Geomechanical Assessment of Fractured Cambrian-Ordovician Reservoirs in Northern Appalachian basin for Carbon Storage

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Abstract

The Cambrian-Ordovician age 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 contributed in the development and distribution of a complex fracture system. Understanding the distribution of the developed fracture network in the region is of significance in screening location for CO_2 storage. In this study, we seek to understand natural fracture distribution on the western flank of northern Appalachian basin and the implication for injecting CO_2 into the fractured reservoirs.
Ten wells with resistivity and acoustic image log were selected for this study. Natural fracture observations were interpreted on the newly acquired image logs collected at multiple well locations ranging in depth from 730 to 4150 meters. Results of observations were used to study fracture intensity variation from west to east of the studied area. Using the structural parameters of the observed natural fractures and well bore failures observed from image logs, we assessed the likelihood of observed fractures to slip under current stress conditions using 3D Mohr diagram for critically-stressed fracture analysis. Multiple scenarios were modelled for injecting CO_2 at varying pressure to understand slip likelihood. Study on fracture intensity variation shows formations on the western part of the studied area to be more fractured and may be more suitable for CO_2 storage. Critically-stressed fracture analysis shows the natural fractures are not critically stressed in the current state but some of these fractures have the potential to slip at elevated pressures.

Objectives

In this study, the aim was to use resistivity and acoustic image log data to categorize observed drilling induced and natural fractures within the Cambrian-Ordovician carbonate reservoirs and evaluate the spatial distribution of natural fractures within individual geologic units.

Open natural fractures are sometimes present in carbonate reservoirs and could act as storage space for CO_2 as well as good fluid conduits that could enhance the injectivity of CO_2 into storage aquifers. 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 to slip at varying pore pressure conditions.

Study area

The study area shown in figure 1 is located on the western flank of northern Appalachian basin within central to eastern Ohio.

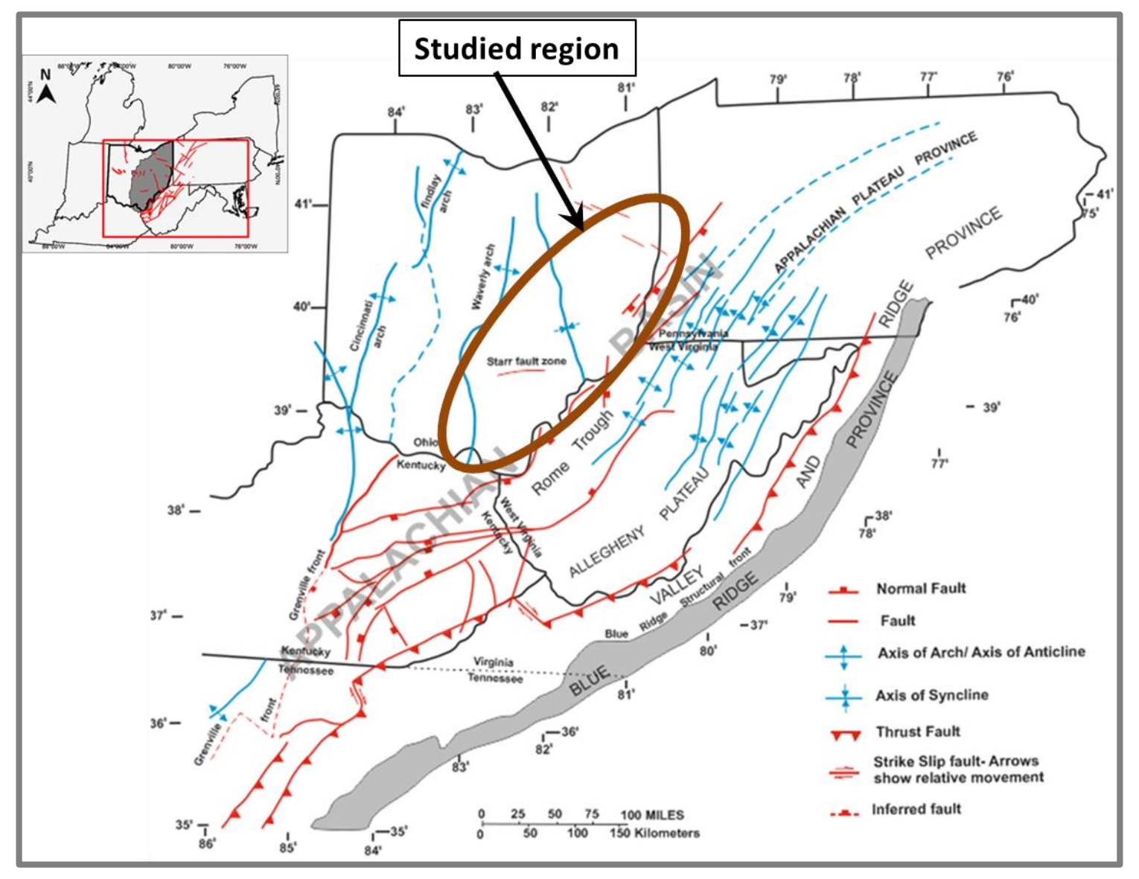


Figure 1: Map of Appalachian basin region showing structural elements (Drawn and Modified after U.S Geological Survey (USGS) Map, 2012)

The Cambrian-Ordovician strata on the western flank of the basin dips gently eastwards into the Rome Trough with increasing thickness of the Beekmantown strata. Figure 2 shows the Knox unconformity surface and the increasing thickness to the east.

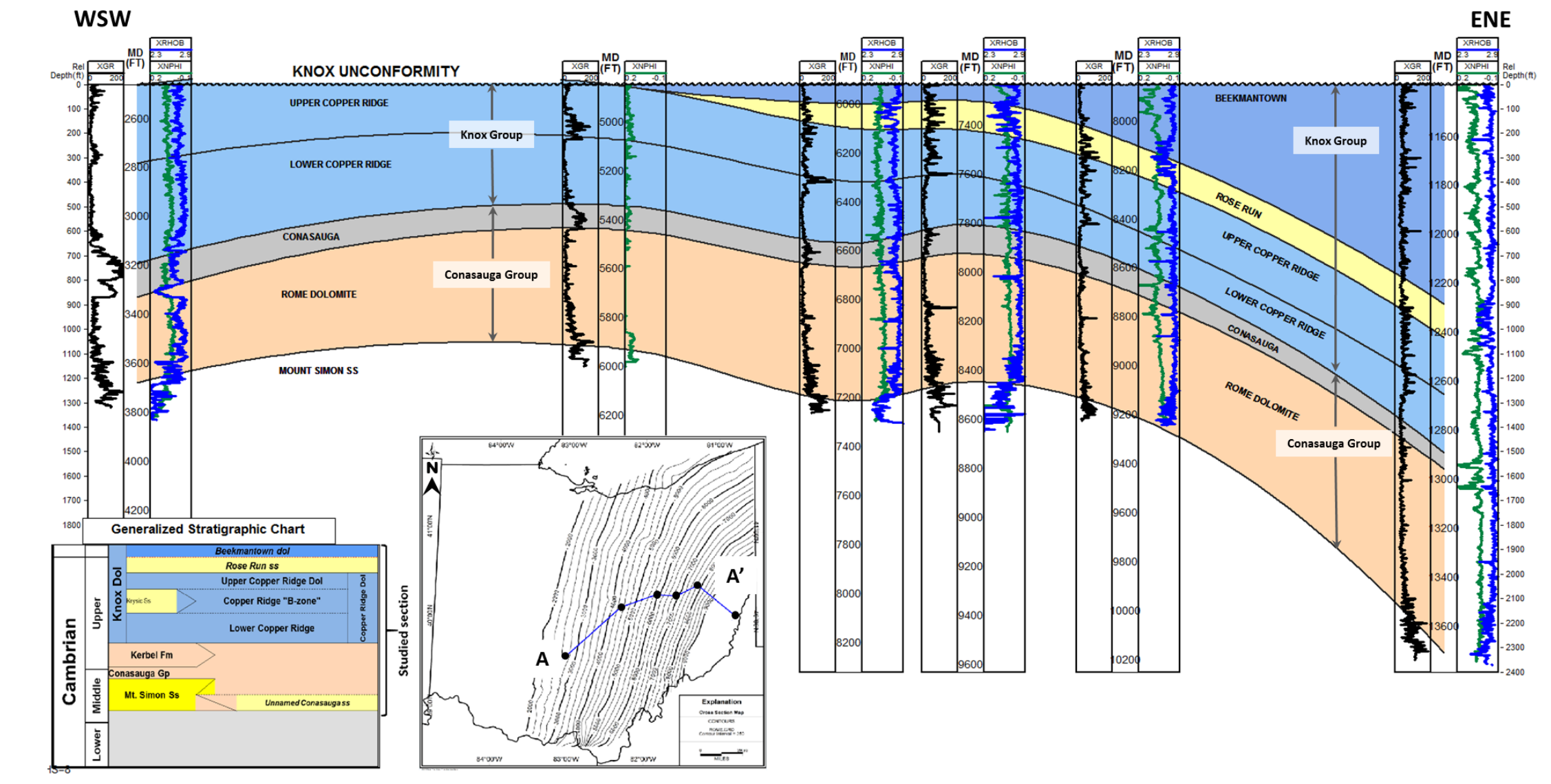


Figure 2:WSW to ENE (A-A') cross section of the study area showing change in sediment thickness in an eastward direction (Note; Knox unconformity surface was used as datum)

Natural fracture interpretation & analysis

Ten resistivity and acoustic log images were collected within the Cambrian –Ordovician interval. The logs were interpreted to identify natural fractures and well-bore failures. Examples of interpreted natural fractures are shown in figures 3 and 4.

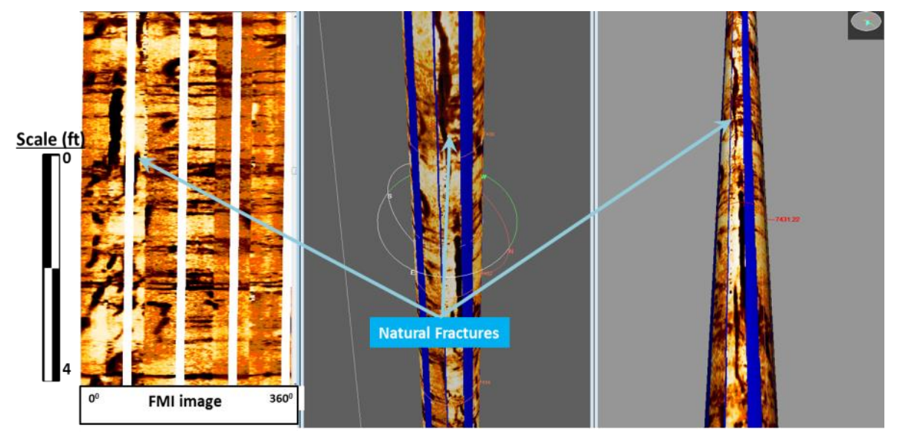


Figure 4: FMI image of natural fractures

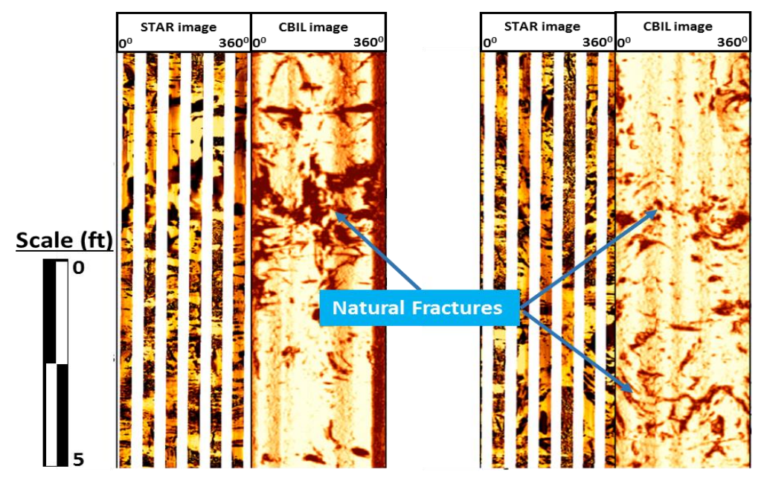


Figure 3: STAR and CBIL images of Natural Fractures

Histograms of observed fractures were produced for each examined well. Produced histogram was used in generating a cross section (figure 5) in order to analyze fracture intensity variation from west to east of the studied area.

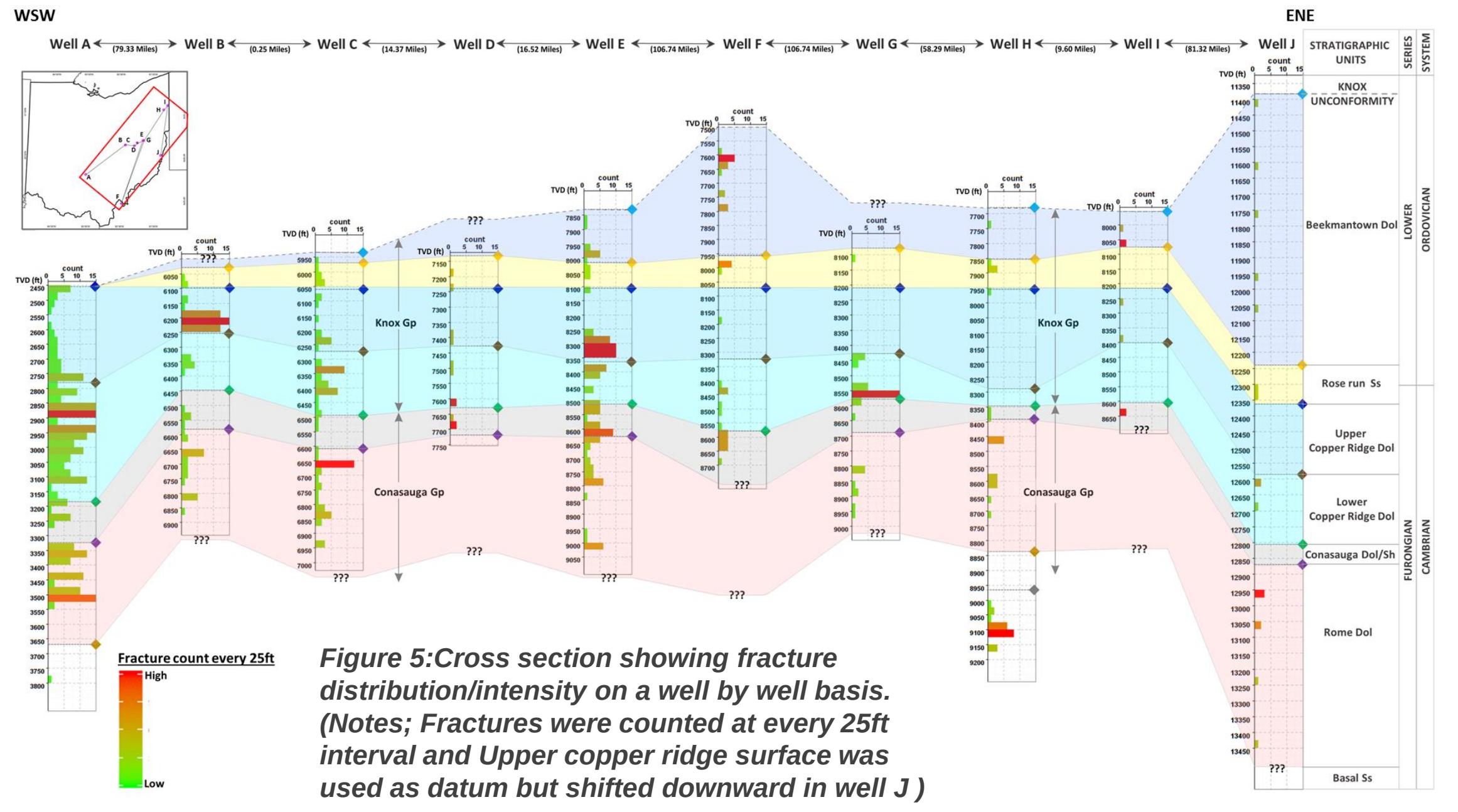


Figure 5:Cross section showing fracture distribution/intensity on a well by well basis. (Notes; Fractures were counted at every 25ft interval and Upper copper ridge surface was used as datum but shifted downward in well J)

Preliminary results 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 under investigation and could have been related to various factors such as basin architecture, brittleness variation, overburden pressure and tectonic history.
In summary, this result could potentially imply that locations that are in the up-dip part of the study area are more favorable for CO_2 injection.

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 fracture slippage likelihood and conducting other geomechanical related assessment associated with injection of CO_2 into fractured reservoir.

Using observations of well bore failures (Figure 6), we derived orientation of S_{Hmax} within the study area.

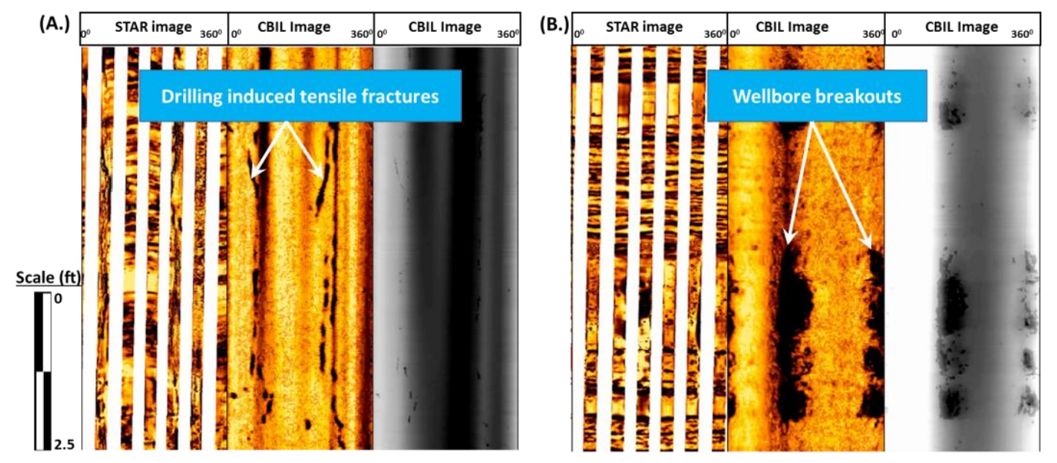


Figure 6: Acoustic and resistivity images of Wellbore failures

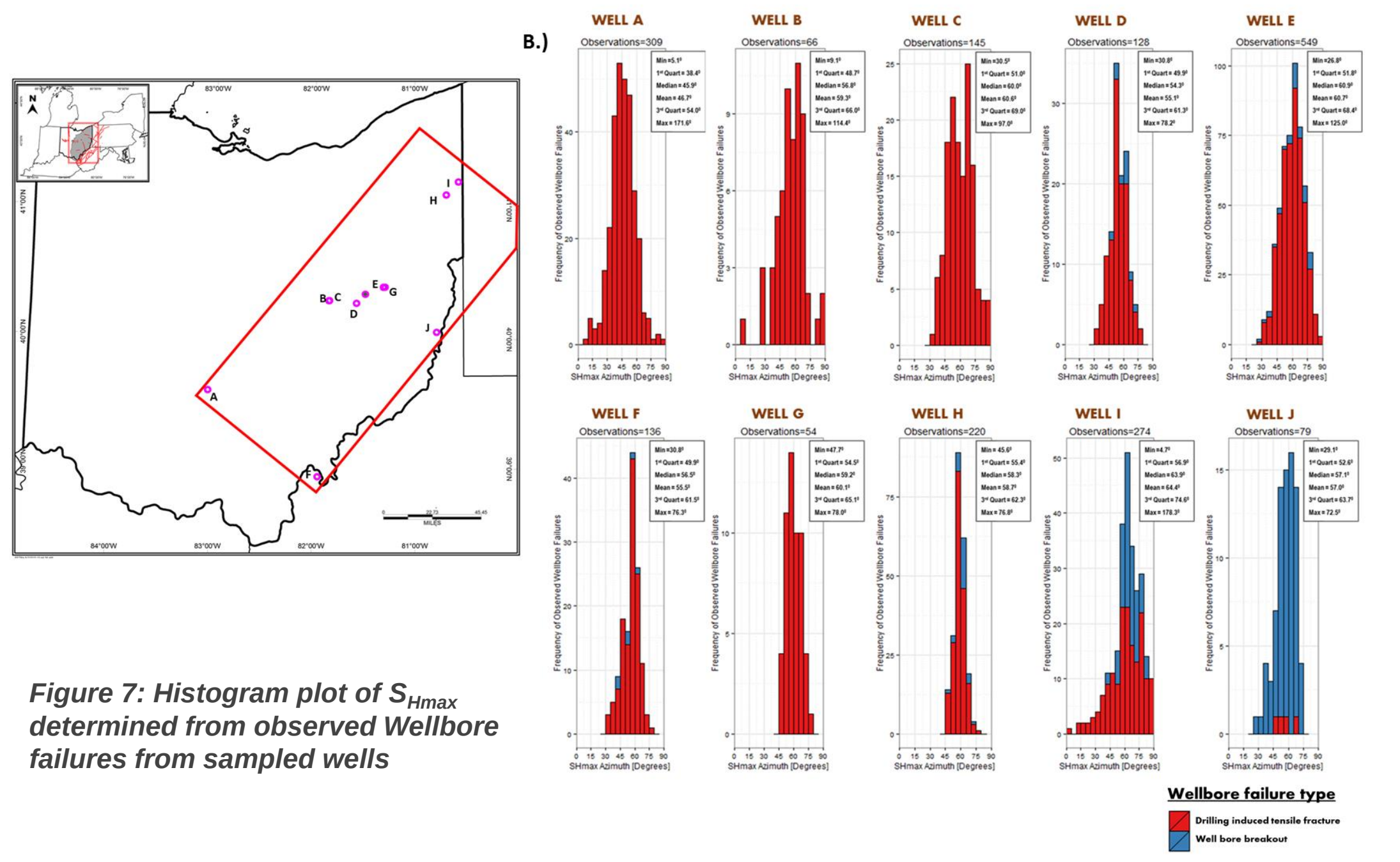


Figure 7: Histogram plot of S_{Hmax} determined from observed Wellbore failures from sampled wells

Updating stress map in the region

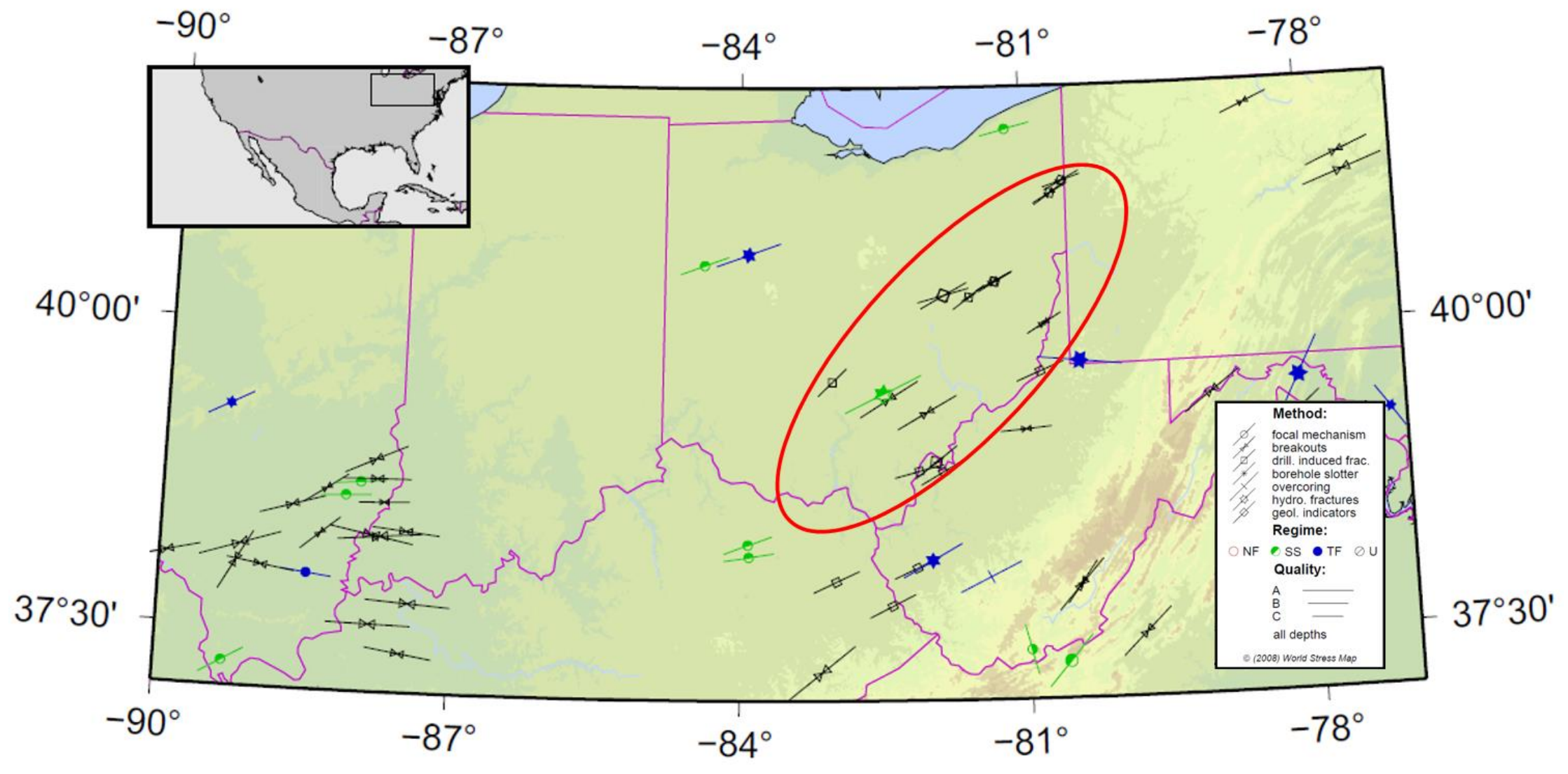


Figure 8: Updated stress map for the studied region

Results on analysis of well-bore failure observations (figure 7) from each well was used in updating stress map of the region by updating locations without data (Figure 8).

Natural fracture analysis *(continued)*

Analysis on natural fracture orientation is important in understanding and modeling possible 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 used in statistical analysis and building a map with superimposed rose diagrams of observed fractures. Example of produced figures is shown in figures 10.

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

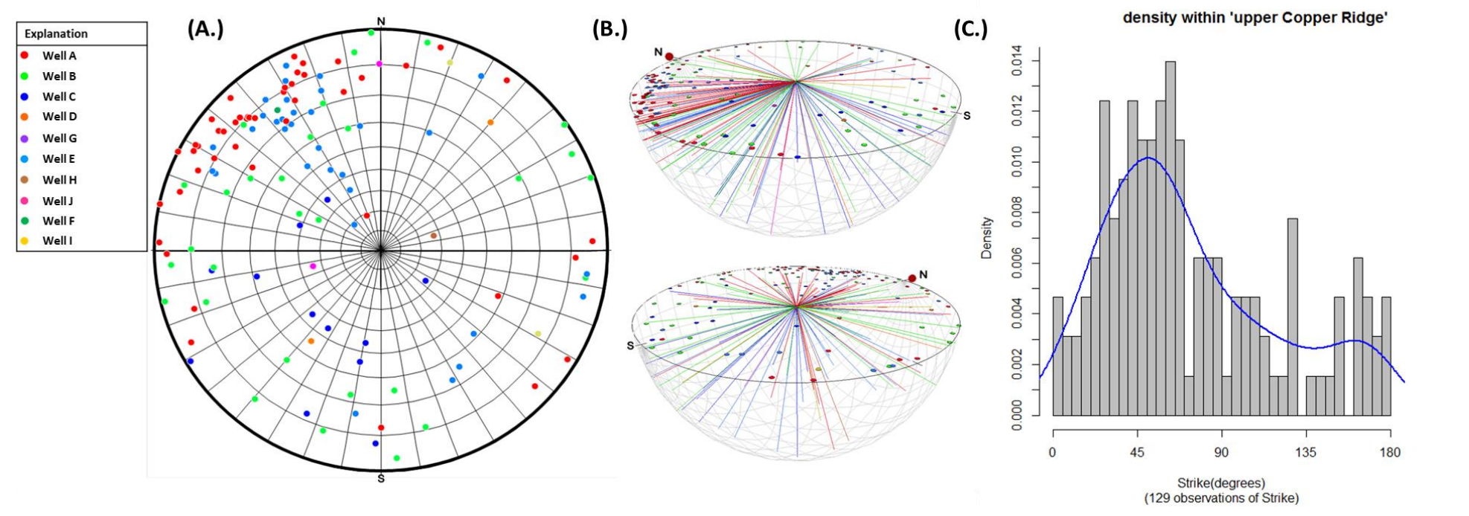


Figure 9: Poles to plane of Upper Copper Ridge fractures and histogram plot of fracture strike (degrees)

Relating natural fractures to present day stress field

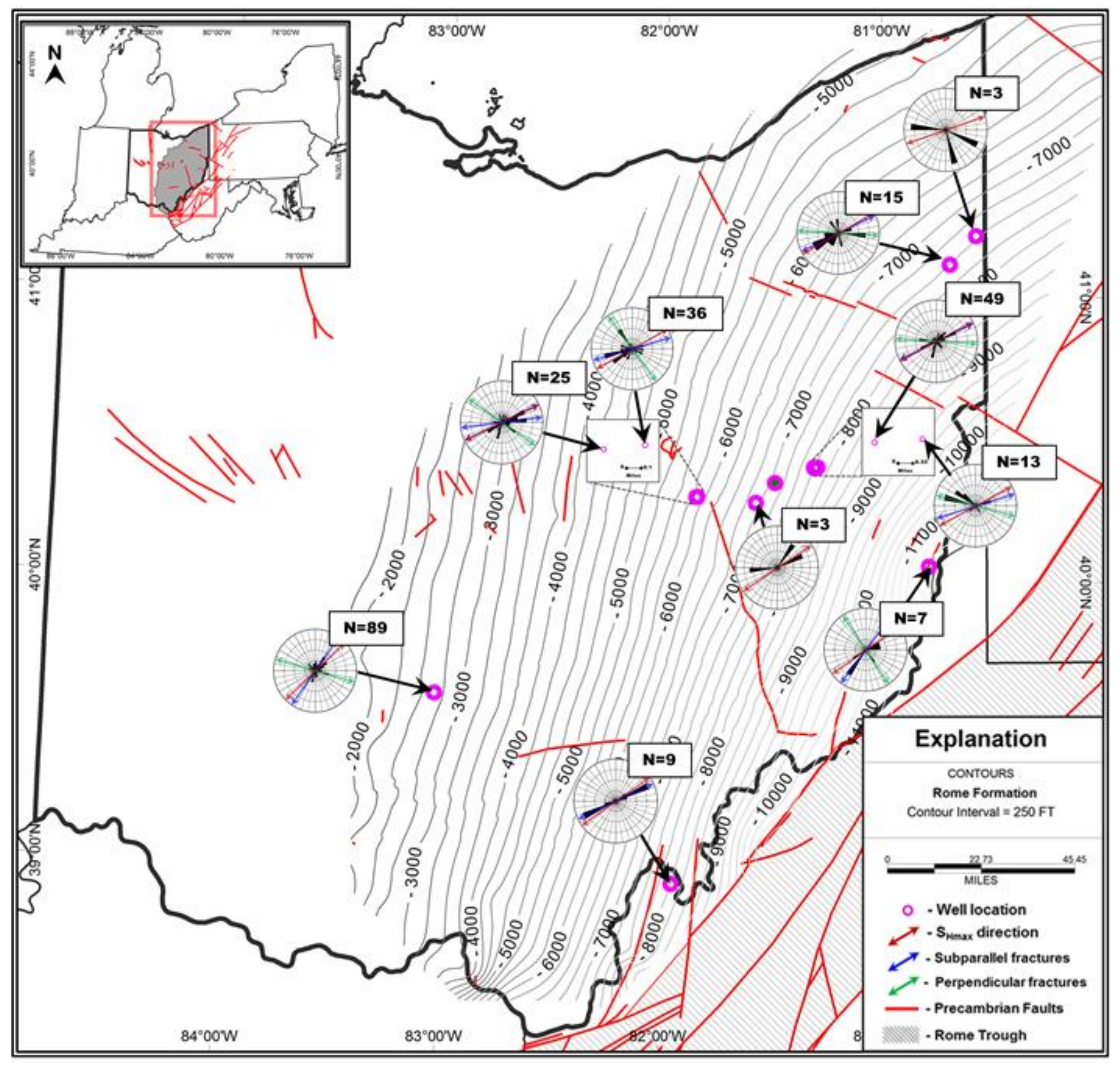


Figure 10: Map showing overlaid Rose diagrams of natural fractures observed in the Conasauga group

Stress magnitudes

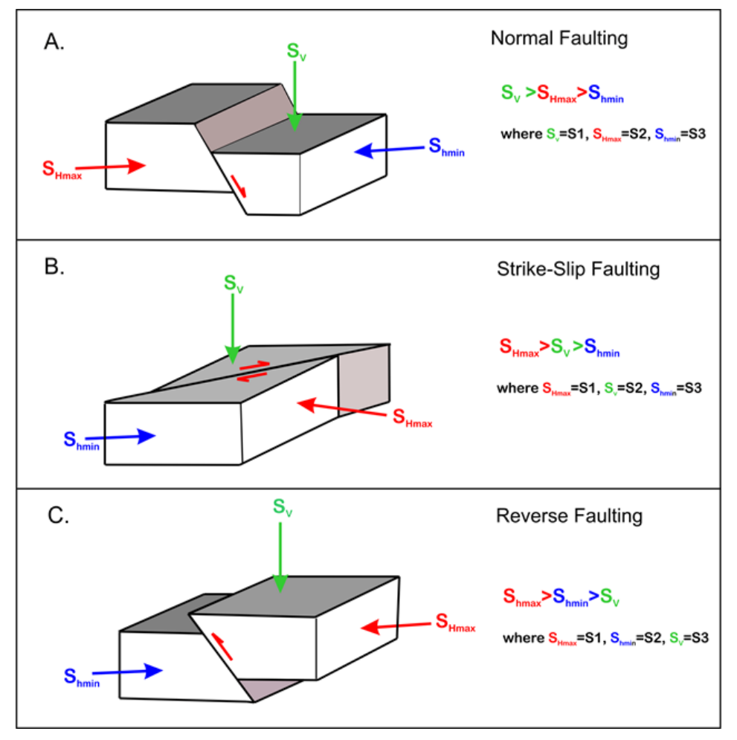
Determination of the stress magnitudes (S_V, S_{Hmax}, and S_{hmin}) acting at depth is important in understanding the prevailing stress regime in the region.

Pore pressure (Pp) data was derived from pressure measurement in the borehole (figure 12).

S_v was determined from integrating density log. (figure 13).

$$S_V = \int_0^z \rho(z) g\,dz$$

Magnitude of S_{hmin} is normally determined from Leak-Off test (LOT). While figure 14, shows how maximum horizontal stress magnitude is constrained using stress polygon approach.



A. $S_v > S_{Hmax} > S_{hmin}$ where S_v=S1, S_{Hmax}=S2, S_{hmin}=S3

B. $S_{Hmax} > S_v > S_{hmin}$ where S_{Hmax}=S1, S_v=S2, S_{hmin}=S3

C. $S_{Hmax} > S_{hmin} > S_v$ where S_{Hmax}=S1, S_{hmin}=S2, S_v=S3

Figure 11: Different types of fault system (Anderson Classification scheme)

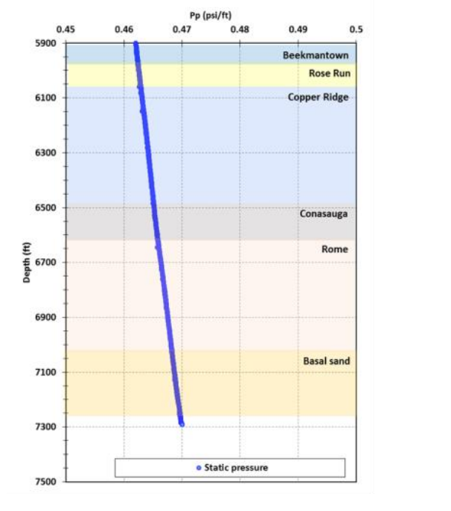


Figure 12: Pore Pressure gradient

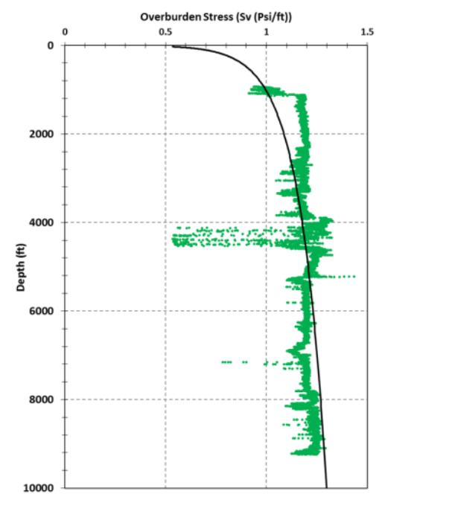


Figure 13: Overburden stress

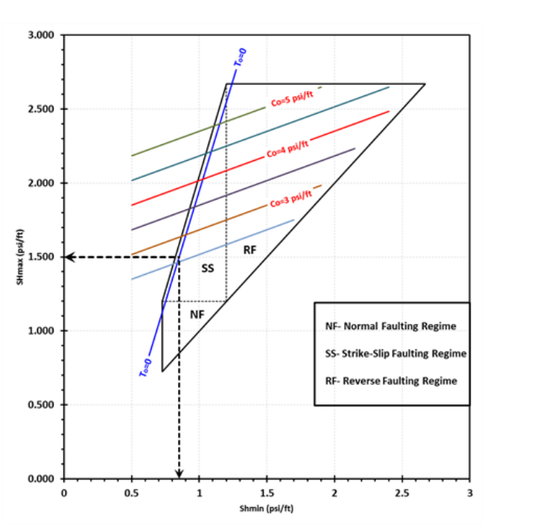
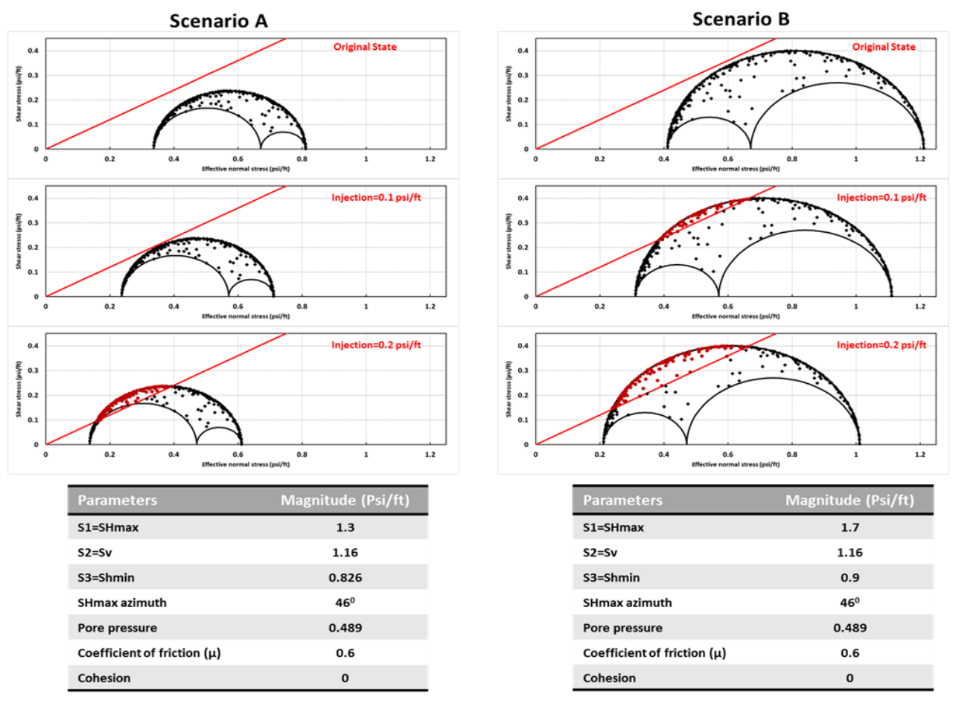


Figure 14: Stress Polygon

Critically stressed fracture analysis

Horizontal stress magnitudes derived in the work by Lucier, 2006 were used as estimates for critically stressed fracture analysis.

Figures 15 shows an example of a 3D Mohr circle analysis on fractures observed in a sampled well. Result shows that these fractures are stable in their original state but have the tendency to slip at elevated pressure during CO_2 injection. This analysis could be useful in CO_2 site screening, characterization, operation and monitoring.



Scenario A

Parameters	Magnitude (Psi/ft)
S1=SHmax	1.3
S2=Sv	1.16
S3=Shmin	0.826
SHmax azimuth	46°
Pore pressure	0.489
Coefficient of friction (μ)	0.6
Cohesion	0

Scenario B

Parameters	Magnitude (Psi/ft)
S1=SHmax	1.7
S2=Sv	1.16
S3=Shmin	0.9
SHmax azimuth	46°
Pore pressure	0.489
Coefficient of friction (μ)	0.6
Cohesion	0

Figure 15: 3D Mohr Circle Analysis

Conclusions

- Western part of the studied area appears to be more fractured than the eastern part
- Dominant northeast – southwest trending fractures are observed in the studied region
- High percentage of fractures tend to strike sub-parallel to the axis of S_{Hmax}
- 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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