A detailed basin modeling, petroleum migration, and pore pressure study of the Arkoma Basin, Oklahoma, was used to identify new exploration opportunities and maximize resources in a heavily exploited province. We determined the specific pathways, timing, and mechanisms of petroleum migration, as well as the timing and location of formerly overpressured compartments. The resulting maps explain known accumulations and delineate new opportunities. This study also provides insights into the effects of uplift on gas migration, pore pressure history, and reservoir quality that are applicable to uplifted basins around the world.

Woodford oil and gas initially migrated laterally in the pre-Atokan autochthon in late Pennsylvanian time through both sandstone and carbonate carrier beds. Vertical migration above the Spiro sand was inhibited by a pressure seal near the base of the Atoka-age synorogenic, foreland sediments. With continued burial, most oil was flushed from the system but remaining oil was cracked to gas in reservoirs. During subsequent uplift, the supra-Spiro pressure seal was breached and large volumes of gas were able to migrate vertically upward into the foreland sediments. Uplift also caused expansion of gas that flushed water from down dip, cemented reservoir sections and created a tight gas play. Today, most of the Arkoma foreland is normally pressured, but we believe that sonic and resistivity logs preserve the record of paleo-overpressure proposed by this study. Gas isotopes and petrography also support the results of the petroleum migration analysis. Deep autochthon and shallow foreland reservoirs have similar isotopic compositions with consistent vertical trends that include very heavy methane compositions, indicating a similar origin. Pyrobitumen is ubiquitous in autochthon petroleum carrier beds but far less common in the synorogenic sequence, indicating that most oil migration was restricted to the autochthon by the paleo-pressure seal.
Regional Petroleum Systems & New Play Identification in an uplifted Paleozoic basin: Arkoma Basin, Oklahoma, USA

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Purpose

- Understand origin, migration, and distribution of gas
- Integrate with other risk elements
- Identify new opportunities

...in a heavily drilled Paleozoic gas basin
Paradigms

- There’s gas everywhere!
  - No need for petroleum systems study
- It’s “unconventional tight” gas
- It’s “basin-centered” gas
- Porosity and permeability are unpredictable

Themes

- Conventional Charge & Traps
- Value of regional understanding petroleum system in a gas basin
Petroleum System Modeling

- Inputs
  - Tectonics, Structure, Stratigraphy
  - Burial + Uplift history
  - Source rock(s)
  - Heat flow / thermal regime
  - Carrier beds
Petroleum System Modeling

Outputs

- T, P, and fluid flow history
- Petroleum expulsion
- Migration pathways
- Maps of accumulations
- New opportunities
Arkoma Basin - SE Oklahoma
Pennsylvanian Convergence
<table>
<thead>
<tr>
<th>Era</th>
<th>Event</th>
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</table>
| **Permian L. Penn**  | Erosion, uplift
                      Thrusting ends;
                      Source rock thru gas window                                       |
| **E. Penn**          | Foreland: Thrusting, rapid
                      subsidence, Paleozoic source rocks enter oil & gas window;          |
| **Miss.**            | Carbonate-Clastic shelf                                              |
| **Devonian**         | Woodford Source                                                       |
| **Silurian**         | Passive margin Carbonate shelf                                        |
| **Ordovician**       | Carbonate shelf                                                       |
| **Cambrian**         | Rift-drift                                                            |
Occurrence of Gas

NORTH SOUTH

FORELAND

THRUSTED

AUTOCHTHON

BASEMENT
Erosion & Uplift

Convergence of data → > 4 km erosion

Denudation Rates

0.025 mm/y

Idaho Mountains

Kolyma

Dnepr

Ob

Zaire

Niger

Yenisei

Amur

Lena

Nile

Murray

La Plata (Parana)

St Lawrence

Zambezi

Rio Grande

Arkoma

Shatt-El-Arab

Orange

Colorado Plateau

Columbia

Mekong

Yukon

Danube

Huang He

Orinoco

Mississippi

Amazon

Colorado

Chiang Jiang

Indus

Himalaya

Himalaya

Himalaya

Ganges

Himalaya

Himalaya

Brahmaputra

Himalaya

Himalaya

Himalaya

Taiwan

Himalaya

Denudation Rate (mm/yr)

Shale Velocities

Coal Rank & Vitrinite

Ro = 0.5-1.0

Ro = 1-1.5

Ro > 1.5

Rock-Eval Maturity

Fluid Inclusions $T_H$

$\delta^{18}O$ Late cements

4 to 4.5 km

Erosion & Uplift
1D Burial & Temperature History

Max Burial 311 Ma
Max T° ~ 290 Ma

Thermal transient effect

Temperature History

Time (my)

Depth (m)

Stratigraphy

Age

C | Ordovici | Sil | Devon | Miss | Penn | Per | Trias | Jurassic | Cretaceous | Tertiary
Arb | Si | MIS | Woodfo | Can | Erosion | End of Erosion | Ara | Te

Depth (m)

Thermal transient effect

Time (my)

Wood | Union V | Erosion | End of Erosion
Devon | Missis | Penn | Permia | Trias | Jurassic | Cretaceous | Tertiary

Temperature (°C)

0 50 100 150 200 250

0 50 100 150 200 250 300
2D Modeling
Need Tectonic & Structural model

Critical to use ‘reasonable’ cross section – need good structural history!
Burial & Temperature History

311 Ma

Maximum burial, but not maximum temperature!

303 Ma

Eroding & Uplifting, but still heating up!

0 Ma

Kinta and Cartersville faults
Pressure History
Loss of Overpressure through Uplift & Erosion

Pressure regime – 311 Ma
Over pressured section
Kinta Fault

Pressure regime – 0 Ma
Normally Pressured
Kinta Fault

Normally Pressured
High Overpressure
The "False Positive" on Logs

Uplifted: Log response does not prove present-day overpressure

Logs give "false positive" reading for over pressure…‘paleo-overpressure’

Over compacted
Compacted “right amount” for lesser burial
Over compacted
Unloading curve

Atokan 317-311 Ma
Miss – Ord. 317 – 520 Ma

Over pressured section

~311 Ma
Post 308 Ma (and today)
Woodford Petroleum Expulsion

By 310 Ma, gas is flushing oil from system
Expulsion & Migration

Expulsion continues after uplift begins …thermal transient

Early migration stays down in autochthon due to overlying pressure seal
Petroleum Migration
Lateral then vertical

1. 314 Ma
   - Woodford petroleum expulsion
   - Kinta Fault

2. 312 Ma
   - Autochthon charged; petroleum stays down;

3. 294 Ma
   - Mature gas is expelled; Most oil is flushed or cracks to gas; Seal is breached on platform
   - Kinta Fault

4. < 290 Ma
   - Pressure seal is breached in thrust belt; Shallow reservoirs are charged
Seal & Pressure State

Early over pressure, then pressure bleed-off

Over pressure
Pressure bleed off
Petroleum Migration Summary

311 Ma (maximum burial)

- Oil charges autochthon.
- Oil stays below hydrodynamic seal.

303 Ma

- Erosion. Gas flushes most oil from system.
- Hydrodynamic seal is breached.
- Gas charges shallower reservoirs.

< 290 Ma

Kinta and Cartersville Faults
Does this make sense?

Are other data consistent with model?

– What do rocks and fluids say?
  – Petrography
  – Isotopes
  – Bitumen seeps
Petrography of autochthonous sands and dolomites

Pyrobitumen pre-dates calcite cement

Rock was permeable during oil emplacement

– Carrier beds
Migration & Pyrobitumen

311 Ma (maximum burial)

< 290 Ma

Oil migrated through autochthon and cracked;
Only gas migrated above the Spiro

Brazil SAND
No pyrobitumen

SPIRO SAND
Pyrobitumen-rich

Bromide
Pyrobitumen-rich
Gas Isotopes

Vertical Migration + High Thermal Stress

13C1  13C2  13C3

-28 -30 -32 -34 -36 -38 -40 -42 -44 -46

Brazil
Coal
Arbuckle
Bromide
Foreland sands

Note: Propane cracking!
Finding New Plays

- Understand petroleum migration
  - Pressure history
  - Petroleum carrier beds
- Integrate basin history, migration, petrography, etc.
  - Does it make sense within tectonic framework?
- Make migration pathway maps!
Migration Pathways in Carrier Beds
Use paleo-structure maps

Migration in key carrier beds explains the major gas accumulations

SPIRO
Bromide

BROMIDE
Wilburton

Kinta
Red Oak

SPIRO
Charge & Trap Risk Maps

Petroleum Pathways

Reservoir Presence

Petroleum Charge Focus

Trap Timing
New Opportunities

- Understand petroleum system
- Map migration and accumulations
- Compare to existing fields
- Look for under exploited accumulations

Implications for reservoir quality?
Reservoir Quality & Burial History: Gas expansion during uplift

Re-bury Spiro reservoir to depth of gas charging

Paleo-water legs
- Zones of high Sw
- Zones of quartz cementation

Today
- Tight gas reservoirs

0 Ma
- 300 BCF
- 693 m gas column
- 110 F, 4100 psi
- 10,000' burial
- H=25 m, 0.6 N/G,
- 14% φ
- 85% Gas Sat.

300 Ma
- 300 BCF Equivalent
- 256 m gas column
- 167 F, 8200 psi
- 16,000' burial
- H=25 m, 0.6 N/G,
- 14% φ
- 85% Gas Sat.
Gas Expansion Upon Uplift

- Early gas charge preserves $\phi$, $K$
- Reservoir in transition zone or water leg suffers $\phi$, $K$ degradation
- Upon uplift, gas expands downward
- Tight gas play on down-dip, flanks of structure
Synthesis

- **Lateral migration** in autochthon, then **vertical gas migration** into foreland sequence
- Oil and early gas remained in autochthon
  - Below pressure seal
- **Pressure seal leaked during erosion & uplift**
  - Mature gas plus cracked-oil gas migrated vertically
  - Shallow gas is underlain by deep gas
- **New opportunities exist**
- Uplift caused **gas expansion** and **re-migration** of gas
  - Paleo-water legs were zones of high Sw & cementation
  - Currently a tight-gas play
Mature & Tight Gas Basins

Tight gas basins are quite conventional!
- Gas migration & charge
- Gas trapping

Conventional geology and petroleum system analysis can explain the accumulations

... and help identify new opportunities

Regional geology matters in mature, tight gas basins
Thanks to BP
And
Thank You!

Harris Cander
Tom Patton
BP
Exploration & Production technology