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SHALE PLAYS:
BASIC GEOLOGIC AND ENGINEERING CONCEPTS

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What is a Shale?

**Definition:**
- A clastic sedimentary rock composed of silt to clay size grains
- The term shale is not indicative of clay content
- Most common sedimentary rock

Source – Pearson Prentice Hall, Inc.
What is a Shale?

- Two types of sedimentary rock:
  - Clastic – Sandstone, Siltstone, Shale
  - Biologic - Carbonates

Sedimentary Rock Classification Diagram
What is a Shale?

- Clastic rock definition:
  - A rock composed of fragments of pre-existing rocks
  - Primary minerals – quartz, feldspars, clays

![Sedimentary Rock Classification Diagram](image.png)

Grain Size (not to scale)

- Shale
- Siltstone
- Sandstone
What is a Shale Play?

• Definition:
  ◦ A shale play is a defined geographic area containing an organic-rich fine-grained sedimentary rock with the following characteristics:

  • Clay to silt sized particles
  • High % of silica (and sometimes carbonates)
  • Thermally mature
  • Hydrocarbon-filled porosity
  • Low permeability
  • Large areal distribution
  • Fracture stimulation required for economic production
Where are the Shale Plays?

North American shale plays
(as of March 2011)

Source: U.S. Energy Information Administration based on data from various published studies.
Updated: April 7, 2011
Why the focus?

- The majority of the large conventional fields have been found
Why the focus?

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Why the focus?

- Geologic perspective
  - Shale plays cover 100’s of thousands of acres – and sometimes millions
  - Homogenous geologic parameters result in statistical drilling
  - Repeatable and predictable results
  - Risk factors shift from reservoir, source, and seal issues to economic thresholds
Why the focus?

- **Engineering perspective**
  - Tremendous potential for growth in bookable reserves, especially w/new SEC rules
  - Opportunity to build large location inventory
  - Steady, predictable growth in production
  - Large drilling program bring the potential for cost optimization
What are the stakes?

- Geologic and Engineering Evaluation and Applications
- Land leasing budget
- Oil/Gas Field
- Goat Pasture
Geologic Concepts

• Formation of a shale play
  • Requirements needed for a commercial oil/gas field

• Unique geologic controls for shale plays
  • Relationship between source, seal, and reservoir (conventional vs. unconventional)
  • Other important variables
    • Organic material
    • Thermal maturity
    • Brittleness

• Geologic settings for shale plays
How does a field form?

- 3 variables for any oil and/or gas field:
  - **Source** – organic rich rock which expels hydrocarbons under heat and pressure
  - **Reservoir** – rock with sufficient porosity (storage) and permeability (the ability of a rock to transmit gas and/or fluids) to hold hydrocarbons
  - **Trap** – impermeable rock that restricts hydrocarbon movement

The loss of any one variable prevents the formation of a field
Conventional Field Development

- In a conventional (non-shale) field, the source, seal and reservoir are all separate variables
Conventional Field Development

- In a conventional (non-shale) field, the source, seal and reservoir are all separate variables.
Shale Field Development

• In a shale play, the source, seal and reservoir are combined into a single discrete zone.

Unconventional Reservoir

- Sandstone
- Siltstone
- Source
- Reservoir
- Seal
- Shale
- Dolomite
Seals

- Historically, shales were viewed as seals to conventional reservoirs
- Low permeability in shales prevent movements of fluid/gas
- Only a fraction of the hydrocarbons generated migrate out of a shale
- The bulk of the hydrocarbons remain in the shale

**Until stimulated, shales are barriers to flow, and function as effective seals**
SHALE PLAYS: SOURCE
Source – Function of Depositional Environment

North American shale plays
(as of March 2011)

Source: U.S. Energy Information Administration based on data from various published studies.
Updated: April 7, 2011
Source – Organic Material

Non-Marine

Generalized depositional environment

Marine

Graph showing the transition from peat to subbituminous, bituminous, and anthracite coal, along with the effects of bacterial decay and thermal alteration.
**Source – Origin of Organic Material**

- Shale plays are found in deep water basinal settings
  - In most shale plays, organic matter is derived from single celled marine organisms
  - Organic matter deposition occurs in deep marine waters
  - As organisms die, they fall to the sea floor (pelagic rain)
  - Organic matter mixes with terrestrial input (mainly clays) and carbonate debris (from shallow marine shelf), along with silica (quartz) from the organisms – forms a siliceous ooze

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![Diagram of sedimentary processes](image-url)
Source – Single Celled Marine Organisms

- Radiolarians
  - Found in deep marine waters
  - Absorb silica from water column

Source – Florida State University
Source – Laminated Reservoir

Submarine canyons

Turbidity current

Turbidite deposits

Deep-sea fans

Graded bedding

© 2010 Tasa Graphic Arts, Inc.
Source – Laminated Reservoir

- Multiple sources of sediment (pelagic rain, terrestrial, carbonate debris)
  - Low overall sediment influx results in thin laminated layers
  - Collectively referred to as “shale”, probably due to dark color (from organic matter)
  - More accurate geologic term – silty shale or limey shale (depending on mineral content)
Source – Thermal Maturity

- As organic matter is buried, it is subjected to increasing pressure and heat
- With sufficient burial, organic matter physically transforms to “kerogen”
- Kerogen transforms to oil, and then gas with additional heat and pressure
- Kerogen type (depositional environment) determines ratio of oil to gas

![Diagram of Thermal Maturity](image)

Increasing heat and pressure
Source – Thermal Maturity

- With increasing heat and pressure, oil transitions to gas, and then CO2
- Generally, the longer and deeper the burial = more oil or gas
  - Too hot for too long = over-mature basin
  - Hydrocarbons are converted to CO2

Conventional vs. Unconventional Reservoirs

- Conventional reservoir:
  - Any reservoir in which fluids flow easily through the rock matrix

- Unconventional reservoir:
  - Any reservoir that requires stimulation post-drilling to initiate economic production

- Differentiating factor?
  - Permeability
Examples of Conventional Reservoirs

Santa Rita #1 – May 28, 1923
Permian Basin (Texas) discovery well
Source – University of Texas BEG

BP Thunder Horse Platform – discovered 1999
Gulf of Mexico

Spindletop – discovered 1903
Texas
Source – National Park Service
Examples of Conventional Reservoirs

Yates reservoir
Pecos County, TX
Yates Field

- **Characteristics:**
  - High porosity, high permeability
  - Low clay content
  - Coarse to medium grained sands or carbonates
  - Low organic content

Sandstone reservoir (field of view is 2mm)
Source: Schlumberger
Examples of Unconventional Reservoirs

Examples:
- Shale Gas
- Shale Oil
- Coalbed Methane
- Heavy Oil Sands
- Tight Gas Sands

Marcellus Shale, Penn. (Source: Universal Well Service)

Woodford Shale, Oklahoma (Source: JPT.com)

Haynesville Shale, Louisiana (Source: JPT.com)
Examples of Unconventional Reservoirs

Barnett Shale core, TX. (Source: The Leading Edge; March 2011; v. 30)
Permeability

- Permeability – a measurement of the ability of fluid to flow through a porous medium
  - Expressed in “darcies”

\[ v = \frac{\kappa \Delta P}{\mu \Delta x} \]

where:
- \( v \) is the superficial (or bulk) fluid flow rate through the medium
- \( \kappa \) is the permeability of a medium
- \( \mu \) is the dynamic viscosity of the fluid
- \( \Delta P \) is the applied pressure difference
- \( \Delta x \) is the thickness of the medium

- A medium with a permeability of 1 darcy will flow 1 cm\(^3\) of fluid with a viscosity of 1 cP under a pressure gradient of 1 atm acting across an area of 1 cm\(^2\)
- A 1 darcy reservoir is an exceptional conventional reservoir
Permeability

Source: CO2CRC
Permeability

- 1 nanodarcy
- 1 microdarcy
- 1 millidarcy
- 1 darcy

- Shale (Gas)
- Shale (Oil)
- Sandstones and Carbonates

Unconventional vs. Conventional
Permeability

Shale (Gas)

Shale (Oil)

Sandstones and Carbonates

Unconventional

Conventional

Pore Throat Sizes in Millimeters

1 nanodarcy

1 microdarcy

1 millidarcy

1 darcy

0.000001

0.00001

0.001

0.1
Permeability

Shale (Gas)

Shale (Oil)

Sandstones and Carbonates

Unconventional

Conventional

1 nanodarcy

1 microdarcy

1 millidarcy

1 darcy

0.000001

0.00001

0.001

0.1

Pore Throat Sizes in Millimeters

Natural gas molecule

Crude oil molecule

Soap film

Human hair

Sheet of paper
Porosity

- Porosity – a measure of a medium’s storage (void) space
  - Expressed as a percentage
  - General correlation to permeability – high porosity usually results in high permeability
  - Shale can exhibit relatively high porosity with low permeability

**Porosity**

- **Sandstones and Carbonates**
  - **Shale (Gas)**
  - **Shale (Oil)**

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<th>Low</th>
<th>High</th>
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AAPL’s 57th Annual Meeting – June 8-11 in Boston, MA
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Permeability and Porosity

- Geologic control on permeability:
  - Grain size – permeability decreases with smaller grain size
Permeability and Porosity

- Geologic control on permeability:
  - Grain size distribution – permeability decreases with poorly sorted grains
  - Fine grained sediment can fill in void space, creating smaller pore throats

![Sandstone and Shale diagrams showing permeability and porosity differences](image-url)
Permeability and Porosity

- Geologic control on permeability:
  - Grain texture—permeability changes with roundness of grain
  - The rounder the grain, the higher the potential permeability
  - Clays tend to be “platy” vs. round

![Diagram of permeability and porosity comparison between Sandstone and Shale](image)
Permeability and Porosity

- Geologic control on permeability:
  - Grain mineralogy – permeability decreases with increasing clay content
  - Clays are plastic, and can deform to their surroundings in response to pressure
Permeability and Porosity

Geologic control on permeability:
- Diagenesis – any physical, biological, or chemical change in the sediment after deposition
- Can increase or decrease permeability

Sandstone

Mineralization

Porosity

Shale

Dissolution
Perm and Porosity in a Shale Play

- Geologic characteristics of a shale play that affect P&P:
  - Grain size: Fine grained sediment
  - Grain size distribution: Most shales contain a mixture of poorly sorted grains
  - Grain texture: “Platy” nature of clays
  - Grain mineralogy: Clay content (up to 30%)
  - Diagenesis: Mineralization within voids, dissolution of existing grains

Effect on reservoir quality

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<th>Grain Size</th>
<th>Grain Size Distribution</th>
<th>Grain Texture</th>
<th>Grain Mineralogy</th>
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Permeability is the differentiating variable between a conventional and an unconventional reservoir
Revisiting Mineralogy

- The correct mineralogy is necessary to ensure “fracability”
  - Clays are ductile, and resist fracture formation
  - A rock must be brittle in order to initiate and propagate a fracture (either naturally or artificially induced)
  - Certain minerals (especially quartz and carbonates) are brittle
    - Successful shale plays usually show quartz content in excess of 40%
  - Clay content above 40% can result in poor stimulation results
    - Certain types of clays (swelling clays) are more problematic than others

Niobrara Shale - Colorado
Source – AAPG Explorer, November 2010
Early shale drilling history

- The first commercial oil well was drilled in Pennsylvania in 1859 by Edwin Drake
- Oil discovered in the Riceville Shale at 69'.
Early shale drilling history

- Some other examples:
  - Devonian Shales (Appalachian Basin) – gas produced since 1821
  - New Albany Shale (Illinois Basin) – gas production since the early 1900s
  - The Antrim Shale (Michigan) – gas produced since the 1940s (2.5 TCF cumulative production)
  - Woodford Shale (Oklahoma) – minimal gas production since 1939

Common Thread – early shale production required no fracture stimulation

- Natural fractures create pathways (and storage space) for oil/gas
- Reservoir is not in the rock matrix itself, but in the fracture network
Recent shale drilling history

- Barnett Shale (Fort Worth Basin) – 1st large scale attempt to produce low perm shales
- Mitchell Energy recognized the large OGIP (original gas in place) potential in the Barnett

Source – Powell Barnett Shale Newsletter
Recent shale drilling history

- In 1981, Mitchell Energy drilled the first well specifically targeting the Barnett Shale
- 20 years of completion design experimentation
- Gradual transition from traditional gel based fracs to slick water fracs
  - First key breakthrough
- First horizontal well in 1992
  - Second key breakthrough
- Improving well results coupled with higher gas prices led to acquisition by Devon Energy in 2002
- Devon quickly transitioned to horizontal wells
- Other operators moved to establish acreage positions, and expanded the boundaries of the play
- Refinements in completion technology resulted in multi-stage fracs
  - Third key breakthrough
- The success of multi-stage fracs allowed the expansion of the play into oilier areas
- The learning curve in other plays was dramatically compressed as a result of the evolution of stimulation technology in the Barnett
  - The Barnett is the only shale play that showcases all 3 key breakthroughs
Recent shale drilling history

Number of New Vertical & Horizontal Producer Wells by Year as of July 1, 2010
All Counties/Fields in the Fort Worth Basin

Barnett Shale Production Summary to July 1, 2010

- Number of Horizontal (Hz) Wells: 9,956
- Number of Vertical/Directional (V/D) Wells: 4,689
- Total Producer Wells: 14,645
- Total Gas Production (MCF): 7,991,783,787
- Total Oil/Condensate Production (BO): 22,237,201
- # of Wells with Peak Month Daily Avg. of 3,000+ MCF/D: 1,164
- Daily Avg. June 2010 - Gas (MCF): 5,002,446
- Daily Avg. June 2010 - Oil/Condensate (BO): 10,506

* 2010 is Six Months to July 1
- Hz projection for 12 months: 1,586
- V/D projection for 12 months: 66
- Total projection for 12 months: 1,652

Source: Railroad Commission of Texas - All Fields & Pending File Wells
Powell Barnett Shale Newsletter, October 25, 2010
Recent shale drilling history

Barnett Shale Daily Avg. Production by Month 1/1/2003 to 1/1/2011

Total Gas MCFGPD
Total Condensate/Oil BOPD

Source: Railroad Commission of Texas
Powell Shale Digest, Mar. 2, 2011
Recent shale drilling history

North American shale plays
(as of March 2011)

40+ distinct shale plays

Source: U.S. Energy Information Administration based on data from various published studies.
Updated: April 7, 2011
Recent shale drilling history

Source: BENETEK Energy LLC
Published By: U.S. Energy Information Administration
What is fracture stimulation?

Hydraulic Fracturing

Hydraulic fracturing, or “fracing,” involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.

Source: ProPublica

Graphic by Al Granberg
What is fracture stimulation?

- Purpose – to increase the surface area exposure of the wellbore to the reservoir
- Increase the effective permeability of the reservoir within the area affected by the frac
- Only effective in brittle rock – ductile clay-rich rock will not fracture!

Source: ProPublica

Graphic by Al Granberg
What is in frac fluid?

0.49% ADDITIVES*

- 99.51% WATER AND SAND

- Most chemicals are either surfactants or clay stabilizers
- Sand is “proppant” – helps keep induced fractures open

Source – Energyindepth.org
Shale Reservoir

- First key breakthrough – Slick water fracs
  - Allows pumping of high volume of proppant at low concentrations
  - Traditional gel-based fracs screen out
    - High viscosity fluids w/high proppant concentrations form a blockage within the fracture and/or low perm reservoir, creating a restriction to further fluid flow and a rapid unsustainable rise in pumping pressure
    - More efficient fracture network created
Shale Completion Technology

- Second key breakthrough – Horizontal wells
  - Maximizes wellbore exposure to potential reservoir
  - Laterals can extend up to 2 miles (10,000’+)

![Diagram of Shale Reservoir with Frac stage and 1-2 miles laterals]
Shale Completion Technology

- Third key breakthrough – Multi-stage fracs
  - Multiple fracs within a single wellbore
  - Greatly increases the volume of rock affected by a frac

![Diagram of Shale Reservoir with 28 frac stages](image)
Shale Completion Technology

- Third key breakthrough – Multi-stage fracs
  - Vendors now touting up to 60 frac stages
  - New downhole mechanical designs significantly reduce time needed to frac

Quick-Frac, Packers Plus
Shale Completion Technology

- Almost all shale plays are now dominated by horizontal wells with multi-stage fracs
- Important exception:
  - Vertical wells are competitive in basins where very thick shaly sections are present
  - Most effective when shales are greater than 500-1,000’ thick
  - Lateral completion design in a vertical wellbore
Vertical vs. Horizontal Wells

640 acres (1 mi²)

- **Generic Vertical Development**
  - 40 acre spacing (16 wells)
  - $1.8MM/well
  - IP 50 boe/d
  - 80 mboe/well EUR

- **Financial Results**
  - $28.8MM total capital spent
  - 1,280 mboe reserves
  - $22.50/boe F&D
  - Low PV (present value)
  - Low ROR

---

**Frac stage**
Vertical vs. Horizontal Wells

640 acres (1 mi²)

• Generic Horizontal Development
  • 160 acre spacing (4 wells)
  • $6.0 MM/well
  • IP 400 boe/d
  • 400 mboe/well EUR

• Financial Results
  • $24.0 MM total capital spent
  • 1,600 mboe reserves
  • $12.50/boe F&D
  • High PV (present value)
  • Higher ROR
Problems Associated with Fracs

- Roughly half of a well’s cost is now associated with completion/stimulation
  - High demand for stimulation services results in rapid cost inflation
- Significant water demands can stretch local water supplies
  - A single well can require up to 2 million gallons of water
- Emerging environmental concerns
  - Alleged contamination of subsurface aquifers
  - Public concern over chemicals used in fracs
  - Air and noise pollution
  - Significant surface disruption (well pad, roads, facilities, etc.)
  - Frac water disposal