# Study of Faults and Fractures by Multi-scale Data Integration: A Geological Modeling Case in the Dickman Field of Ness County, Kansas State*

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## Abstract

Fault and fracture analysis is an important step to guide the 3D reservoir property gridding for the Dickman Filed as a potential $CO_2$ sequestration site. Due to the lack of standard logs and borehole images for such analysis, discontinuity patterns visualized by multiple seismic attributes were displayed in their original geological occurrence and tied to stratigraphic units at the reservoir scale to evaluate their geological integrity. The evaluation was based on the understanding of regional deformation history; the distribution patterns of fault/fracture zones predicted by a carbonate deformation model; the structural-controlled maturity of karst topography; and the fault and fracture indicators from sparse well logs, core descriptions and measurements.
The motion of major faults visualized by the SPICE attribute volume reflects the influence of the latest structural episode. Well tops, thickness and lithology data were used together with seismic images to determine the relative motion of blocks across faults during earlier structure episodes. Indirect indicators of differential uplifting across faults, such as the relative roughness of karst-topography extracted from attributes, were also used to restore the multi-episode deformation associated with faults. Possible fractured zones extracted from six geometry attributes revealed different vertical and lateral patterns of discontinuity. These patterns were classified into two geometric categories: the unconfined features penetrating multiple litho-zones; and confined features mostly within an individual litho-zone. The former, best viewed by plane-extraction from ANT volumes, are mostly structural and associated with major faults. The latter are mostly none-structural and best viewed as varying density patterns while marching depth slices of Chaos and Variance volumes. These patterns can be more indicative of post-depositional changes, and some could be related to the “intra-strata” features observed in the Middle Mississippian cores in nearby Schaben Field.

Multi-scale data integration improved the confidence of fault and fracture interpretation based on seismic attributes. Such interpretations helped in the reconstruction of multi-episode deformation history of the area. Several major NW-trending faults and associated fractured zones are likely fluid conduits, and a NE-trending fault served as the sealing fault for the hydrocarbon-producing structure.

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# Study of Faults and Fractures by Multi-Scale Data Integration

## -A geological modeling case in the Dickman Field, Ness County, Kansas State

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**S**eismic **M**icro **T**echnology (Kingdom)
Computer **M**odeling **G**roup (CMG Simulator).



Presenter's notes: The work is funded by US DOE awards with software donation by Schlumberger, SMT and CMG.

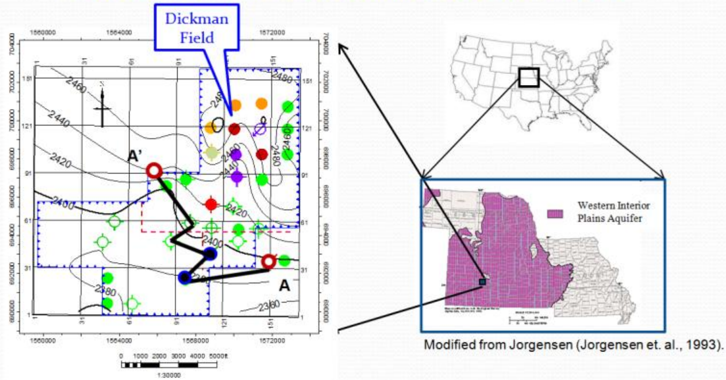
# Contents





Presenter's notes: Fault and fracture analysis was an important part in the 3D modeling of the Mississippian carbonate reservoir and saline aquifer as potential $CO_2$ sequestration targets. This talk will focus on this part of the work flow after a general introduction.

# Location and Data: Dickman Field

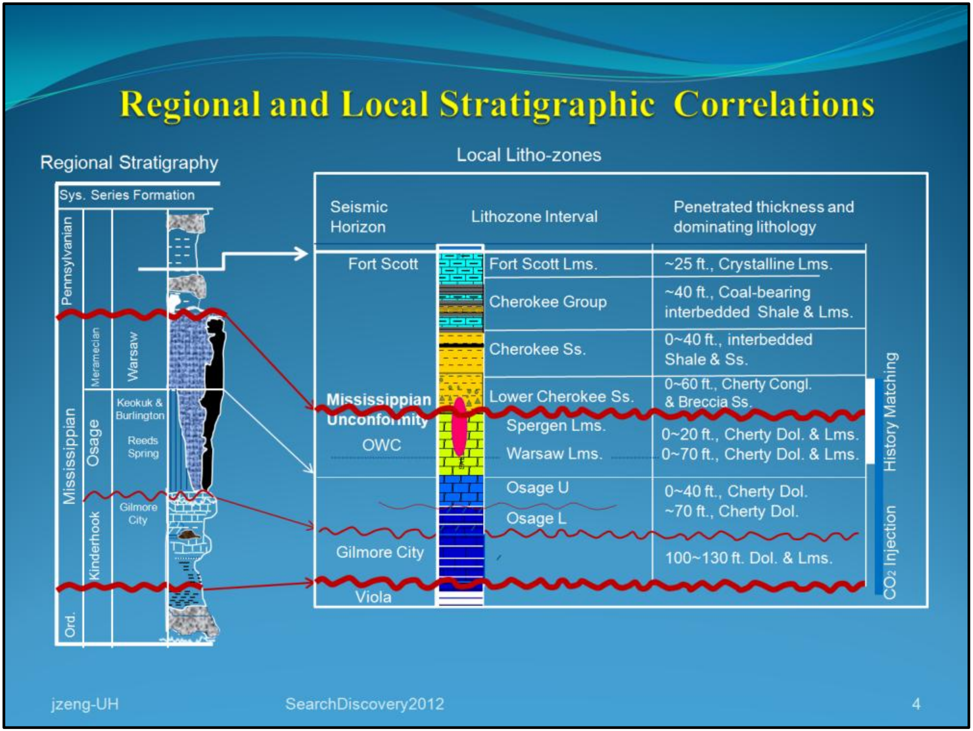



Modified from Jorgensen (Jorgensen et. al., 1993).

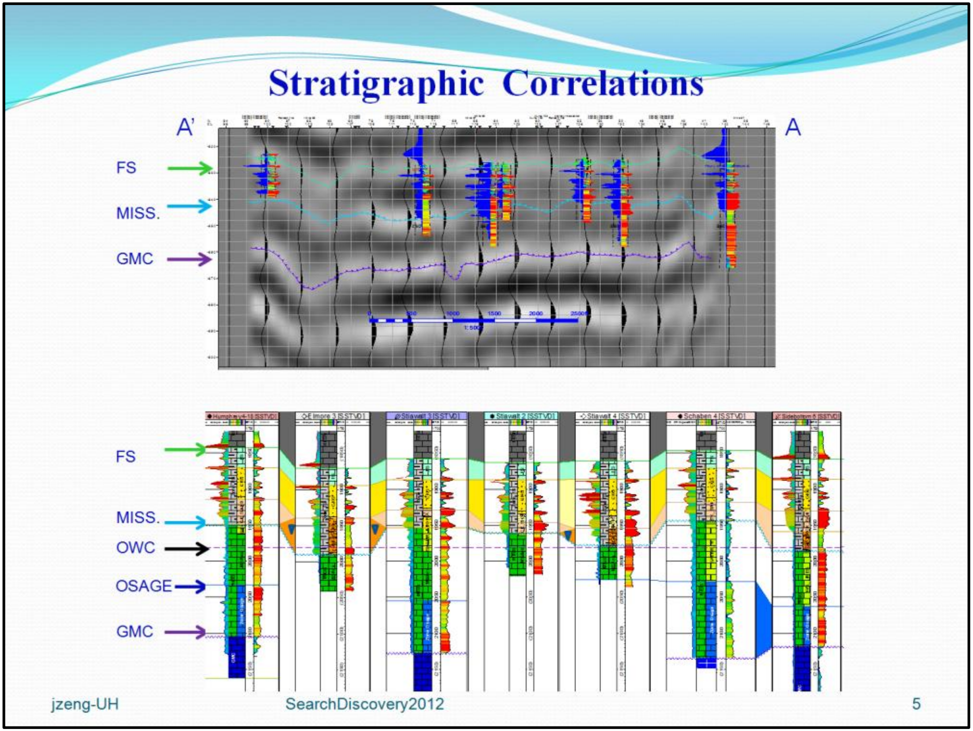
- Full penetration through saline aquifer and full well log suits
- Full penetration through saline aquifer and Gamma Ray(GR) and /or Neutron logs
- Cores from carbonate reservoir
- Both GR logs and cores
- GR, Neutron and sonic logs



Presenter's notes: The studied area is the Dickman Field in Ness County, Kansas. The studied strata are representative of the Western Interior Plains of aquifer, a potential target for $CO_2$ sequestration. Data for this study included two 3D seismic surveys merged together. All wells shown on this map have Gamma ray logs, 17 wells with neutron porosity logs, five with sonic and two with density logs. Seven wells were cored, with over one hundred porosity/permeability measurements. Four wells on section A-A' have the full penetration through the entire target stratigraphic window.

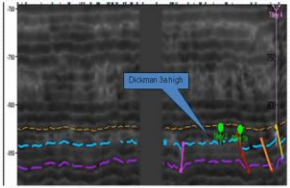



Presenter's notes: The stratigraphic window hangs on the Fort Scott Limestone of Middle Pennsylvanian age. The reservoirs include the Mississippian carbonate below the Miss. Unconformity and a small pay-zone of sandstone and cherty conglomerate from the Basal Penn. channel fill. The reservoirs are bottom-water driven from the underlying Osagian-Gilmore City Limestone saline aquifer. The detailed stratigraphic correlation is shown by both seismic and well logs.

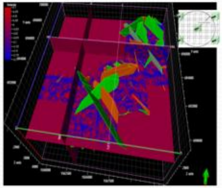



Presenter's notes: From top down, the stratigraphic units include Fort Scott Limestone, the Base Penn. channel-fill sandstone above the MISS Unconformity and carbonate reservoirs and saline aquifer between the MISS Unconformity and the Gilmore City Unconformity, with Oil Water Contact in pink. Without dip logs and borehole images, seismic attributes were taken as major tools to start the fault-fracture interpretation.

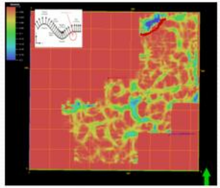
# Seismic Attributes Used



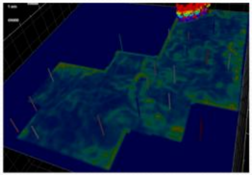

SPICE (Liner et. al., 2004)



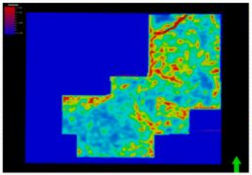
ANT (Schlumberger patent)



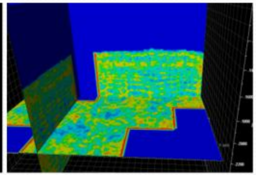
Curvature (Marfurt, 2006)



Variance



Chaos

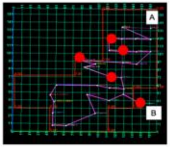


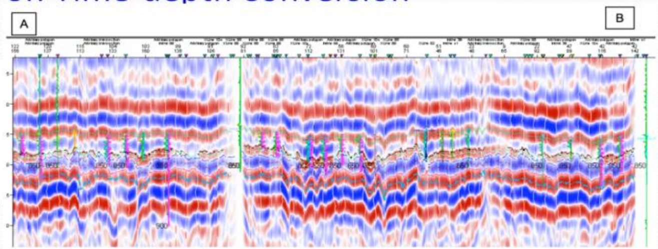
Structure Dips

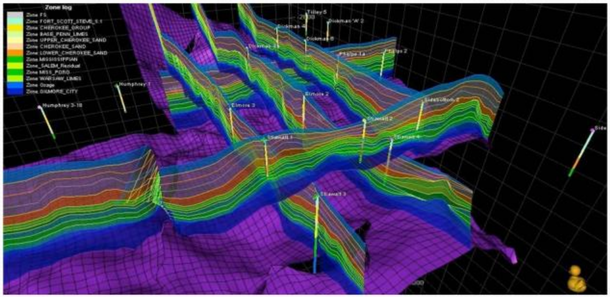


Presenter's notes: The major six attributes used are: 1. **SPICE**, based on wavelet transform decomposition and singularity analysis of migrated seismic data, providing a layered model rich in structural and stratigraphic details. 2. **ANT** based on a *4-step algorithm for mapping subtle disruption* of *seismic amplitude*, resulting in an attribute volume for extracting planes of discontinuity in 3D. 3. **Curvature** used to visualizes concave or convex features on seismic reflectors at varying arc-length, or geological scale. Other attributes used include Variance, Coherence, Chaos and local structural dips.

# Control on Time-depth Conversion






Presenter's notes: To bridge the gap between features revealed be attributes at seismic scale and the geological evidences at borehole scale, all attributes volumes were depth-converted based on the five sonic logs (red dots in the map to the left) and corrected by time-depth marker pairs at 17 well locations (seismic-log overlay profile in the upper-right). This made it possible to display seismic features in their real geological occurrence and tied to corresponding stratigraphic units (cross-section correlations on stratigraphic units).

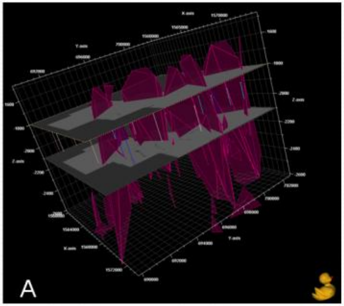
# Contents



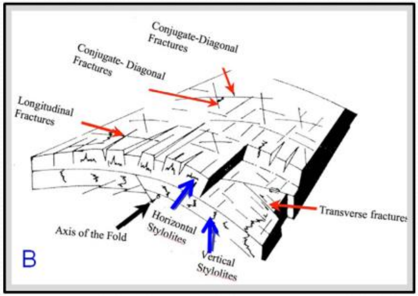


Presenter's notes: This in turn enabled us to classify seismic discontinuity patterns into unconfined and confined features relevant to the stratigraphic framework.

# Unconfined Features in Seismic




Planes extracted from ANT volume. Vertical exaggeration =10. Depth slices at -1750 ft and -2600 ft defining the target stratigraphic window. Duck is facing to north.

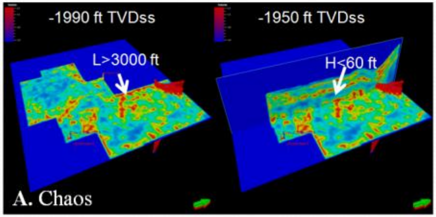


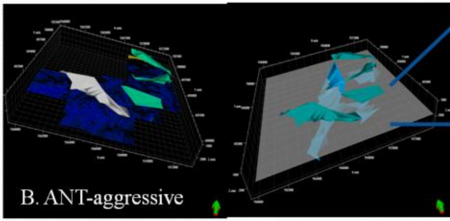

Ideal types of plane features resulted from brittle deformation of carbonates, predicted by a 3D simulation model (Modified from OuYang, 1994).

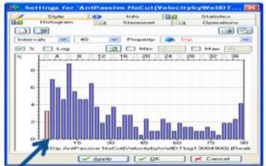


Presenter's notes: Unconfined features are high angle planes penetrating more than one stratigraphic unit up to the entire stratigraphic window. They were picked easily on SPICE profiles and best visualized by ANT plain extraction (Diagram A). Unconfined features are mostly structural due to the brittle deformation of carbonates. Their ideal 3D distribution patterns are shown in Diagram B: mostly bedding-perpendicular, with three set of orientations relative to the regional stress field. The real distribution pattern, however, become more complicated in the studied area experiencing multiple deformation episodes. There are also some features confined within the stratigraphic units – for instance the stylolites due to pressure-solution (blue arrows in Diagram B), falling within our category of confined features. Confined features have limited vertical penetration, can be bedding-perpendicular or bedding-parallel, and non-linear or linear in plain view.

# Confined Features in Seismic



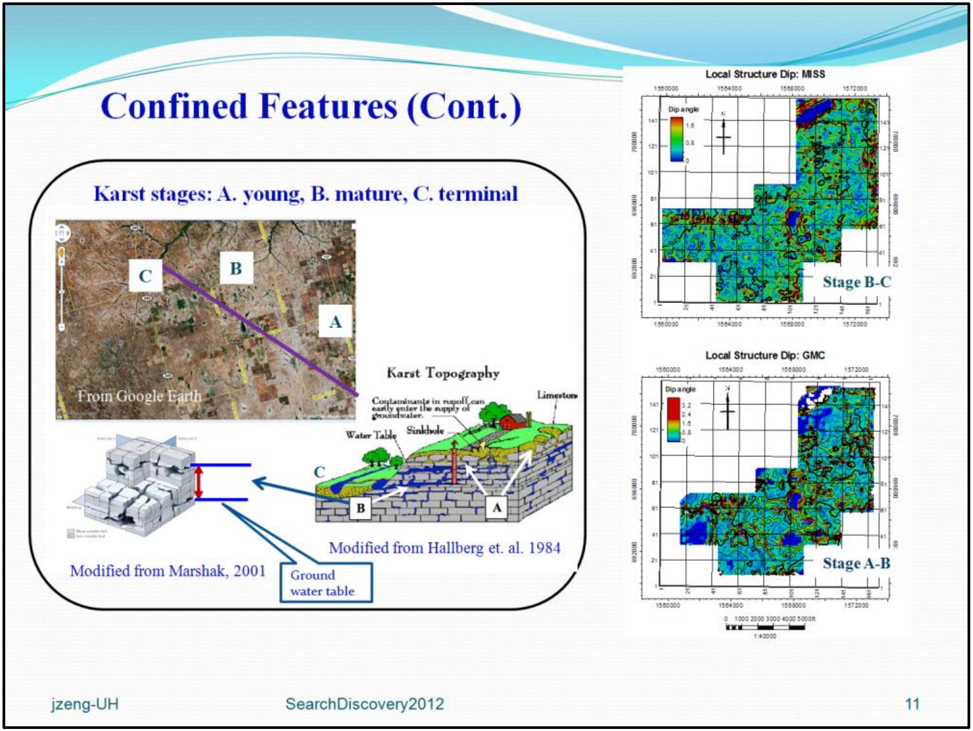

| | Dip azimuth | Dip | Surface area | Azimuth in seismic | Dip in seismic |
|---|---|---|---|---|---|
| 1310 | 168.73 | 2.71 | 1719.00 | 237.47 | 89.01 |
| 357 | 129.82 | 2.93 | 1522.00 | 228.07 | 84.71 |
| 263 | 215.51 | 3.03 | 13445.00 | 318.06 | 89.58 |
| 330 | 117.41 | 3.05 | 1379.00 | 227.87 | 88.80 |
| 428 | 302.88 | 3.20 | 2697.00 | 36.57 | 70.35 |
| 481 | 134.75 | 3.28 | 1692.00 | 236.85 | 76.77 |
| 803 | 320.73 | 3.48 | 1373.00 | 59.34 | 67.98 |
| 303 | 164.37 | 4.31 | 4576.00 | 227.54 | 87.26 |
| 417 | [illegible] | 4.46 | 2050.00 | 228.40 | 88.90 |
| 702 | 322.50 | 4.51 | 1427.00 | 51.75 | 79.36 |
| 1317 | 255.48 | 4.58 | 2786.00 | 319.51 | 85.34 |
| 240 | 317.46 | 4.69 | 13492.00 | 47.51 | 67.34 |
| 325 | 314.19 | 4.78 | 2156.00 | 46.47 | 73.96 |
| 1257 | 64.03 | 5.41 | 3115.00 | 143.46 | 86.12 |
| 1187 | 309.99 | 5.75 | 2400.00 | 38.45 | 88.25 |
| 1210 | 57.22 | 5.84 | 1989.00 | 147.36 | 79.82 |
| 1209 | 242.08 | 5.98 | 3551.00 | 321.92 | 85.66 |
| 1444 | 286.02 | 6.43 | 5561.00 | 55.19 | 89.82 |

Vertical to horizontal scale=1:1.

Reference surfaces in B: GMC(left), OWC (right).



Presenter's notes: Confined features can be best viewed by walking through depth slices from Variance, Coherence, and Chaos volumes. A linear feature in Diagram A is about 3000 ft. long (Diagram A, left) but its linearity is visible only from several depth slices. From the vertical profile (Diagram A, right), it is almost bedding-perpendicular with a vertical penetration limited to 60 ft then terminated here. Another type of confined features revealed by ANT extraction (Diagram B) are with low dip angles, 2-5 degrees and large areas of planes (Histogram and table to right), almost bedding-parallel. Confined features can be structural, like the stylolite in the previous slide, but mostly could be erosional. Some bedding-parallel confined planes may be related to carbonate dissolution following the depositional architecture as observed in Osagian carbonates and termed as "intra-strata" features by other researchers. Some bedding-perpendicular ones may be related to erosion and karst development along fractured zones. The framework of their lateral and vertical extension is related to the varying karst development stages.



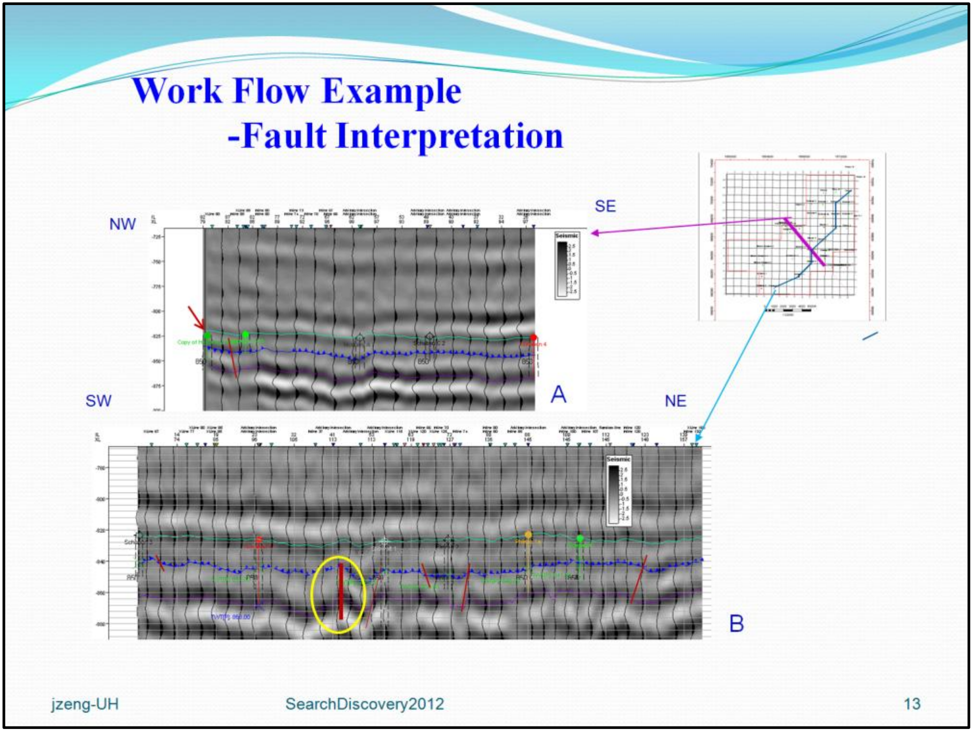

Presenter's notes: The block diagram to left shows a conceptual model of three karst development stages and the related topographic features. In reality those stages rarely occur at the same time and same places, since they reflect temporal or long-term carbonate exposures associated with structural uplifting or sea-level changes. Stage A. a young stage dominated by vertical features like sinkholes confined between the palaeo-surface and palaeo-ground water table, distorting the surface drainage system; Stage B. a mature stage characteristics by both vertical features in A and horizontal features like caves and tunnels near the palaeo-ground water table, and, Stage C. terminal stage of peneplain with rolling hills and restored surface drainage system. Different stages can be shown by topographic features on local structure dip maps at Dickman on two seismic horizons: GMC top with a lot of steep-sided vertical features like sinkholes relating to younger stage A-B, and Mississippian Unconformity with rolling hills and a channel bend inheriting the clasped tunnels resulted from much long duration of exposure for erosion, during more mature stage B-C.

# Contents

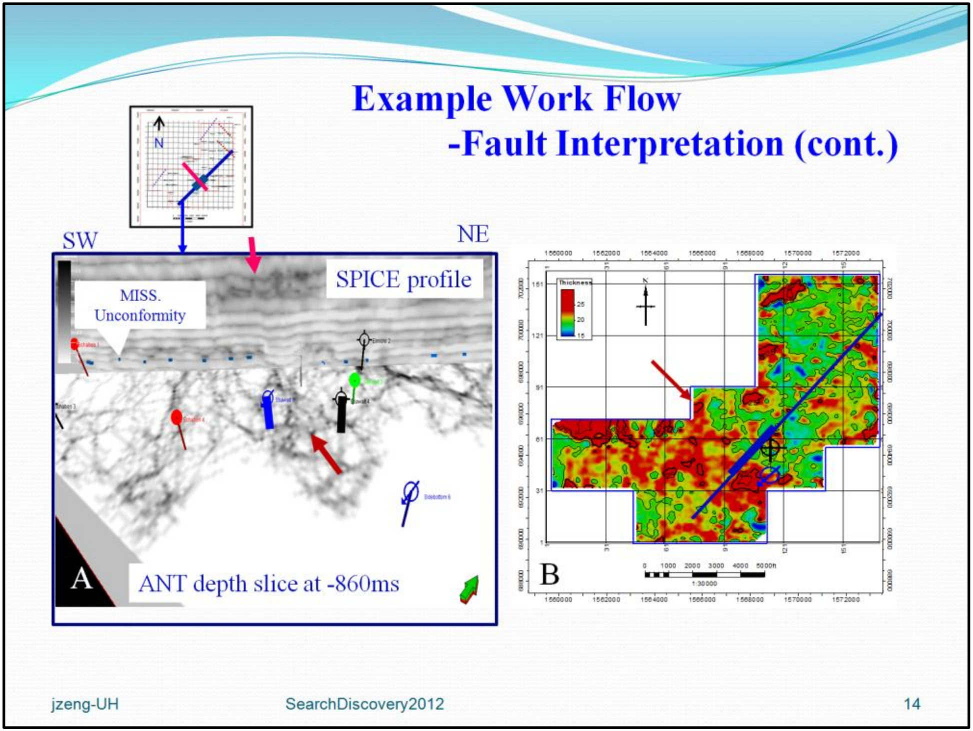




Presenter's notes: Given the two ideal spatial distribution models for the unconfined and confined features, the next few slides show an example work flow in faults and fractured zone interpretation.

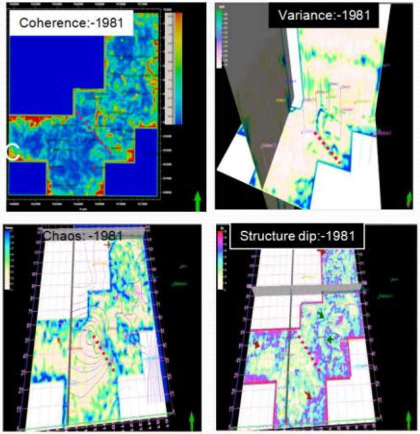



Presenter's notes: Fault interpretation started on the amplitude and SPICE profiles. Some NE-trending or NW-trending discontinuities were picked from the profiles perpendicular (upper) and parallel (lower) to the present structural axis. The fault in yellow circle is used as an example to show how to evaluate the geological integrity using attribute volumes and geology data.

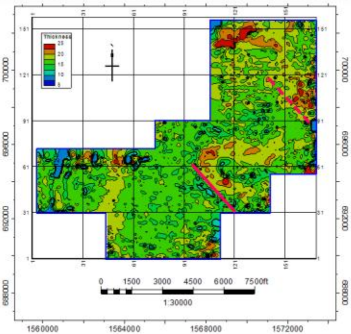



Presenter's notes: The NW-trending fault shown in the previous slide was best visualized by SPICE profile with an intersecting ANT slice below the Mississippian Unconformity indicated by blue dots (Diagram A). The offset on SPICE profile suggests a down-thrown northeast block to the right. However well top data from two wells across the fault trace indicate that the Mississippian strata between the Mississippian Unconformity and GMC is up to 60 feet thicker on the southwest side of the fault (blue well symbol) than to the northeast side of it (black well symbol). This is supported by the thickness isochron between the Mississippian and the GMC Unconformities (Diagram B). Both well data and thickness isochron indicate thinner strata on an up-thrown NE block with stronger erosion. This is in contract to the current fault occurrence formed during the last structural episode.

## Indirect Evidences : Karst Geomorphology




A. Depth slices at -1981 TVDss, near the OWC (referencing plane) below the Mississippian Unconformity.

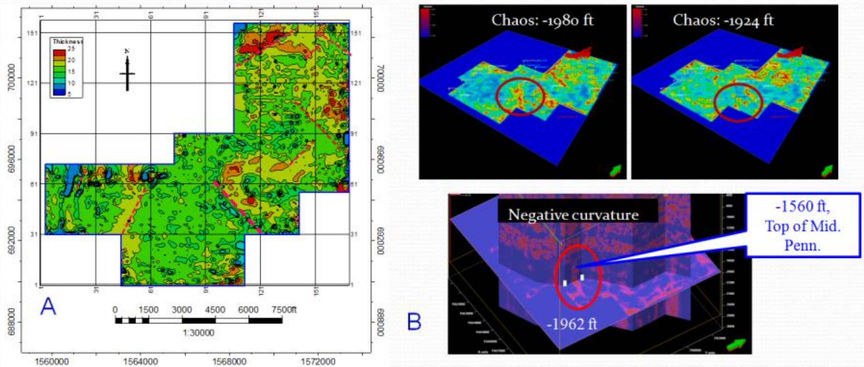



B. Palaeo-topography at Mississippian Unconformity



Presenter's notes: The up-thrown of NE block was supported by indirect evidences. The differential maturity of karst topography exists across the fault trace shown by the density of discontinuity patens or the "relative topographic roughness" on seismic slices shown in Diagram A. On slices at or slightly below the Mississippian Unconformity, the topographic roughness is more significant, with complicated patterns of edges and discontinuities on the northeast side compared with the southwest side of the fault trace. On the map of palaeo-topography at the Mississippian Unconformity during the deposition of Middle Penn. Strata (B), the relief by down-cutting is the deepest on the immediate northeast side of this fault. Moving away from the fault trace to NE, the channel shape became less significant as topographic roughness is reduced, until reaching the next possible NW-trending fault.

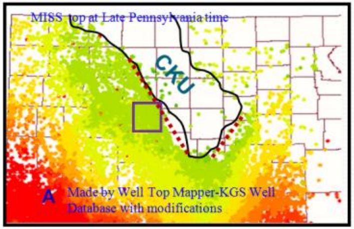
# Extended Interpretations

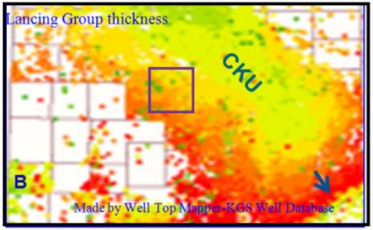


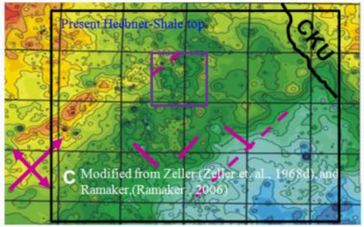



Presenter's notes: Several NW-trending planes were fund with the same story. Many of them are more visible below the Miss unconformity and mostly disappeared above it (Diagram B, upper). A few of them are visible up to Middle Pennsylvanian strata viewed from the negative curvature volume (Diagram B, lower). The same work flow is applied to identify the NE-trending faults that also experienced multiple episodes. The NE-trending ones looked sharper or fresher even in the youngest Pennsylvanian strata. The multi-episode faulting history in the studied area can be attributed to at least three major regional structural episodes around the Central Kansas Uplift.

# Regional Structure History



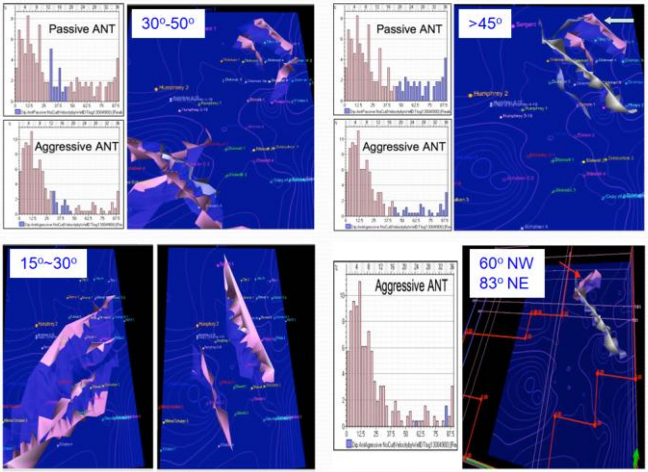






Presenter's notes: Structural episode A (Map A, made by Kansas Geological Survey, Well Top Mapper) is the faulting and up-lifting of the Central Kansas Uplift (CKU) along major boundary fault zones during the Mid Mississippian to Early Pennsylvanian, probably related to the plate convergence along the Ouachita Mountains Orogenic Belt. During this event both NW- and NE trending faults in the studied area (within the purple square) had similar motion of bounding faults of CKU, different from their current occurrences. The event affected more strongly the NW-trending faults parallel to the direction of main compression. Episode B (Map B, mad by Kansas Geological Survey, Well Top Mapper) is the faulting and uplifting of CKU during the Late Pennsylvania time. This caused not only the thinning of strata (Lancing Group) on top of the CKU, but also abrupt thickness changes across SE boundary faulting zones (Diagram B, blue arrow). Driven by this motion, the NE-trending faults in the studied area were more active with up-thrown southeast blocks, similar to their present day occurrence. However, the relative movement of the NW-trending fault is not at the similar significance, still with an up-thrown NE block. Episode C (Diagram C) is the formation of the Eldrich Anticline, a secondary structure due to the strike-slip motion during the Late Cretaceous and later. Some NW-trending faults could be reversed to their present day occurrence during this episode or between episodes B and C. The understanding of the faulting history allows us to better understand numerous discontinuity patterns revealed by the seismic attributes.

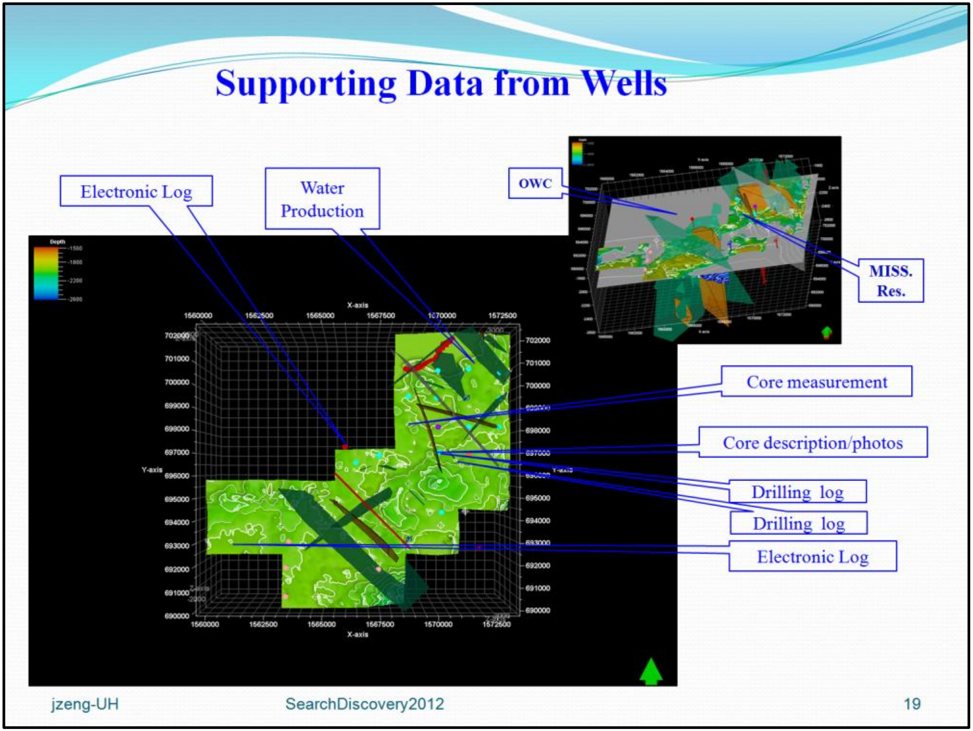
# Work Flow Example
## -Fractured Zones Interpretation




Planes penetration the target stratigraphic window and with high degrees of confidence.
The referencing plane is the OWC. Histograms are the distributions of dip angles of planes

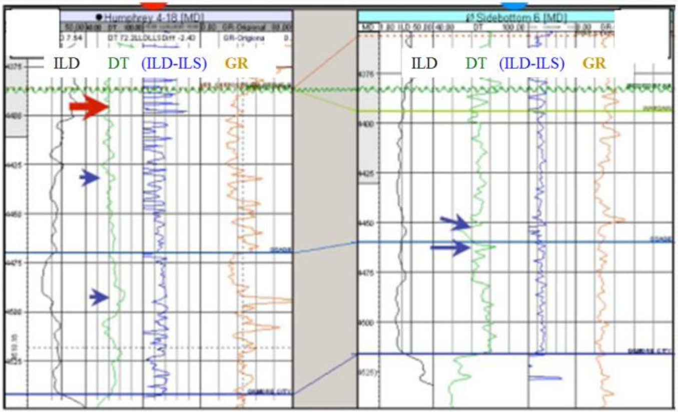


Presenter's notes: This slide shows the results of plane-extraction from the ANT volumes. Starting with over 270 planes, we first filtered them by degrees of confidence. Then the remaining features penetrating the target stratigraphic window were sort by their dip-angle, strike orientation and vertical penetration and areas. Although closely associated with the unconfined fault planes, many selected features were confined within the Mississippian reservoir and saline aquifer zones as indicated by the OWC surfaces.




Presenter's notes: Planes with high-confidence were plotted against the Mississippian reservoir top with well locations and well types to seek support from well data (3D view to upper right and map view). Evidences includes: electronic logs, drilling time logs, core measurements and descriptions of core photographs, and reducing water production away from the NW-trending plane according to the 5-year water production record in Dickman Filed.

# Log Indicators



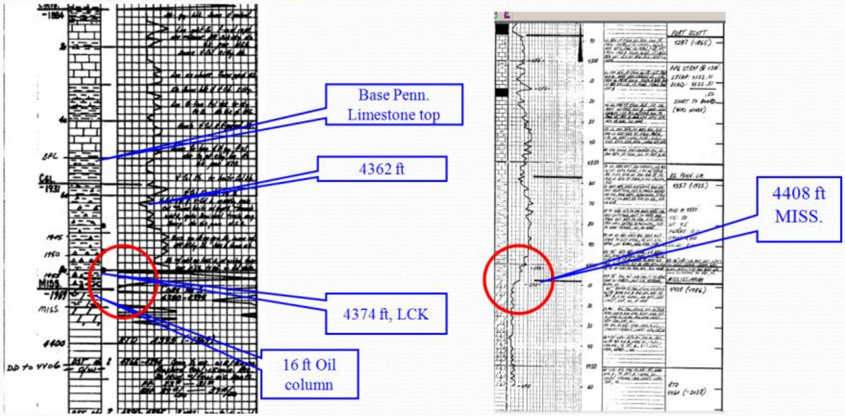

Mississippian Unconformity

The pay zone: indicated by red arrow . (ILD-ILS): the differences between the formation and flushed zone resistivities, positive kicking to right and negative kicking to left.



Presenter's notes: The fractured zones (blue arrows) were shown by log spikes of GR and/or sonic logs associated with highly variable and reversed formation and flushed zone resistivity. For all Mississippian fractured carbonate lithozones, over 80% of (ILD-ILS) values are negative from -10 to 0.

# Drilling Time Indicators

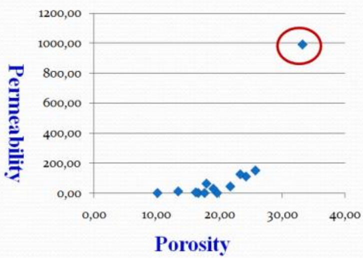


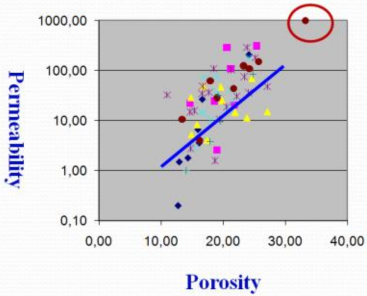

Left: Well Elmore 1 with a 16 ft pay zone above the OWC. Right: Well Elmore 3, from Kansas Geological Survey, Oil and Gas Production Data and Well Data Base



Presenter's notes: The fractured zones (red circles) were indicated by the sharp drop of, or fluctuations in, drilling time when entering the zones from basal Pennsylvania sand-conglomerates.

# Core Property Indicator




Core Measurement: extreme porosity and permeability values in Dickman 5 (left), not seen in all other wells (right).



Presenter's notes: Fractured zones are indicated by the extremely high permeability in cores with similar porosity. The preferred orientations of selected fractured zones were used to guide the 3D reservoir property modeling. The contact between the Mississippian dolomite and the overlying Pennsylvanian shale is at a 45 degree angle as seen from the core of Well Elmore 1 (Nissen et. al., 2006).

## Summary and Conclusions

1. Pre-requests
   - Stratigraphic framework
   - Depth conversion
2. Unconfined and confined features from seismic attributes
   - Unconfined: fault/fractures related to brittle deformation of carbonate
   - Confined: vertical and horizontal related to carbonate dissolutions
3. Effective seismic attributes as visualization tools
   - Unconfined features: SPICE and ANT
   - Confined features: Variance, Coherences, Chaos, Dip…
   - Helpful in both: Curvature, ANT
4. Validating geological integrity of seismic attribute patterns by
   - Regional deformation history
   - Well and core data
   - Predictive carbonate deformation models
   - Karst geomorphology and development stages



Presenter’s notes: Summary and conclusions: to improve the geological integrity of fault/fracture interpretation by seismic attributes: we need 1. Depth conversion of seismic attribute volumes for tying seismic features to local stragtigraphic framework at true geological occurences; 2, the understanding of spatial distribution models for unconfined and confined features; 3. selections of attribute tools that can best visualize two types of features; and 4. Geological evidences from regional to local, and at well-scales to nail down the interpretations.

# Thank You !