PSStructural and Geomechanical Analysis of Fractured Cambrian-Ordovician Reservoirs in the Northern Appalachian Basin*

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Abstract

The Cambrian-Ordovician Conasauga and Knox Groups constitute a regional succession of carbonates punctuated by brief periods of clastic deposition. Diagenesis and a history of multiple orogenic events resulted in the development of a complex fracture system. Understanding the orientation and distribution of the natural fracture sets within the Conasauga and Knox Groups is of significance in seeking potential CO_2 storage zones and building reservoir models with fracture networks.

Preliminary fracture studies were carried out to determine natural fracture orientation and distribution within the Conasauga and Knox Groups on the western flank of northern Appalachian Basin. Over 700 observations of fractures were interpreted on newly acquired resistivity and acoustic image logs collected at multiple well locations ranging in depth from 730 to 4150 meters. We evaluated structural parameters of the fractures using statistical analysis. Additionally, we evaluated the likelihood of observed fractures to slip under current stress conditions using 3D Mohr diagram for critically stressed fracture analysis.

Analysis and interpretation of fracture orientation clusters shows the regional fracture systems are highly complex with possibly systematic and non-systematic fractures within the evaluated lithologic units. Fracture density is observed to increase up-dip within the studied area. Overall, a high percentage of fractures with varying dip direction were observed to strike sub-parallel to the contemporary maximum horizontal stress direction (SHmax) determined from wellbore failure, while a lower percentage strikes perpendicular to the SHmax direction. Critically stressed fracture analysis shows the natural fractures are not critically stressed in the current state.

This project was supported by U.S. Department of Energy's National Energy Technology Laboratory (Award DE-FE0023330) and Ohio Development Services Agency (Grant OER-CDO/D-14-16).

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ABSTRACT

The Cambrian-Ordovician Conasauga and Knox Groups constitute a regional succession of carbonates punctuated by brief periods of clastic deposition. Diagenesis and a history of multiple orogenic events resulted in the development of a complex fracture system. Understanding the orientation and distribution of the natural fracture sets within the Conasauga and Knox Groups is of significance in seeking potential CO_2 storage zones and building reservoir models with fracture networks. Preliminary fracture studies were carried out to determine natural fracture orientation and distribution within the Conasauga and Knox Groups on the western flank of northern Appalachian Basin. Over 700 observations of natural fractures were interpreted on newly acquired resistivity and acoustic image logs collected at multiple well locations ranging in depth from 730 to 4150 meters. We evaluated structural parameters of the natural fractures using statistical analysis. Additionally, we evaluated the likelihood of observed fractures to slip under current stress conditions using 3D Mohr diagram for critically-stressed fracture analysis. Analysis and interpretation of natural fracture orientation clusters shows the regional fracture systems are highly complex with possibly systematic and non-systematic fractures within the evaluated lithologic units. Fracture density is observed to increase up-dip within the studied area. Overall, a high percentage of natural fractures with varying dip direction were observed to strike sub-parallel to the contemporary maximum horizontal stress direction (S_{Hmax}) determined from wellbore failure, while a lower percentage strikes perpendicular to the S_{Hmax} direction. Critically-stressed fracture analysis shows the natural fractures are not critically stressed in the current state.

OBJECTIVE

In this study, observations from resistivity and acoustic image log data were used to categorize the drilling induced and natural fractures within the Cambrian- Ordovician carbonate reservoirs and evaluate their distributions within individual geologic units. These observations were then evaluated regionally on the western flank of northern Appalachian basin.

Open natural fractures are sometimes present in carbonate reservoirs and could enhance the effectiveness of the reservoir for applications such as CO_2 storage, brine disposal, and hydrocarbon production. While the presence of natural fractures in carbonate reservoirs are beneficial for increasing injectivity and storage volume, there are other underlying concerns related to what role fracture systems play concerning induced seismicity. Using 3D Mohr circle diagram, we assess the likelihood of observed natural fractures within our study area to slip under varying pore pressure conditions.

STUDY AREA AND EXTENT OF THE APPALACHIAN BASIN

The Appalachian basin is a stretched asymmetric retro-arc foreland basin with a preserved northeast-southwest trending central axis that extends from central Alabama through West Virginia, Pennsylvania, and New York into Canada.

Figure 1 shows extent of the Appalachian basin and approximate location of the study area relative to known structures in the basin. Study area is located on the western flank of northern Appalachian basin within central to eastern Ohio.

The structure map of the Precambrian unconformity surface is shown in figure 4a along with other known structural features.

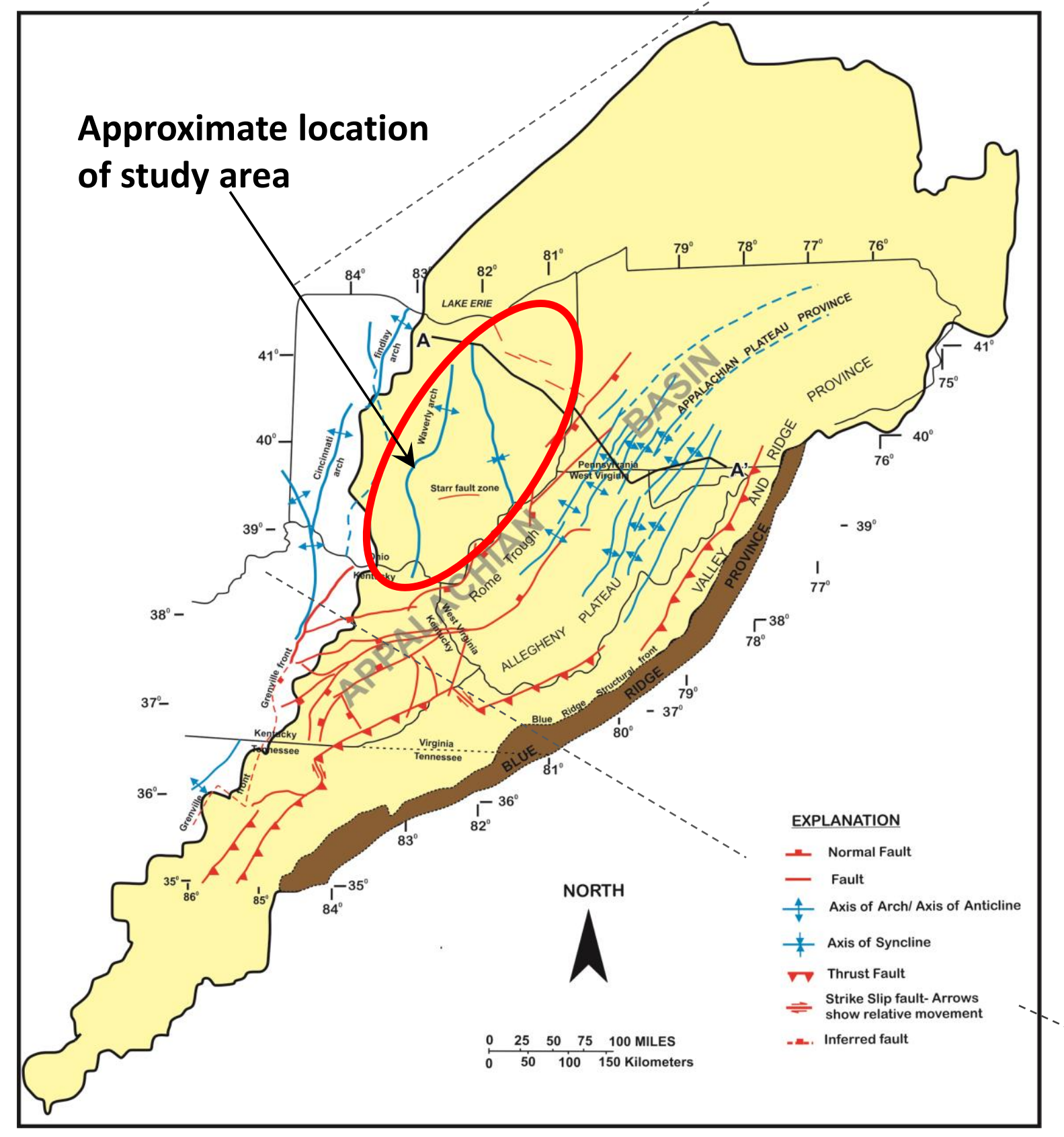

Figure 1: Generalized structural map of the Appalachian basin region showing Appalachian basin extent and known structural elements with selected features. Line A-A' shows approximate trend of cross section shown in Figure 2. (Prepared and modified after Ryder, 2012)

CROSS SECTION ACROSS STUDY AREA

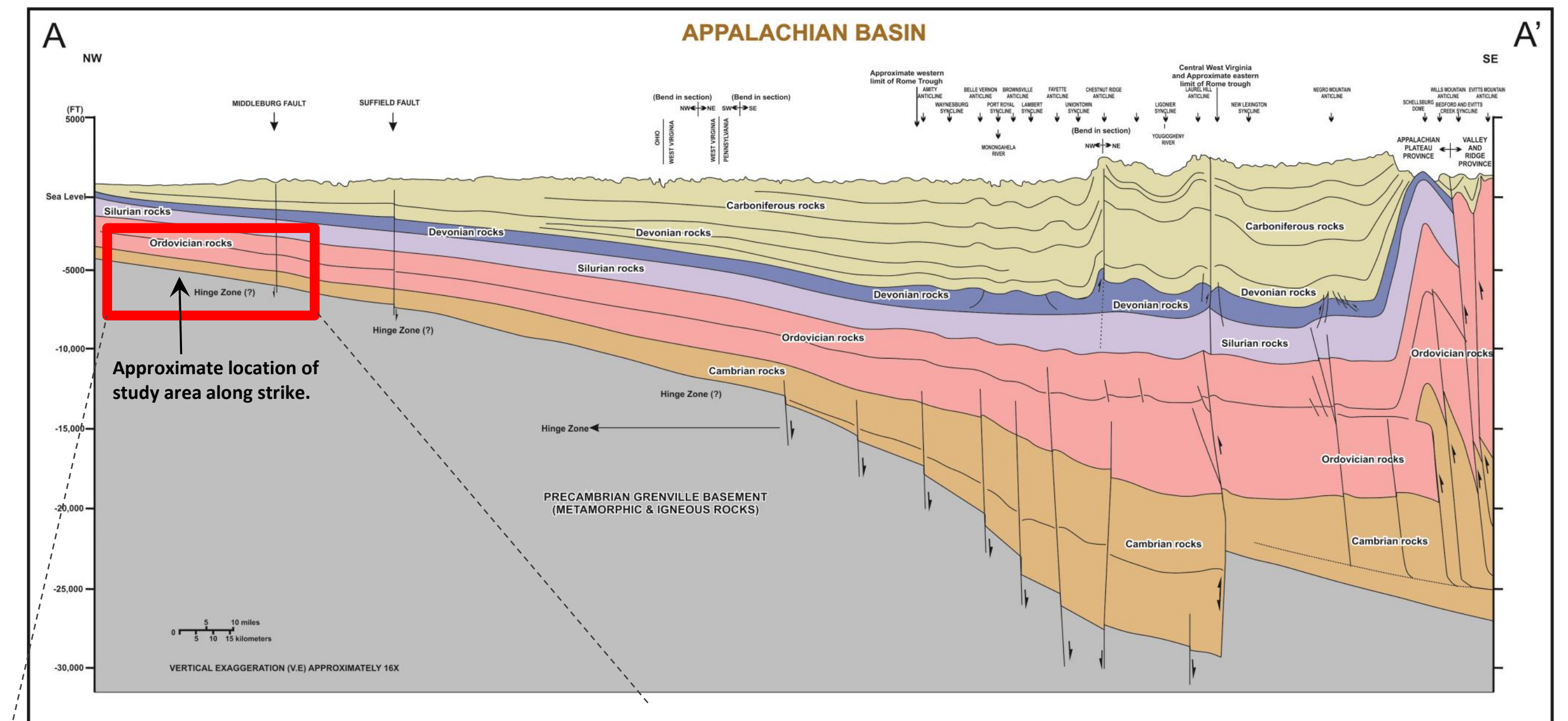

Figure 2:Generalized geologic cross section across Appalachian basin trending northwest to southeast. (Prepared and modified after Ryder,2012)

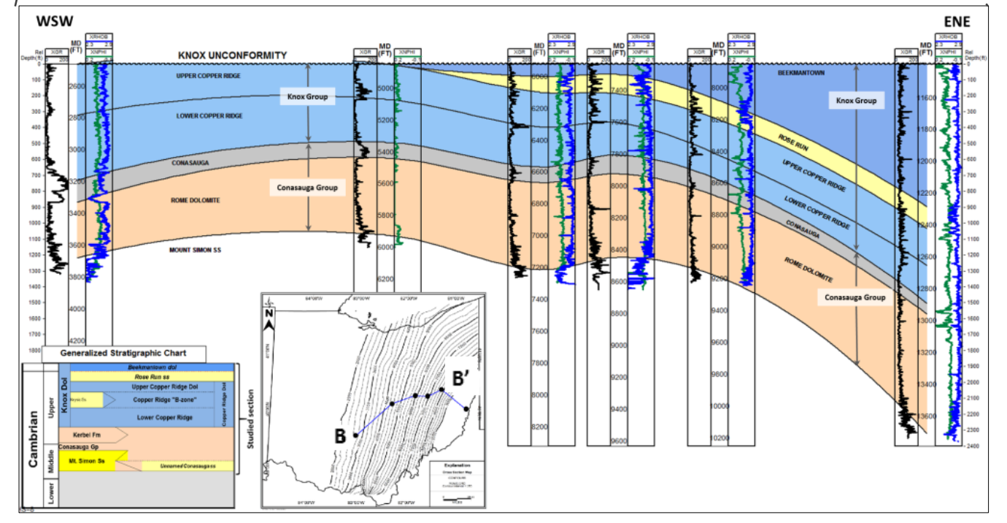

Figure 3: A representative WSW to ENE (B-B') cross section of the study area showing change in sediment thickness in an eastward direction (Note; Knox unconformity surface was used as datum)

Regional Cross section shown in Figure 2 illustrates how the Cambrian-Ordovician strata on the western flank of the basin dips gently eastwards into Rome Trough. The Insert cross section (Figure 3) shows the obvious increase in the thickness of the Beekmantown strata. Note that Knox unconformity surface is used as datum.

STRUCTURE MAP OF THE PRECAMBRIAN UNCONFORMITY SURFACE

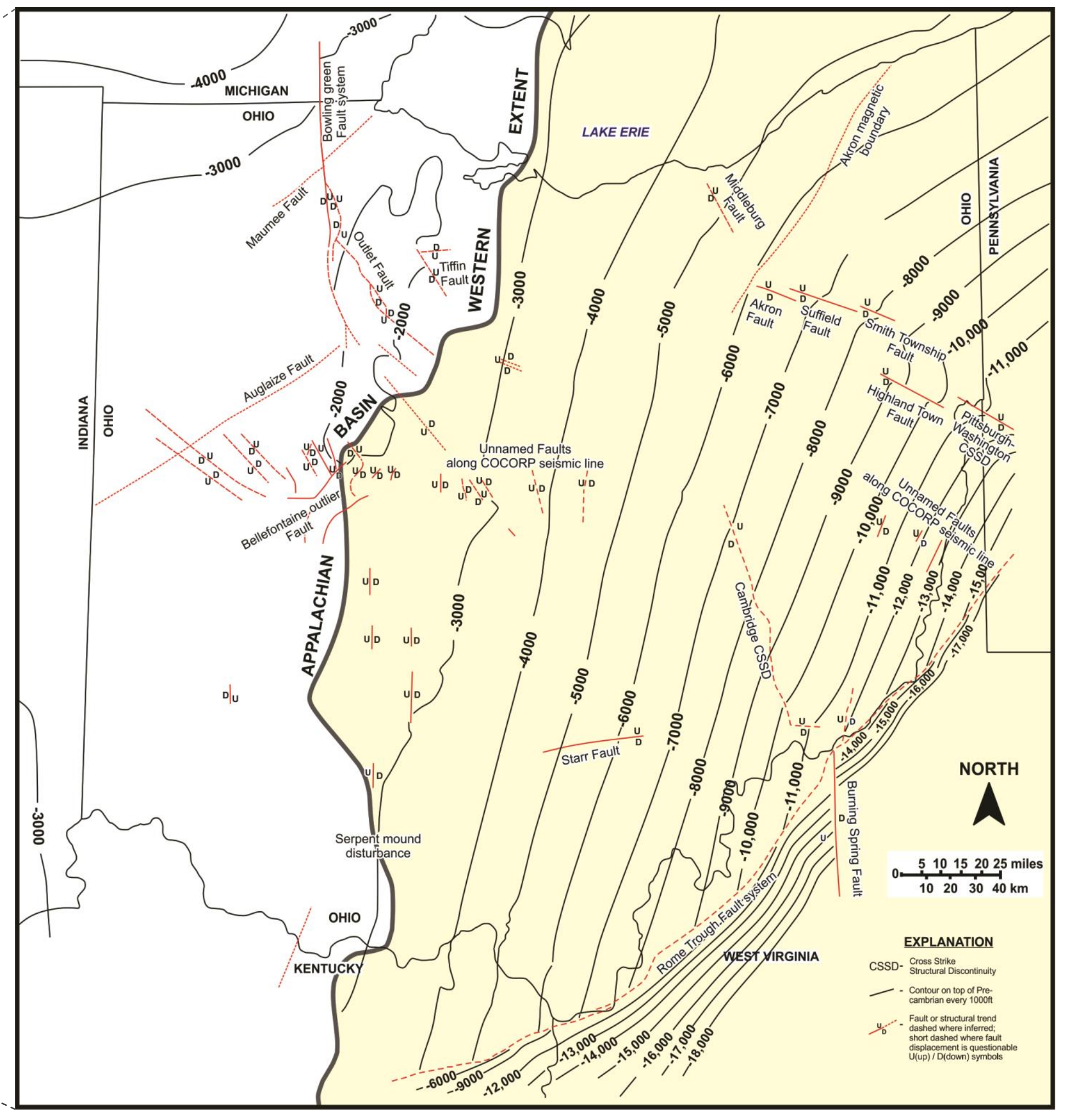

Figure 4a: Precambrian unconformity surface map illustrating extent of the Appalachian basin and structural components of the Precambrian surface. (Prepared and modified after Baranoski, 2002)

Figure 4b: Summary of Chronostratigraphic chart of Appalachian basin region, tectonic events affecting North America, sea level chart, Paleo-climate chart, ice volume chart. (Compiled and modified after Battelle, 2013; MRCSP, 2005; Ettensohn, 2008)

The tectonic history (Figure 4b) of Appalachian basin is characterized with multiple orogenic events that resulted in crustal deformation and development of folds, thrust faults, strike-slip faults, and other structures associated with a compressional regime.

NATURAL FRACTURE INTERPRETATION & ANALYSIS

Ten resistivity and acoustic log images were collected within the Cambrian –Ordovician interval from a vertical well. The logs were interpreted to identify natural fractures and well-bore failures. Examples of interpreted natural fractures are shown in Figures 5 and 6. Assessment was done using a systematic approach by plotting numbers of natural fractures observed at every 25ft for each well on a histogram

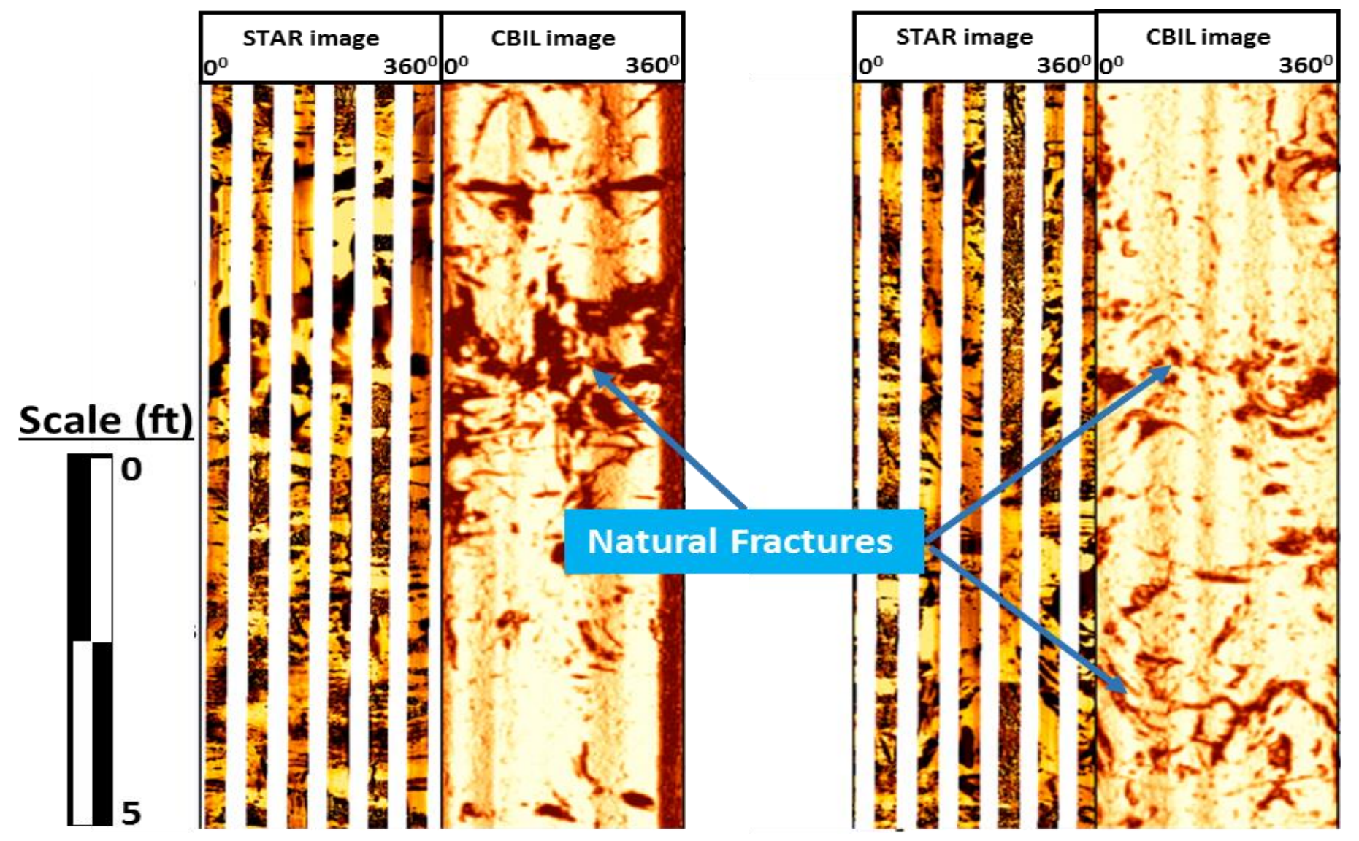

Figure 5: Examples of STAR and CBIL images of Natural Fractures

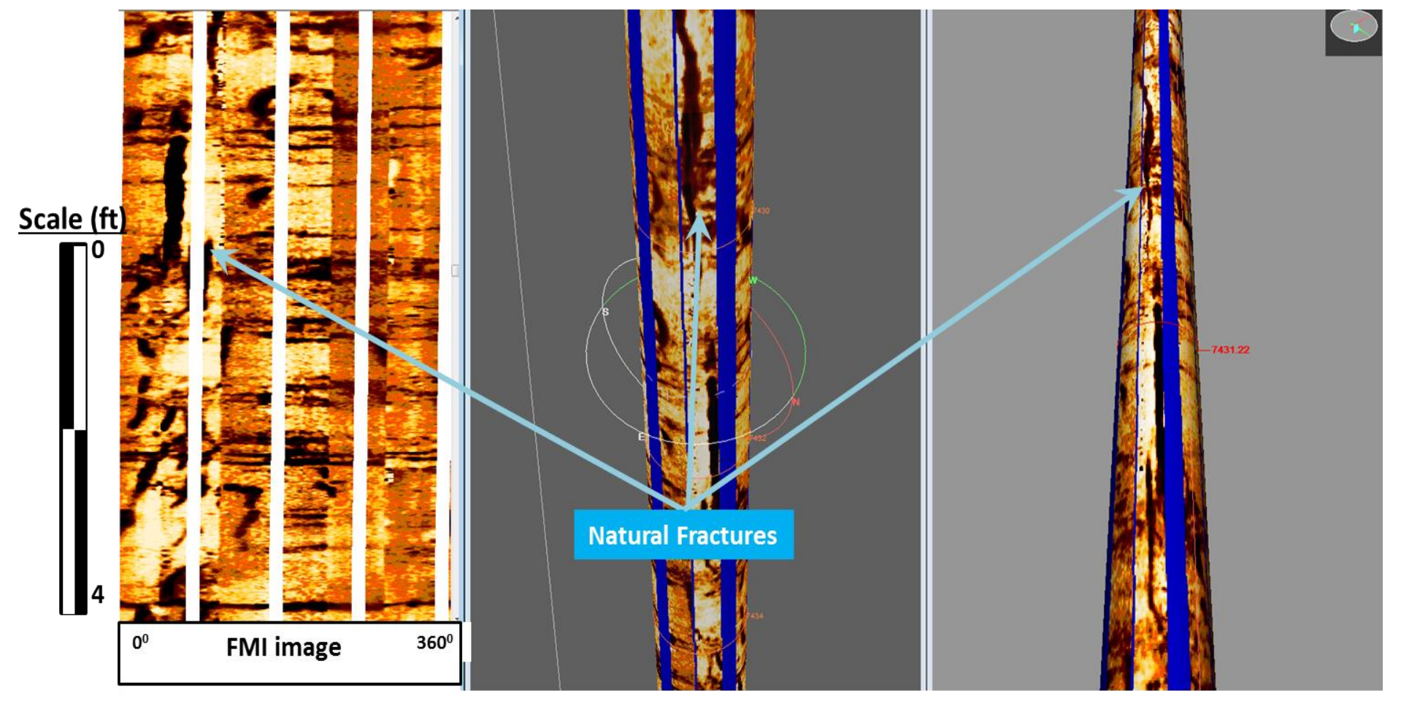

Figure 6: Examples Natural Fracture from FMI log in 2D and 3D view

Histogram of observed natural fractures was produced for each examined well. Produced histograms were used in generating a cross section (Figure 7) in order to analyze fracture intensity variation from west to east of the studied area.

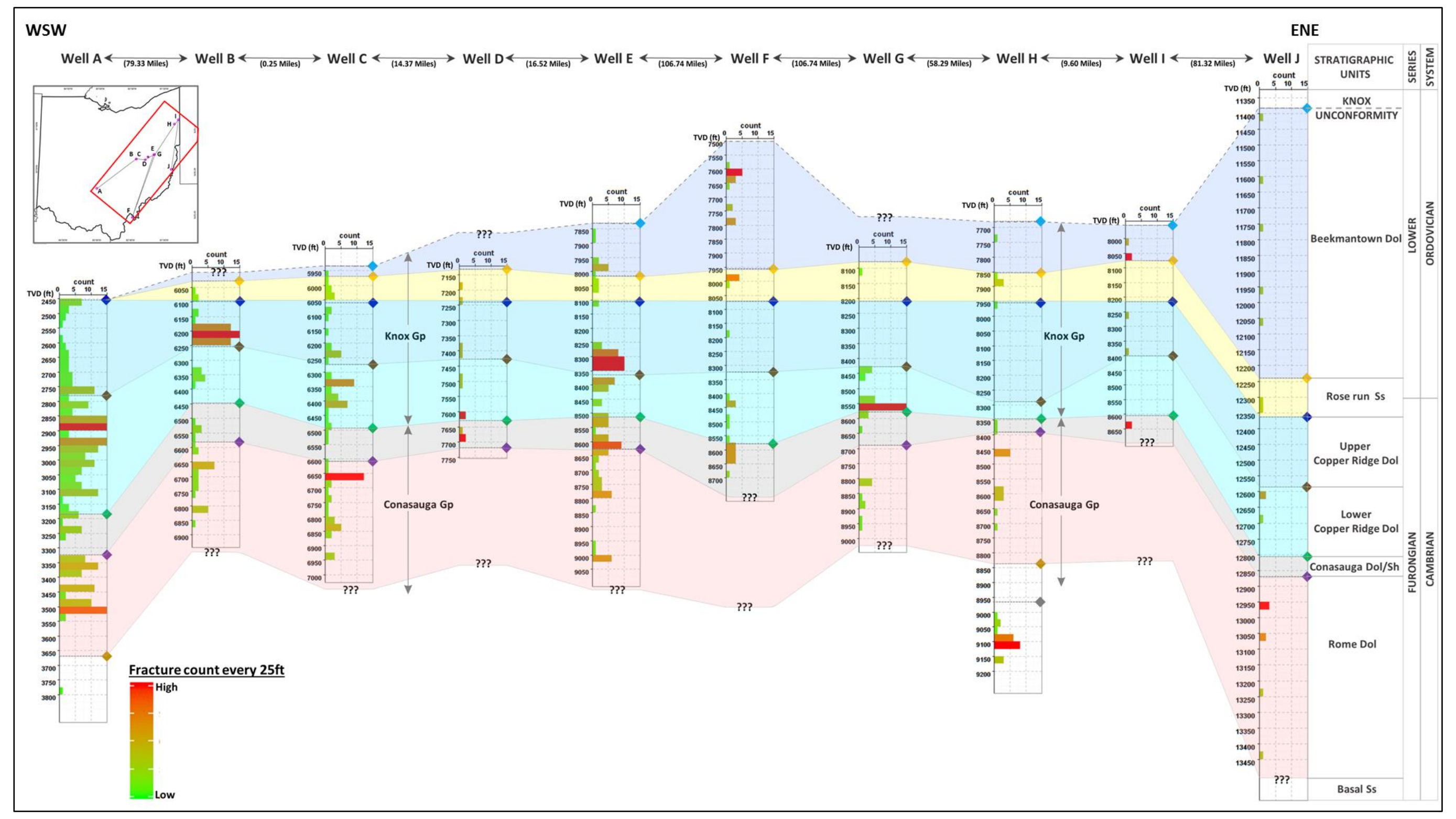

Figure 7:Cross section showing fracture distribution/intensity on a well by well basis.
(Notes; Fractures were counted at every 25ft interval and Upper copper ridge surface was used as datum but shifted downward in well J)

Preliminary result of analysis on fracture intensity variation showed that the western region of the studied area is more fractured than the eastern region. Reasons for this observed intensity variation is still under investigation and could have been related to various factors such as basin architecture, brittleness variation, overburden pressure and the prolonged tectonic history of the basin. In summary, this result could potentially imply that locations that are in the up-dip part of the study area could be more favorable for CO_2 injection if fractured reservoirs are primary target.

NATURAL FRACTURE ANALYSIS

Analysis on fracture orientation is important in understanding and modeling possible natural fracture network within examined formations in the region. Results of structural parameters derived from interpretation of natural fractures on acoustic and resistivity image logs was statistically analyzed. Results of analysis is shown in Figures 8 and 9. Rose diagrams were also produced to understand any dominant trend in observed natural fractures. Rose diagrams were overlaid on maps shown in Figures 13 to 16.

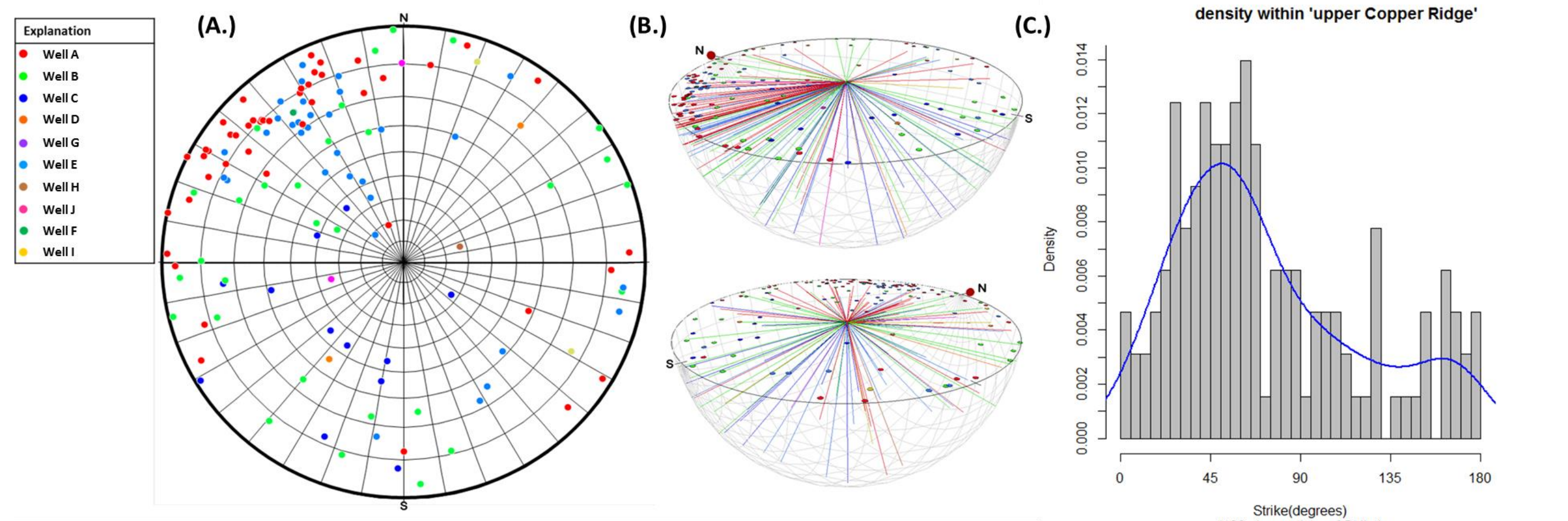

Figure 8: Poles to plane of Upper Copper Ridge fractures and histogram plot of fracture strike (degrees)

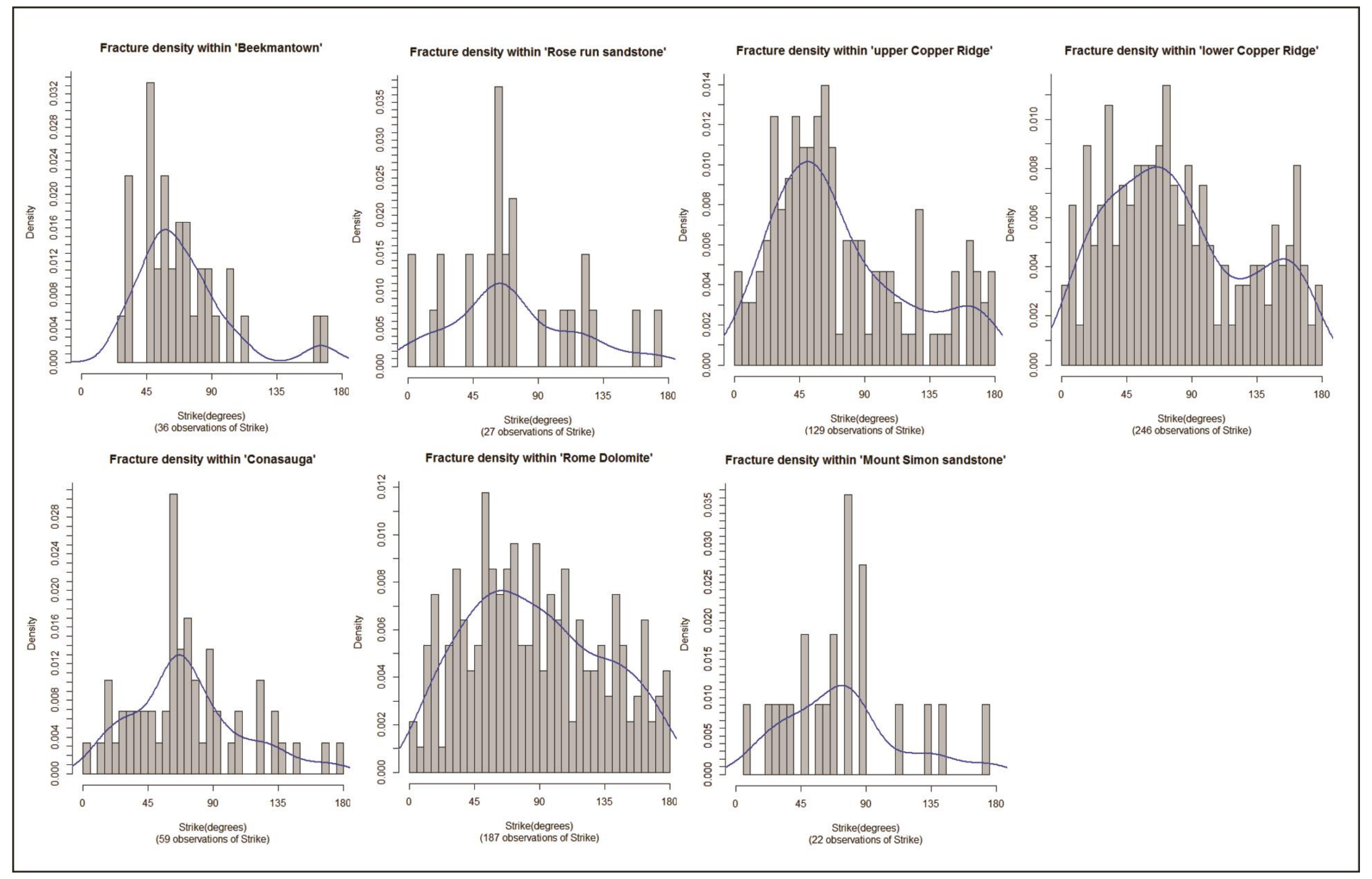

Figure 9: Histogram and kernel density plot of fracture strike observed within the different formations

Histogram and kernel density plot support inference that a denser portion of the natural fractures observed trend in a northeast direction

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DETERMINATION OF AZIMUTH FOR MAXIMUM HORIZONTAL STRESS

In a geomechanical related study, the knowledge of the stress field at a location is important in evaluating pre-existing natural fracture slippage likelihood and conducting other geomechanical related assessment with injection of fluid into fractured reservoir.

Using the well bore failure approach (Figure 10), proposed by Zoback, 2007, we derived orientation of S_{Hmax} within the study area.

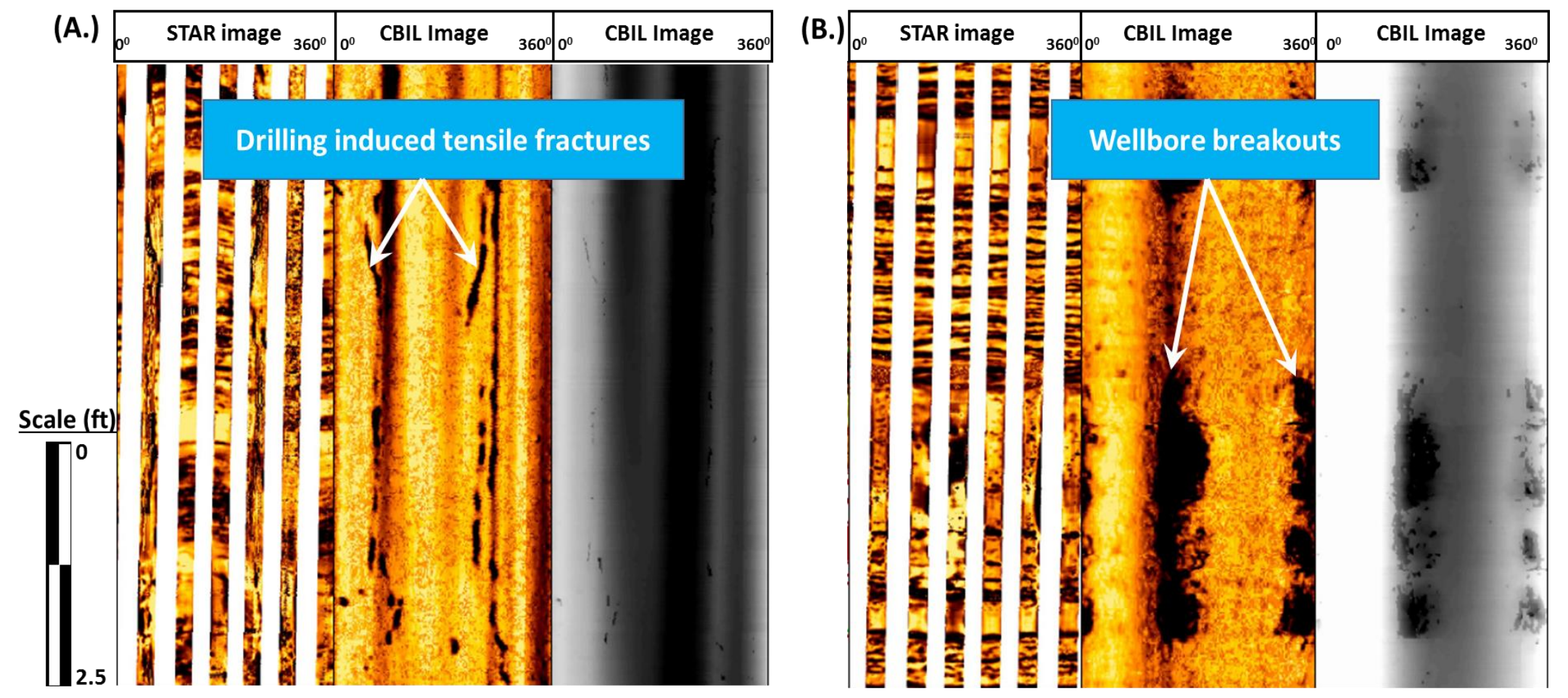


Figure 10: Example of acoustic and resistivity images observed from Wellbore failure

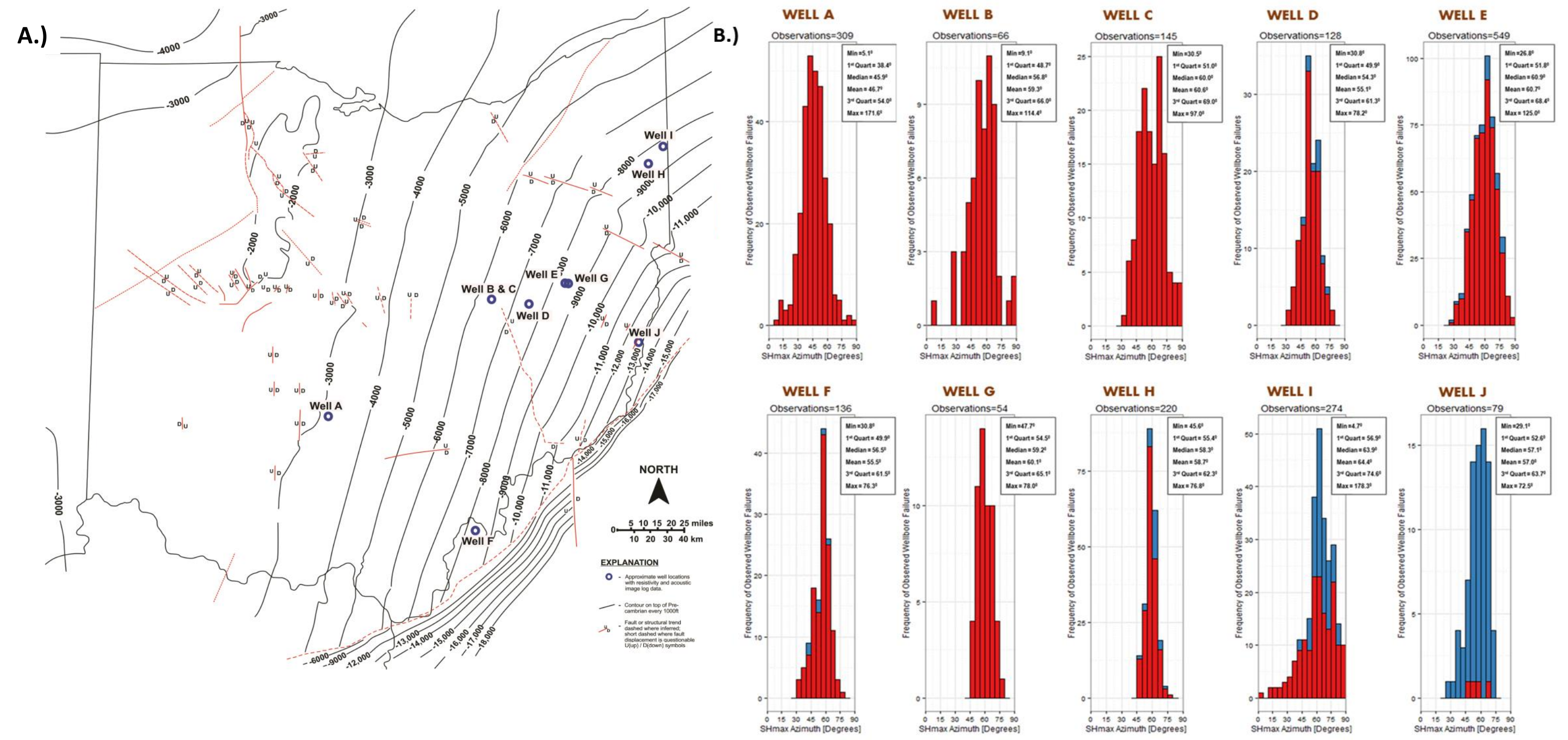


Figure 11: (A) Map showing locations of vertical wells with log data and (B)Histogram plot of S_{Hmax} determined from observed wellbore failures in sampled wells

UPDATING STRESS MAP IN THE REGION

Results on analysis of well-bore failure observations (figure 10) from each well was used in updating stress map of the region by updating locations without data (Figure 12). Results show consistency in the stress field.

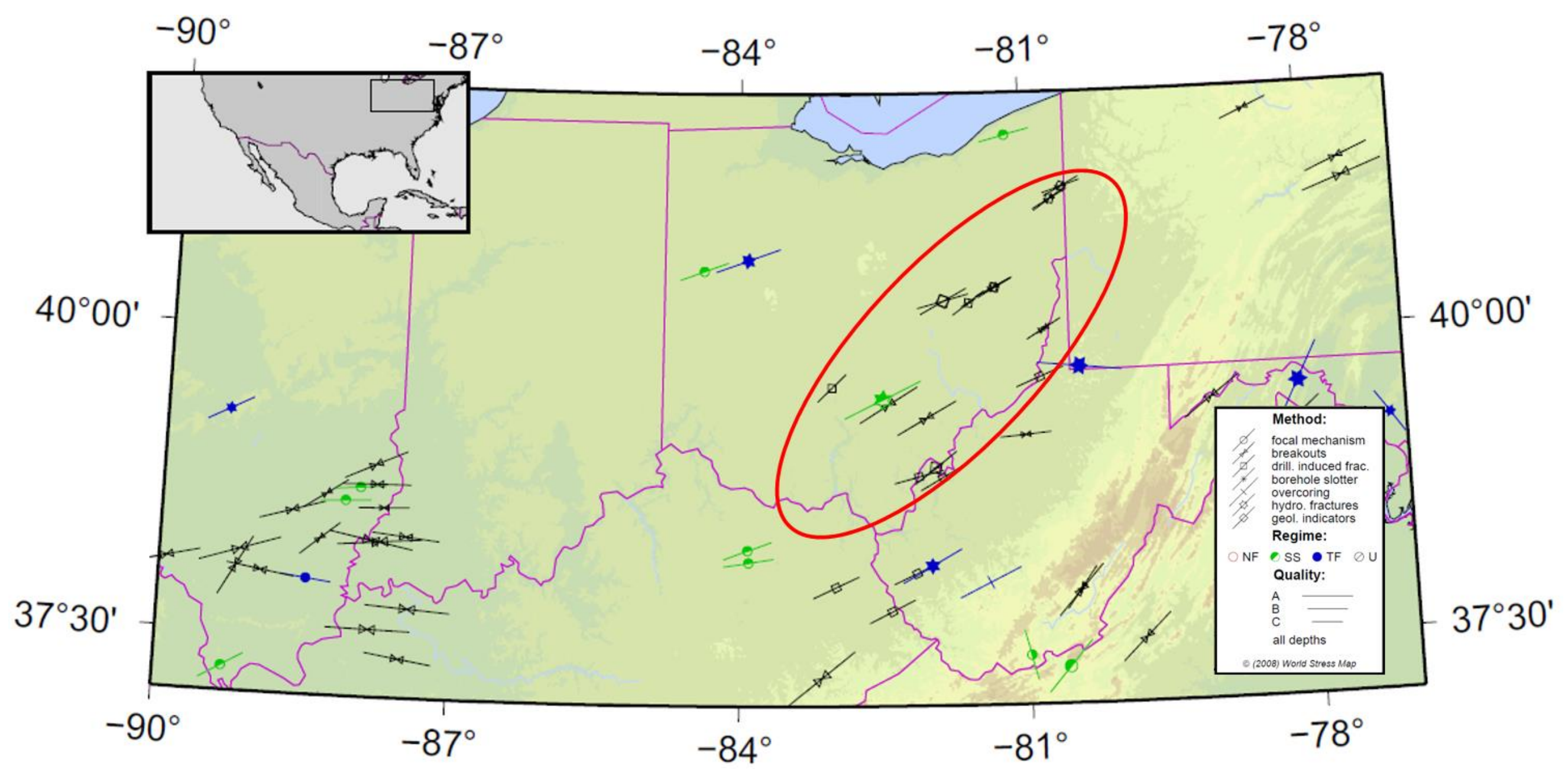


Figure 12: Updated stress map for the studied region (updated area is highlighted with red oval circle)

RELATING OBSERVED NATURAL FRACTURES TO PRESENT DAY STRESS FIELD

On the rose diagram plots for each well, careful observation shows most of the clusters tend to trend in a northeast- southwest orientation implying that if fracture networks are present in the vicinity of the wellbore, there is a high likelihood that the natural fractures would be striking in this orientation.

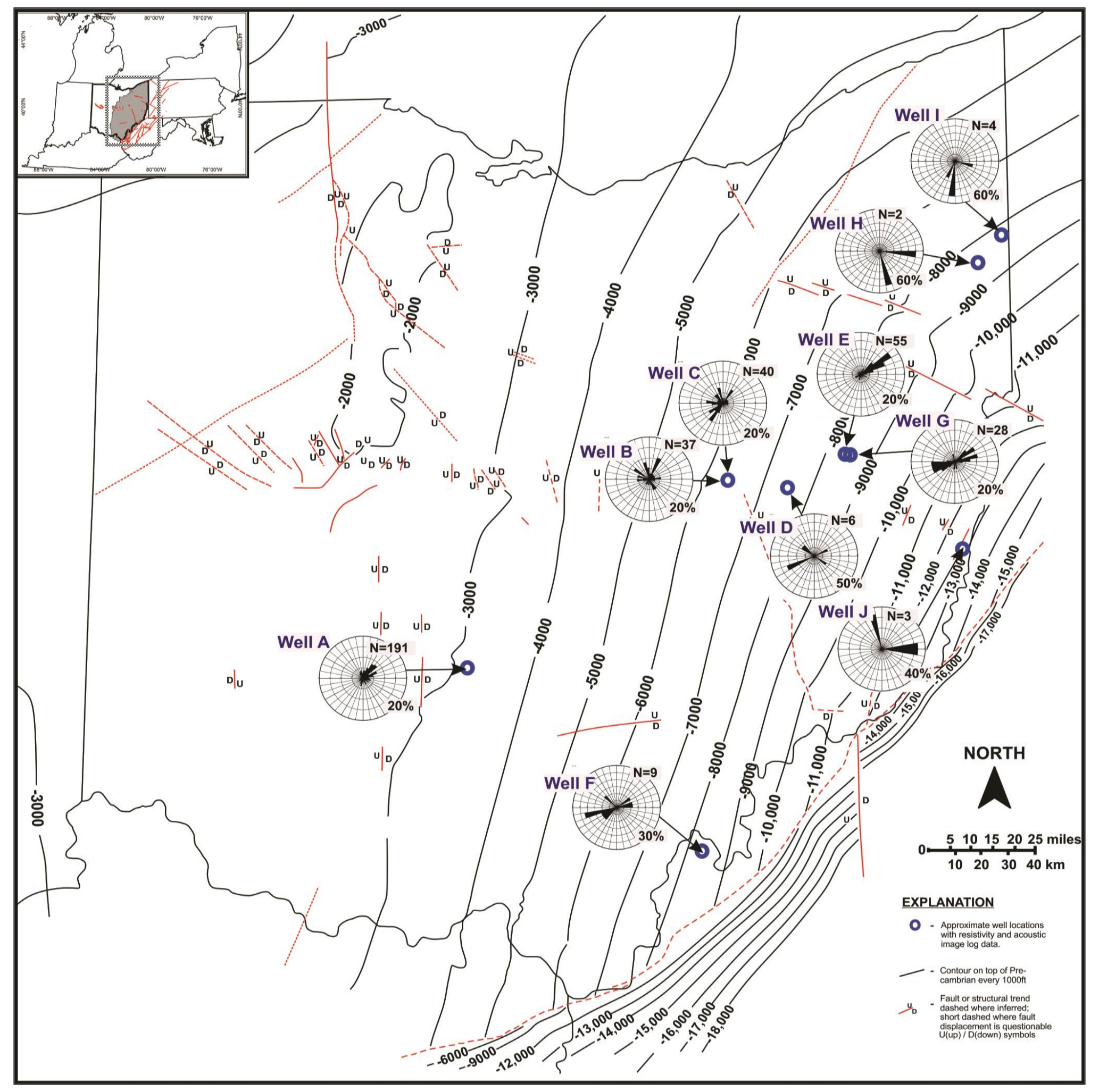


Figure 13: Rose diagrams of natural fractures observed within the Knox dolomite group overlaid on structure map of the Precambrian basement

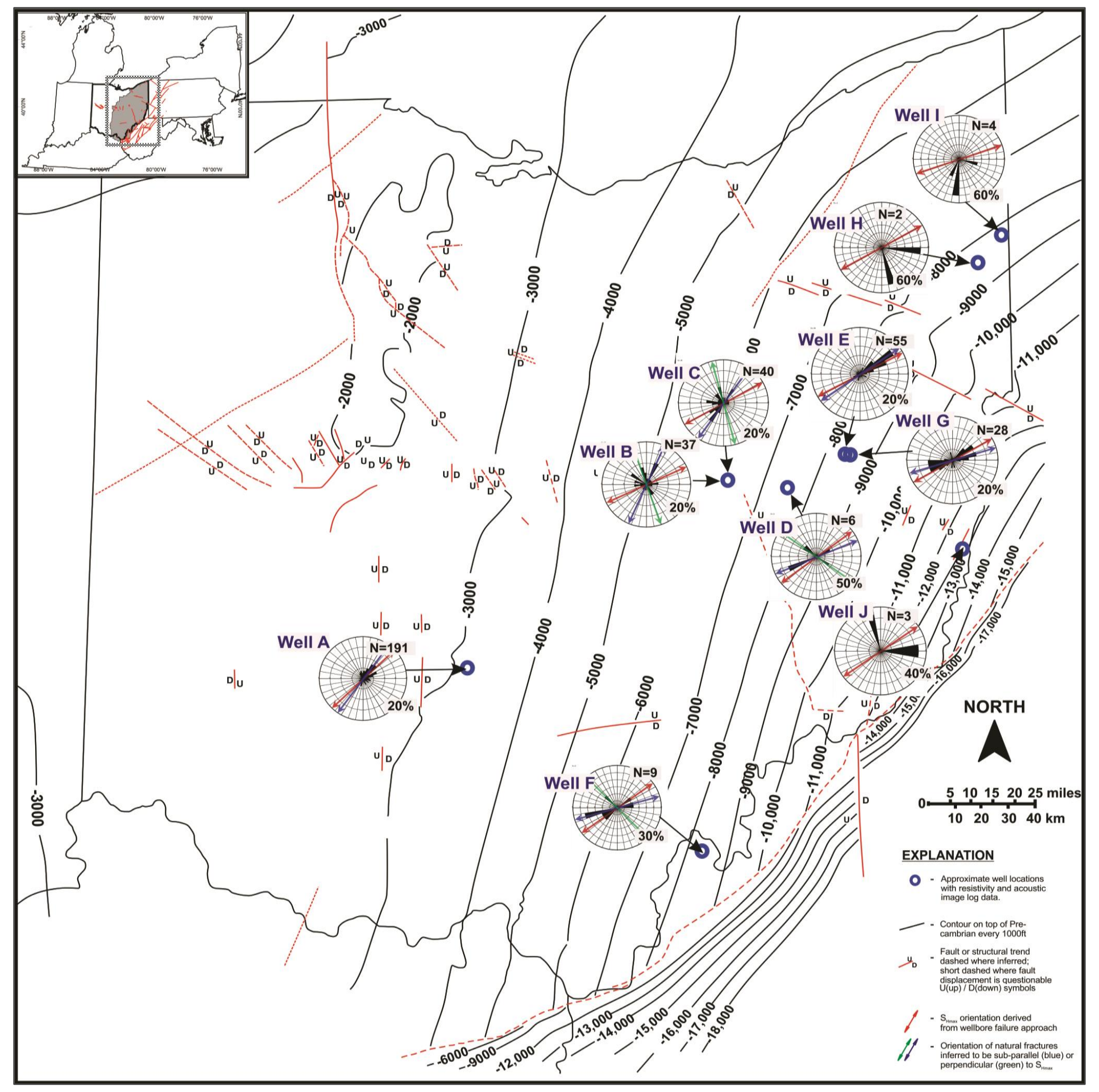


Figure 14: Rose diagrams with pre-determined S_{Hmax} orientation along with inferred orientation of natural fractures observed within the Knox dolomite group overlaid on structure map of the Precambrian basement

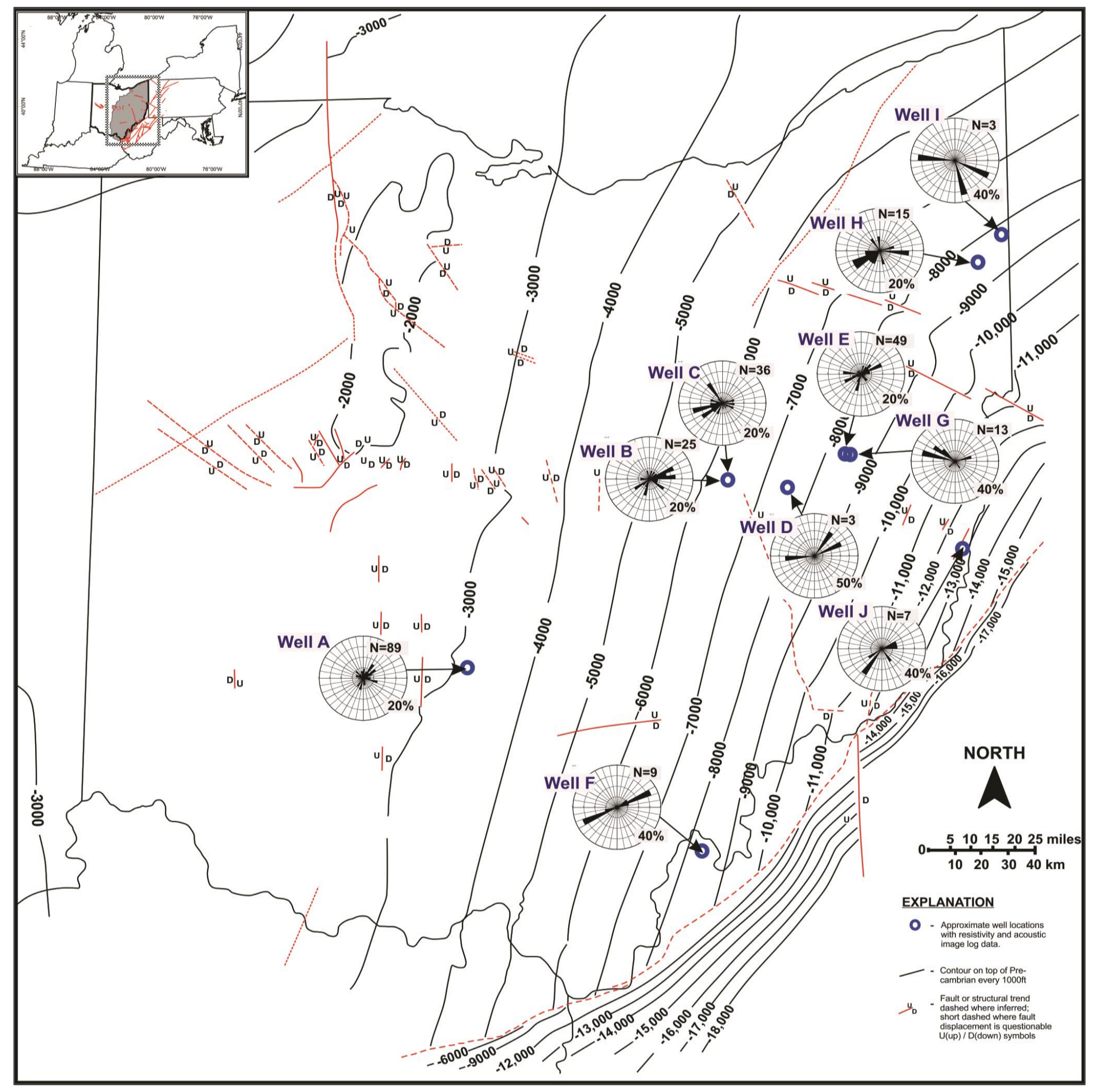


Figure 15: Rose diagrams of natural fractures observed within the Conasauga dolomite group overlaid on structure map of the Precambrian basement

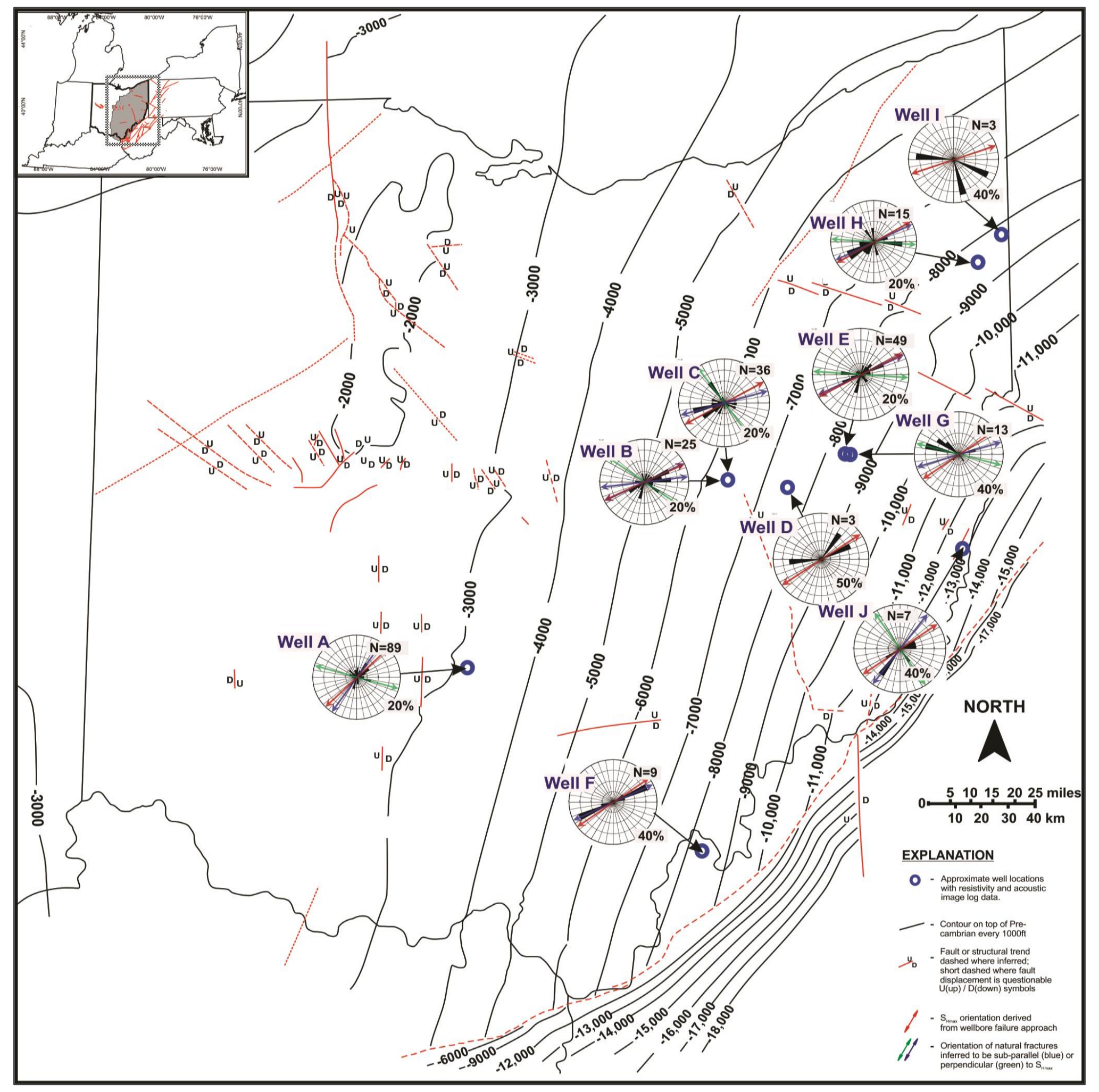


Figure 16: Rose diagrams with pre-determined S_{Hmax} orientation along with inferred orientation of natural fractures observed within the Conasauga dolomite group overlaid on structure map of the Precambrian basement

STRESS MAGNITUDES & REGIME IN THE LITHOSPHERIC CRUST

Determination of the stress magnitudes (S_v, S_{Hmax}, and S_{hmin} illustrated in Figure 15) acting at depth is important in understanding the prevailing stress regime in the region.

Pore pressure (Pp) data was derived from direct pressure measurement in the borehole (Figure 16). S_v was determined from integrating density log. (Figure 15).

$$S_v = \int_0^z \rho(z) g dz$$

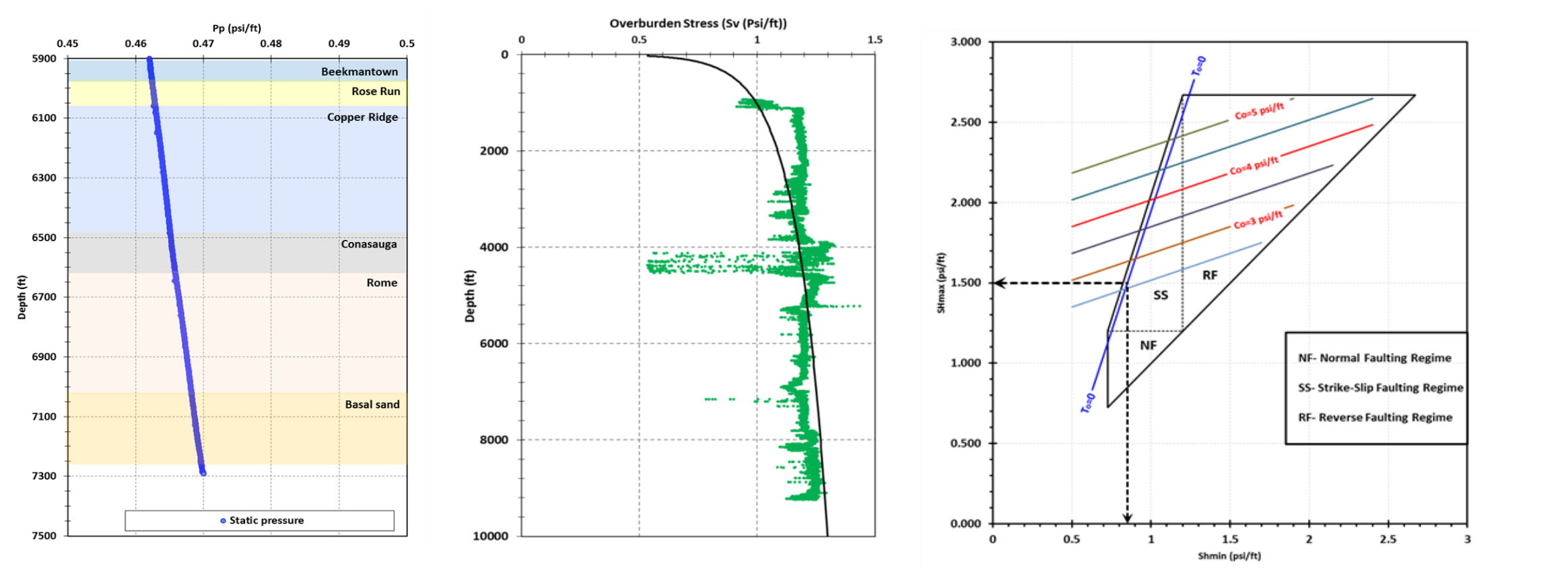


Figure 16: Pore Pressure gradient, integrated density data (Overburden stress) and stress polygon for constraining S_{Hmax}

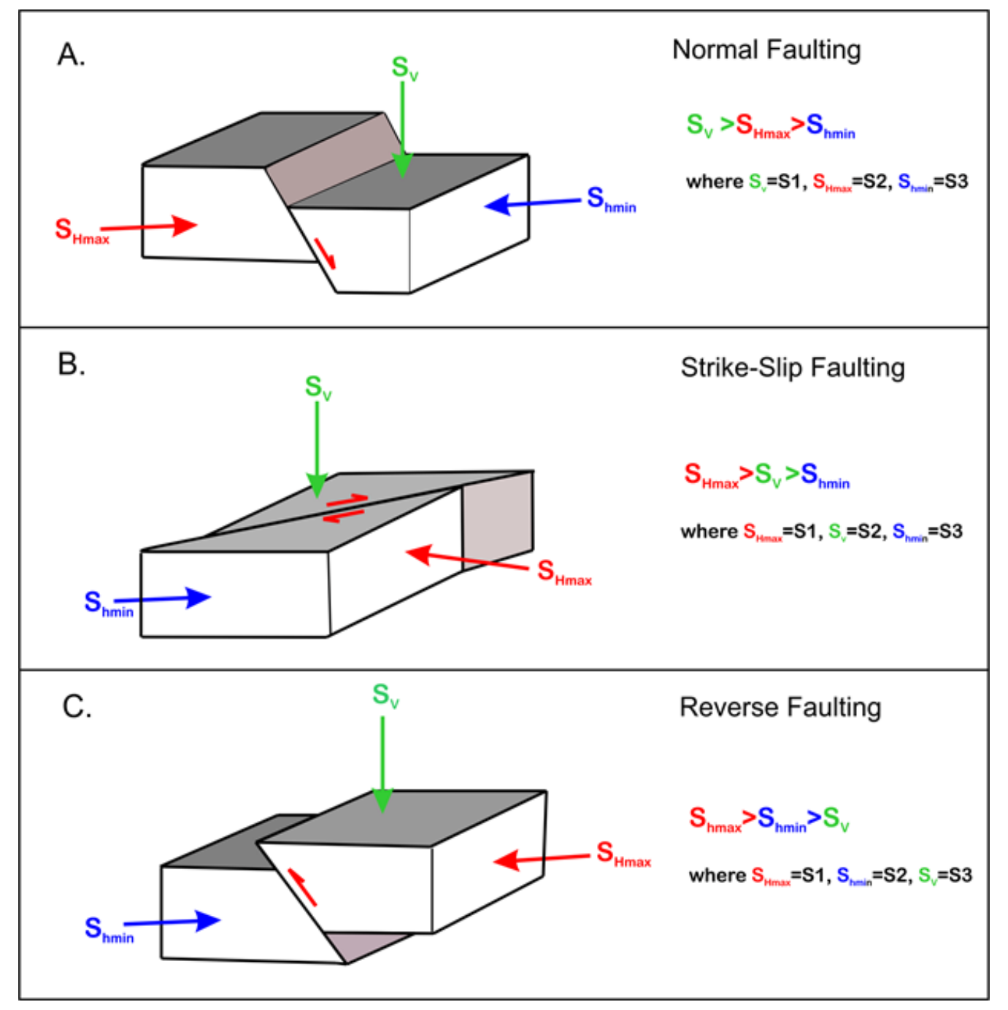


Figure 15: The different types of stress regimes (Anderson classification scheme)

Magnitude of S_{hmin} is normally determined from Leak-Off test (LOT). While stress polygon in Figure 16, shows how maximum horizontal stress magnitude is constrained.

CRITICALLY STRESSED FRACTURE ANALYSIS

Horizontal stress magnitudes derived in the work by Lucier, 2006 were used as estimates for critically stressed fracture analysis. Figures 17 shows an example of a 3D Mohr circle analysis of fractures observed in a sampled vertical well (A). Figure 18 shows plots of the poles to plane on a lower hemisphere. Results shows that these fractures are stable in their original state but some of these natural fractures have the tendency to slip at elevated pore pressure during fluid injection. This analysis could be useful in site screening, characterization, operation and monitoring at injection sites.

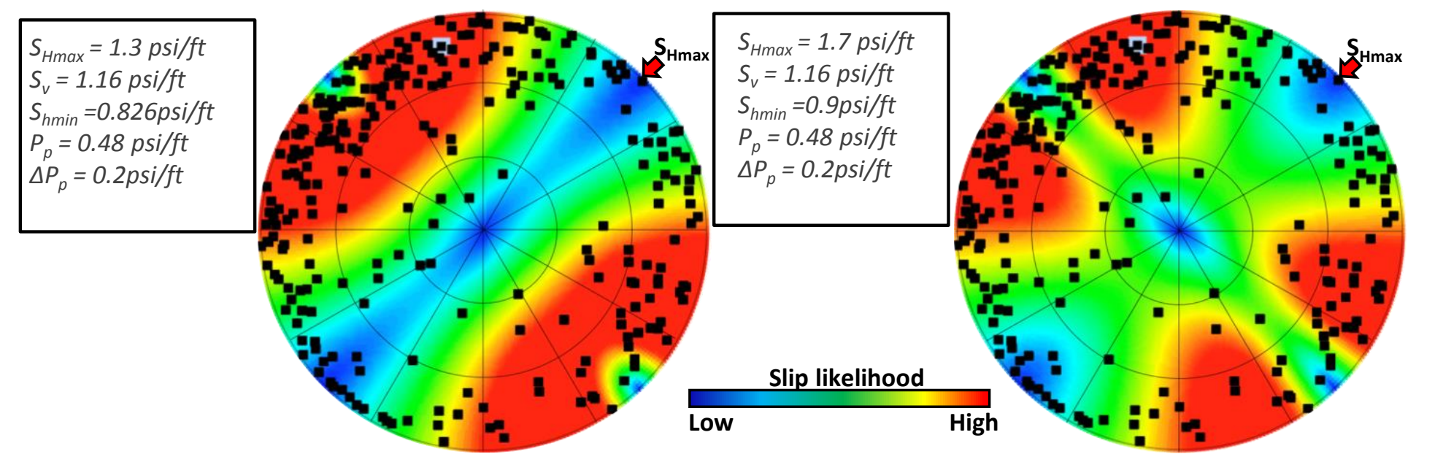
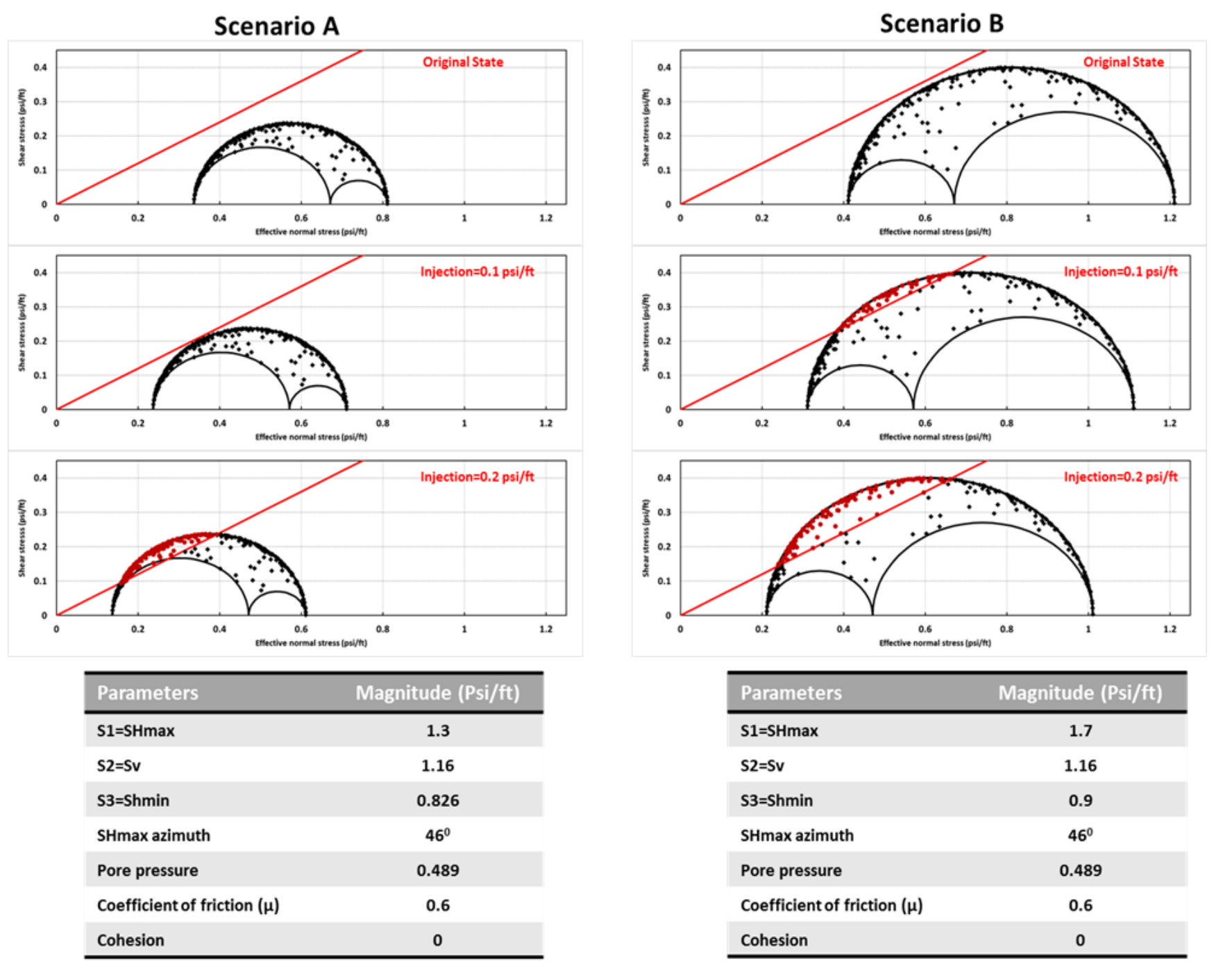


Figure 18: Slip likelihood for observed natural fractures. Points on stereo net represents poles to fracture planes



Parameters	Magnitude (Psi/ft)
S1=SHmax	1.3
S2=Sv	1.16
S3=Shmin	0.826
SHmax azimuth	46⁰
Pore pressure	0.489
Coefficient of friction (μ)	0.6
Cohesion	0

Parameters	Magnitude (Psi/ft)
S1=SHmax	1.7
S2=Sv	1.16
S3=Shmin	0.9
SHmax azimuth	46⁰
Pore pressure	0.489
Coefficient of friction (μ)	0.6
Cohesion	0

Figure 17: 3D Mohr circle Analysis of fractures observed in Well A

CONCLUSIONS

- Western part of the studied area appears to be more fractured than the eastern part
- Fracture system appears complex with little or no evidence for systematic joint set.
- High percentage of natural fractures tend to strike sub-parallel to the axis of S_{Hmax} thereby indicating linkage to Neotectonic stress field
- Fractures are not stressed in their original state but have the tendency to become critically stressed at elevated pressure.
- Detailed management of pressure during injection could mitigate the risk of induced seismicity

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