Earthquakes in the southern midcontinent: What we know and what we need to know - Current research at KU and the Kansas Geological Survey

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Kansas Geological Survey – University of Kansas
Outline

• Seismicity
  – Historical seismicity in Kansas
  – Earthquakes in southern Kansas
  – Trends from the CEUS
• Why care about seismicity?
• Mechanics of induced events
• Mississippian Lime Play
  – Geology
  – Production trends
  – Brine disposal
• Current research
  – Seismic monitoring
  – Fault mapping and stress field analysis
  – Geologic and simulation models
• Future research and need for collaboration
Historical seismicity in KS

Felt earthquakes 1867-1977

Summary
- 2 ~M≥5 events
- Largest: 1867, Wamego, KS

Modified from Hildebrand et al. (1988)
KS-NE Network, 1977-1989

264 Earthquakes located

Results
- 2 M≥3 events
- 1 M≥4 event

Modified from Hildebrand et al. (1988)
Seismicity in southern KS

- 112 earthquakes reported
- 35 events $M \geq 3$
- 2 events $M \geq 4$

Source: USGS NEIC catalog (11/21/14)
Trends in the central & eastern US

- Long-term average of 20 EQs/year
- Rapid increase since 2009

Modified from Ellsworth (2013)
Documented examples

• RMA, CO, M 5.3, 1962-1968 (Healy et al., 1968)
• DFW, M 3.3, 2008-2011 (Frolich, 2013)
• Guy, AR, M 4.7, 2010-2011 (Horton, 2012)
• Youngstown, OH, M 4.0, 2010-2011 (Kim, 2013)
• Raton Basin, CO/NM, M 5.3 2001-2011 (Rubenstein, 2014)
Mechanics of induced earthquakes

1. Increase pore fluid pressure acting on a fault
   - Brine disposal (e.g., Healy et al., 1968)
   - Fracking (e.g., Holland, 2011)
   - Hydraulic connection needed

2. Change shear or normal stress acting on fault
   - Reservoir depletion or repressurization (e.g., McGarr, 1991)
   - No direct connection to fault

After Ellsworth, 2013
Why care about seismicity?

Surface hazard

- Injuries
- Property damage
Subsurface hazard

47 active UIC Class I wells in state
46 dispose of fluid within the Arbuckle

http://maps.kgs.ku.edu/co2/
Why care about seismicity?

Gutenberg-Richter recurrence relationship

Modified from Kanamori and Brodsky (2001)
Mississippi Lime Play – Definition
-- on Anadarko Basin side of Nemaha Uplift

Relevant structural elements of Arkoma and Anadarko Basin as basis for the MLP

- Concurrent and post Mississippian structural deformation
- Systematic reactivation of basement weaknesses defined by potential fields & basement terrain
- Inherited fracture systems
- Major wrench fault systems directed stress into craton during Late Paleozoic
- Major influence on regional/local maturation of organic matter, migration routes and trapping of oil and gas

John Mitchell,
retired
SM Energy Co.
Tulsa, Oklahoma
TGS, March 2012

Seismicity in north Oklahoma & southern Kansas late Oct → Early Nov. 2014

Seismicity in north Oklahoma & southern Kansas late Oct → Early Nov. 2014
Spectrum of potential reservoir lithofacies
Inner Ramp Tripolite to Outer Ramp Basinal Shale Depositional Model


- Tripolite
- Cherty dolomite
- Dolomitic spiculite
- Argillaceous, organic dolomitic siltstone

Subaerial Exposure
Dolomitization

Related terms:
- bedded spiculite
- lenticular/nodular/flaser-bedded spiculite
- green shale matrix
- light- to dark-gray shale matrix
- increasing amount of spiculite relative to shale
- increasing bioturbation
- synsedimentary slump features

200um
High bound water saturations in the tripolitic chert have led to difficulty in estimating reserves and determining producible zones. This problem in water saturations is further complicated by difficulty in establishing free water level. While some fields exhibit apparent structural closure greater than 200 feet, the presence of nearly isolated blocks of production within these fields surrounded by nonproductive areas may indicate that there is not a continuous hydrocarbon column and that free water level is independently established for each block. -- Watney, Guy, Byrnes (2001)
Focus of MLP in Sedgwick Basin in south-central Kansas

Horizontal wells drilled since January 2011
Mississippian structure (450 ft C.I.) and notable faults (green lines)

Wellington Field

Central Kansas Uplift

Sedgwick Basin

Spivey-Grabs

Aetna Field

http://maps.kgs.ku.edu/co2/

Horizontal wells drilled since January 2011
Mississippian structure (450 ft C.I.) and notable faults (green lines)
Mississippian cherty dolomite reservoir at Wellington Field
Toplap (East) and Prograde (West)
Complex offlapping geometries of porous lithofacies resulting from the westward progradation of the Mississippian -- Looking SW

Porosity seismic Inversion in Petrel using core, log, 3D seismic volume for modeling CO2-EOR recovery
Permeability fence diagram of Mississippian oil reservoir within 3D seismic, Wellington Field

--Small faults that tip out above the top of the Mississippian reservoir

• View looks to the northeast
• Fault juxtaposes reservoir and non reservoir facies (at arrow tip)
• Fault offset ~30 ft and laterally discontinuous
• Faults serve as potential barriers to flow or redirect CO$_2$ plume depending on fault damage and juxtaposed rocks
• Faults aligned SW-NE oblique to maximum horizontal compressive stress
Mississippian isopachous map with horizontal (■) and Class II wells (▲)

- 75 ft of localized thinning;
- Miss units thicken on flanks due to increased accommodation, not differential erosion

Stratigraphic correlations and mapping by Gerlach and Nicholson, DOE-CO2

Earthquakes and magnitude 2.2
Mississippian -- stacked cyclic carbonates deposited on ramp

Tripolitic chert - proximal, inner ramp

Increasing chert to top

Shaly “Cowley”

Chattanooga Sh.

Cuttings lithofacies

Mississippian -- stacked cyclic carbonates deposited on ramp

Horizontal length = ~8 miles

Log lithofacies

Stratigraphic correlations by Gerlach & Nicholson – DOE-CO2

Primary Rock Lithofacies
- Shale
- Sand
- Sandstone
- Chert
- Limestone
- Dolomite
- Anhydrite

Secondary Rock Lithofacies
- Shaly, shale
- Sandstone
- Sandy, sand
- Cherty, chert
- Dolomite, Dolostone
- Anhydrite, Anhydrite
- Carbonate, Carbonate
- Oilfield
- Coalfield
- Dolomite
- Anhydrite, Anhydrite

Fossils
- Brachiopod
- Foraminifer
- Invertebrate
- Invertebrate
- Vertebrate
- Invertebrate

Penalty Types
- High
- Low
- Medium
- Medium
- High

NW-SE structural cross section across updip edge of Miss ramp

400 ft
Heart of MLP in the core of the southern extension of the Midcontinent Rift System (magnetic low)

Total magnetic field intensity reduced to pole 910 m + top Mississippian structure

Harper County (yellow outline)

Earthquakes along edges of magnetic lineaments
-- Suggest link of earthquakes to basement structure
Production trends

Change in Gas Production, 2012 to 2013

Figure courtesy of D. Adkins-Heljeson (KGS)
Production trends

Change in Oil Production, 2012 to 2013

Figure courtesy of D. Adkins-Heljeson (KGS)
• Well count has doubled since 2005
• 6-fold increase in yearly disposal volumes since mid-1990s
• Yearly volumes have tripled since 2011

*Data courtesy of the KCC*
Brine disposal trends

- Daily disposal data from 22 of 131 SWD wells
- Expect large increase between 2013 and 2014

Data courtesy of the KCC
Current research

1. Where are faults or potential hazards located?
   – Seismic monitoring
   – Lineament and fault mapping

2. What are the pressures or stress changes needed to trigger or reactivate those faults?
   – *In situ* stress field analysis
   – Reservoir-geomechanical modeling of fluid injection
Seismic monitoring: USGS

M4.8, Nov. 12
Seismic monitoring: Wellington Field
Wellington seismic network

Courtesy of R. Miller and S. Petrie, KGS
Seismic monitoring: KGS network

Figure courtesy of R. Miller (KGS)
Subsurface lineaments

Well tops database

- Well tops from 18 regional stratigraphic surfaces
- Most surfaces have >10,000 picks

Structure contour maps

- Surface analysis techniques (e.g., slope, curvature, residual analysis, etc.)
- Compare to surface lineaments and potential field discontinuities
Fault mapping: Subsurface lineaments

Edge Detection on Top Arbuckle Surface

Legend
- Lineaments
- Well Status:
  - SWD
  - Daily Rates
  - SWD-P&A
  - EOR
  - EOR-P&A
- EQ Magnitude:
  - 1.9 - 2.3
  - 2.3 - 2.8
  - 2.8 - 3.3
  - 3.3 - 3.8
  - 3.8 - 4.3
  - 4.3 - 4.8

M4.8, Nov. 12
Fault mapping: Wellington area

- Map fault orientations and geometries
- Evaluate slip and dilation tendency
- 3D stress state

Arbuckle edge detection
Stress field analysis: Orientation

Modified from Tingay et al. (2008)
Stress field analysis: Magnitudes

- Principle stresses at depth:
  - $S_v$ - Overburden (density logs)
  - $S_{h\text{min}}$ - Minimum horizontal stress (LOTs, SRTs, stimulation pressures)
  - $S_{H\text{max}}$ - Maximum horizontal stress (dipole sonic logs)

- Other parameters:
  - $P_p$ - Pore fluid pressure
  - Poisson’s ratio, Young’s modulus (sonic data; lab tests)
Stress field analysis: Statewide

240 well logs available in Kansas

- 109 are scanned
- 131 in paper form
Project Location:
Wellington Field, Sumner County, KS
Reservoir characterization data

- What we know about Arbuckle reservoir we have learned from the \( \text{CO}_2 \) characterization study
- 2 wells were drilled into Arbuckle Fm
- Core was obtained from well KGS 1-32
- Whole set of modern logs for both wells
- 3D and 2D Seismic data
- Geochemical data
  - Water samples
  - Mineral composition
- Step Rate and Drill Stem tests
Reservoir temperature

Temperature (Fahrenheit)

Depth Below Land Surface (ft)

- KGS 1-32
- KGS 1-28
- DST well 22519
- DST no 2 from 1-32
- Temperature in well 69
Reservoir pore pressure

Graph showing pressure in psi against depth in ft, with two layers indicated: Mississippian and Arbuckle.
Connected vugs
Nonconnected vugs
Interparticle/matrix

Step rate test perforations

Layered injection zone
- Probable communication between layers along boundaries and fractures
- Geochemical data suggests homogeneous hydrostratigraphic unit

Doveton, 2012
Well
KGS 1-32
Arbitrary seismic impedance profile – Wellington Field

distinct caprock, mid-Ar buckle tight, lower Arbuckle injection zone

Impedance = ρ x Ø

- Baffle or potential barrier to vertical flow (high impedance)
- Low impedance injection interval
Step-rate test results in 1-32

- Gauge depth: 4869’
- Test interval: 4995-5020’
- $k = 113$ mD based on Lorenz plot
- Vertical barriers above and below
- Compare to log $k = 74$mD
Interference test results in 1-32 with 1-28 as an observation well

- Distance between 1-32 and 1-28 is 3500ft
- Composite model with dual porosity-permeability
- k around well 1-28 to a radius of 2493 ft (region 1) has a lower value (100 mD)
- k in the zone 2 is 124 D (2493ft).
- Permeability for the farther radius can be associated with fault/fracture between wells.
Br⁻/Cl⁻ and SO₄²⁻/Cl⁻

Baffles and lack of vertical communication

- Br⁻ and Cl⁻ are conservative during water/rock interactions
- Very useful in detecting brine sources and mixing
- Values for brine of Lower Arbuckle vary substantially from Upper Arbuckle
- Lower Arbuckle brines cluster together
- Upper Arbuckle values more spaced out, suggests smaller baffles
Arbuckle reservoir model considerations

- Highly complex system with many sub-zones and different conditions
- Highly fractured system may require dual porosity/permeability model in future
- Unclear medium zone permeability
- Discrepancies in log, core, and SRT permeability estimations
Arbuckle reservoir model assumptions

- Performed with CMG GEM software
- 9 cases with varying porosity and permeability
- Infinite acting Carter-Tracy aquifer with no leakage
- Relative permeability tables from literature sources for carbonates
- Solubility is included in the model
- No mineral reactions were considered
Dynamic simulation model

Well KGS 1-28
40 kt of CO₂/9 months

Top of Arbuckle
4100 ft

Baffle Zone

Perforation Zone
4910-5050 ft, 140 ft

Permeability, md

Bottom of Arbuckle
5175 ft
Maximum Delta Pressure Response (psi)

Sources: ESRI, USGS, Kansas Geological Survey
Vertical pressure distribution at max. stress (before the injection stops)

Perforation Zone: 4910-5050 ft, 140 ft

Baffle Zone

9 months after start of CO$_2$ injection
Injection stops

4,910 ft
Perforated Zone

5,050 ft

Bottom of Arbuckle: 5,160 ft

KGS 1-28

Delta Pressure, psi

- 265
- 240
- 215
- 190
- 165
- 140
- 115
- 90
- 65
- 40
- 15
Delta pre pressure profile at max stress (9 months after start of injection)
Southern Kansas CO$_2$ storage model
10 sites
Total area gas injection

Max CO2 Injection Rate 5 bcf/day

Cum CO2 Injection 9.096E12 lb
4.1345 billion tonnes
Southern Kansas CO$_2$ injection model

gas saturation 100 years after injection stops
Delta pressure after 20 years of water disposal in Harper County, KS (open boundary)
Delta pressure after 20 years of water disposal in Harper County, KS (closed boundary)
Summary

1. The systematic characterization of the structural framework is needed to ascertain stress-strain history.

2. Based on current seismicity, faults appear to be reactivated by large volume brine injection. Elements being investigated --
   a) size and orientation of faults,
   b) basement heterogeneity (size and length of features),
   c) maximum and minimum stress direction and magnitudes,
   d) critical stress and orientation of larger faults,
   e) time series changes in fluid levels and pore pressure,
   f) refined reservoir-type model for disposal zone (Φ, kv, kh, flow unit definition and correlation).

3. High angle reverse faults common in Kansas
   a) many faults are also likely related to regional transpression/strike-slip movement (late Mississippian and early Pennsylvanian) with diagnostic fault geometries,
   b) faults and associated structures act to conduits for fluid migration and trapping of oil and gas in this region and therefore important to understand.
Future research collaboration with industry

1. Map faults and refine flow-unit reservoir model of the Arbuckle using seismic and well logs.
2. Evaluate earthquake source and mechanisms, refine fault locations.
3. Analyze well tests including daily and cumulative volume, rates, pressures, and compare with ambient pre-2011 fluid levels/pressures in the Arbuckle.
4. Evaluate stress potentially induced by withdrawal of fluid and pressure decline in Mississippian reservoirs near brine disposal.
5. Refine dynamic models of brine disposal in the Arbuckle saline aquifer in areas affected by increased seismicity.
6. Continue to explore means to reduce amounts of produced water in the MLP and develop best practices for brine disposal.
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• Justin Rubinstein, USGS

• Induced Seismicity Task Force -- Rex Buchanan, Chair
Response Plan

A. The occurrence of a recorded seismic event will trigger the Response Plan. KGS will determine the magnitude, location, and depth of the event.

B. KGS will determine the seismic action score (SAS) for the event by adding the numeric value of the magnitude of an earthquake to the sum of the individual weighted scores for each of the variables listed in Table 1.

\[
SAS = \text{Magnitude} + \text{Score}_{\text{felt}} + \text{Score}_{\text{structure}} + (2 \times \text{Score}_{\text{number}}^3) + \text{Score}_{\text{local}}^3 + \text{Score}_{\text{recursion regional}} + \text{Score}_{\text{recursion time}}
\]