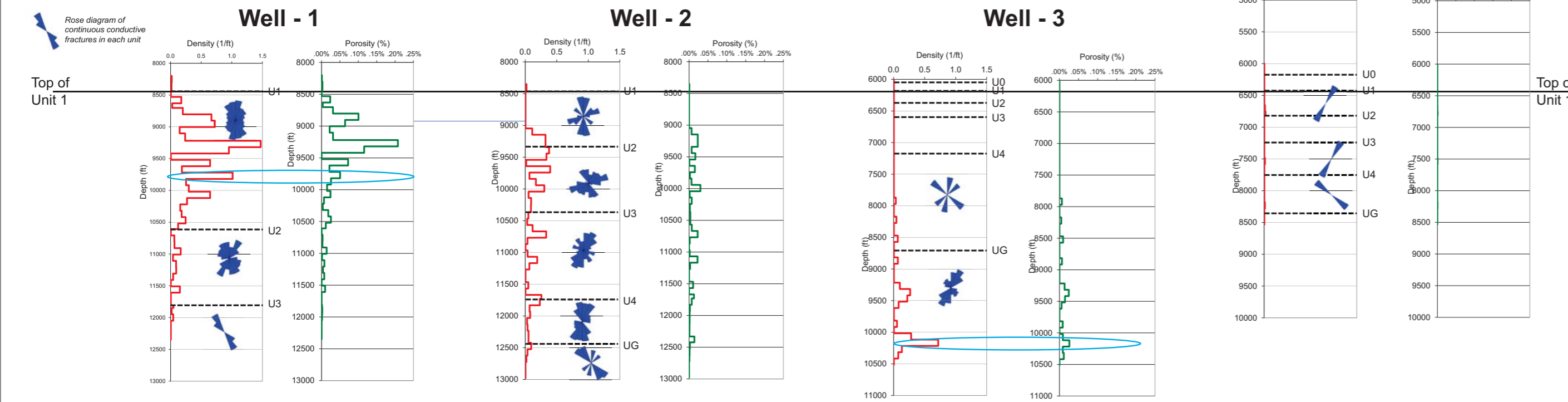
Fracture density and porosity curves for **Bed-bound Conductive Fractures**

Rose diagram of bed-bound conductive fractures in each unit

Well - 1 | Well - 2 | Well - 3 | Well - 4
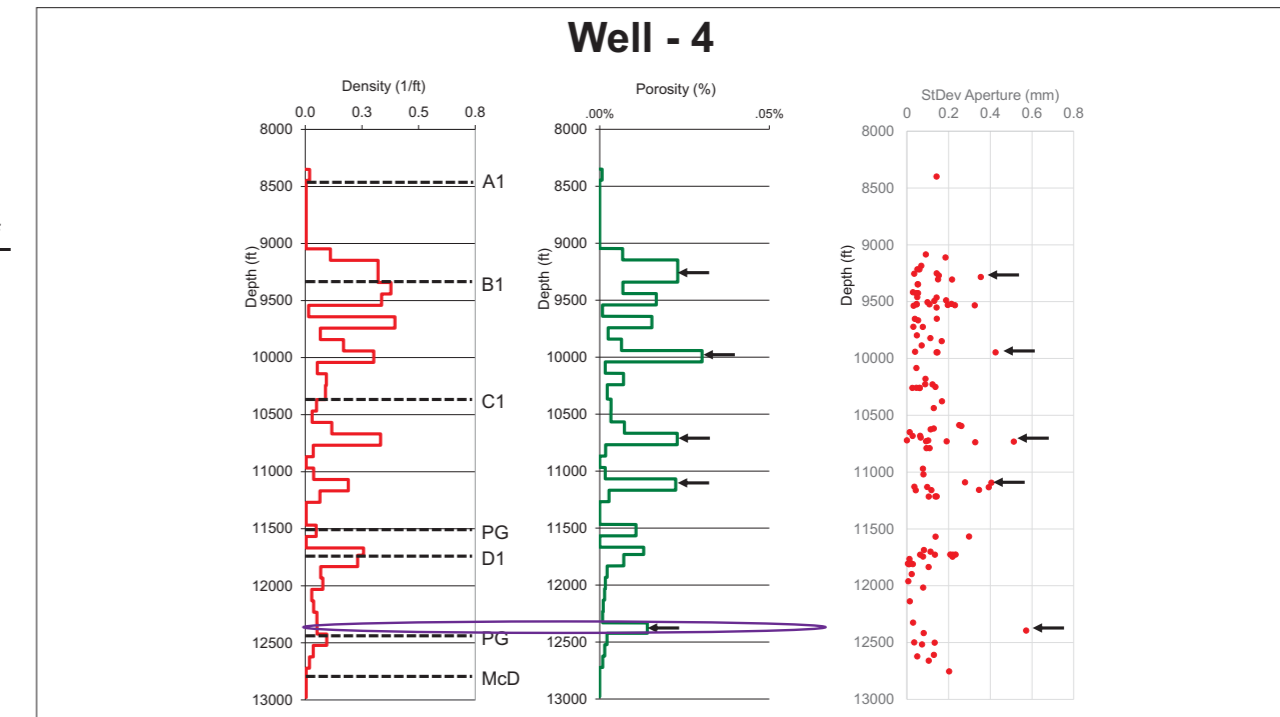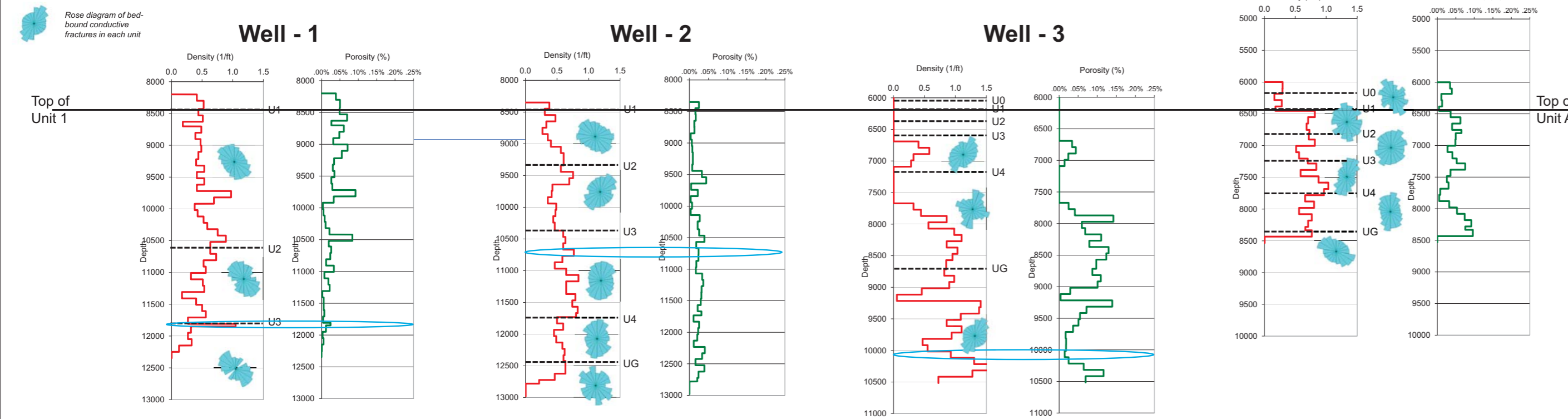
Some observation from the plots

- In most intervals the density and porosity curves are tracking each other
- In some intervals the density curve shows a spike which is not followed by the porosity curve, indicating zones of low aperture (marked by 〇)
  - Either it is a zone of high fracture density with very low primary apertures or it is a zone where the apertures were partially cemented
- In one of the interval in well-4 the porosity curve spikes but not the density curve (highlighted by 〇)
  - This zone represents an interval of fractures of high aperture.
  - It is also an interval where the standard deviation of aperture is high suggesting that the fracture aperture was likely influenced by dissolution
- In most intervals peaks in porosity are associated with one or more fractures with high standard deviation
  - Borehole image of these fractures suggests these are the fractures with some dissolution effect (*Images provided in poster-2)
  - Suggesting dissolution related apertures boosting porosity in those intervals
- This analysis provides a quick way to reveal dissolution affected fracture aperture
- Ultimate goal in field wide evaluation is to look for trend of occurrence of dissolution (or cementation) affected fractures that can be tied spatially

Bed bound vs Continuous fractures

- Bed-bound fractures occur as short fractures truncated at bed boundaries
- They are represented by partial sine curves on borehole image unlike continuous fractures that are interpreted as full sine curves
- Continuous conductive fractures and Bed-bound conductive fractures are analyzed separately because the nature of their difference in connectivity.
  - Continuous fractures tend to be more connected than the bed bound fractures thus contributing to higher permeability
- In fractured reservoirs this might have significant implications about the type of fluid each group of fracture is draining.
  - Based on the frequency of bed-bound fractures they might form high flow zones that can be related to the mechanical stratigraphy of the reservoir
    - In the example above, due to the higher frequency of bed-bound fractures, the porosity added by this group is significantly higher in some wells (eg. Well-4) compared to the continuous fractures

Summary of analysis

- Fracture density is calculated as surface area over volume rock – (P_{32} density measurement)
  - This approach of density calculation takes the bias of fracture orientation to wellbore angle out of the equation
  - It is a scale dependent measurement
  - For this project density is calculated over an interval of ~100' conditioned at formation tops
  - Interval for density calculation is selected as appropriate for the goal of the project
- Fracture porosity is calculated as Fracture Density * Aperture
  - Aperture is the average value of fracture aperture recorded in all the pads
- Ideally fracture porosity will track porosity when the characteristic aperture is more or less uniform for the set
  - It will differ in cases where there are solution enlarged fractures – there will be porosity peak but no density peak
  - Or tall fractures or high frequency of short fractures with very little 'open' aperture – there will be density peak but no porosity peak
  - As the density/porosity is calculated over an interval, the effect of dissolution may go un-noticed.
- **The precise method of measuring aperture at multiple points enables derivation of an aperture profile**
  - **That provides direct evidence of dissolution effect**
- **The analysis shows that presenting the aperture variation as standard deviation renders a quick way of highlighting intervals of fracture dissolution**

Bed-bound fractures and through-going fractures in outcrop photos

Photo: Michael Gross & Kajari Ghosh

Bed-bound fracture in porcellanite | Through-going fracture | Bed-bound fracture in porcellanite

In borehole image log, bed bounds fractures are partial sine curves that do not appear in all pads

Bed bound fractures are generally more abundant and occur in zones within certain mechanical stratigraphic boundaries (as demonstrated in the outcrop photos above)

In borehole image log, through-going fractures are continuous sine curves that appear in all pads