Geological Principles and Types of Unconventional Hydrocarbon Reservoirs:

Focus on Shale Gas and Oil

Thomas W. Grimshaw, Ph.D.

Grimshaw & Associates, LLC

December 3, 2012

Unconventional Natural Gas and Oil Resources

- Generally 6 to 7 recognized…

Shale gas	*Coalbed methane*
Shale oil	*Oil sands*
	Oil shale
	Methane hydrate
	Tight sands (sometimes)

- Focus today on <u>shale gas and shale oil</u>

Proposed Agenda

- Organic Shale Source Rock
- Depositional Basins
- Gas and Oil Generation from Organic Shale
- Technology Developments
- Shale Gas History
- U.S. Examples: Barnett, Eagle Ford, Utica Shales
- Worldwide Importance of Shale Gas
- Shale Gas in Columbia
- Summary

ORGANIC SHALES:
OIL AND GAS SOURCE ROCK

What Is Shale?
Where Does It Come From?

- Starts as deposits of fine-grained sediment (mud)
- Deposited in low-energy (quiet) environments (e.g., deep sea)
- Contains clay minerals and other constituents
- Often also contains organic matter deposited with sediment
- Converted to rock (lithification) by heat and pressure

Hand Specimen (Boring!)

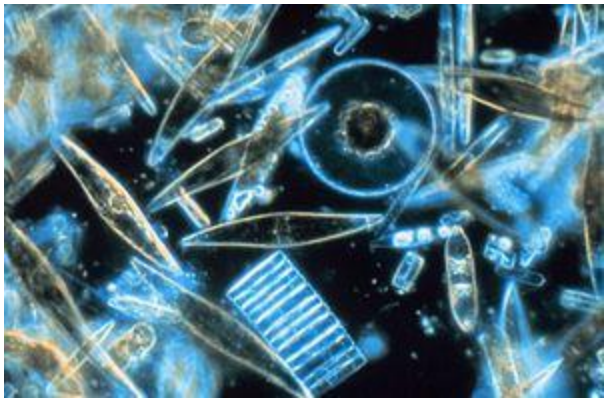
http://www.nvcc.edu/home/cbentley/gol_135/sideling_hill/readings.htm

Outcrop: Shale under Limestone

http://nn.wikipedia.org/wiki/Fil:Limestone_on_shale.jpg

Organic Matter in Shale

- Consists mostly of marine plankton
  - Microscopic, unicellular organisms
  - e.g., diatoms, algae, bacteria
- Converted with increasing temperature to **kerogen** (diagenesis)
- At same time as mud and clay lithification to shale



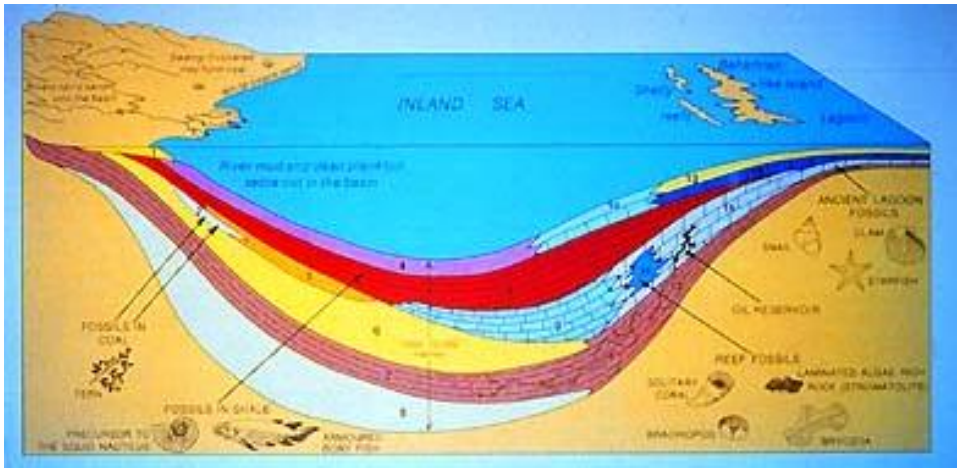
http://en.wikipedia.org/wiki/Phytoplankton

http://www.hihostels.ca/westerncanada/374/HI-Yoho-National-Park/About-the-Area/index.hostel

DEPOSITIONAL BASINS

Depositional Basins

- Areas on the earth of sediment accumulation
- Often subsides into crust as sediment is deposited
- Many layers of sedimentary rock – shale, sandstone, limestone, others

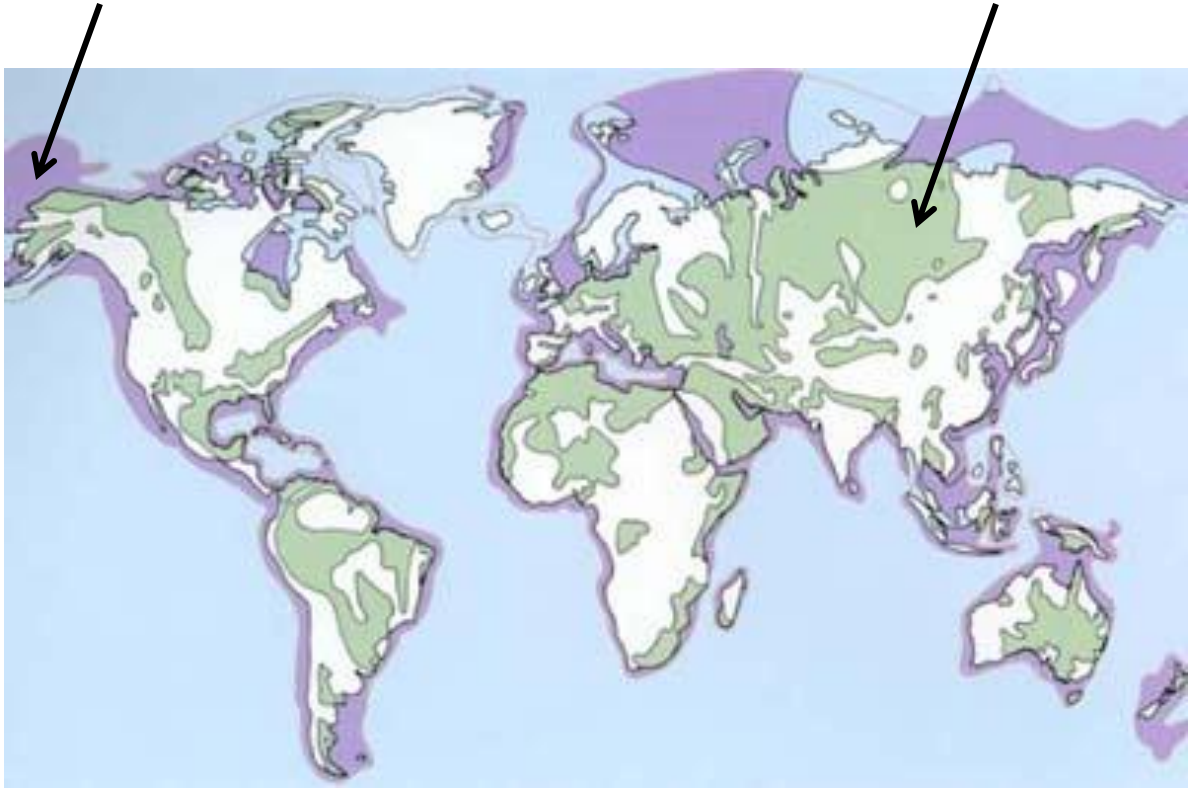


http://www.lithoprobe.ca/media/slideset/slides/tools18.asp

Sedimentary Basins of the World: Offshore and Onshore

Offshore basins (purple)

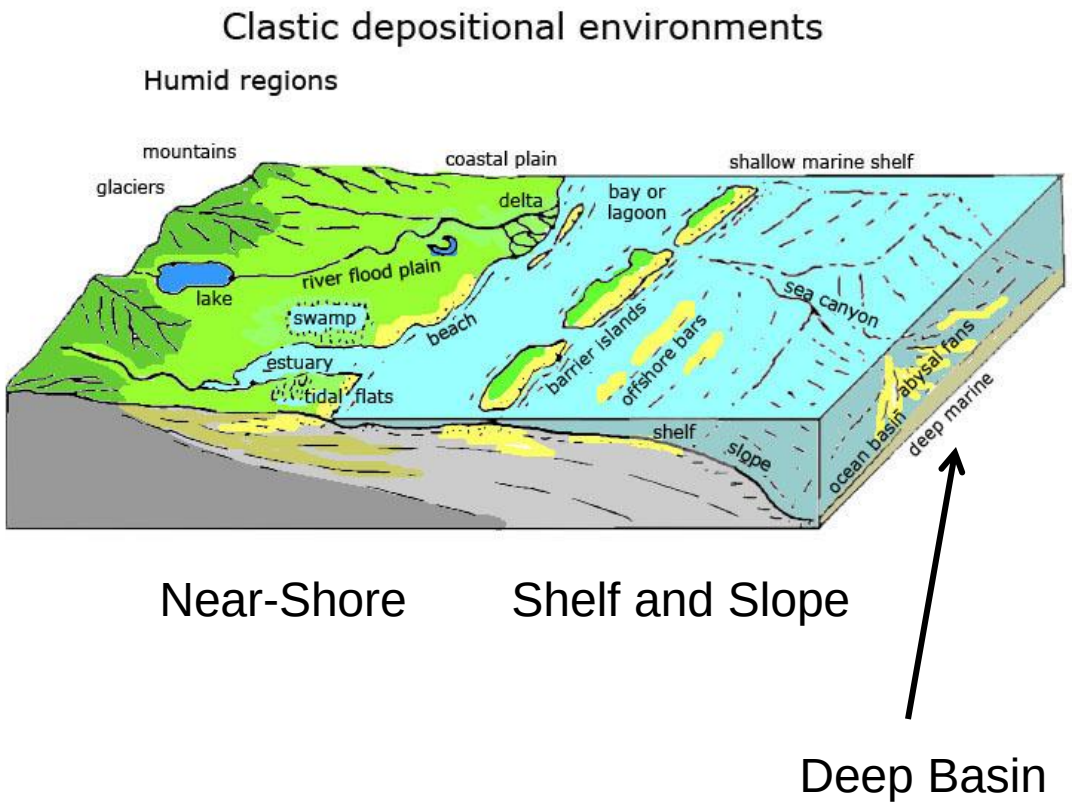
Onshore basins (green)



http://www.glossary.oilfield.slb.com/DisplayImage.cfm?ID=15

Depositional Environments in Sedimentary Basins

- Near-shore
  - Beach
  - Bay and lagoon
  - Barrier island
  - Tidal flat
  - Delta
- Shelf and slope
- Deep basin
  - Density current
  - Pelagic (open ocean)

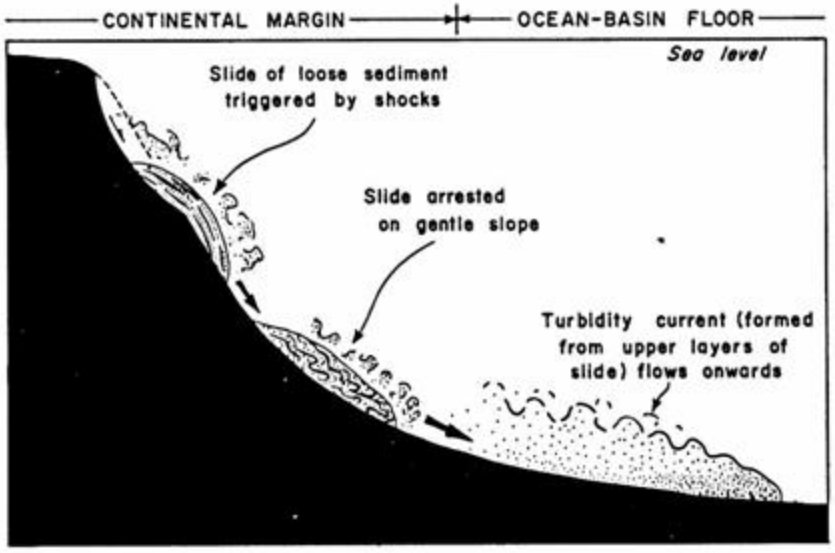


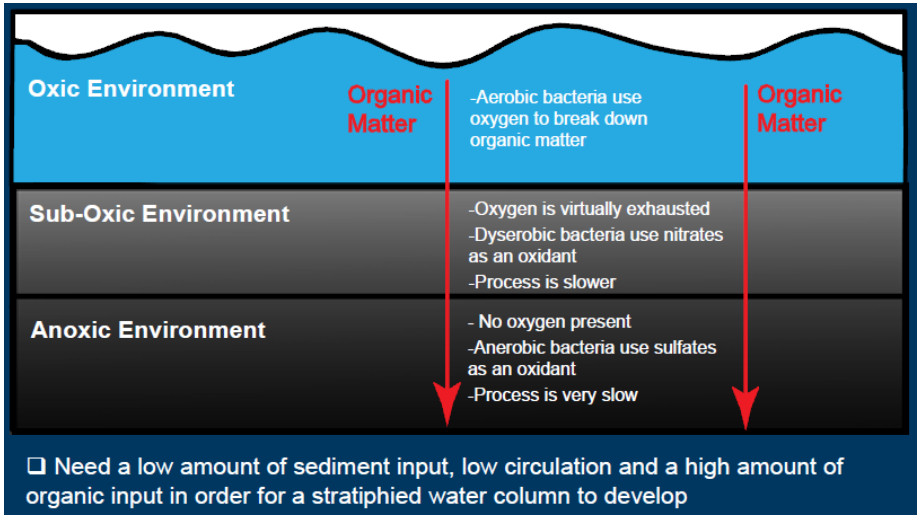
http://geologycafe.com/erosion/deposition.html

Organic Shale Deposition

- Deep marine environment; low energy
- No (very low) oxygen: anoxic
- Two sources of organic matter
- Mixed organic matter and fine-grained sediment
- Organic matter preserved – no oxygen for breakdown
- Amount of organic matter highly variable

Density Current and Pelagic Sources

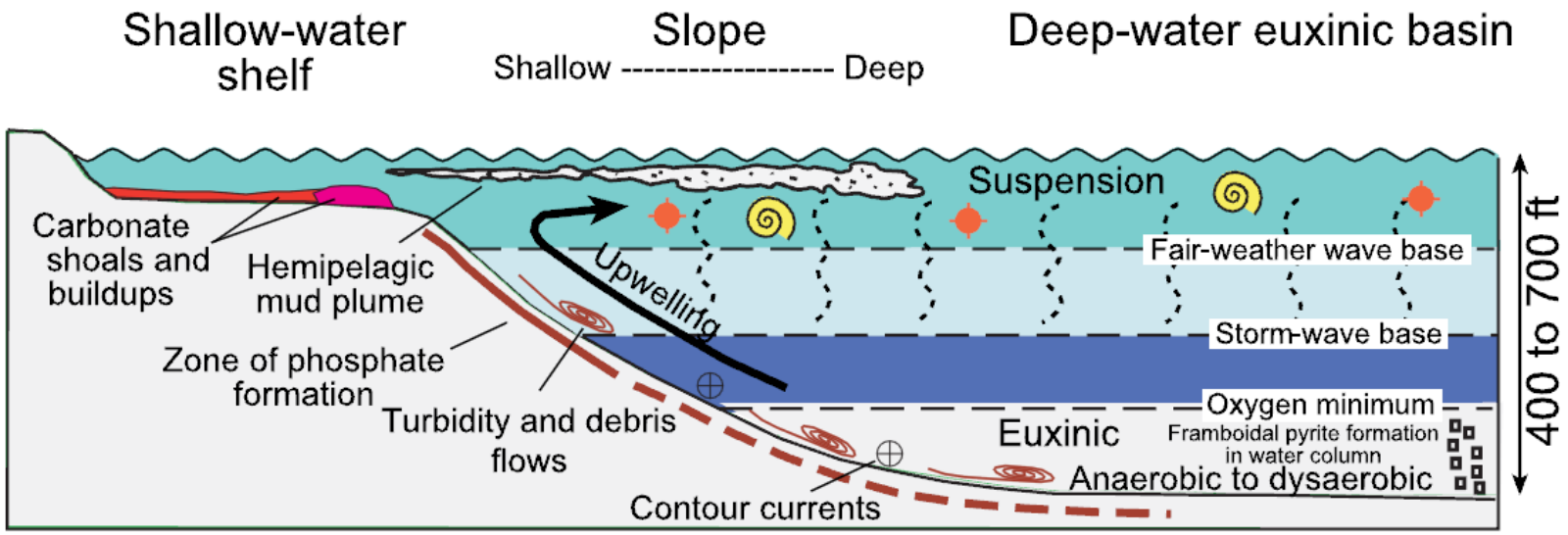




Deposition of both sediment and organic matter in deep basin environment

http://instruct.uwo.ca/earth-sci/200a-001/11rifts.htm *http://www.geo.wvu.edu/~jtoro/petroleum/10_Origin%20of%20Source%20rocks.pdf*

Organic Matter Deposition in Deep Basin



Depositional Model for the Barnett Shale

Loucks and Ruppel, 2007

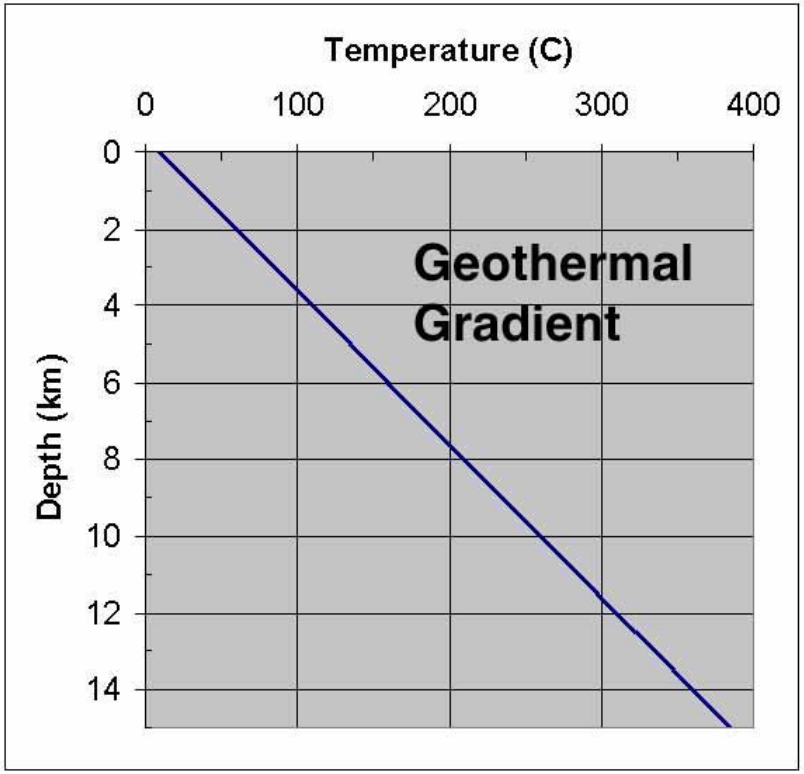
OIL AND GAS FORMATION IN ORGANIC SHALES

Oil and Gas Formation in Source Rocks (Organic Shales)

- Organic matter content (TOC) may be as high as 10% (or higher)
- TOC must be >1% to generate hydrocarbon
- Stepwise conversion of organic matter to oil and gas
- Simultaneous with lithification of mud to shale
- Increasing temperature due to geothermal gradient
- Stages of conversion: THERMAL MATURITY

Geothermal Gradient

- Increasing temperature with depth below earth's surface
- About 25° C per kilometer
- Shale bed temperature rises with basin subsidence
- Increasing temperature converts organic matter to oil and gas



Increasing THERMAL MATURITY shale

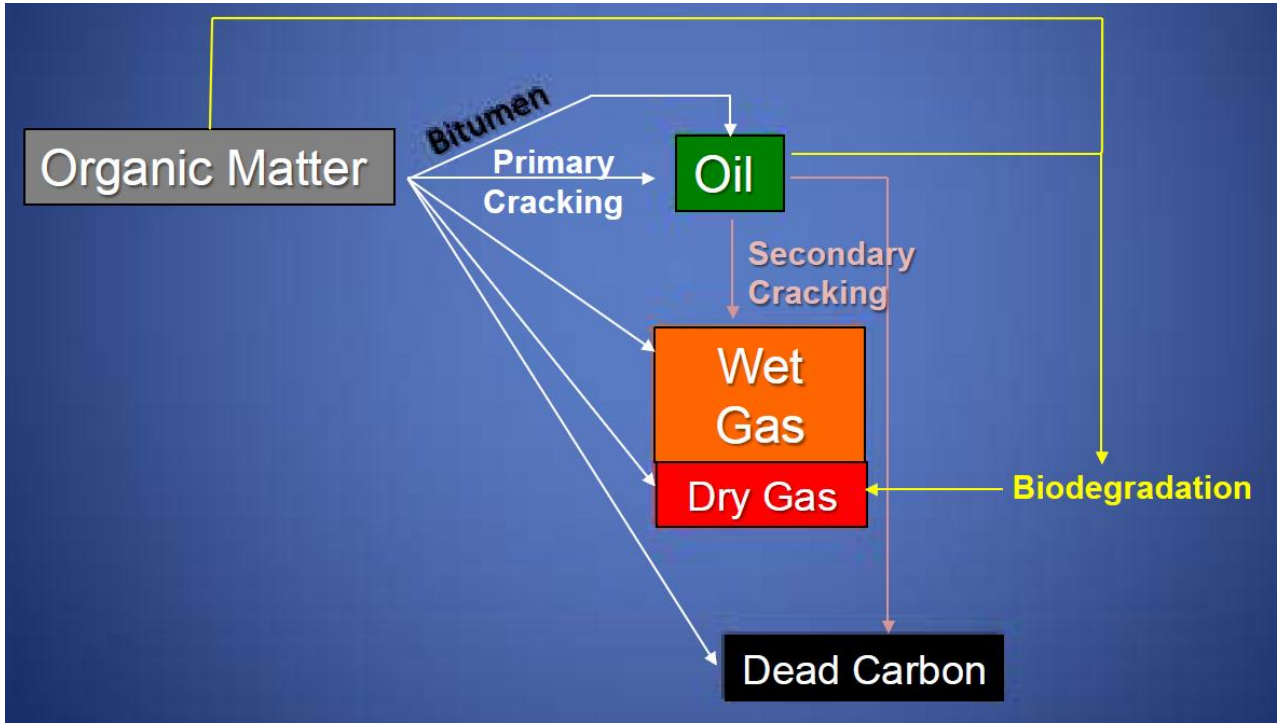
http://www.geo.wvu.edu/~jtoro/geol101/Outline-2.html

Thermal Maturity in Petroleum Generation

Thermal Maturity (Oil)	Approximate Temperature	Process	Product
Immature	<60° C	Organic matter converted to kerogen	Methane from bacterial activity
Mature	<60° – 160° C	Oil generated and expelled	Oil
Postmature	>160° C	Postmature for oil, Mature for gas	Thermogenic methane

http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/marcellus/sourcerock_index/sourcerock_maturation/index.htm

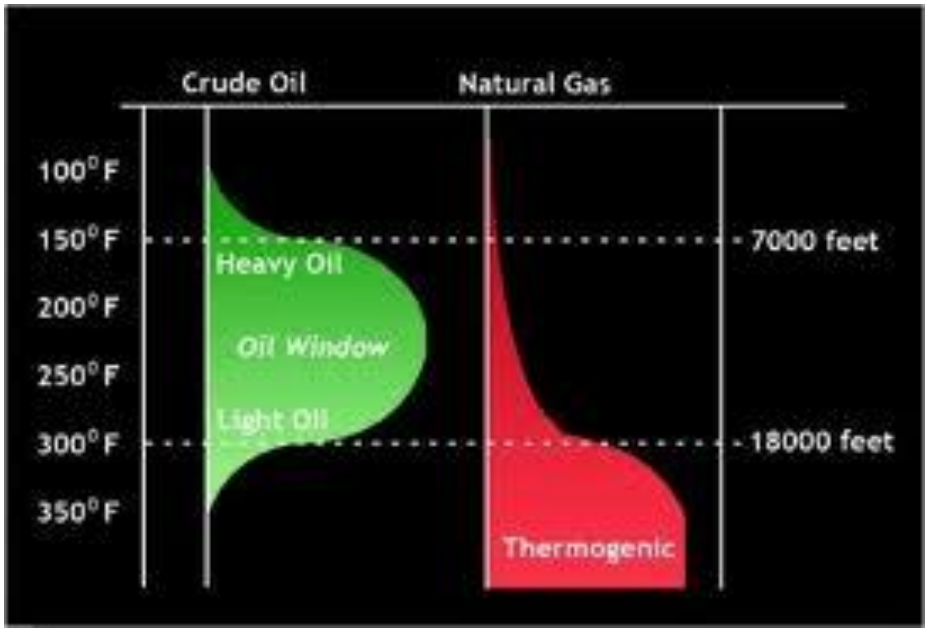
Stages of Organic Matter Conversion



Jarvie 2008

Thermal Maturity with Depth

- Geothermal gradient
  ⟶ increasing maturity with depth
- Kerogen converted first to oil, then gas at greater depths
- Kerogen:
  <150°F (65°C)
- Oil window:
  150°-300°F (65°-160°C)
- Gas window:
  >300° F (156°C)
- “Wet gas” between



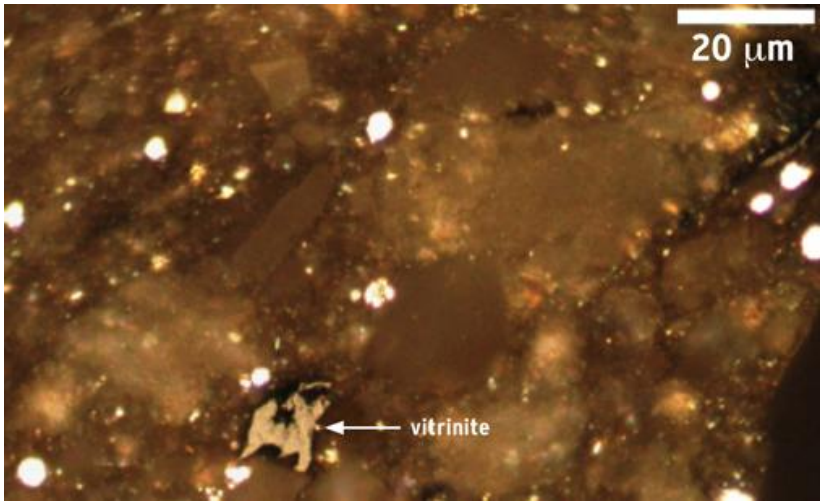
Oil Window 7,000 to 18,000 Feet

Gas Window >18,000 Feet

http://my.opera.com/wandererbynature/blog/show.dml/3907824

Vitrinite Index: Measure of Thermal Maturity

- Vitrinite – one of compounds of organic matter in shale
- Formed from plant cells
- Measure of light reflected by vitrinite in microscope
  - Light reflectance
  - Typical values 0-3%



- Temperature range sensitivity corresponds to hydrocarbon generation (60° to 160°)
  - Onset of oil: VI – 0.5-0.6%
  - Gas generation: VI > 1.5%

http://www.astm.org/SNEWS/SO_2009/d0528_so09.html

Oil Expulsion Mechanism

- Kerogen content is load bearing (geostatic pressure)
- Maturation changes kerogen to fluid, becomes pressurized
- High pressure fractures shale, allowing outward migration
- Some oil leaves shale to surrounding strata
- Remainder stays in shale fractures

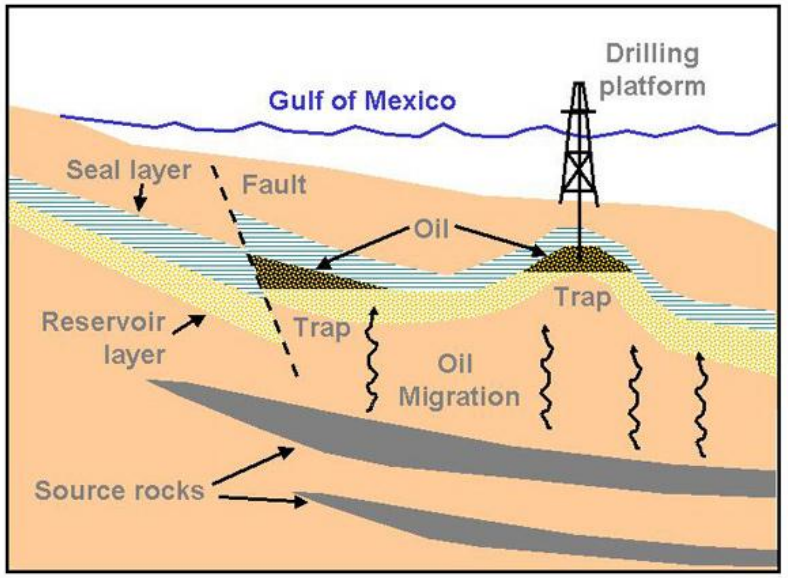
http://www.geo.wvu.edu/~jtoro/petroleum/Review%202.html

SHALE OIL AND GAS: TECHNOLOGY DEVELOPMENTS

Horizontal Drilling and Hydraulic Fracturing

Conventional: Natural Gas and Oil

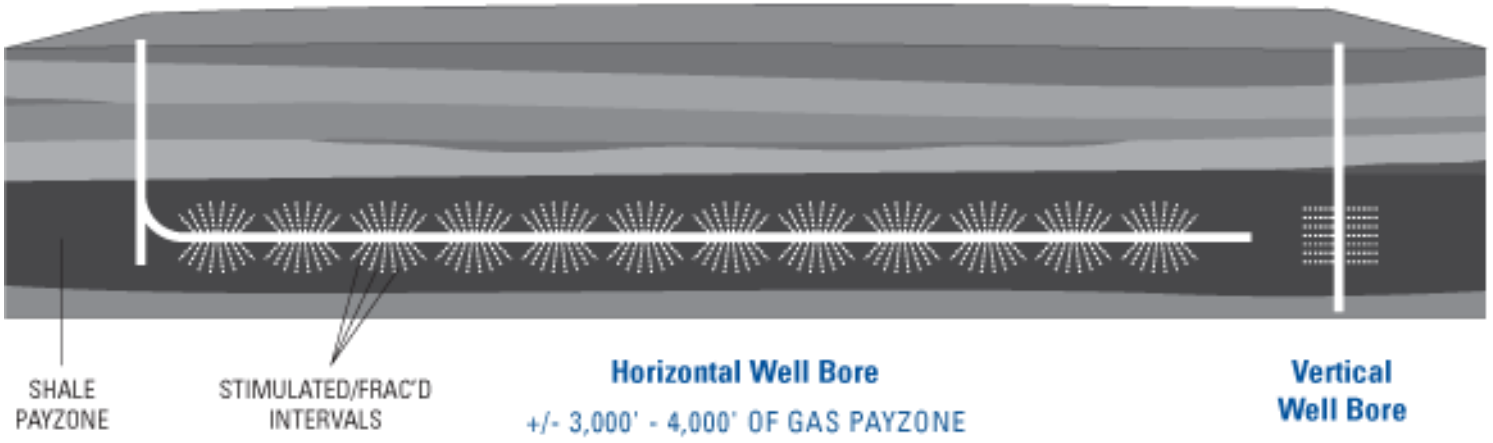
- Three Conditions
  - Source rock
  - Reservoir rock
  - Trap (seal)
- Oil fields difficult and costly to locate and develop
- Conventional drilling with vertical wells



http://www.energybc.ca/profiles/naturalgas.html

Unconventional: Shale Gas and Shale Oil

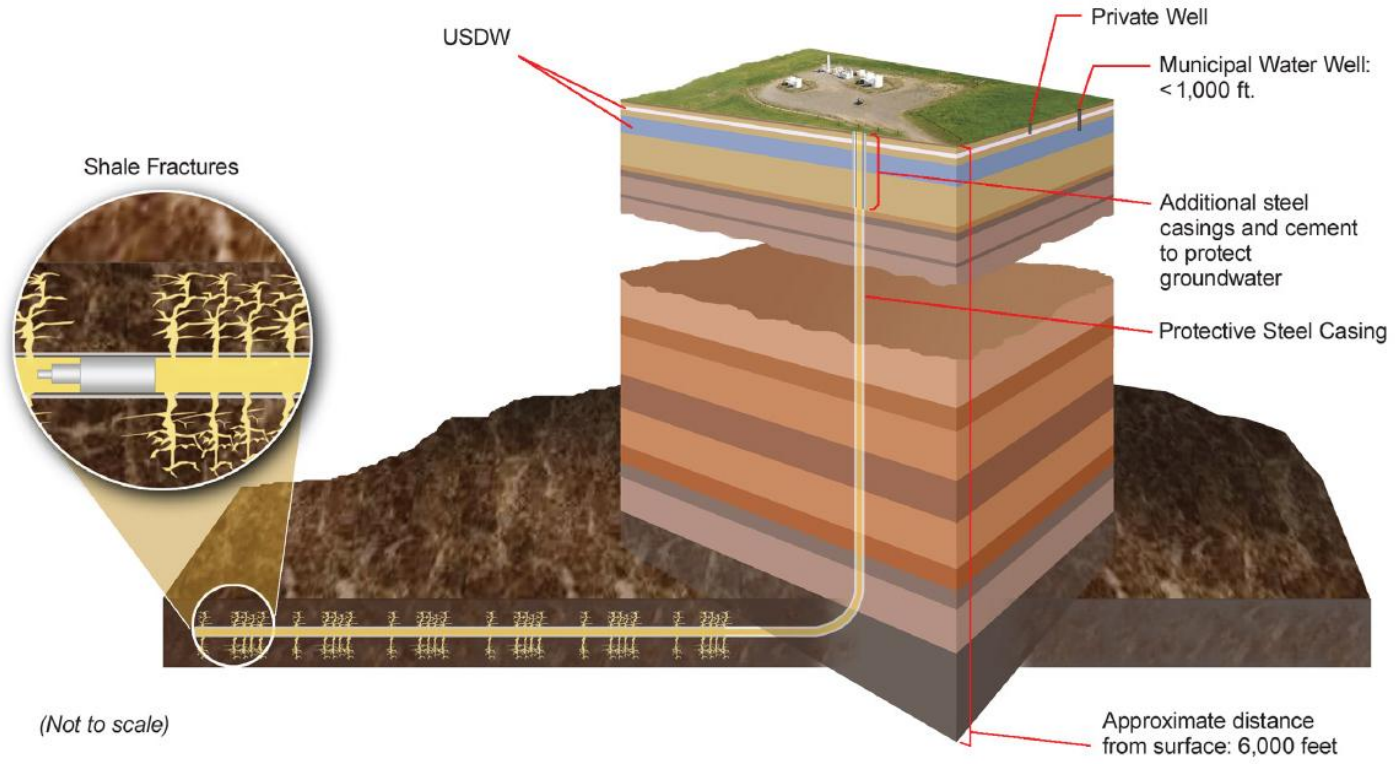
- Oil and gas tapped in source rock
- Reservoir is the shale itself
- Hydrocarbons trapped in shale where formed
- Much greater exposure of well bore in shale
- Fracturing permits greater flow to well bore



4,000 ft vs 150 ft of formation exposure

http://www.wvsoro.org/resources/marcellus/horiz_drilling.html

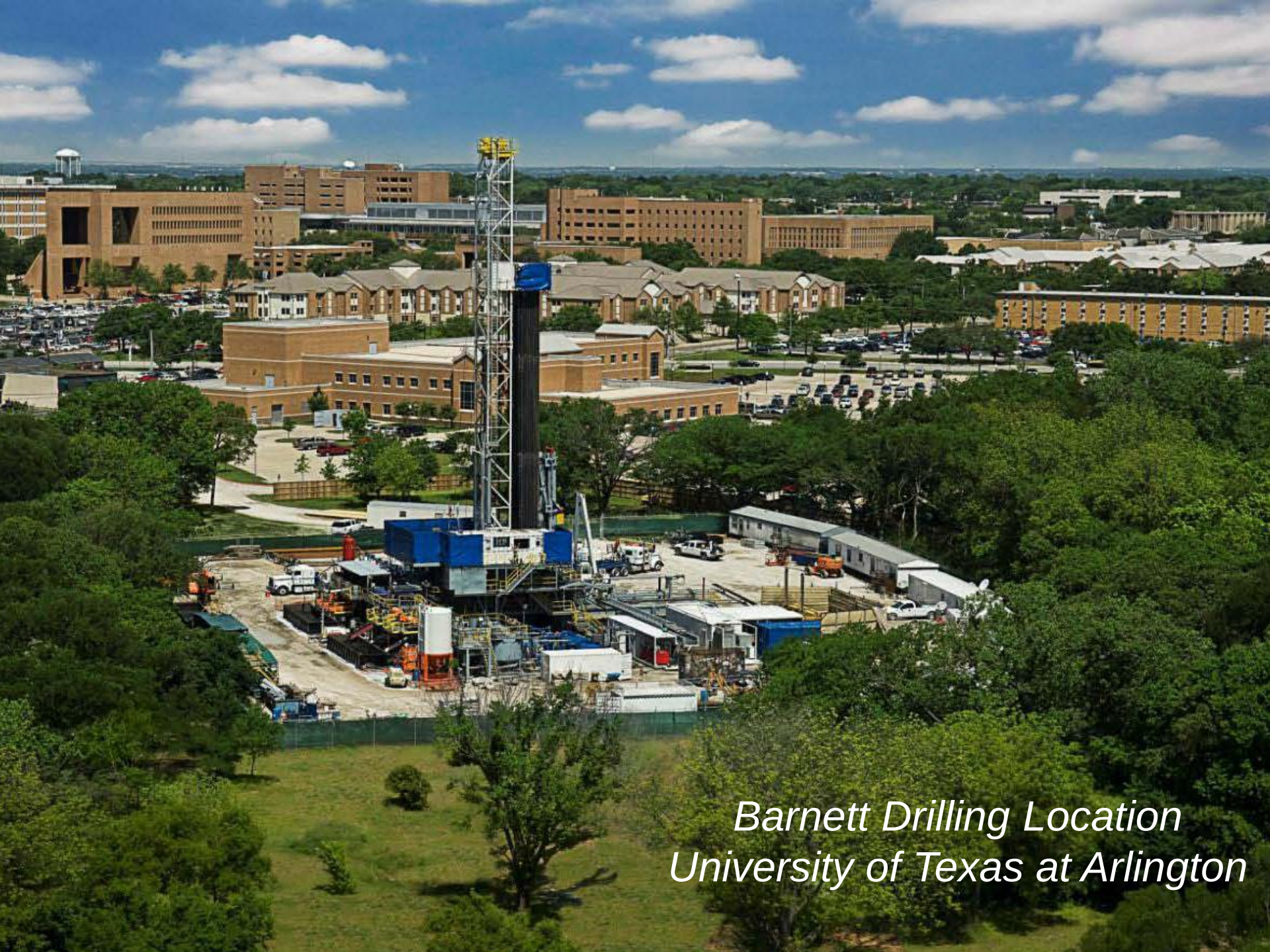
Horizontal Drilling and Hydraulic Fracturing



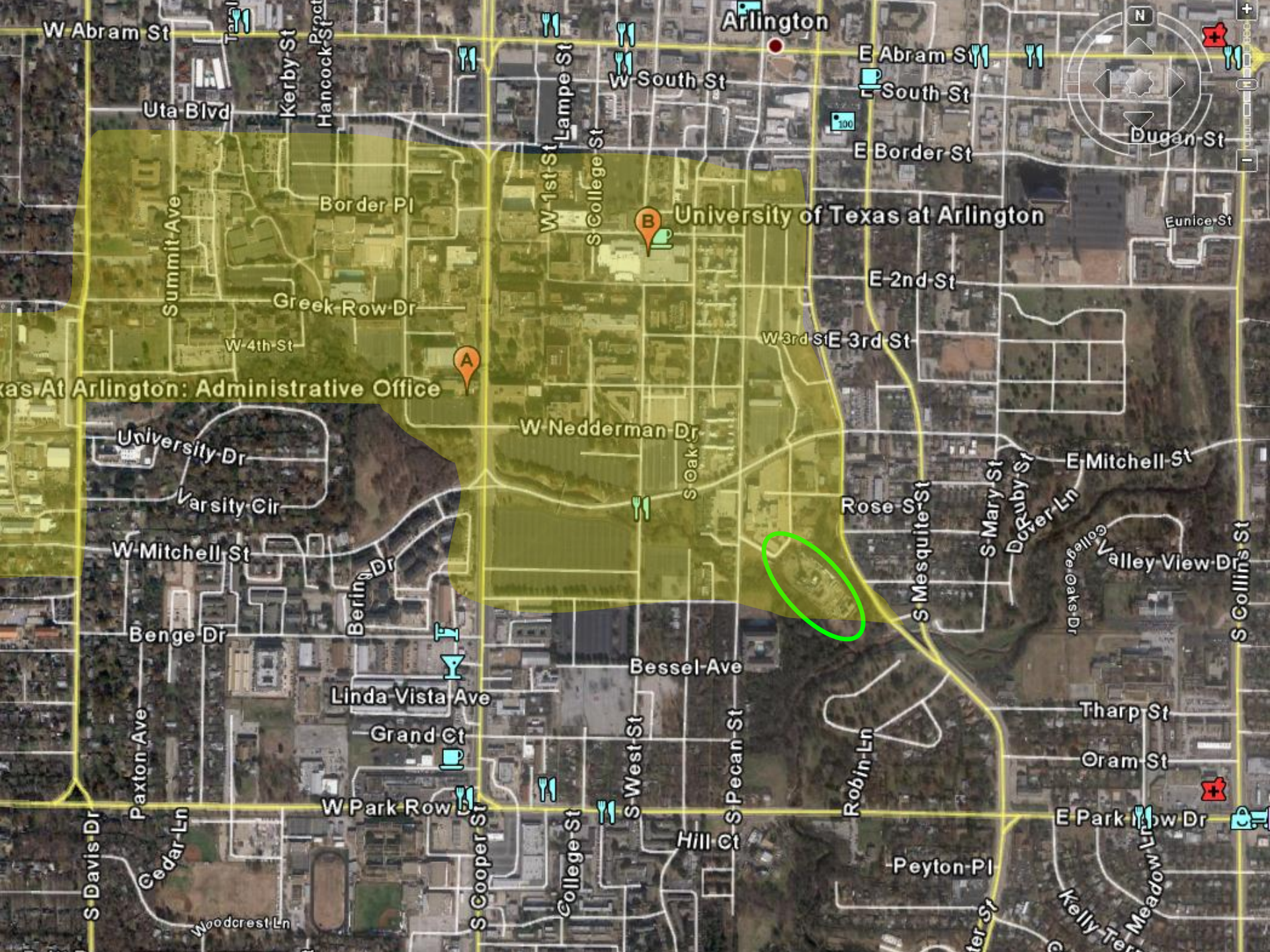
http://www.fossil.energy.gov/programs/oilgas/shalegas/hydraulicfracturing.html

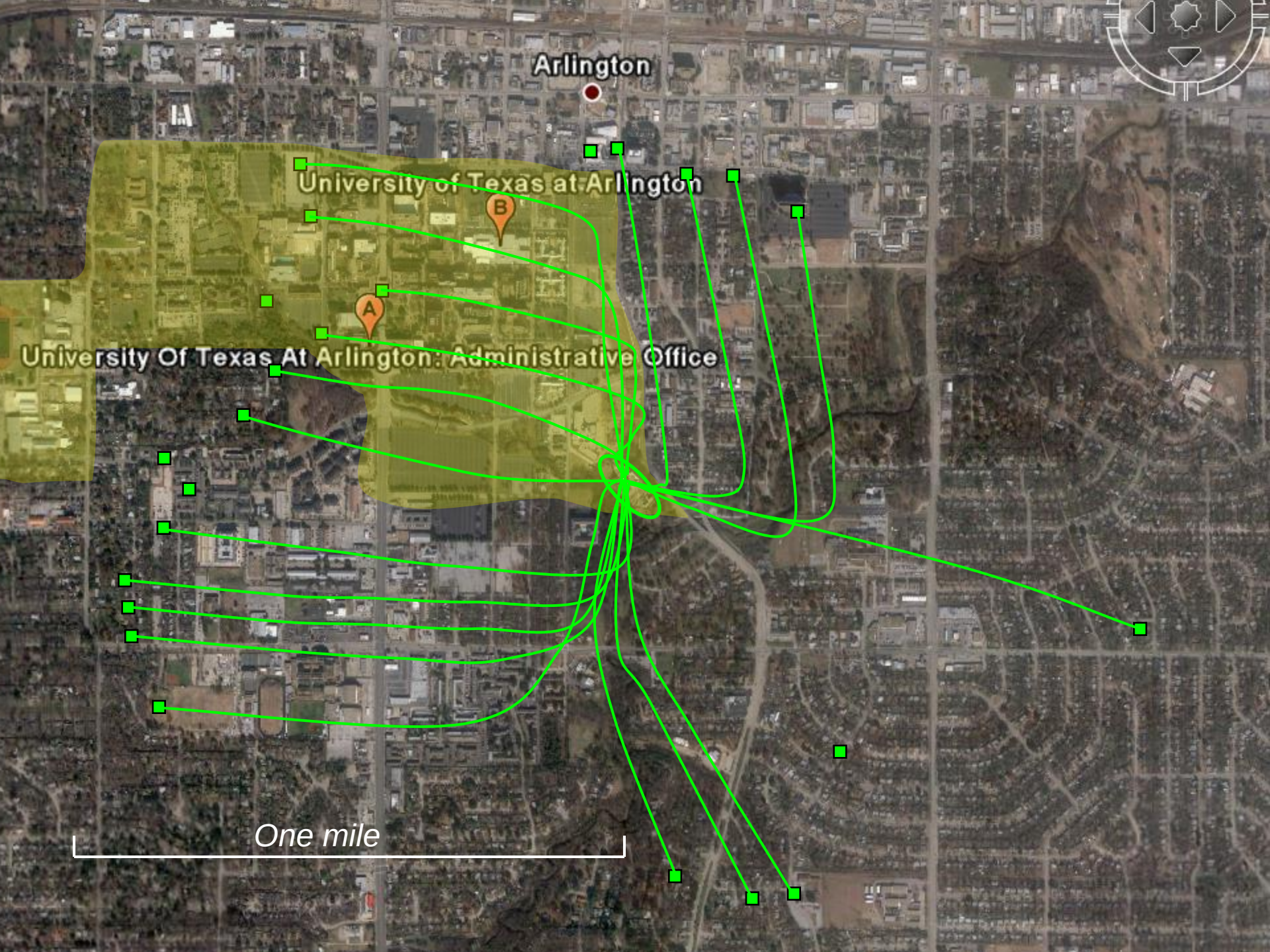
An Example from the Barnett Shale

- Near Fort Worth, Texas
- University of Texas at Arlington campus
- Total of 22 shale gas wells, 5 Bcf per well
- Estimates of 110 Bcf production over 25 years
- Developed by Carrizo Oil & Gas, Inc.



Barnett Drilling Location
University of Texas at Arlington


W Abram St
Arlington
E Abram St
W South St
E South St
Uta Blvd
Kerby St
Hancock St
Lampe St
S College St
W 1st St
E Border St
Dugan St
Border Pl
Summit Ave
University of Texas at Arlington
Eunice St
E 2nd St
Greek Row Dr
W 4th St
W 3rd St
E 3rd St
A
B
xas At Arlington: Administrative Office
W Nedderman Dr
University Dr
Varsity Cir
S Oak St
E Mitchell St
Rose St
S Mesquite St
S Mary St
Dover Ln
S Ruby St
College Oaks Dr
Valley View Dr
S Collins St
W Mitchell St
Bering Dr
Benge Dr
Bessel Ave
Linda Vista Ave
Tharp St
Grand Ct
Oram St
Paxton Ave
S West St
S Pecan St
Robin Ln
W Park Row Dr
E Park Row Dr
S Davis Dr
Cedar Ln
S Cooper St
College St
Hill Ct
Peyton Pl
Woodcrest Ln
Meadow Ln


Arlington
University of Texas at Arlington
B
A
University Of Texas At Arlington: Administrative Office
One mile

HISTORY OF SHALE GAS DEVELOPMENT

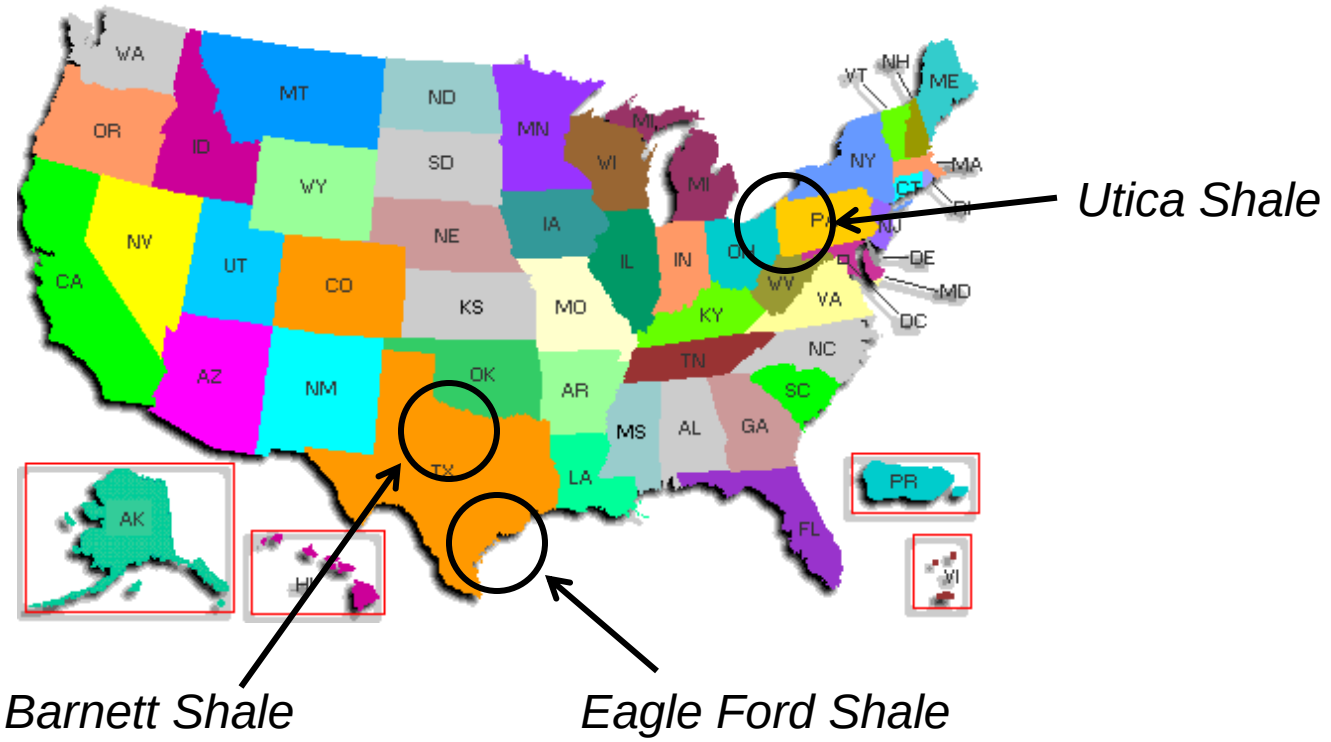
Pioneer in Shale Gas (and Oil) Development

- Mitchell Energy & Development Corporation
- New application of existing oilfield technologies
  - Horizontal drilling
  - Hydraulic fracturing
- Barnett Shale, Fort Worth Basin, Texas
- Started in 1981, achieved success in early 1990s
- Mitchell Energy sold to Devon in 2002

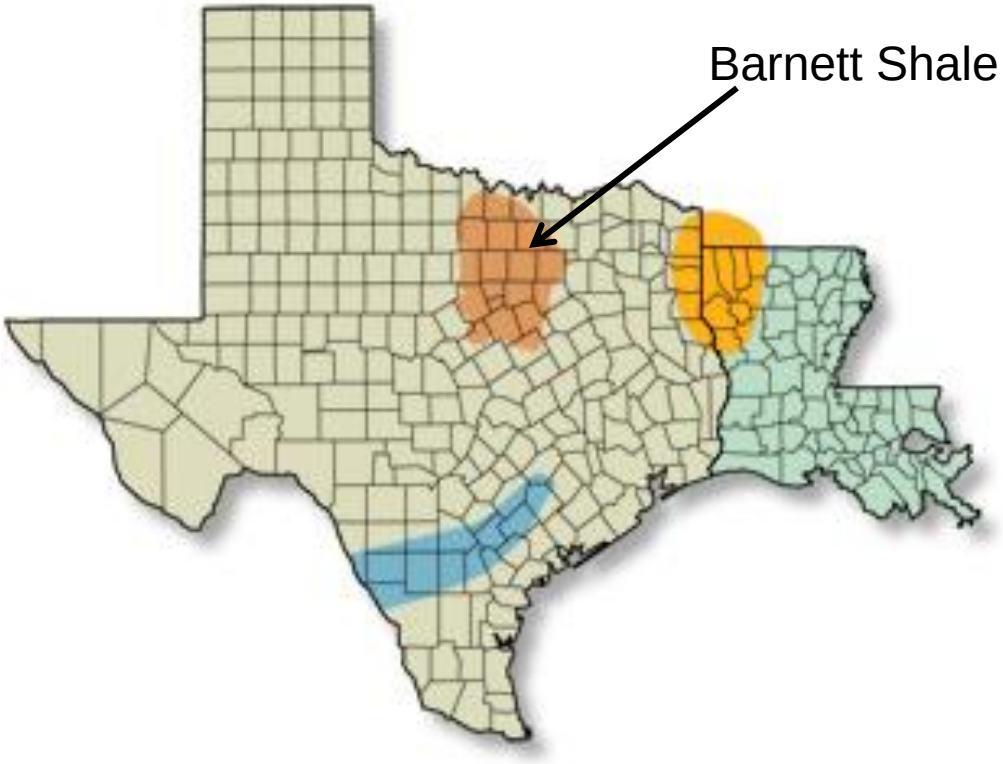
George Mitchell: "Father" of Shale Gas (and Oil) Development

http://thinkprogress.org/politics/2009/01/21/35082/mitchell-foxman-envoy/?mobile=nc

SHALE GAS AND OIL: U.S. EXAMPLES



Barnett Shale Example



http://hosted-p0.vresp.com/303462/84ad169188/ARCHIVE

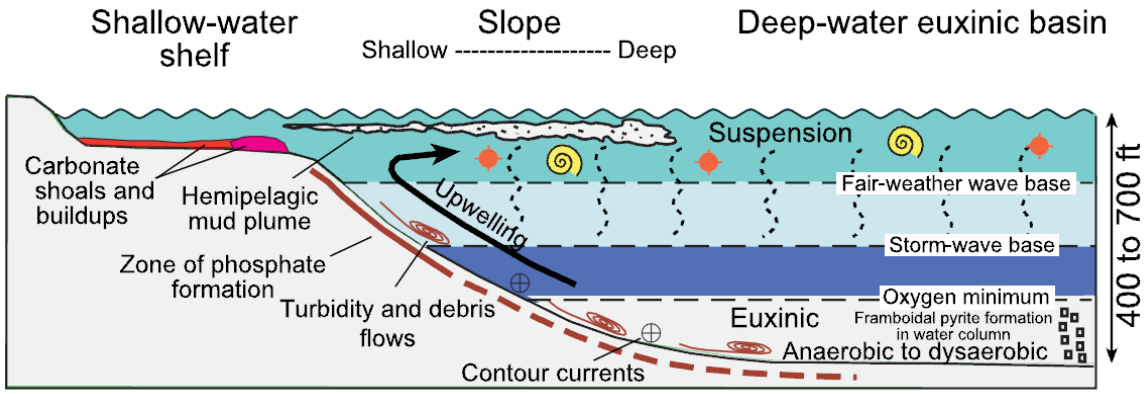
Geological Characteristics

- Core, Tier 1, and Tier 2 areas
- Organic-rich shale
- Deposited in Mississippian geologic period
- 4000-9000 feet deep
- 300-800 feet thick

http://stocksonwallstreet.net/2009/09/eog-resources-a-top-natural-gas-play/

Fort Worth Basin Organic Shale Deposition

Barnett Shale Outcrop

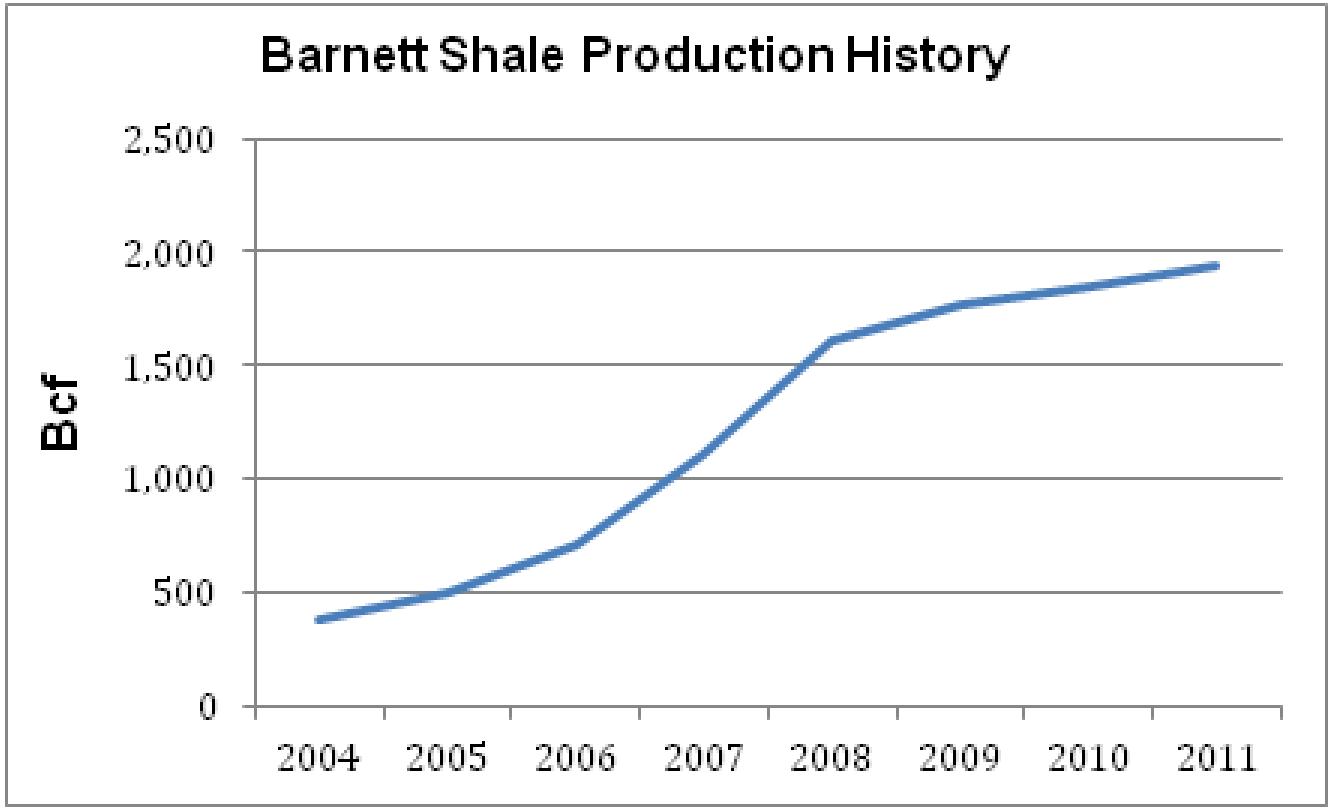


Depositional Model for the Barnett Shale

Loucks and Ruppel, 2007

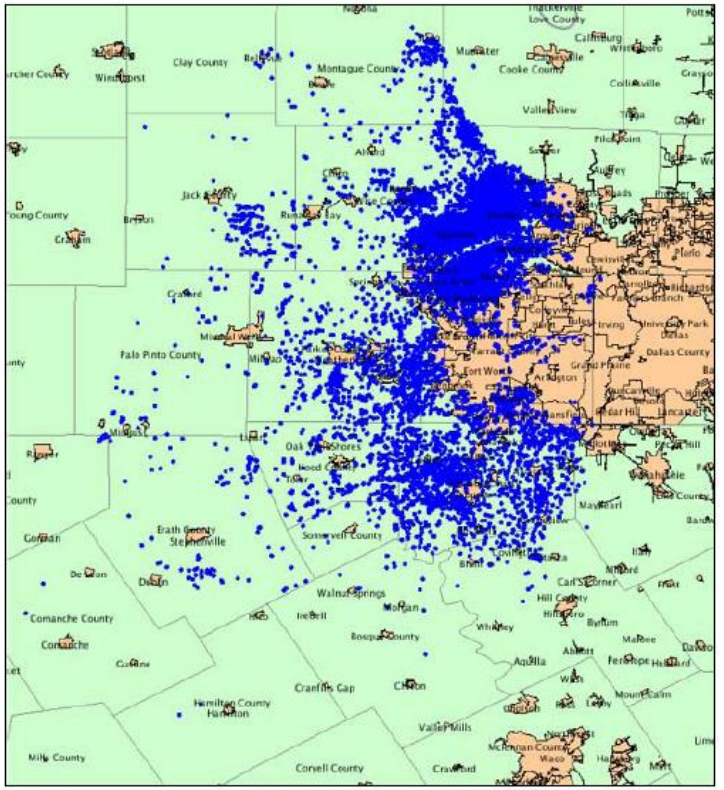
http://www.beg.utexas.edu/frac/news%20achive/2004-currentevents.php

Barnett Shale Production History



Barnett Shale “Urban Drilling”

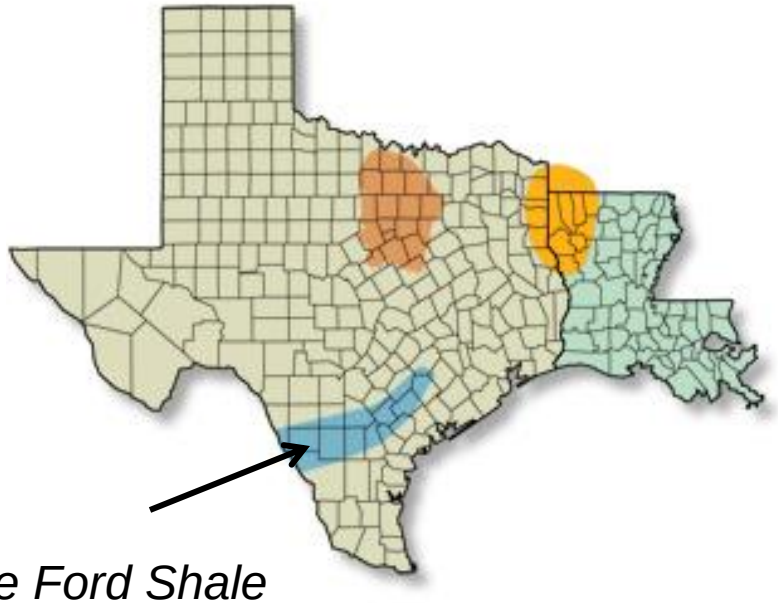
- Shale gas deposits under urbanized area
- Competition for water resources
- Impacts on public infrastructure
- Convergence of shale gas controversies



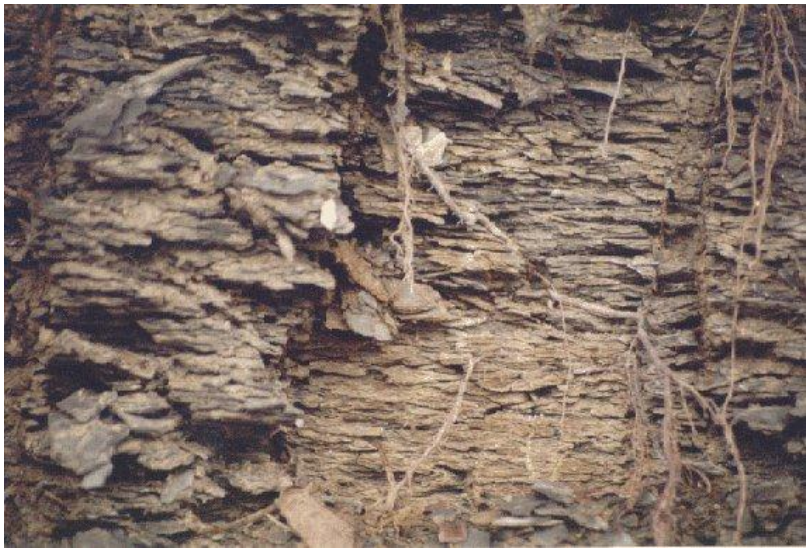
Tan: DFW Urban Area
Blue Dots: Shale Gas Wells

http://www.barnettshalenews.com/documents/A%20History%20and%20Overview%20of%20the%20Barnett%20Shale.pdf

EAGLE FORD SHALE EXAMPLE



Eagle Ford Shale

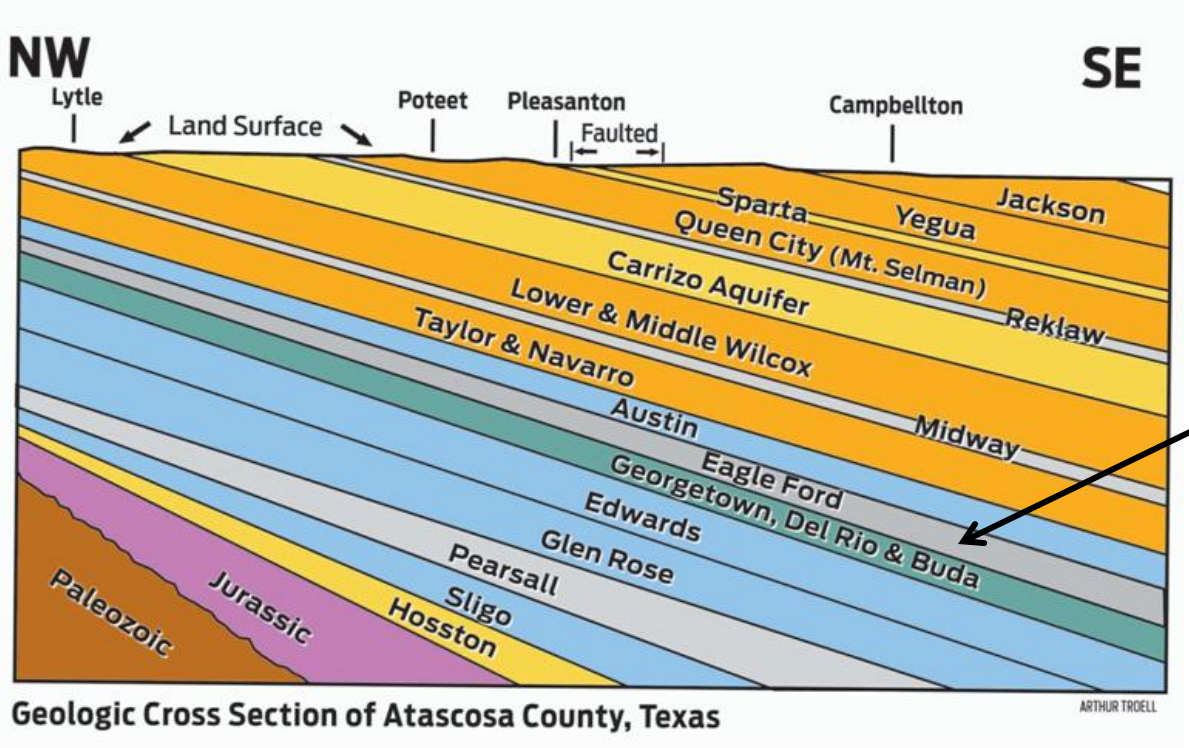


Eagle Ford Shale Outcrop

http://hosted-p0.vresp.com/303462/84ad169188/ARCHIVE

http://geography.unt.edu/~williams/GEOL_1610/fieldtripsites/eagle_ford_shale.htm

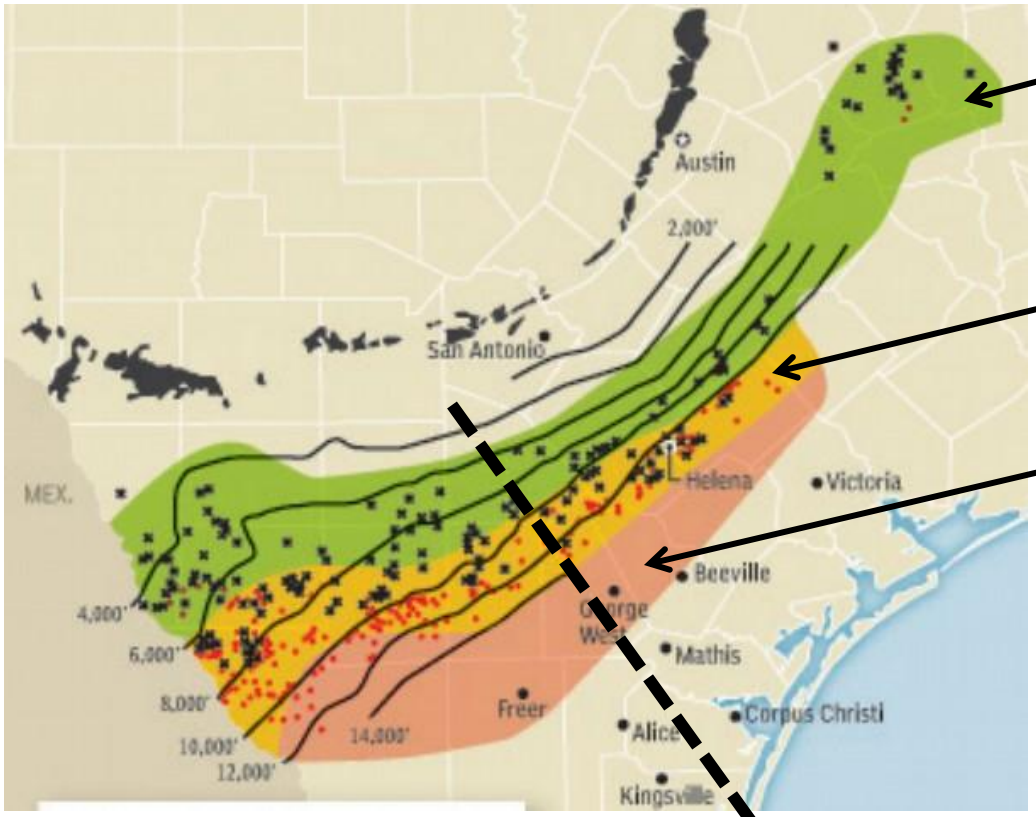
Gulf Coast Basin



Eagle Ford Shale

http://www.championgroup.com/news/the-eagle-ford-shale-and...what-else-is-down-there/

Oil, Wet Gas, and Dry Gas Windows



Oil Window (Shallowest)

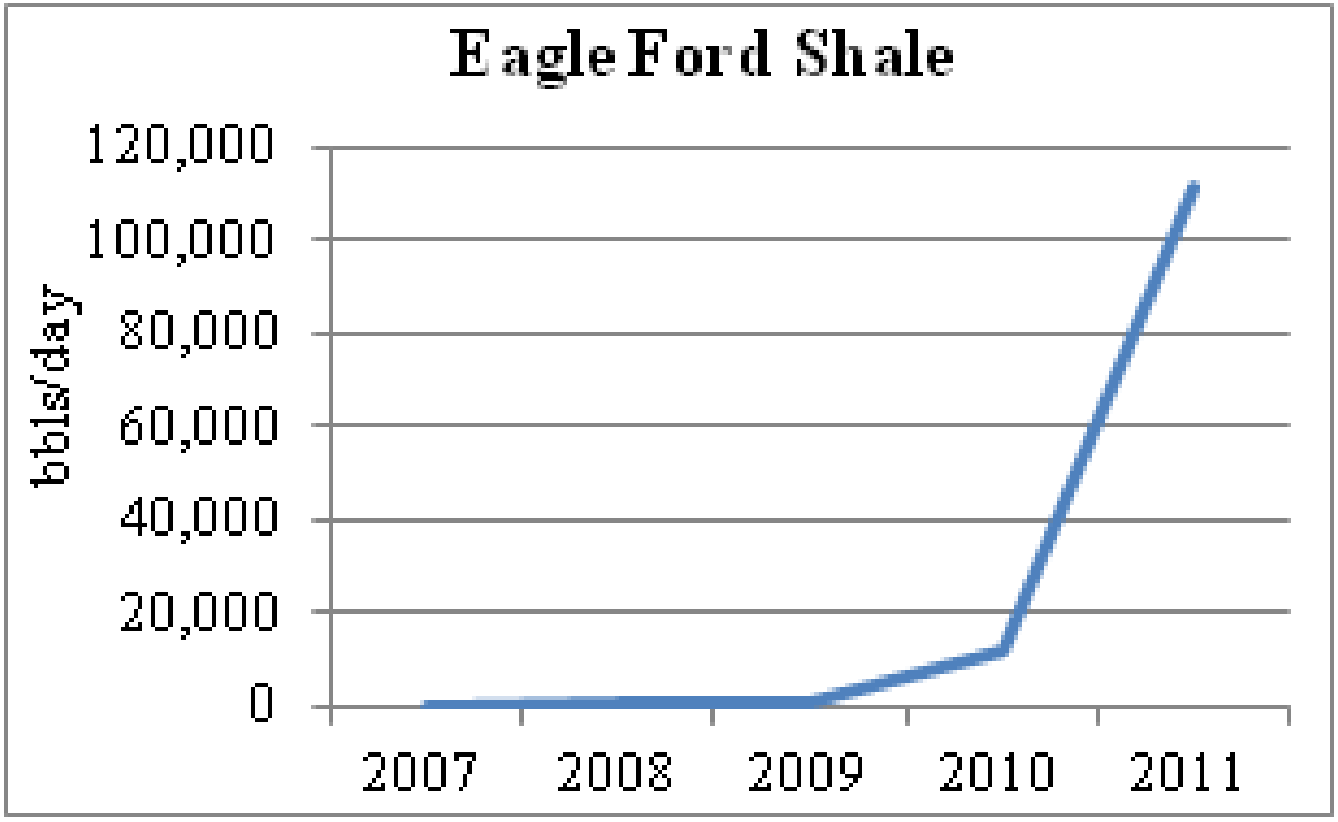
Wet Gas

Dry Gas (Deepest)

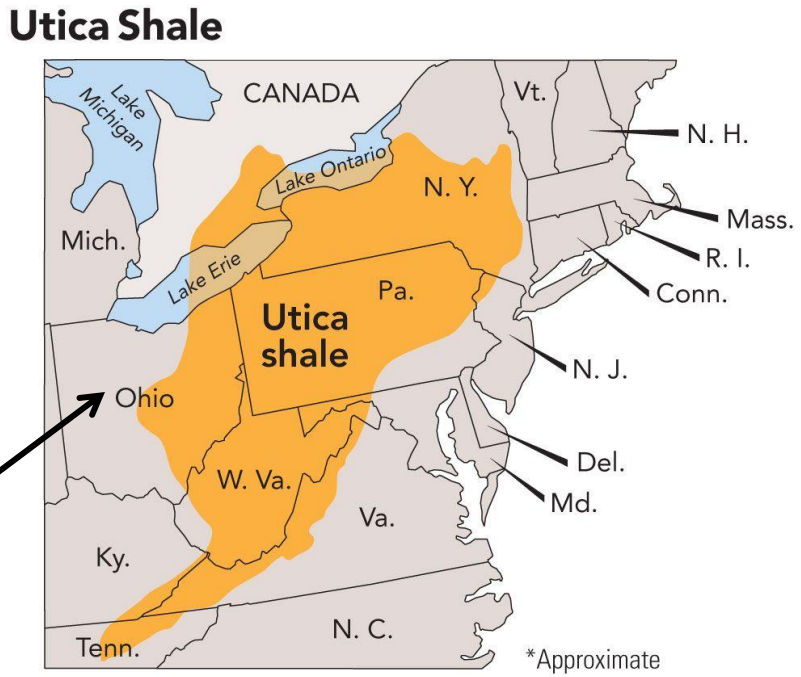
Deeper in Basin

http://www.caller.com/photos/galleries/2011/oct/03/eagle-ford-map/

Eagle Ford Production History

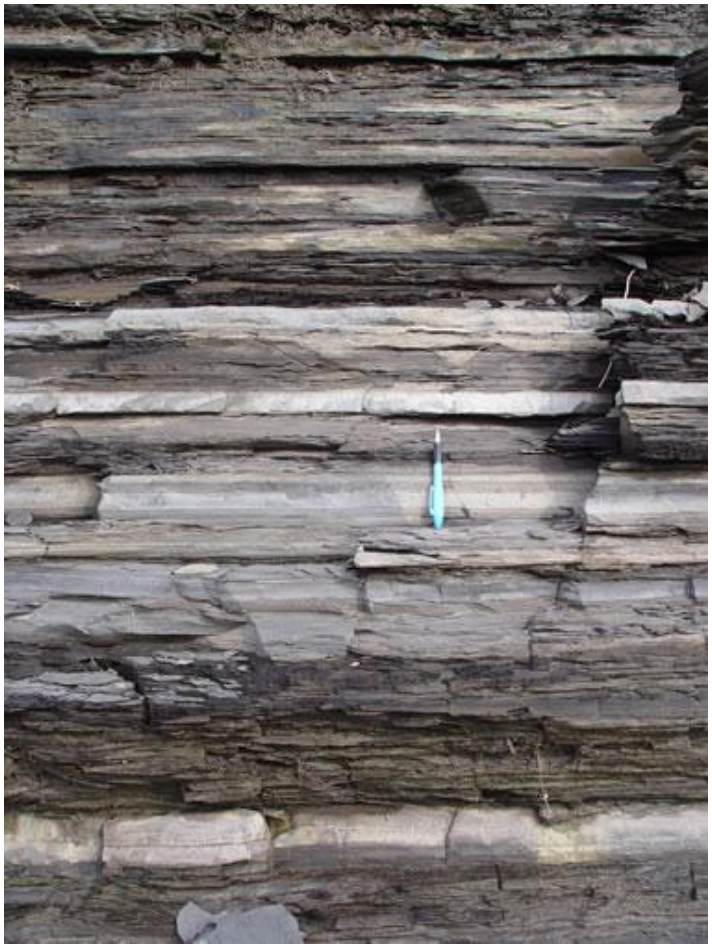


UTICA SHALE EXAMPLE



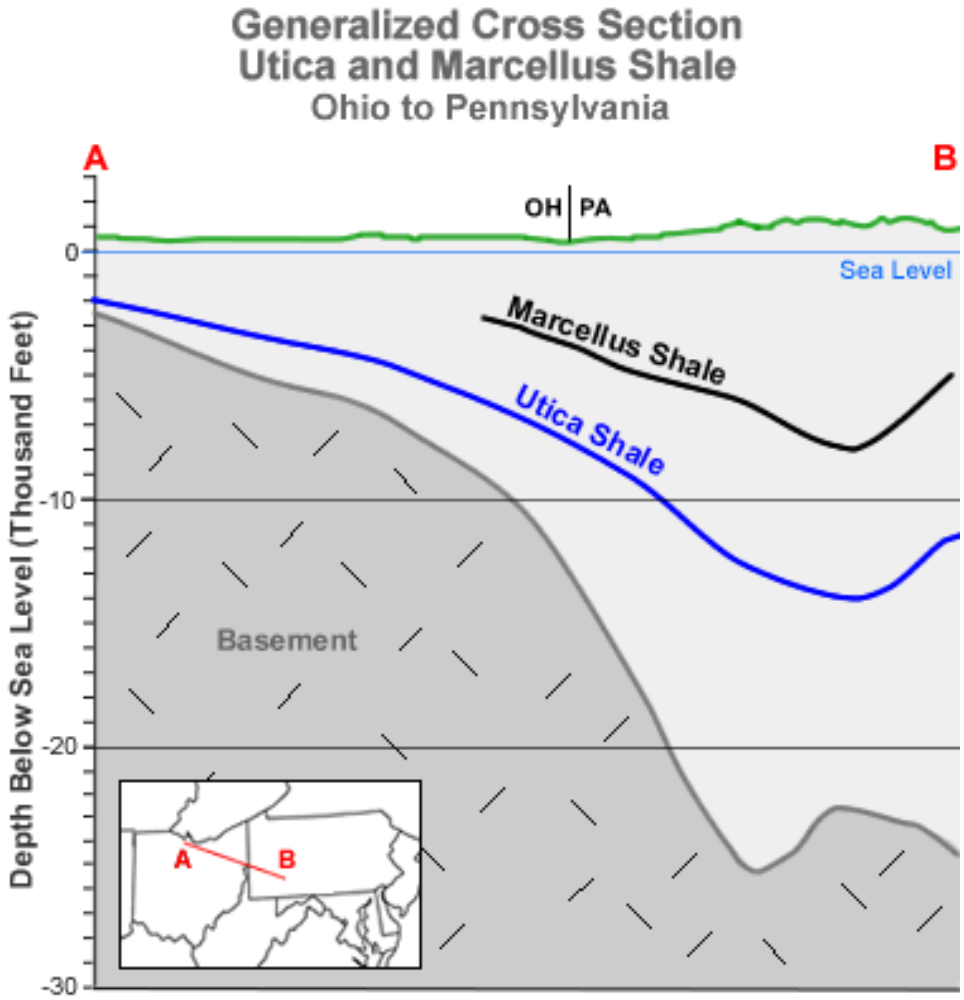
Ohio

Utica Shale Outcrop



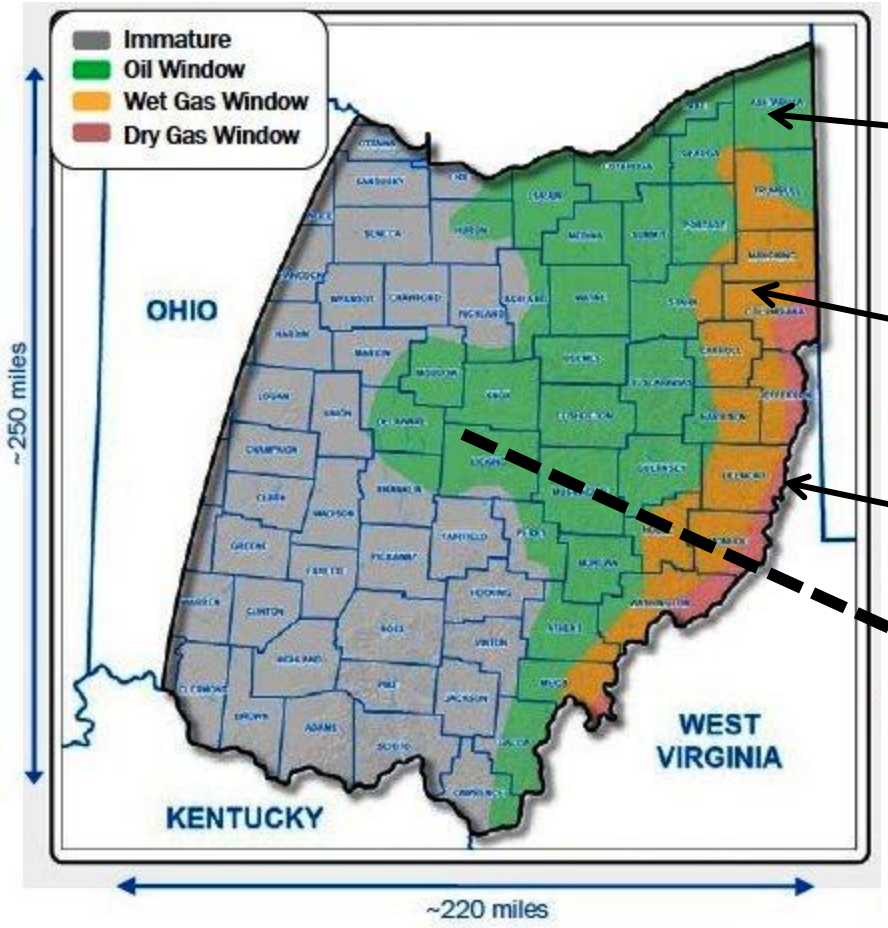
http://geology.com/articles/utica-shale/

Diagrammatic Cross Section



http://geology.com/articles/utica-shale/

Oil, Wet Gas, and Dry Gas Windows in Ohio



Oil Window (Shallowest)

Wet Gas

Dry Gas (Deepest)

Deeper in Basin

Map source: Modified from Rowan, 2006, Geological Survey

http://www.harrisonnewsherald.com/?p=7131

WORLDWIDE IMPORTANCE OF SHALE GAS

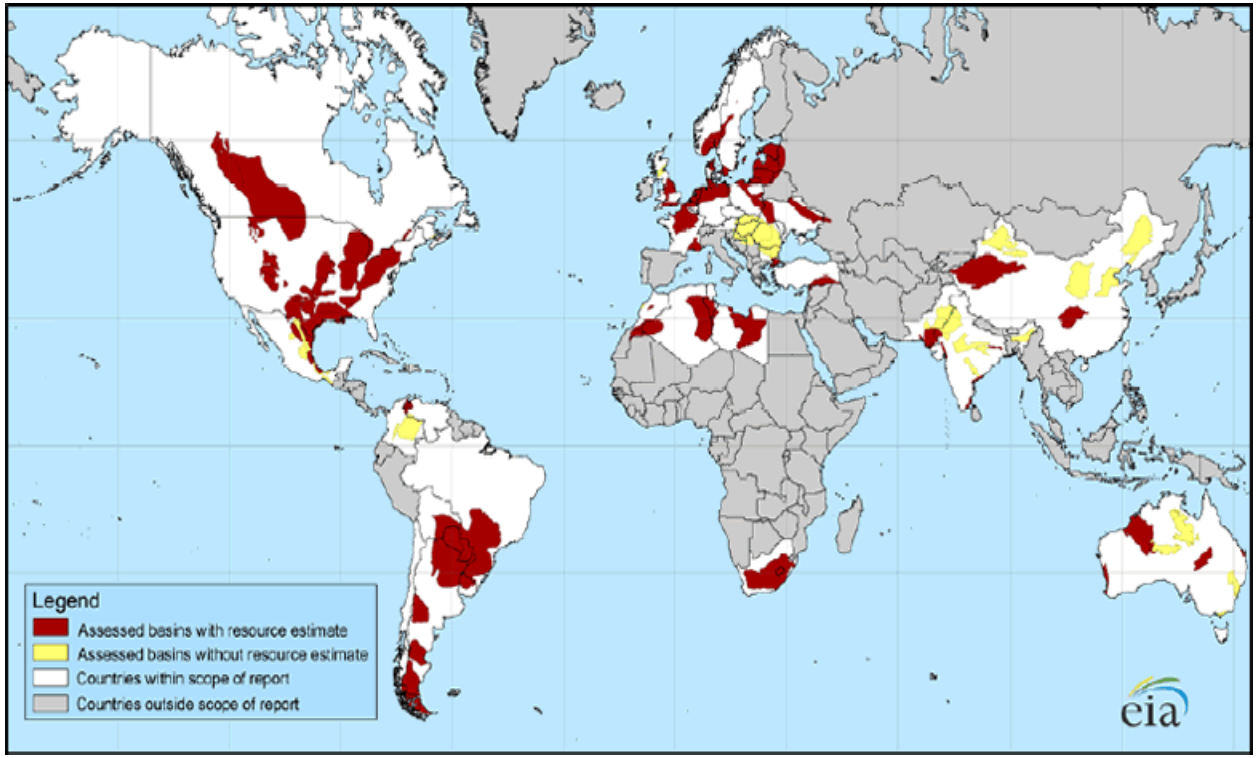
Worldwide Shale Gas Resource Estimates

Area	Tcf
South America	1,825
North America	1,551
Asia	1,404
Africa	1,042
Europe	624
Australia	396
Total	6,242

Note!

Source: U.S. Energy Information Agency

Shale Gas Occurrence Worldwide



32 Countries, 48 Shale Gas Basins

Source: U.S. Energy Information Agency

The U.S. Case

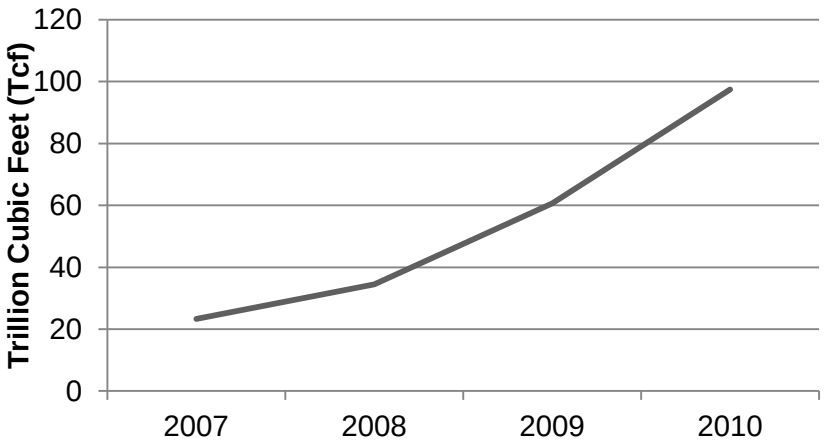
- Current U.S. resource estimate: 482 Tcf
- Just 8% of worldwide total
- Current reserve estimate: 100 Tcf

- Annual production 4.8 TCF in 2010
- Currently 25% of natural gas production
- Expected to increase to 49% by 2035

Source: U.S. Energy Information Agency

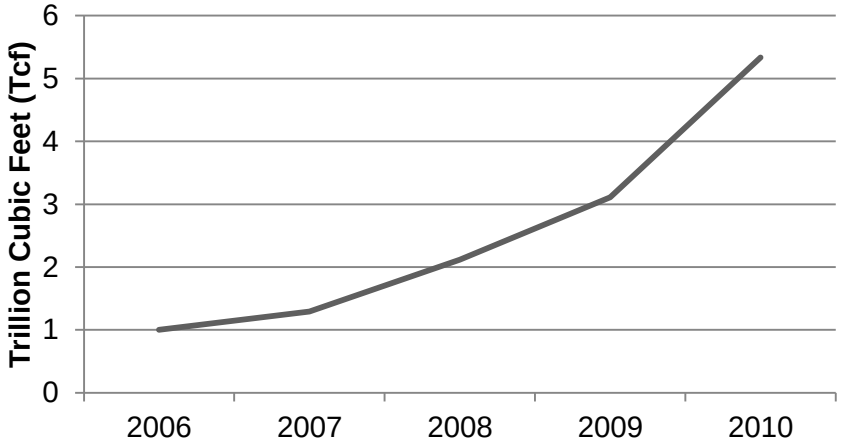
U.S. Reserves and Production Trends

U.S. Shale Gas Proved Reserves



Five-Fold Increase, 2007-2010

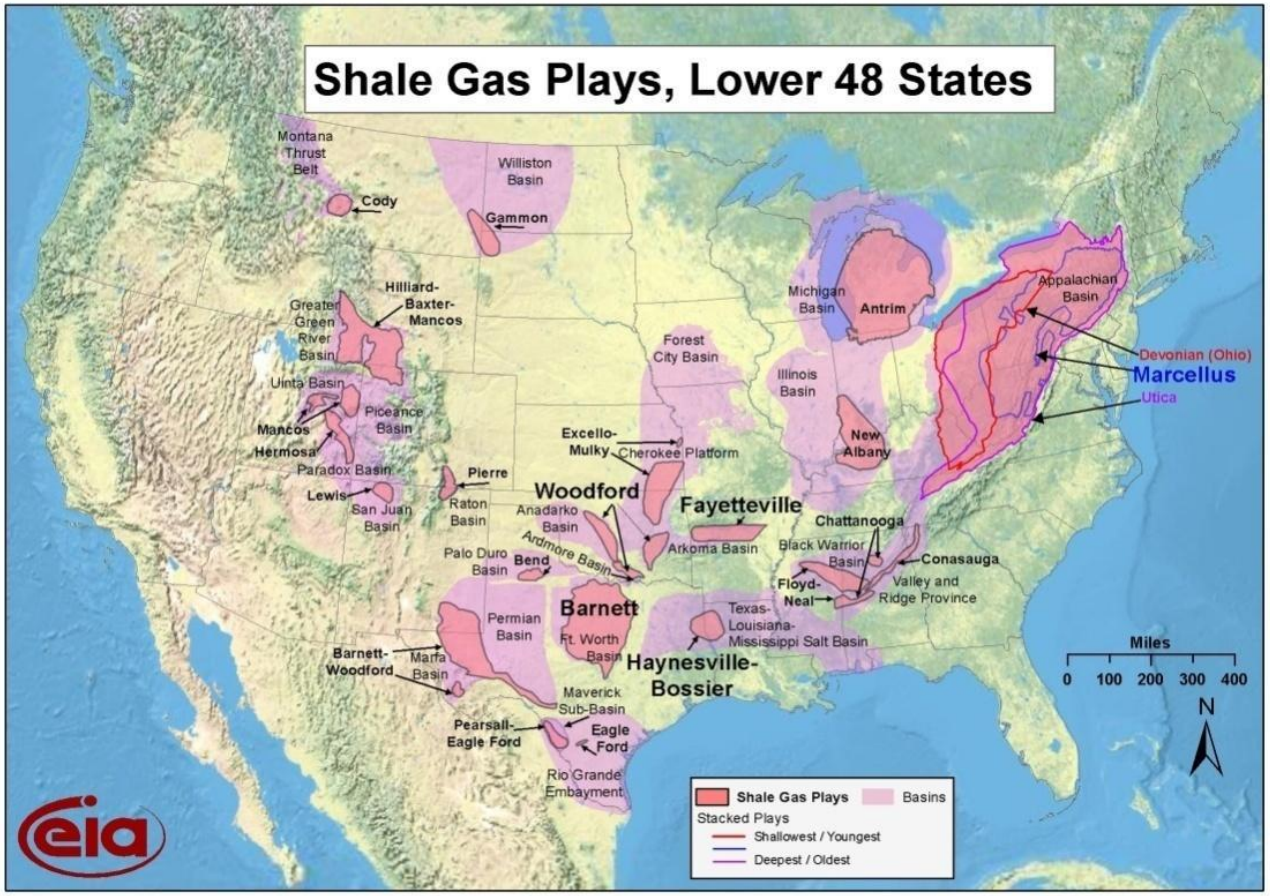
U.S. Shale Gas Production



Five-Fold Increase, 2006-2010

Source: U.S. Energy Information Agency

Shale Gas Occurrences in the U.S.

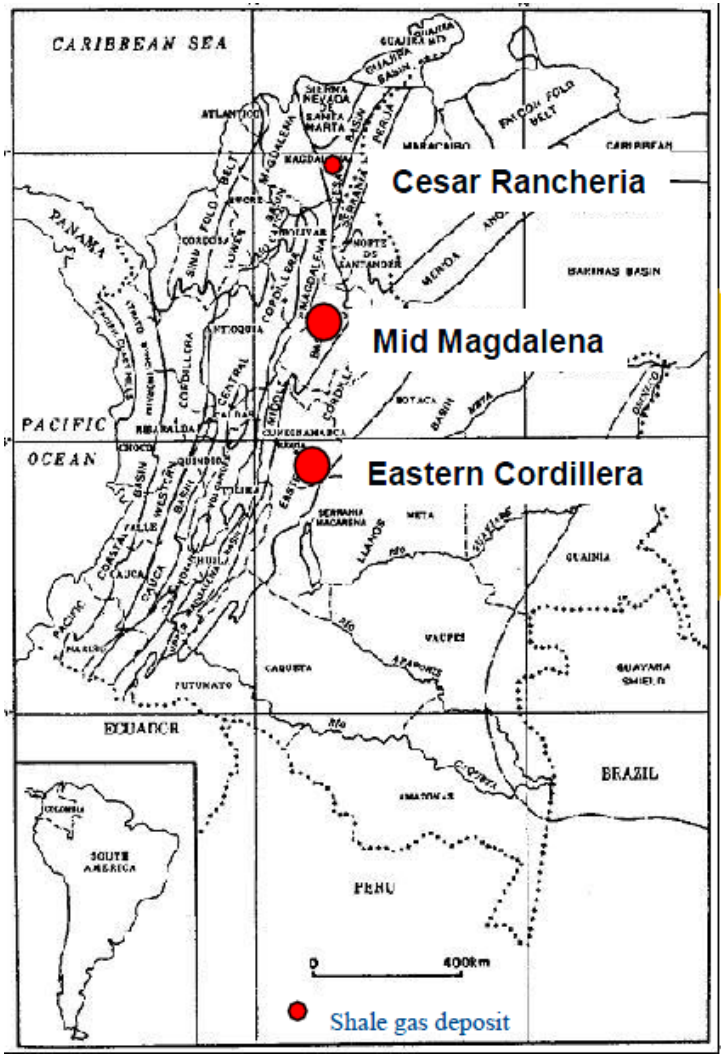


Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

Source: U.S. Energy Information Agency

SHALE GAS IN COLUMBIA

Shale Gas in Columbia



Arthur D. Little, 2011

Shale Gas in Columbia

Basin	Area (sq km)[1]	Net pay (meters)[2]	Gas in place (Tcf)[3]	Recoverable reserves (Tcf)[4]
Mid Magdalena	7,500	100	289.5	29.0
Eastern Cordillera	500	100	19.3	1.9
Cesar Rancheria	200	100	7.72	0.8
Total Shale Gas	**8,200**		**316.5**	**31.7**

Mid-Magdalena: 91% of total

Arthur D. Little, 2011

SUMMARY

Summary

- Unconventional natural gas and oil resources include 6 or 7 types
- Shale gas and oil are important unconventional hydrocarbon resources
- Organic shale is the source rock for conventional oil and gas reservoirs
- Shale strata are deposited in basins and become deeply buried by subsidence
- Oil and gas is generated from organic shale by rising temperature of geothermal gradient

Summary (continued)

- Shale gas and oil are exploited from organic shale source rock by horizontal drilling and hydraulic fracturing
- Exploitation of shale gas began in Texas' Barnett Shale by Mitchell Energy in the 1980s & 1990s
- Shale gas and oil are revolutionary developments for energy supply worldwide
- Most of Columbia's shale gas is in the Mid-Magdalena basin

OTHER UNCONVENTIONAL NATURAL GAS AND OIL RESOURCES

Columbia Unconventional Resources

ANH
AGENCIA NACIONAL DE HIDROCARBUROS

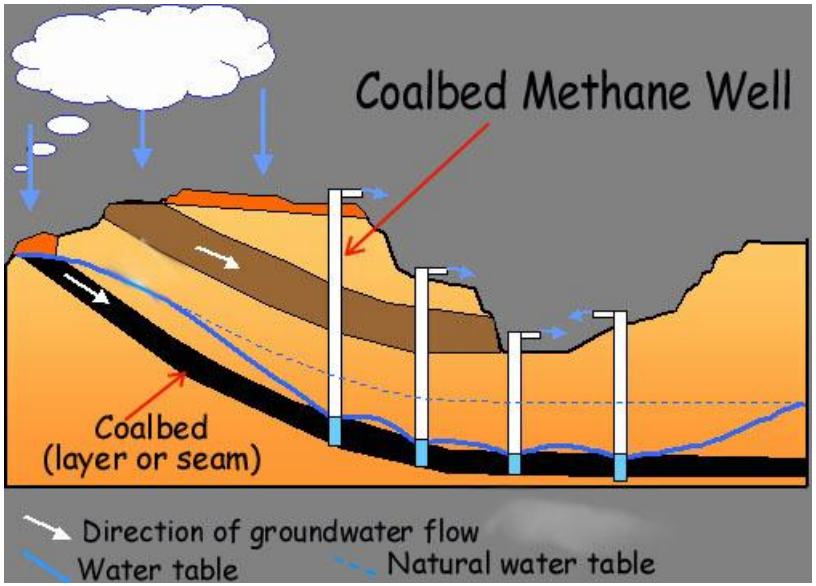
Colombia Resource Base

- Types of unconventional resources:
  - Coal bed methane (CBM)
  - Shale Gas
  - Tar sands
  - Oil shale
  - Tight gas
  - Gas hydrates

Arthur D. Little, 2011

Coalbed Methane

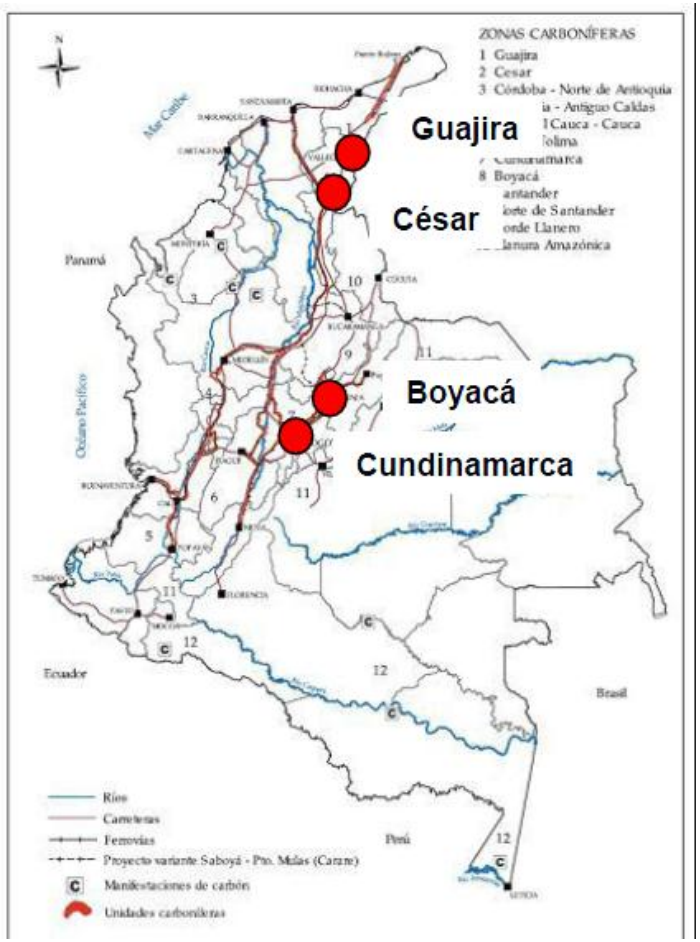
- Methane generated in coal beds
- Formed by coal breakdown (bacteria, heat & pressure)
- Usually extracted from shallow coal seams (10s to 100s m)
- Generally lower cost than shale gas
- Gas occurs in coal fractures (cleats)



- Removal of water makes cleats permeable
- Large volumes of produced water must be managed

http://formontana.net/coalbed.html

Coal Bed Methane in Columbia



Arthur D. Little, 2011

Oil Sands

- Often called “tar sands”
- Bitumen formed from bacterial breakdown of petroleum
- “Parent” oil forms at depth, migrates toward surface
- Too viscous for recovery by pumping
- Two methods of extraction
  - Surface mining (<100m)
  - Subsurface (in situ) recovery (>100m)

http://m.minneapolisfed.org/article.cfm?id=1865

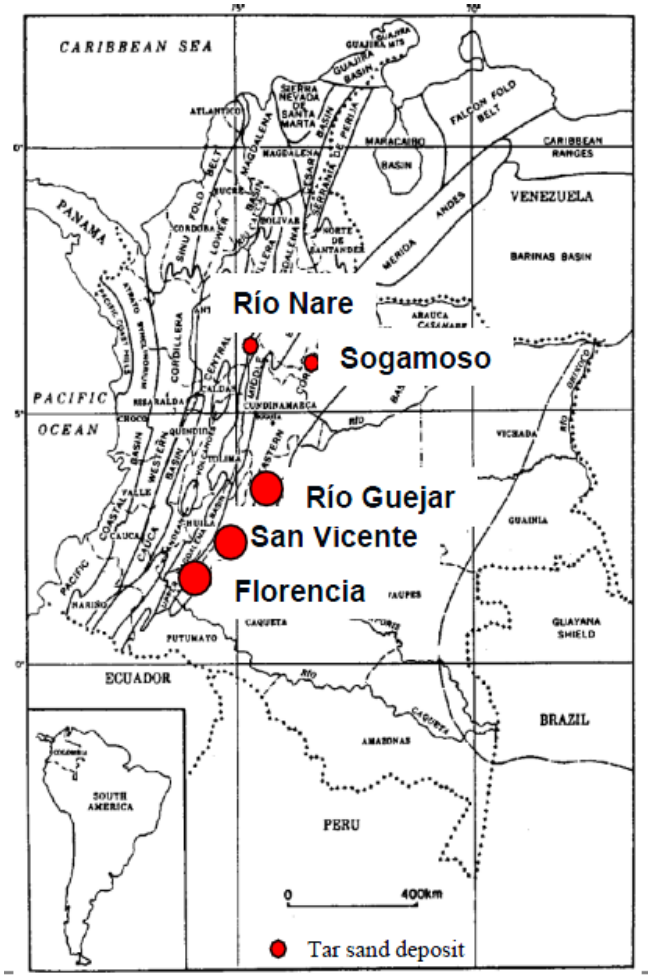
Oil Sands (continued)

- Principal deposits in Alberta, Canada (Athabasca Oil Sands)
- Large quantities also in Venezuela (Orinoco)

http://en.wikipedia.org/wiki/History_of_the_petroleum_industry_in_Canada_(oil_sands_and_heavy_oil)

http://www.rigzone.com/training/heavyoil/insight.asp?i_id=185

Oil Sands in Columbia



Arthur D. Little, 2011

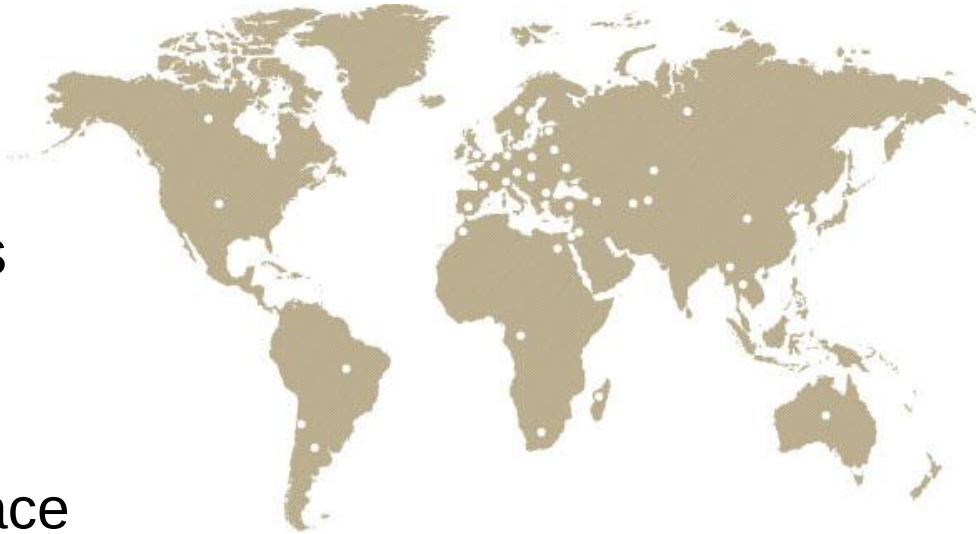
Oil Sands in Columbia

Region	Area (sq km)[1]	Net pay (meters)[2]	Initial Volume in Place (acre-feet)[3]	Initial Volume in Place (Mbbl)[4]	Oil in place (Mbbl)[5]	Reduction factor[6]	Recoverable reserves[7] SAGD (Mbbl)	Recoverable reserves[7] Mining (Mbbl)
Florencia	460	50	18,646,403	144,659	20,252	30%	7,088	11,625
San Vicente	656	50	26,591,393	206,296	28,881	30%	10,109	16,578
Rio Guejar	350	50	14,187,481	110,066	15,409	30%	5,393	8,845
Sogamoso	40	20	648,571	5,032	704	30%	247	404
Rio Nare	50	60	2,432,140	18,869	2,642	30%	925	1,516
Total Tar Sands	**1,556**		**62,505,987**	**484,921**	**67,889**		**23,761**	**38,968**

Arthur D. Little, 2011

Oil Shale

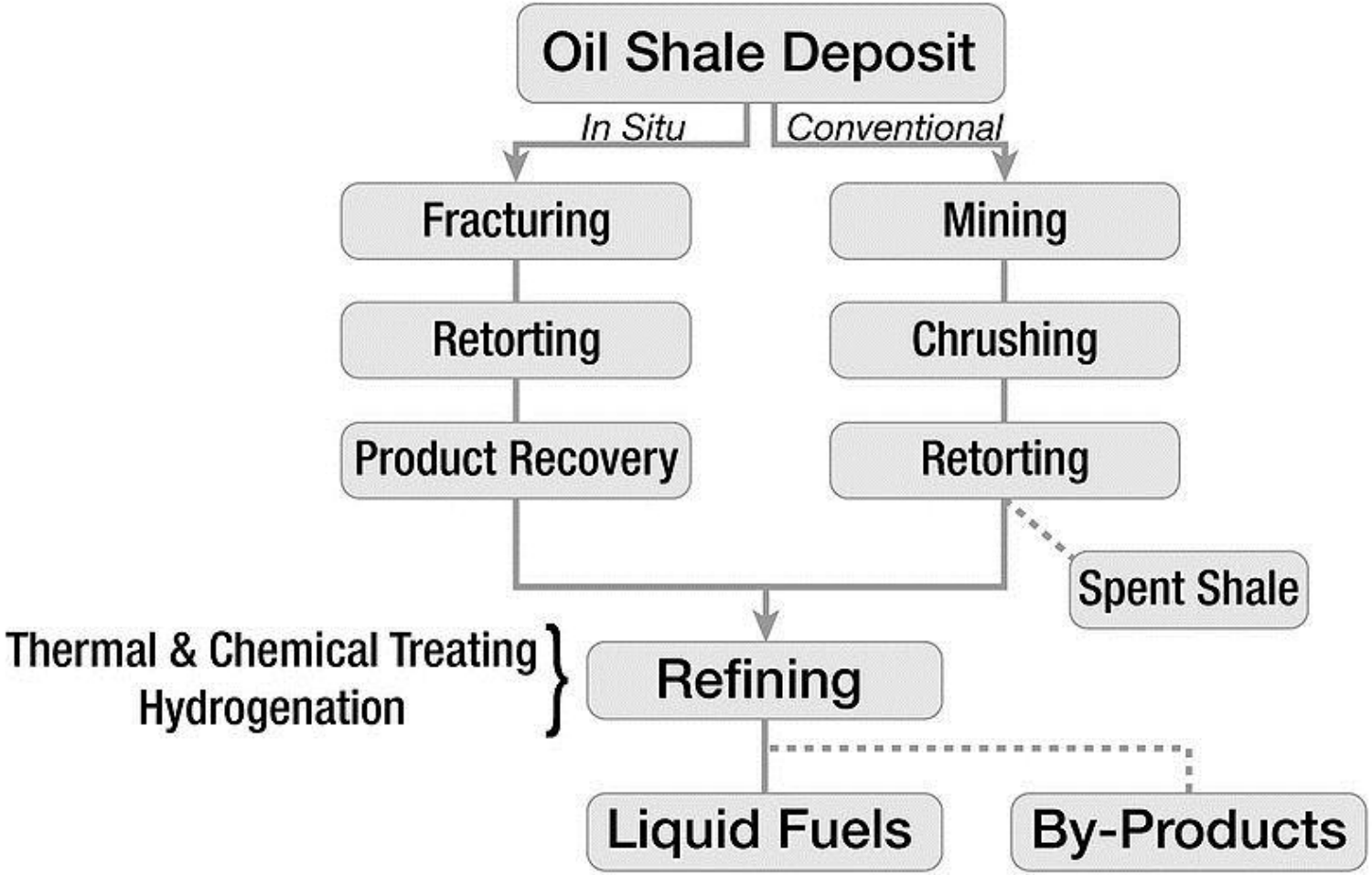
- Shale with kerogen not converted to oil and gas
- Two technologies for extraction
  - Mine and retort at surface
  - Underground (in situ) heating and pumping
- Many occurrences worldwide
- Major deposits in the U.S. (Piceance Creek)



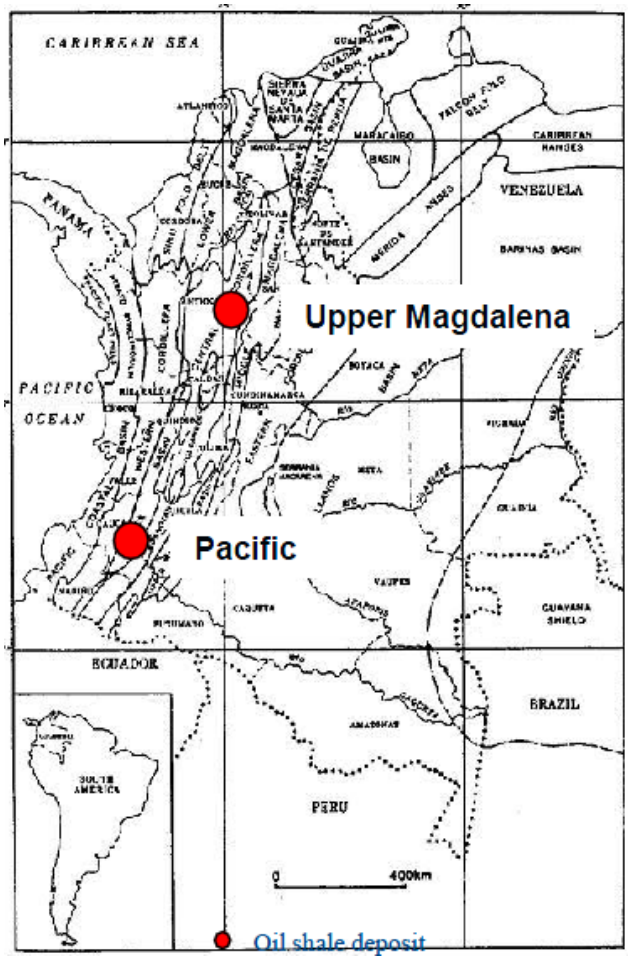
http://www.diyaudio.com/forums/lounge/190836-shale-oil-6.html

Source: http://www.utsa.edu/hydrogis/PiceanceBasin.html

Oil Shale Production Technologies



Oil Shale in Columbia



Arthur D. Little, 2011

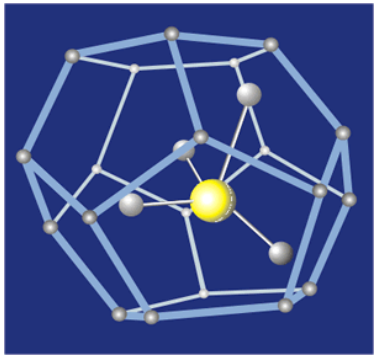
Oil Shale in Columbia

Basin	Area (sq km)[1]	Net pay (meters)[2]	Gas in place (Tcf)[3]	Recoverable reserves (Tcf)[4]
Mid Magdalena	7,500	100	289.5	29.0
Eastern Cordillera	500	100	19.3	1.9
Cesar Rancheria	200	100	7.72	0.8
Total Shale Gas	**8,200**		**316.5**	**31.7**

Arthur D. Little, 2011

Methane Hydrate – Methane in an Ice Lattice

- Methane molecule trapped in water molecule lattice (ice)
- “Ice that burns”
- Formed by bacterial action
- Two types of occurrence
  - Continental
  - Arctic permafrost
- Not yet technologically (or economically) feasible

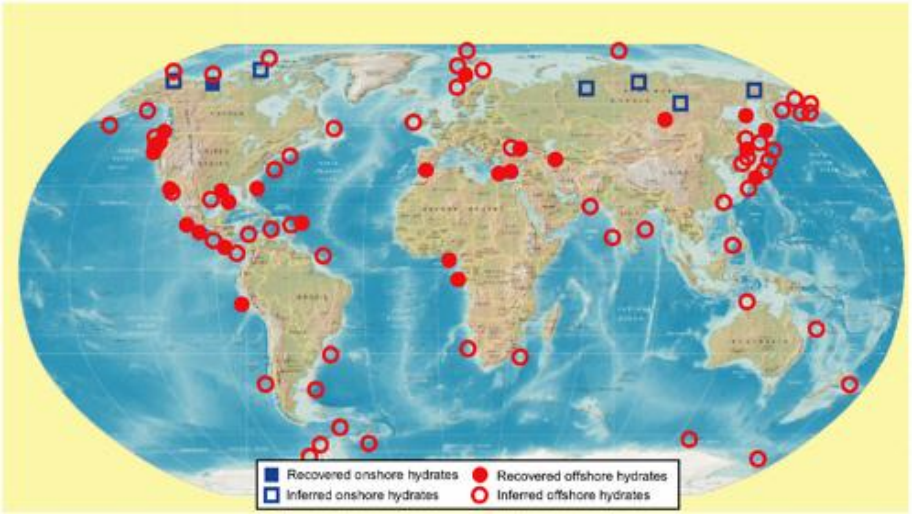


http://www.cedre.fr/en/spill/deepwater_horizon/methane-hydrates.php

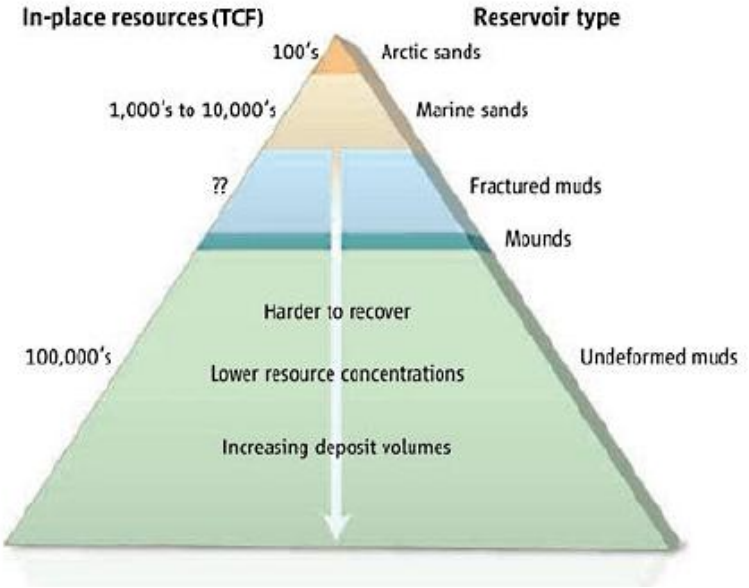
http://www.realclimate.org/index.php/archives/2005/12/methane-hydrates-and-global-warming/

Methane Hydrate – Methane in an Ice Lattice

- Occurs at many locations worldwide



- Resource pyramid



http://www.nap.edu/openbook.php?record_id=11094&page=193

http://www.energybulletin.net/stories/2010-02-11/methane-hydrates

Methane Hydrate in Columbia

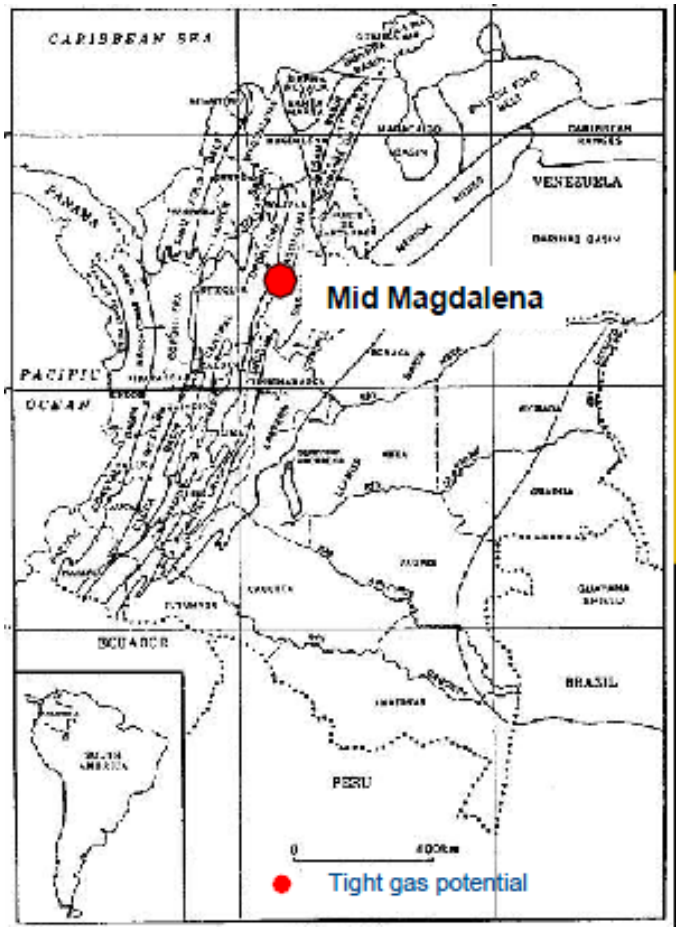
Arthur D. Little, 2011

Methane Hydrate in Columbia

Basin	Area (sq km)[1]	Net pay (meters)[2]	Gas content (m^3 natural gas/ m^3 hydrate)[3]	Gas in place (tcf)[4]
Caribbean	37,500	1	164	217.1
Pacific	37,500	1	164	217.1
Total Gas Hydrate Potential	**75,000**			**434.2**

Arthur D. Little, 2011

Tight Gas in Columbia



Arthur D. Little, 2011

Tight Gas in Columbia

Region	Area (sq km)[1]	Gross pay (meters)[2]	Pay Volume (acre-feet)[3]	Pay Volume (Tcf)[4]	Gas in place (Tcf)[5]
Eastern Cordillera/Mid Magdalena	4,000	200	648,570,555	28.3	1.2
Total Tight Gas Potential	**4,000**		**648,570,555**	**28.3**	**1.2**

Arthur D. Little, 2011

SUMMARY

Summary

- Unconventional natural gas and oil resources include 6 or 7 types
- Shale gas and oil are important unconventional hydrocarbon resources
- Organic shale is the source rock for conventional oil and gas reservoirs
- Shale strata are deposited in basins and become deeply buried by subsidence
- Oil and gas is generated from organic shale by rising temperature of geothermal gradient

Summary (continued)

- Shale gas and oil are exploited from organic shale source rock by horizontal drilling and hydraulic fracturing
- Exploitation of shale gas began in Texas' Barnett Shale by Mitchell Energy in the 1980s & 1990s
- Shale gas and oil are revolutionary developments for energy supply worldwide
- Most of Columbia's shale gas is in the Mid-Magdalena basin