# State of Stress in the Illinois Basin and Constraints on Inducing Failure*

**R.W. Lahann[1], J.A. Rupp[1], and C.R. Medina[1]**

[1]Indiana Geological Survey, Indiana University, Bloomington, IN, USA (rupp@indiana.edu)

## Abstract

The stress regime in the Illinois Basin was investigated to assess how the rock column might respond to the injection of fluids, including co-produced formation brines and supercritical $CO_2$. This response is a concern as injection practices could increase pore pressure and potentially induce seismicity. Data were collected to determine the magnitude and orientation of a three-component stress field: vertical (Sv), minimum (Sh), and maximum (SH) horizontal stresses. Sv was evaluated with a six-layer lithostratigraphic column. A two-layer pressure-depth Sv model for the central portion of the basin and a single pressure gradient model for the surrounding region were generated. In the central portion of the basin, the Sv gradient is 1.11 psi/ft to a depth of 7000 ft, followed by a gradient of 1.20 psi/ft below 7,000 ft. In the area surrounding the deep basin, the Sv gradient was calculated as 1.13 psi/ft. Sh was evaluated from multiple data sources, primarily fracture closure values from either hydraulic fracture records or extended leak-off tests. Sh gradient calculations ranged from 1.07–1.21 psi/ft. The Sh values for the basal clastic units that directly overlie the crystalline basement complex are lower than those for units in the overlying horizons. SH was based on a critically stressed model yielding values between 1.77 to 2.65 psi/ft, which is significantly greater than the gradient values for Sv or Sh. Stress orientation data for the Illinois Basin were collected from multiple sources. The orientation of the principal stress, SH, across the study area relatively uniform in strike at approximately N 60 E but has marked deviations. These deviations result from localized structural discontinuities in the crust.

## References Cited

Bauer, R.A., 2015, Compilation of in situ stress measurements and directions in Illinois: Illinois State Geological Survey, Personal Communication.

Engelder, T., 1993, Stress Regimes in the Lithosphere: Princeton University Press, Princeton, 492 p.

Keranen, K.M., M. Weingarten, G.A. Abers, B.A. Bekins, and S. Ge, 2014, Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection: Science, v. 345/448, p. 448-451, DOI: 10.1126/science.1255802

Lucier, A., M. Zoback, N. Gupta, and T.S. Ramakrishnan, 2006, Geomechanical aspects of $CO_2$ sequestration in a deep saline reservoir in the Ohio Valley region: Environmental Geoscience, v. 13, p. 85-103.

Zhang, Y., M. Person, J. Rupp, K. Ellett, M.A. Celia, C.W. Gable, B. Bowen, J. Evans, K. Bandilla, P. Mozley, T. Dewers, and T. Elliot, 2013, Hydrogeologic controls on induced seismicity in crystalline basement rocks due to fluid injection into basal reservoirs: Groundwater, v. 51, p. 525-538.

# State of Stress in the Illinois Basin and Constraints on Inducing Failure

R. W. Lahann[1], J. A. Rupp[1], and C. R. Medina[1]

[1] Indiana Geological Survey
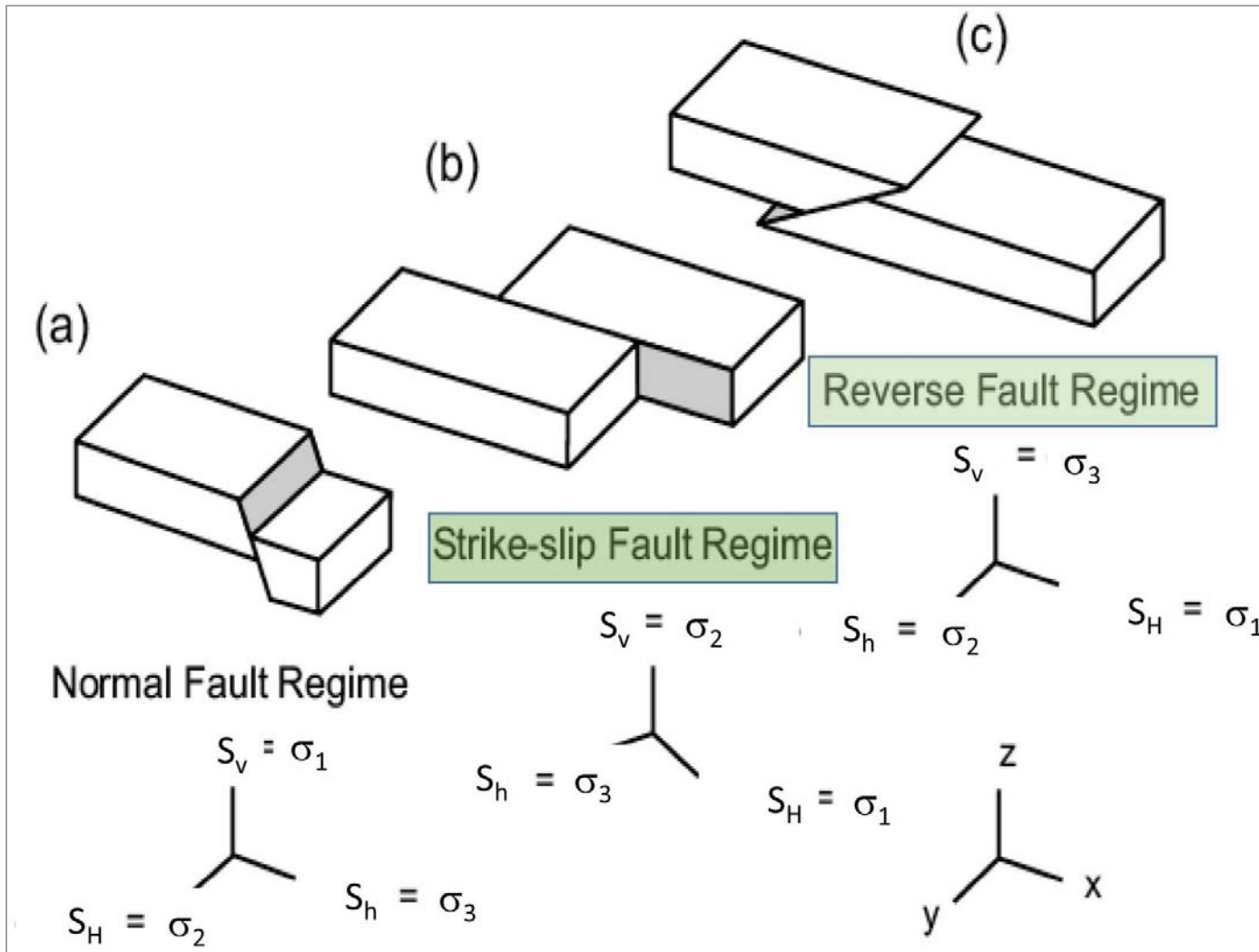
ES AAPG Meeting

Lexington, KY

September 26, 2016

# Outline

- Overview
- Methods
- Results
  - Stress magnitudes
  - Regional stress field orientation
- Conclusions

- Thanks to Bob Bauer (ISGS), Kaj Johnson and Grace Carlson (IU DOGS), Sallie Greenberg (MGSC ISGS)

- Primary Focus: Investigate and model the state of the stress field that exists in the MGSC region
  - Orientation of three principle stresses
  - Magnitudes of these forces
- Primary Research Question:
  - How is the stress field oriented throughout the IB and surrounding region?
  - What are the stress (pressure/depth) gradients in the region?
  - How much can the pore pressure be enhanced, via injection, before faults are activated?
- Results are of value for:
  - Seal and reservoir integrity evaluations, seismic risk assessment, and storage efficiency estimates
  - Regulators of subsurface injection

# Stress Field

- Stress files characterized by three mutually orthogonal tensors, denoted as $\sigma 1$, $\sigma 2$ and $\sigma 3$
- This configuration can be situated anywhere in space but, assuming one is vertical, the others become horizontal, denoted as S vs. $\sigma$
- Vertical stress = $S_V$
- Maximum ("Principle") horizontal stress = $S_H$
- Minimum horizontal stress = $S_h$

(c)

(b)

(a)

Reverse Fault Regime

$S_v = \sigma_3$

Strike-slip Fault Regime

$S_v = \sigma_2$    $S_h = \sigma_2$

$S_H = \sigma_1$

Normal Fault Regime

$S_v = \sigma_1$

$S_h = \sigma_3$    z

$S_H = \sigma_1$

$S_H = \sigma_2$    $S_h = \sigma_3$    y    x

Presenter's notes: Relationships between principle stresses (Sv, SH and Sh) and fault styles. Modified from Engelder (1993).

# Coulomb Failure in Poroelastic Material

- Occurs when the ratio of the shear stress to the normal stress $\tau/\sigma$ exceeds a critical value (e.g. 3/1)

- The critical value is influenced by $\mu$, the friction of the fault surface (function of lithology)

- The ratio of $\tau/\sigma$ is determined by the values of $S_H$ ($\sigma 1$) and $S_h$ ($\sigma 2$), the angle of the fault $\beta$ and, the pore pressure $p$

- When all other influences are held
  constant, increasing pore pressure
  increases the ration of $\tau/\sigma \longrightarrow$ failure

$\beta_{crit}$ = Critical angle of faulting
$P_{crit}$ = Critical pore pressure
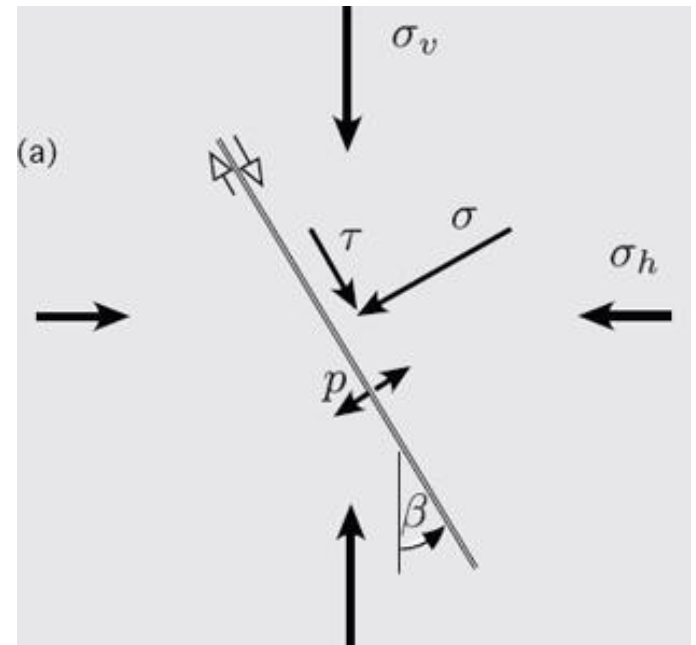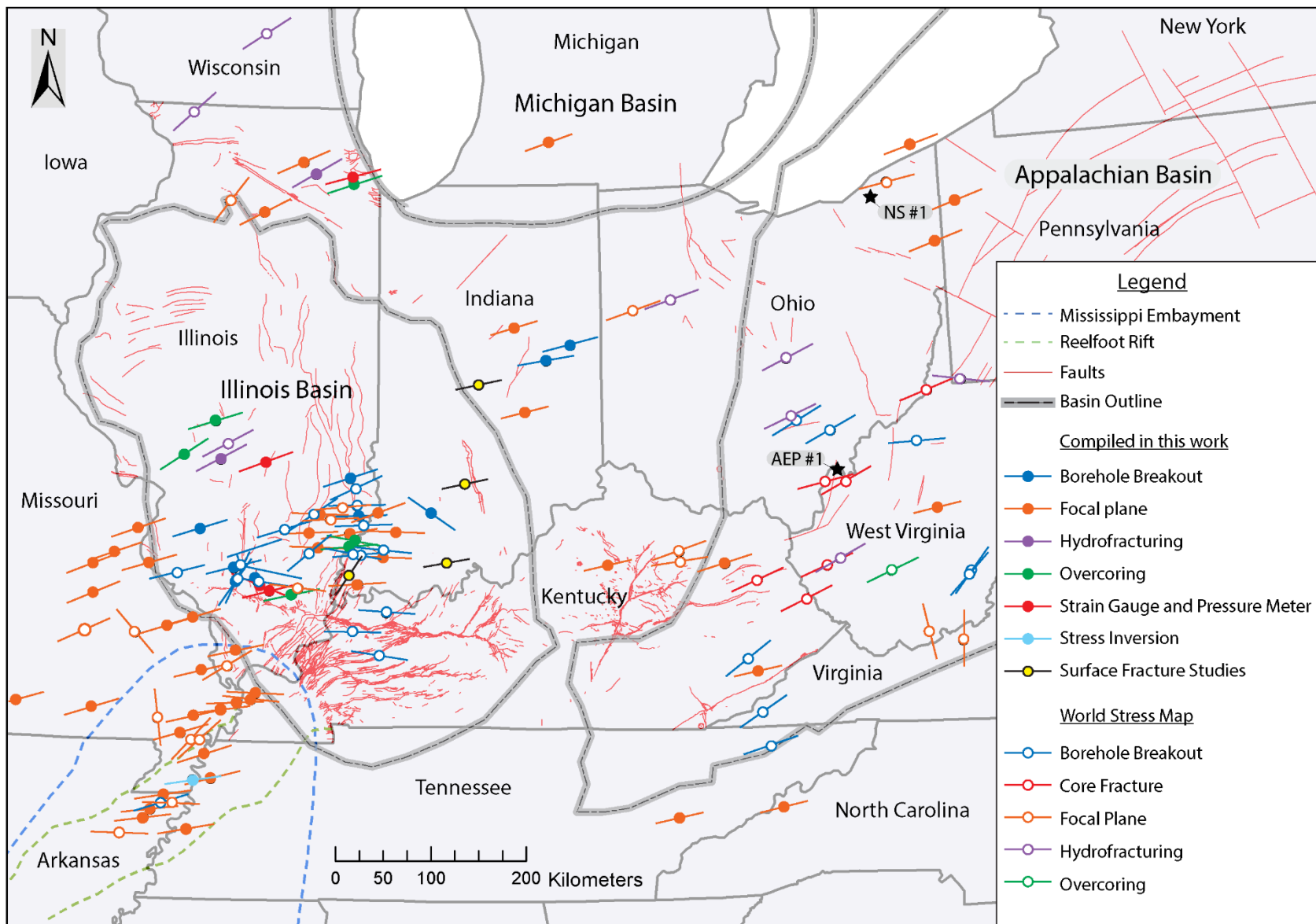
# Methods

Determination of $S_v$

- Simplified the stratigraphic sequence into six layers based on generalized lithofacies of rock units

- Examined a series of density logs to determine average density of layers across the region

- Mapped their spatial distribution and then determined $S_v$ gradient in two areas – basin margin and basin deep

# Stratigraphy based on lithofacies – six units
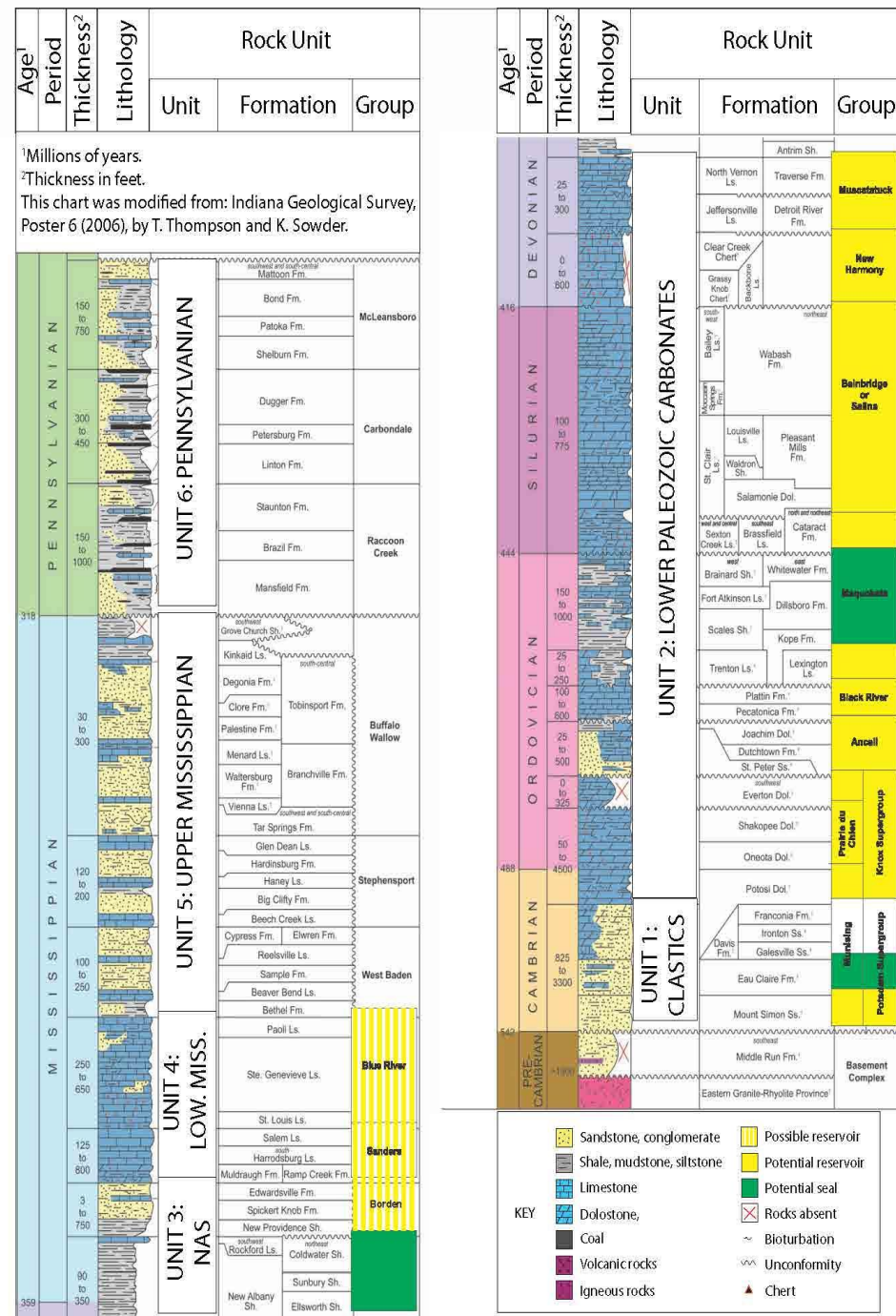
# Example of log used to determine average density of units



Well id#150128. Knox County, Indiana.
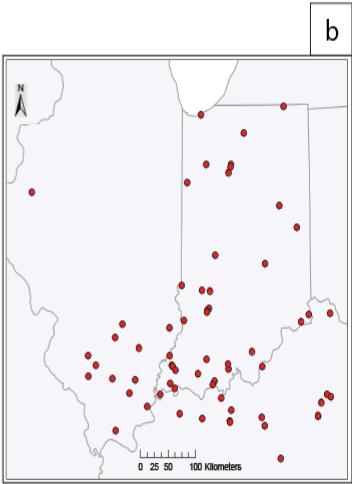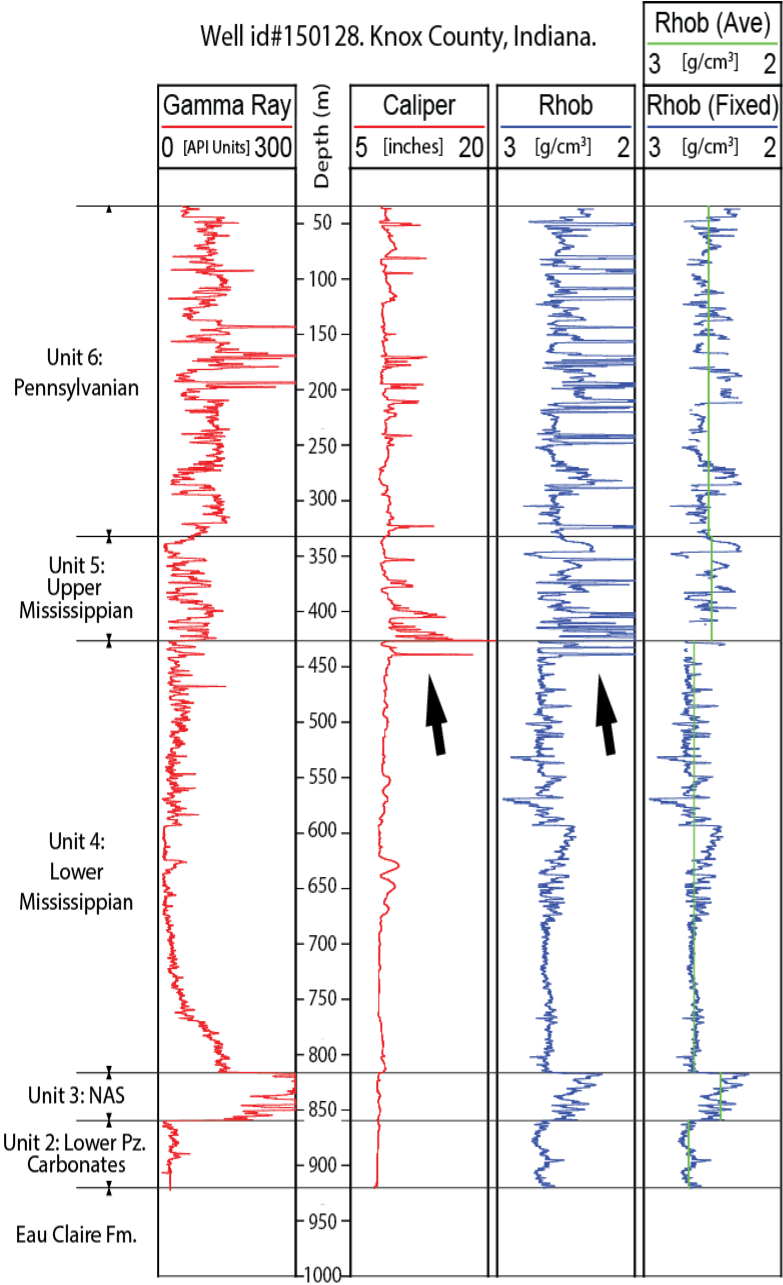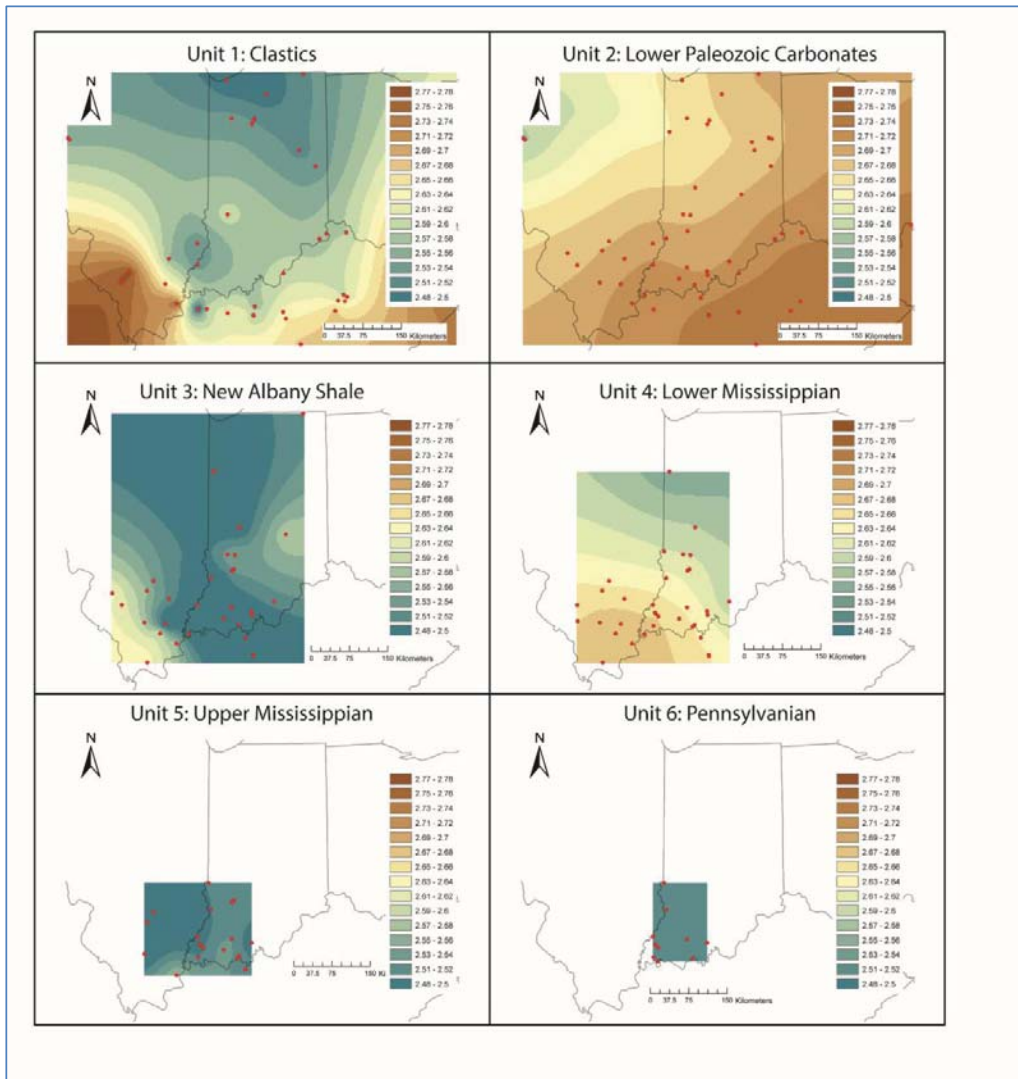
Presenter's notes: Regional density variation for major lithostratigraphic units, 1) (Cambrian clastics), 2) (Ordovician-early Devonian carbonates), 3) (late Devonian clastics) and 5) (late Mississippian clastics). The densest unit on the figure is the Ordovician-early Devonian carbonates. Cambrian clastics, values from 2.5 to 2.68 sg.
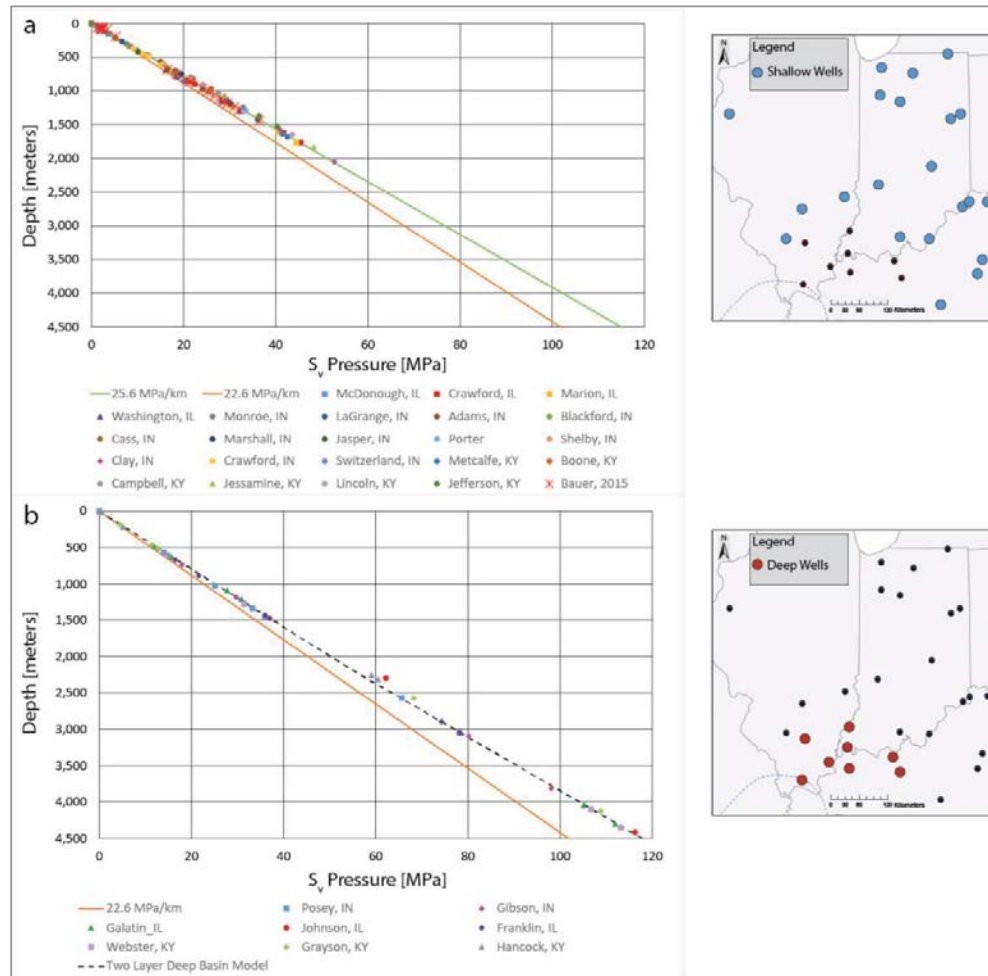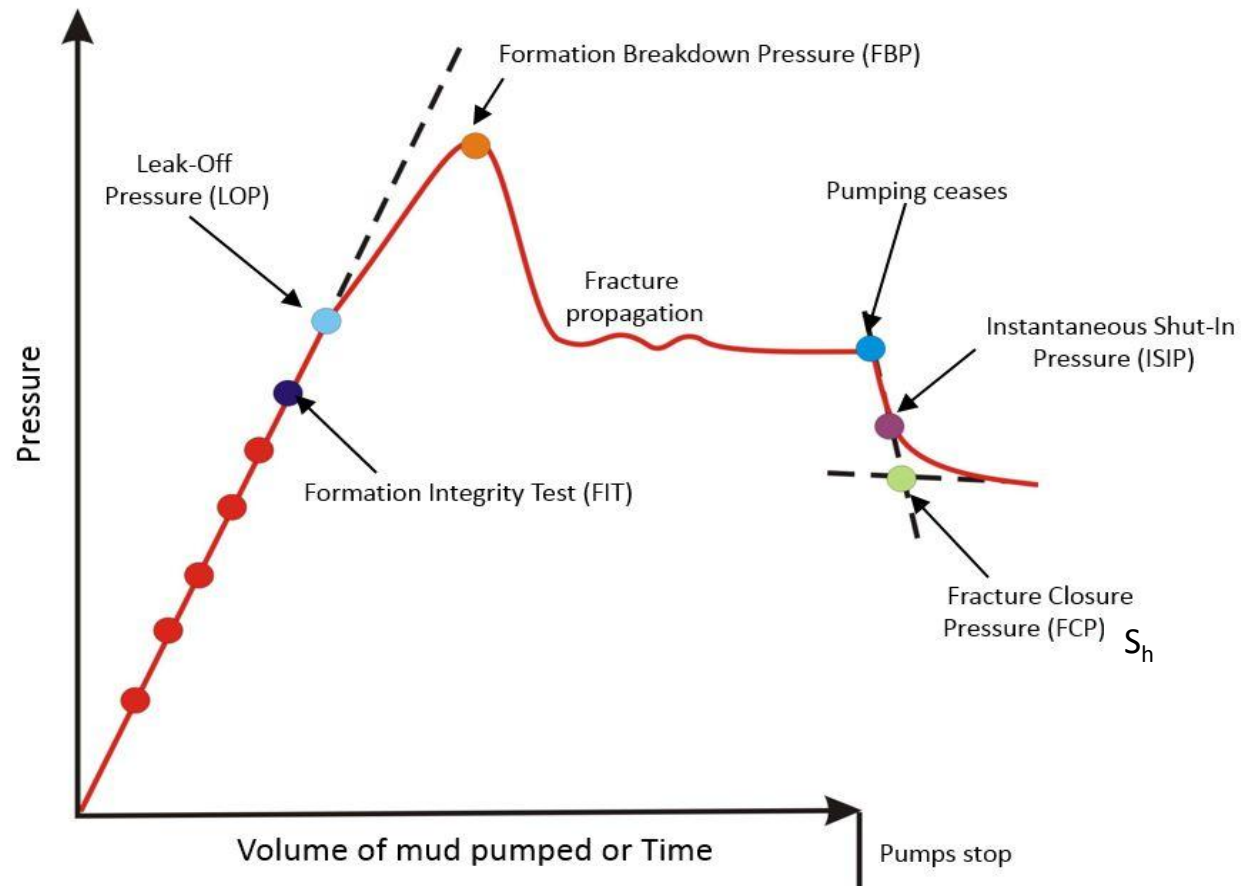
Presenter's notes: (a) $S_v$/depth profile calculated for 22 Indiana, Illinois and Kentucky wells with TD< 2130 meters (7000 feet). The green line, 25.6 MPa/km (1.13 psi/foot), represents the combined $S_v$ profiles from individual wells. The insert map shows the location of the wells represented in this plot. A series of $S_v$ values from four locations in Northern Illinois are also posted on this plot and are in agreement with the work from this study; (b) $S_v$ profiles calculated for Indiana, Illinois and Kentucky deep basin wells with TD > 2130 meters (7000 feet). The green line is a two-layer $S_v$ model with slope of 25.1 MPa/km (1.11 psi/foot) to 2130 meters and then a slope of 27.1 MPa/km (1.20 psi/foot) to total depth. In both plots, the orange line represents the frequently assumed gradient of 22.6 MPa/km (1 psi/foot). 1 Mpa = 145 psi.
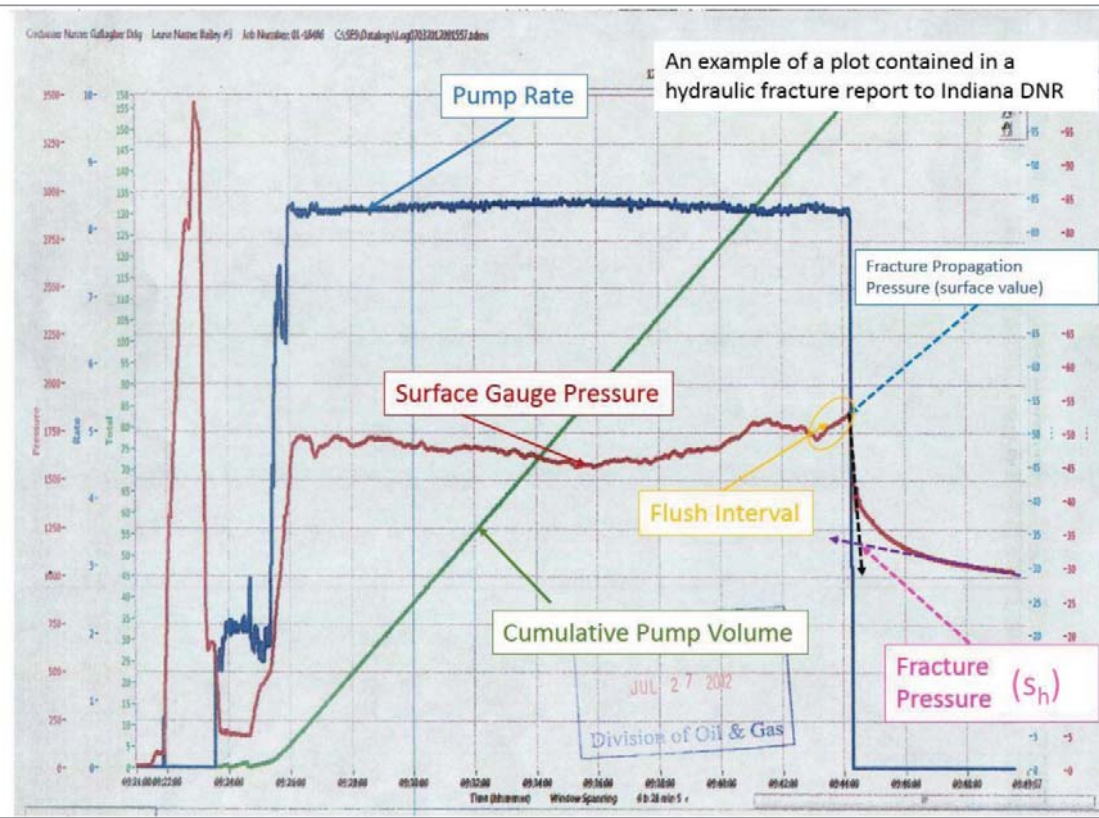
# Determination of $S_h$

- Based on the strength of the formations
- Strength came from:
  - Formation integrity tests (FIT)
  - Leak off tests (LOT)
  - Fracture closure values (hydraulic fracturing)

# Idealized Pump Test



Formation Breakdown Pressure (FBP)

Leak-Off Pressure (LOP)

Pumping ceases

Fracture propagation

Instantaneous Shut-In Pressure (ISIP)

Pressure

Formation Integrity Test (FIT)

Fracture Closure Pressure (FCP) $S_h$

Volume of mud pumped or Time

Pumps stop

Example of hydraulic fracturing record

Presenter's notes: Example of hydraulic fracture stimulation record used to determine $S_h$. The fracture closure pressure ($S_h$) is determined by interpolating two portions of the post fracture propagation pressure curve (red). The pink arrow indicates the intersection of the two rates of pressure decline after pumping has stopped.
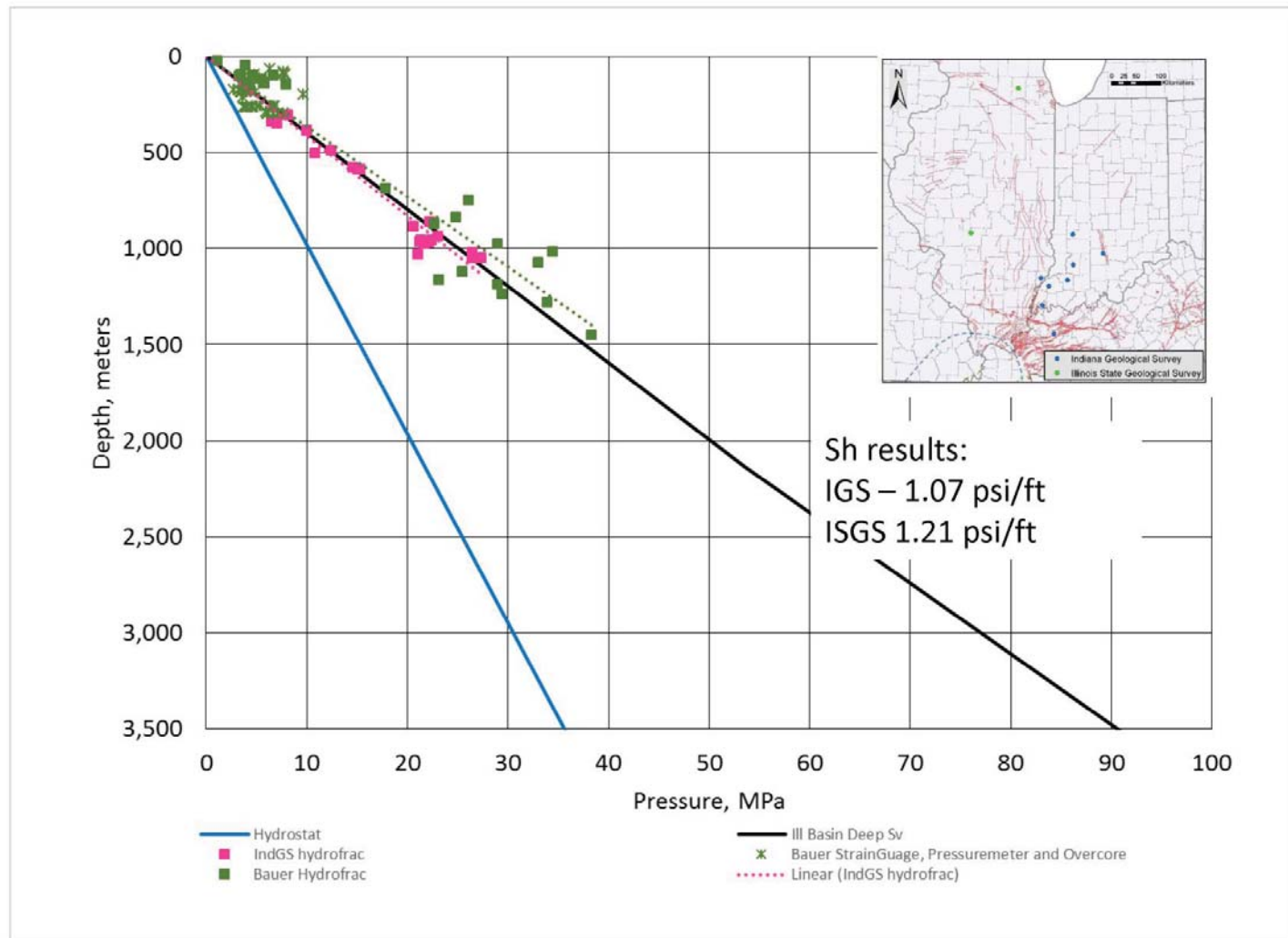
Presenter's notes: $S_h$/depth plot from IndGS hydrofracture data and Bauer (2015) Illinois $S_h$ interpretations by hydrofracture, overcoring, strain gauge and pressure meter data. The pressure/depth gradient $S_h$ from IndGS data is 24.1 MPa/km (1.07 psi/ft); the gradient of $S_h$ from the IllSGS data is 27.4 MPa/km (1.21 psi/ft). Inset map shows the location of wells with hydrofracture data.

# Determination of $S_H$

- $S_H$ was calculated based on the values of $S_h$
- Based on a critically stressed crustal model
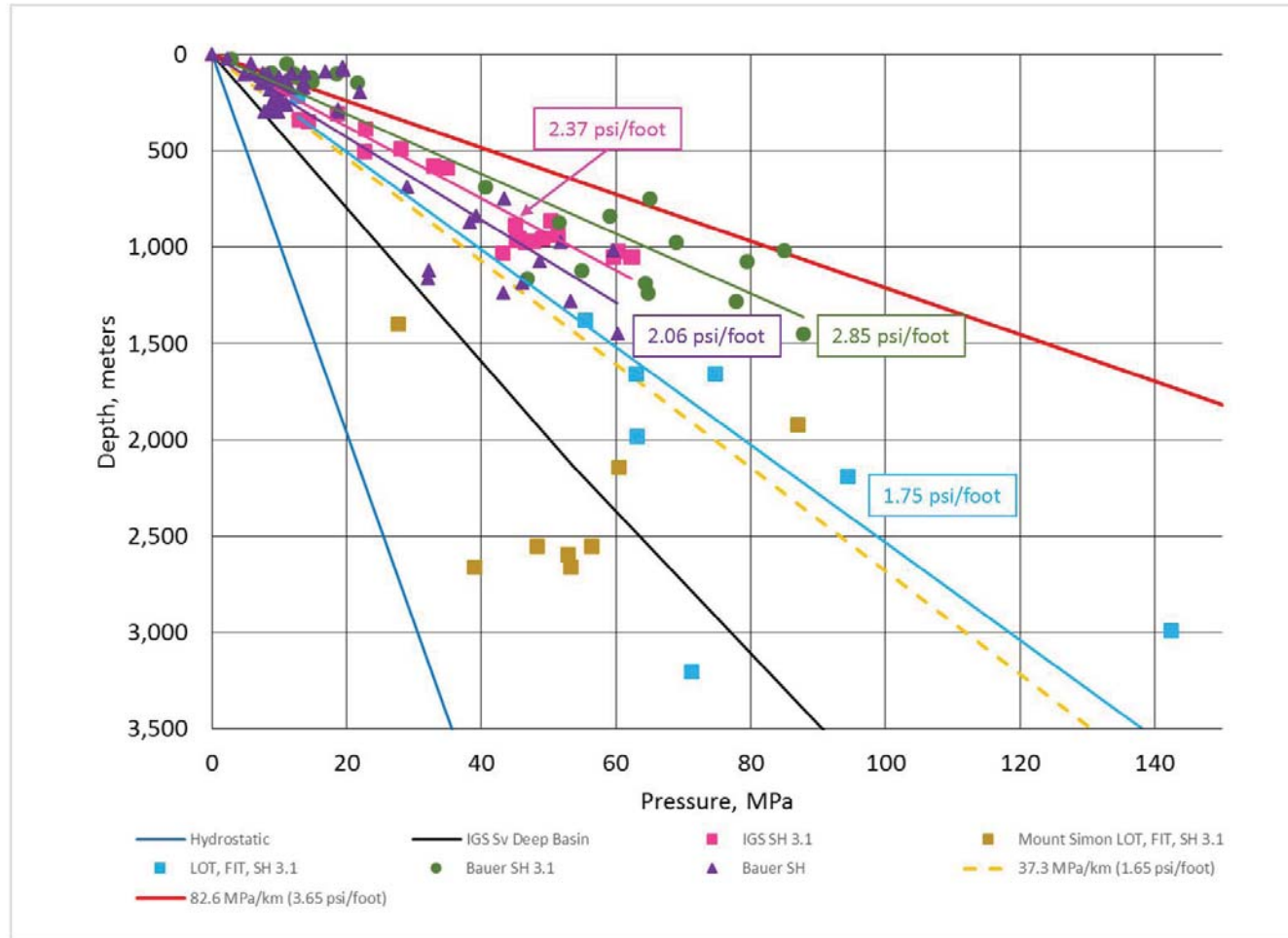
Presenter's notes: $S_H$ data includes values reported by Bauer (2015) (purple) and values calculated from Illinois basin hydraulic fracture data (pink) and $S_h$ values from Bauer compilation (green) using an effective stress ratio of 3.1. Additional data includes $S_H$ values calculated from $S_h$ values from LOT and FIT tests (blue and ocher).
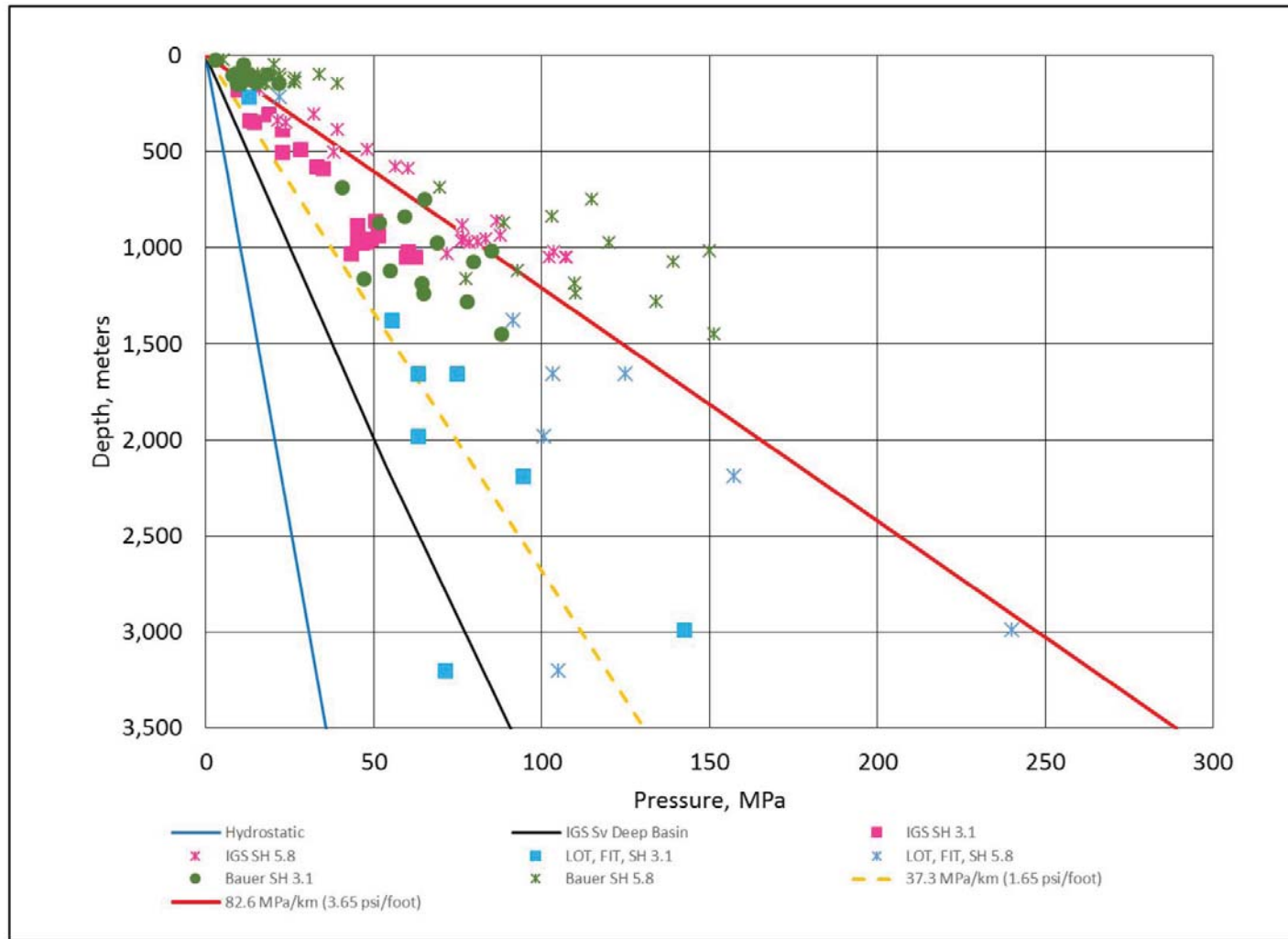
Presenter's notes: Comparison of $S_H$ values calculated using effective stress ratios of 3.1 and 5.8. When using 3.1 as an input variable in the calculation, most values fall above 37.3 MPa/km (1.65 psi/ft). The maximum gradient for $S_H$ appears to be less than 82.6 MPa/km (3.65 psi/ft).

# S$_v$ Results

- Central portion of the basin:
  - Shallower portion of the section 0-7,000', gradient is 1.11 psi/foot
  - >7,000' gradient is 1.20 psi/foot
- Area surrounding the deep basin, the gradient is 1.13 psi/foot

  *The calculated Sv values are _greater_ than some Sv values employed in earlier Illinois Basin studies.

# $S_h$ Results

- Using various sources of information, values of $S_h$ gradients range from 1.07- 1.21 psi/foot

- Because these values are very close to the values for $S_v$ (1.11-1.20 psi/foot), fault mechanisms may change from predominantly strike slip ($S_H > S_v > S_h$) to reverse/thrust ($S_H > S_h > S_v$) in some local circumstances.

- $S_h$ values for the basal clastic units that directly overlie the crystalline basement complex (Eau Claire/Mount Simon Sandstone) are lower than those of overlying sedimentary units

# $S_H$ Results

- $S_H$ gradient values were calculated to be between 1.77 to 2.65 psi/foot

- $S_H$ is modeled based on a critically-stressed model.

- As these values are derived from other calculated values, which themselves have some degrees of uncertainty, values for $S_H$ are assumed to be significantly uncertain

# SH Orientation

- $S_H$ is interpreted to be the maximum stress ($\sigma_1$) based on fracture patterns in the basin

- Horizontal orientation data compiled from multiple sources

- Relatively uniform in strike at approximately N 60 E

- Localized deviations could be the result of localized structural discontinuities in the crust
  - These areas include the Wabash Valley Fault Zone, the Rough Creek Graben and the New Madrid Fault Zone.
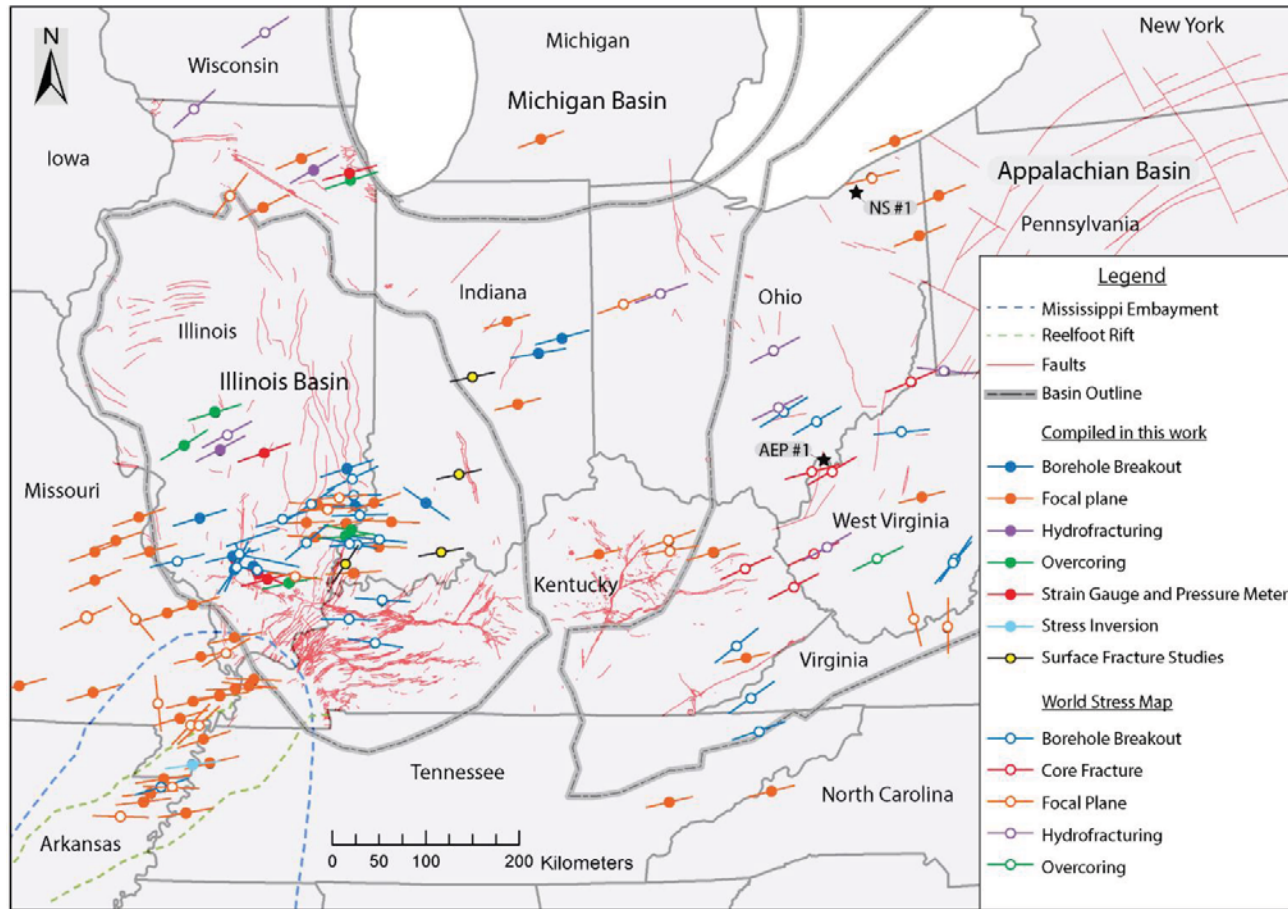
Presenter's notes: Regional setting and structures relating to the Illinois Basin. Also shown are regional stress directions from the World Stress map and multiple sources. The Illinois Basin is an oval-shaped intracratonic basin that lies in the east central portion of the North American craton. Several prominent structural features are found within and directly adjoining the basin. These features include the Wabash Valley Fault System, which is a northeast-southwest trending set of dominantly normal and transtensional faults located on the Indiana-Illinois border, adjoining the deepest portion of the basin. The Wabash Valley fault system is truncated by the Rough Creek-Pennyrile-Shawneetown Fault System. The truncating faults strike east-west, are strike-slip in nature and span the southern portion of the basin. South of this system is a complex array of northeast-southwest trending faults located in the Fluorspar District. The steepest dips of strata in the basin are found in close proximity to these major fault systems and along the southwest margin of the basin where the Ozark Uplift (and Ste. Genevieve fault System) bound the basin.
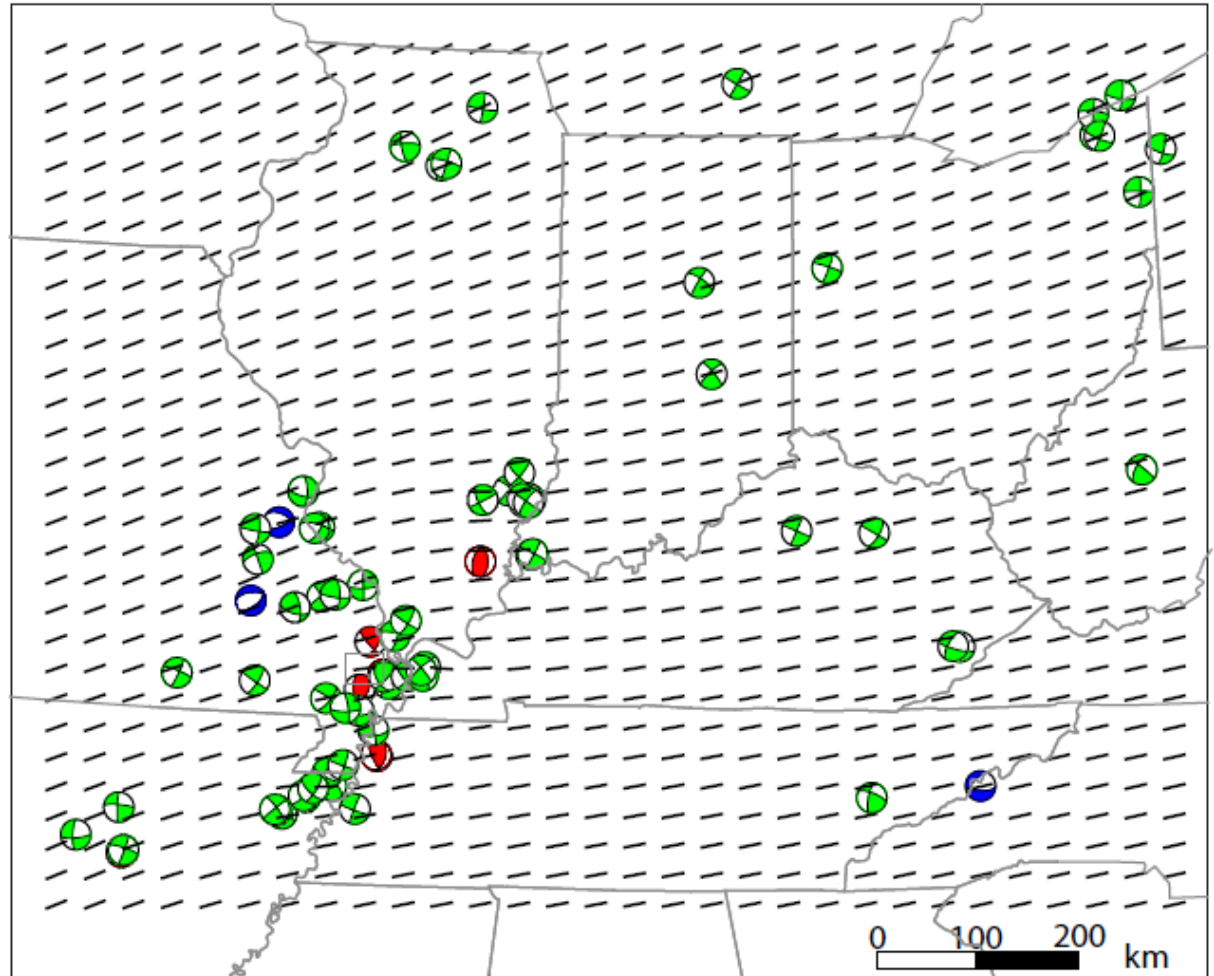
# Focal Mechanism Inversion

- Inverted the focal mechanisms for earthquakes in the region to generate a gridded array of maximum horizontal stress (SH) orientations

- Contrasted this result with other sources of SH orientation information

- Highlighted areas where local stress field deviated from regional trend (N 60 E)

# Inversion Results Based on Focal Mechanisms

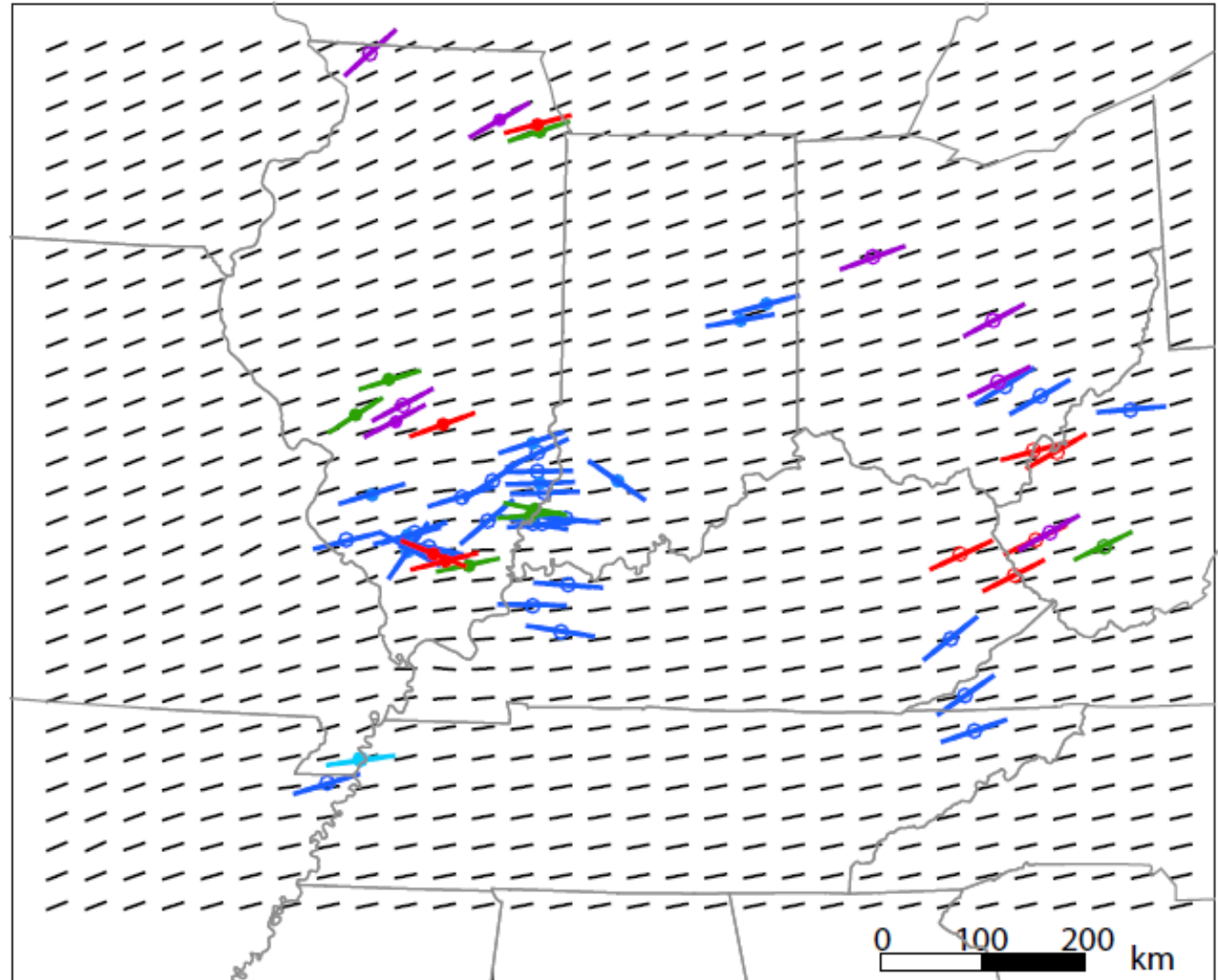Green = Strike slip
Red = Reverse
Blue = Normal



Focal Mechanisms from:
- OIINK Moment Tensor Catalog
- Saint Louis University North America Moment Tensor Catalog
- Global Centroid-Moment-Tensor Catalog

# S~H~ data compared to stress field from inversion of focal mechanisms

- Borehole Breakout
- Hydro-fractures
- Over-coring
- Strain Gauge
- Stress Inversion (World Stress Map)



Map of maximum horizontal stress orientations determined from focal mechanism inversion overlain by $S_H$ orientations from sources listed above.

# Maximum Horizontal Stress Orientation Incorporating S$_H$ Data
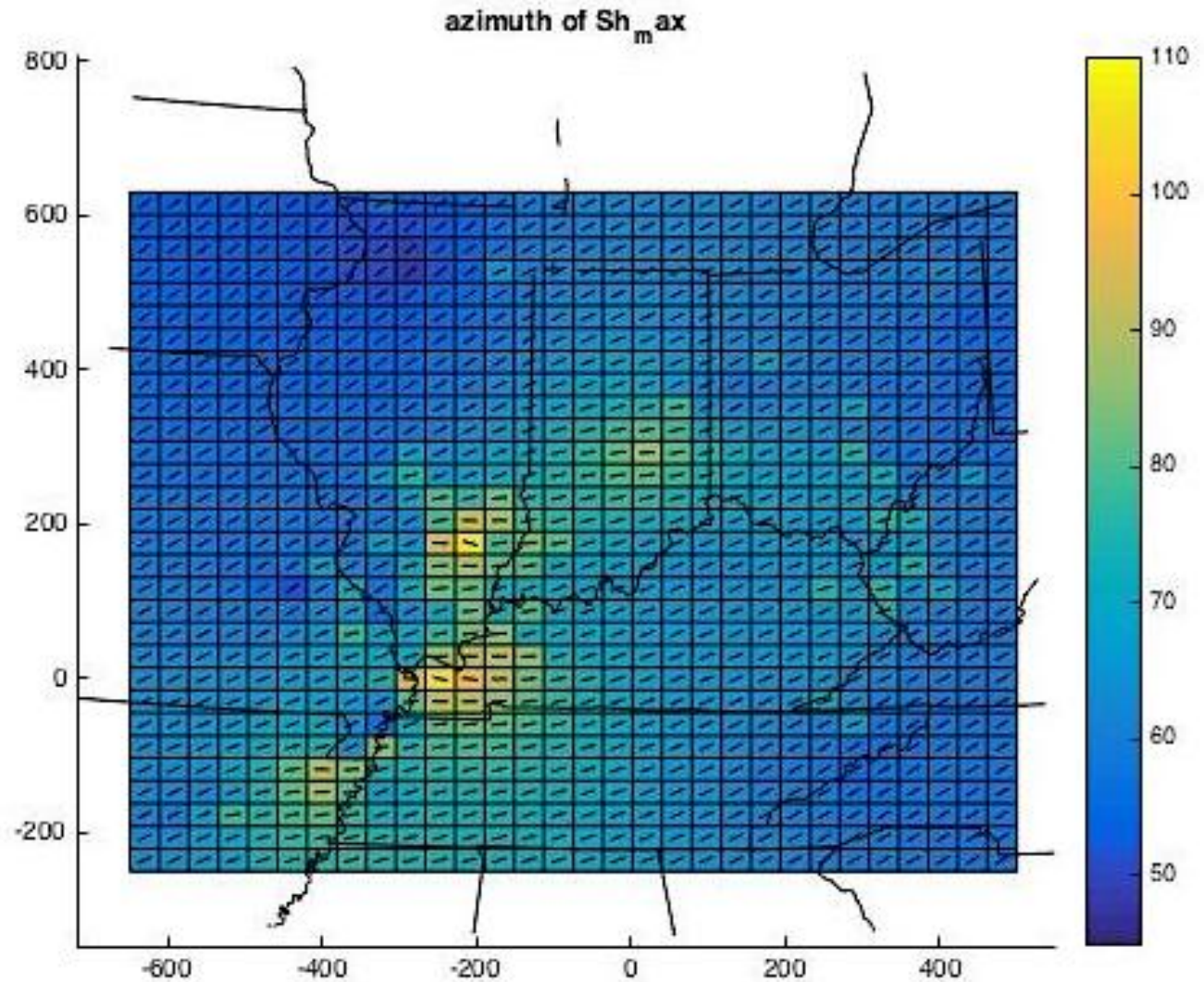


Azimuth of maximum horizontal stress directions incorporating focal mechanism and S$_H$ data.

# Summary

- Investigation yielded new ranges of values for $S_v$, $S_h$ and $S_H$

- Results can help inform policy/management decisions on magnitude of pressures that can be safely tolerated by the rocks of the basin

- Information can help inform decision makers of regions where additional stress (from elevated pore pressure) could potentially activate faults at lower pressures
  - Theory→zero tolerance ($P_{crit}$ =0) or, modeling of limits based on empirical data→management ($P_{crit}$ 10-100 psi)

# Future Work

- Evaluate the orientations of the major fault systems in the region to assess their degree of criticality relative to the regional $S_H$ orientation

- Investigate the magnitude and orientation of the fracture system in the basement complex

- Model pressure changes on a basin scale in given saline aquifers/evaluate the role of a bottom seal

- Communicate results to interested stakeholders