Integrated Approaches to Modeling Late Paleozoic Petroleum Reservoirs in the Greater Midcontinent, U.S.

Short Course

AAPG - Southwest Section

December 8, 2008 -- Abilene, Texas

December 9, 2008 -- Ft. Worth, Texas

W. Lynn Watney
Senior Scientific Fellow
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047
Ph: 785-864-2184
Fax: 785-864-5317
Email: lwatney@kgs.ku.edu

Integrated Approaches to Modeling Late Paleozoic Petroleum Reservoirs in the Greater Midcontinent

Who Should Attend:

- Geologists and engineers who are characterizing late Paleozoic reservoirs to optimize oil and gas recovery.
- Geoscientists exploring for new fields and extensions in the greater Midcontinent.

Objectives:

- Describe oil and gas plays and reservoir characterization in the context of tectonic/structural framework, sequence stratigraphy, and lithofacies distribution.
- Illustrate integrated geomodel development using core descriptions and analyses, wireline log analysis techniques, well tests, 3D seismic, and production histories.
- Effectively integrate recent analogs and surface exposures to define and model reservoir heterogeneity and design appropriate recovery technologies.
- Highlight case studies of carbonate, sandstone, and chert reservoirs ranging from Mississippian (Lower Carboniferous) through Lower Permian age.
- Integrate reservoir characterization in the context of reservoir systems and hydrocarbon accumulation – *re-exploration and exploitation*.
- Provide tools and insights for efficient prospecting and development for remaining oil and gas resources.

Integrated Approaches to Modeling Late Paleozoic Petroleum Reservoirs in the Greater Midcontinent

Content:

- Regional structural/tectonic framework during the late Paleozoic.
- Variations in sequence stratigraphy and reservoir architecture of late Paleozoic strata in the Midcontinent.
- Common reservoir lithofacies and their Recent analogs.
- Petrofacies and pore typing approach to quantitative reservoir analysis and modeling petroleum reservoirs, roles of diagenesis.
- Case studies based on integrated geo-engineering modeling of Mississippian, Pennsylvanian, and Permian reservoirs:
  - carbonate ooid and grainstone shoals
  - phylloid algal mounds and related lithofacies
  - incised valley and estuarine sandstones
  - Low resistivity, often low permeability spiculitic bioclastic buildups that comprise shelf and shelf margin environments.

Schedule

- **9:00-10:00 – 1. Approach to Modeling Late Paleozoic Petroleum Reservoirs.**
- **10-12 noon – 2. Regional structural and tectonic framework during the late Paleozoic and significance to reservoir systems.**
  - **~10:30-11:00 -- Break –**
- **Noon-1:00 pm – Lunch**
- **1:00-3:00 pm -- 3. Sequence stratigraphy and reservoir architecture of late Paleozoic strata in the Midcontinent.**
  - **~3:00-3:15 – Break –**
- **3:00-4:30 pm -- 4. Reservoir lithofacies and Petrofacies.**
- **4:30-5:00 pm –- 5. Wrap-up & Summary**.

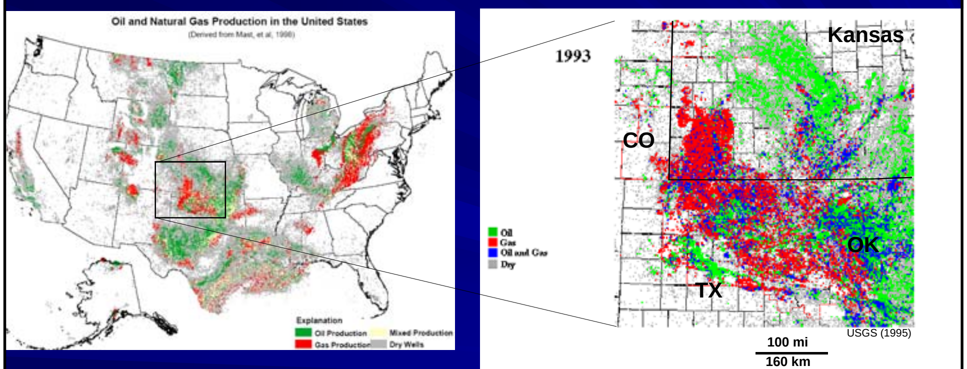
Take Home Points of Short Course

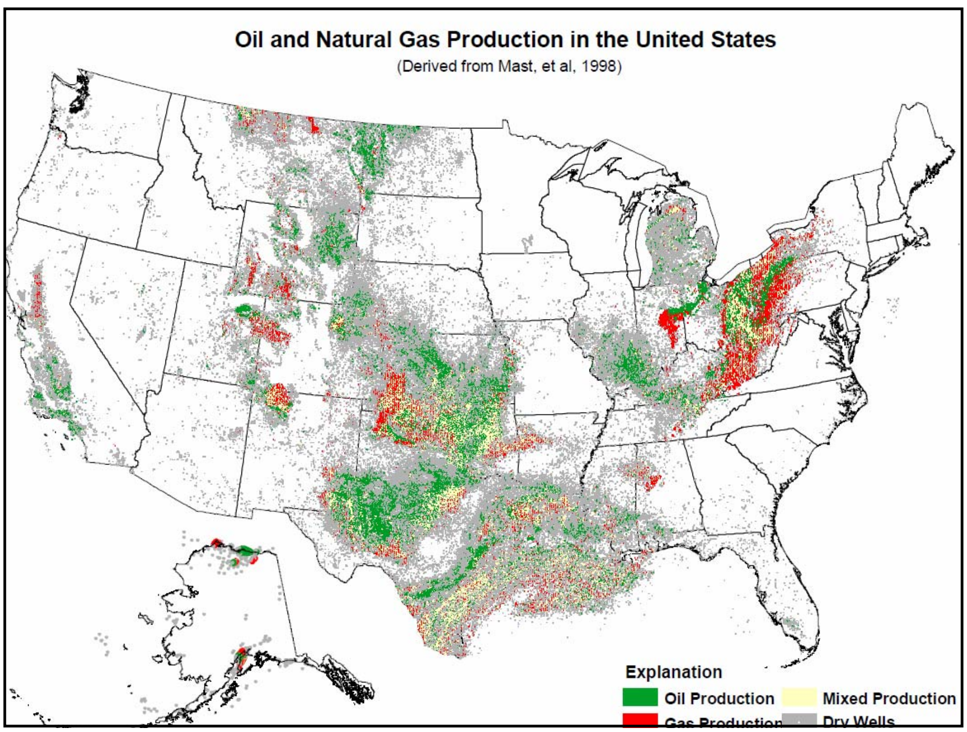
- Basement structures and tectonic events affecting them are important in defining location and properties of reservoirs.
- Process-based field, outcrop, and Recent analogs provide more appropriate, accurate interpolation of reservoir properties.
- Late Paleozoic reservoirs are dominated by depositional fabric selective diagenesis.
- Establishing petrofacies and pore types is essential to accurate calculations of water saturations, volumetrics, ROIP, establishing permeability correlations and predicting fluid flow.
- Infill locations and new pays within oil and gas fields remain significant targets for IOR in mature regions; requires comprehensive, integrated approach.
- Re-exploration and exploitation of mature producing areas can be substantially benefited by access to and mining of large data sets – digital and electronic data – logs, production, core/samples and descriptions, *in an integrated and quantitative manner.*

9:00-10:00 – 1. Approach to Modeling Late Paleozoic Petroleum Reservoirs.

- Overview:
  - Similarities of Kansas and North-Central Texas petroleum geology and business
  - Similar resources remaining in conventional reservoirs
  - Perspective and insights from Kansas

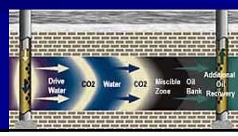
TX-OK-KS are Mature Oil and Gas Provinces

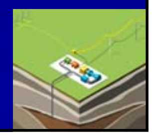




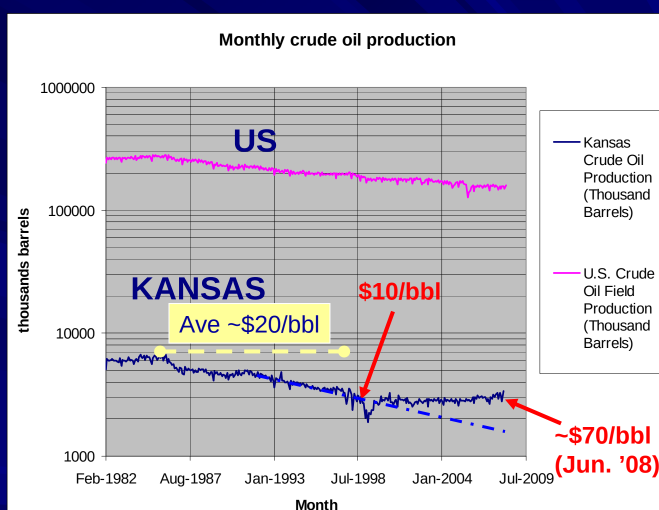
Independents Drive Domestic Oil and Gas Business

- Mature fields, conventional oil and gas fields
- Commodity price significant impact oil and gas production
- Production responds to favorable economics & technologies
- New technologies driven by price & opportunity
- Profit margin on marginal wells has improved (average production of Kansas well ~3 BOPD/well)
- The future of domestic oil and gas industry:
  - Re-explore and redevelop old fields (*eliminate current constraints*)
  - Develop unconventional oil and gas resources
  - Utilize carbon dioxide sequestered from power plants, ethanol plants, cement plants, and other industries; Store air/gases for wind generation; participate in *linked energy systems*

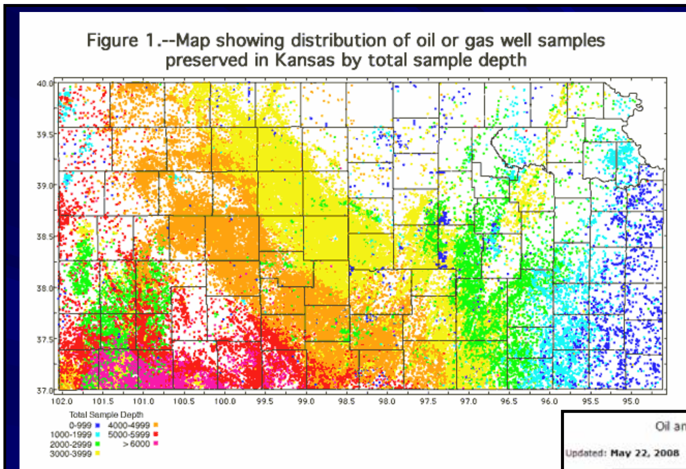




Production Trends



- **Kansas crude oil production is actually increasing (slightly) compared to continued decline in U.S. production**
- **Average well produces ~3 BOPD (100 BPM).**



Kansas is a mature oil and gas producing province with an extensive database documenting geology and production.

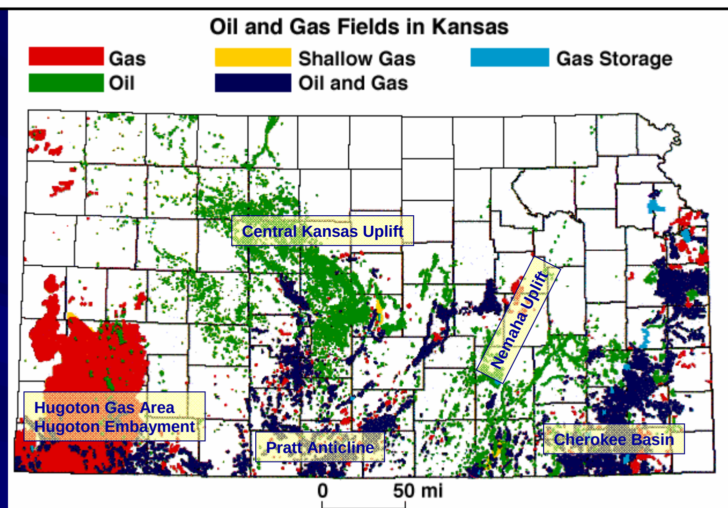
Oil and Gas Well Statistics for Kansas

Updated: **May 22, 2008**

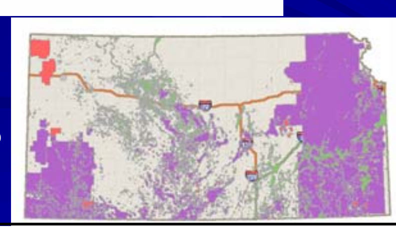
New Wells Drilled	2006	2007	2008
New oil wells drilled	1,435	1,500	152
New gas wells drilled	1,938	1,582	231
Dry holes drilled	697	667	138
Service wells drilled	223	310	30
Suspended wells drilled			
Total New Wells Drilled	4,302	4,066	551
Total New Footage Drilled	11,233,382	10,746,690	1,593,639
Coalbed methane well permits issued	52	75	130
Coalbed methane wells drilled	1,512	1,136	74

	Number of wells (as of update date)
Total Producing oil wells	51,522
Total Producing gas wells	22,005
Total Producing coalbed methane wells	5,754

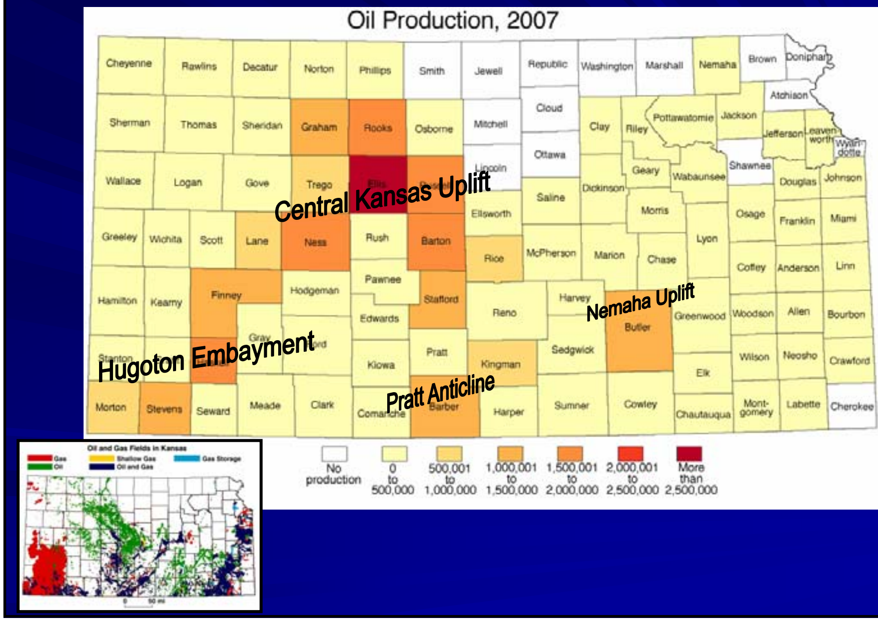
KANSAS GEOLOGICAL SURVEY
The University of Kansas
www.kgs.ku.edu

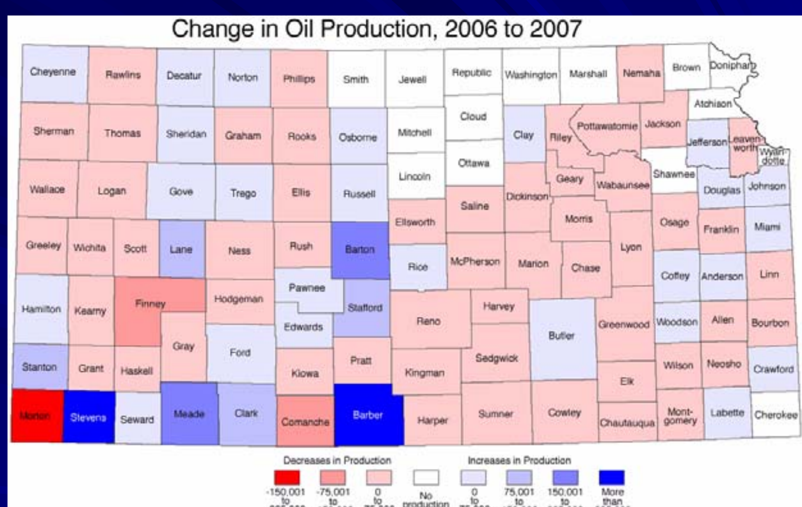


New Online Interactive Oil and Gas Map
http://maps.kgs.ku.edu/oilgas/index.cfm



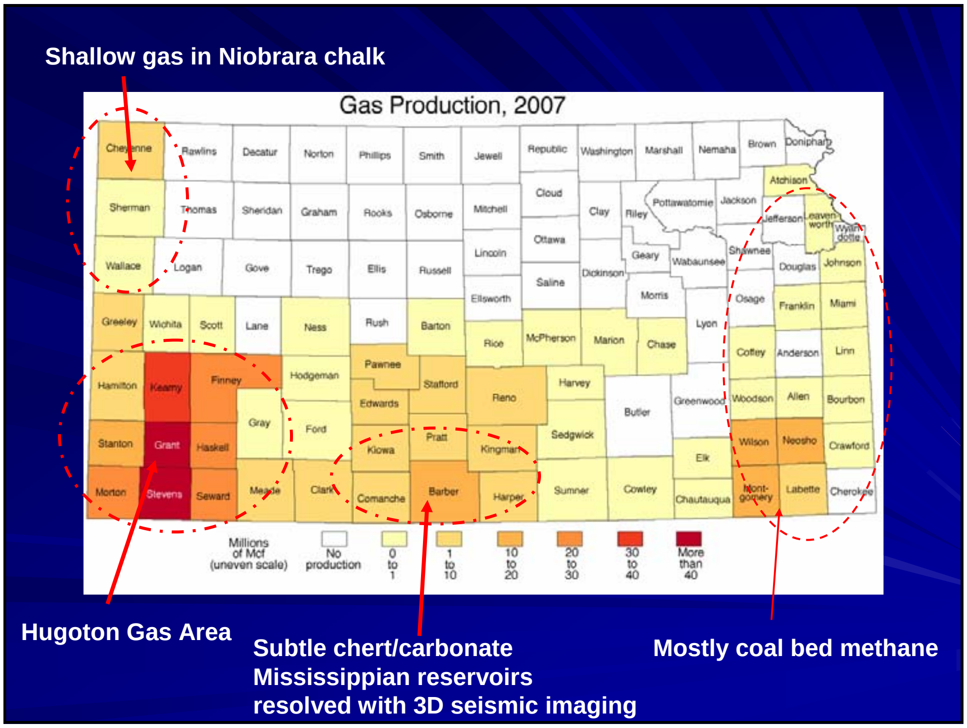
Oil Production in 2007

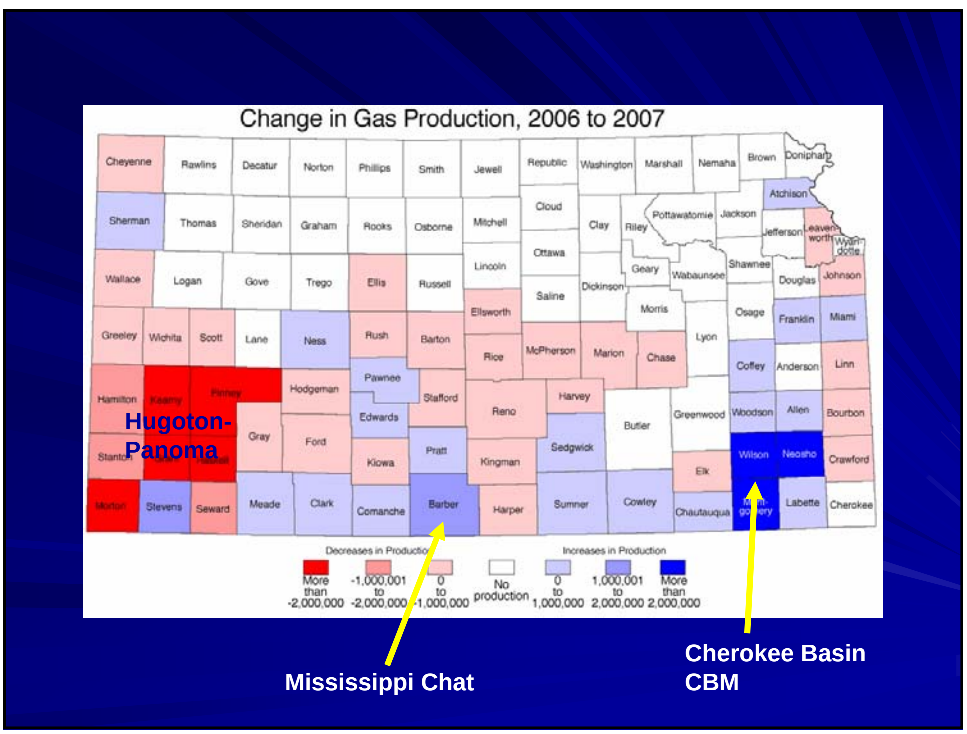




Price, technology, opportunity

- Deeper Hugoton Embayment
- Pratt Anticline
- Central Kansas Uplift
- Shallow marginal oil in Eastern Kansas


Shallow gas in Niobrara chalk
Gas Production, 2007
Cheyenne
Rawlins
Decatur
Norton
Phillips
Smith
Jewell
Republic
Washington
Marshall
Nemaha
Brown
Doniphan
Atchison
Sherman
Thomas
Sheridan
Graham
Rooks
Osborne
Mitchell
Cloud
Clay
Riley
Pottawatomie
Jackson
Jefferson
Leavenworth
Wyandotte
Wallace
Logan
Gove
Trego
Ellis
Russell
Lincoln
Ottawa
Geary
Wabaunsee
Shawnee
Douglas
Johnson
Saline
Dickinson
Morris
Ellsworth
Osage
Franklin
Miami
Greeley
Wichita
Scott
Lane
Ness
Rush
Barton
Rice
McPherson
Marion
Chase
Lyon
Coffey
Anderson
Linn
Hamilton
Kearny
Finney
Hodgeman
Pawnee
Stafford
Reno
Harvey
Butler
Greenwood
Woodson
Allen
Bourbon
Gray
Ford
Edwards
Stanton
Grant
Haskell
Kiowa
Pratt
Kingman
Sedgwick
Elk
Wilson
Neosho
Crawford
Morton
Stevens
Seward
Meade
Clark
Comanche
Barber
Harper
Sumner
Cowley
Chautauqua
Montgomery
Labette
Cherokee
Millions of Mcf (uneven scale)
No production
0 to 1
1 to 10
10 to 20
20 to 30
30 to 40
More than 40
Hugoton Gas Area
Subtle chert/carbonate Mississippian reservoirs resolved with 3D seismic imaging
Mostly coal bed methane


Change in Gas Production, 2006 to 2007
Cheyenne
Rawlins
Decatur
Norton
Phillips
Smith
Jewell
Republic
Washington
Marshall
Nemaha
Brown
Doniphan
Atchison
Sherman
Thomas
Sheridan
Graham
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Chase
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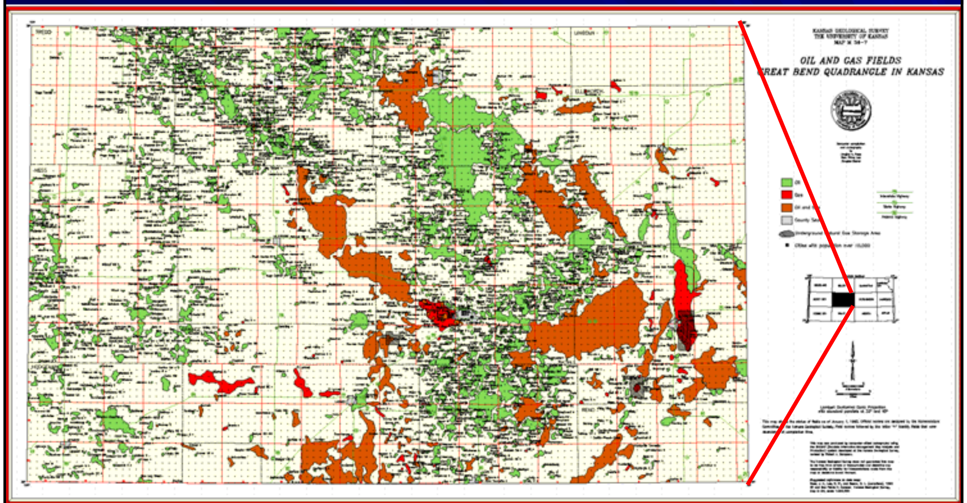
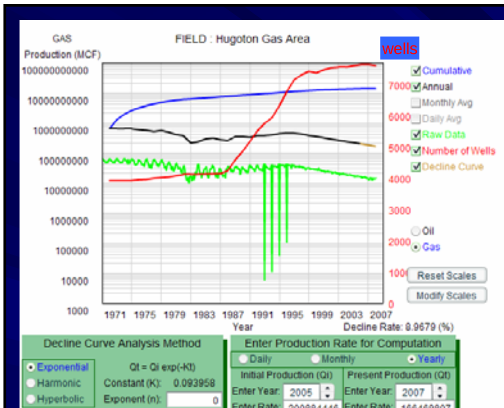
Pawnee
Stafford
Reno
Harvey
Butler
Greenwood
Woodson
Allen
Bourbon
Gray
Ford
Edwards
Kiowa
Pratt
Kingman
Sedgwick
Elk
Wilson
Neosho
Crawford
Morton
Stevens
Seward
Meade
Clark
Comanche
Barber
Harper
Sumner
Cowley
Chautauqua
Labette
Cherokee
Hugoton-Panoma
Decreases in Production
Increases in Production
More than -2,000,000
-1,000,001 to -2,000,000
0 to -1,000,000
No production
0 to 1,000,000
1,000,001 to 2,000,000
More than 2,000,000
Mississippi Chat
Cherokee Basin CBM

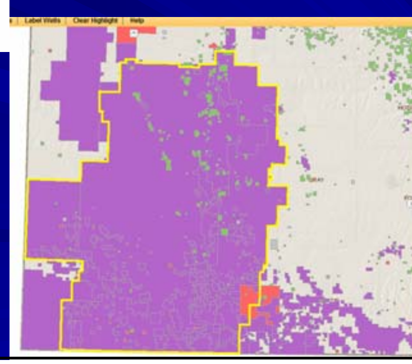
Many fields in core producing areas – official reporting by field and leases that comprise fields
- *much information in digital form*

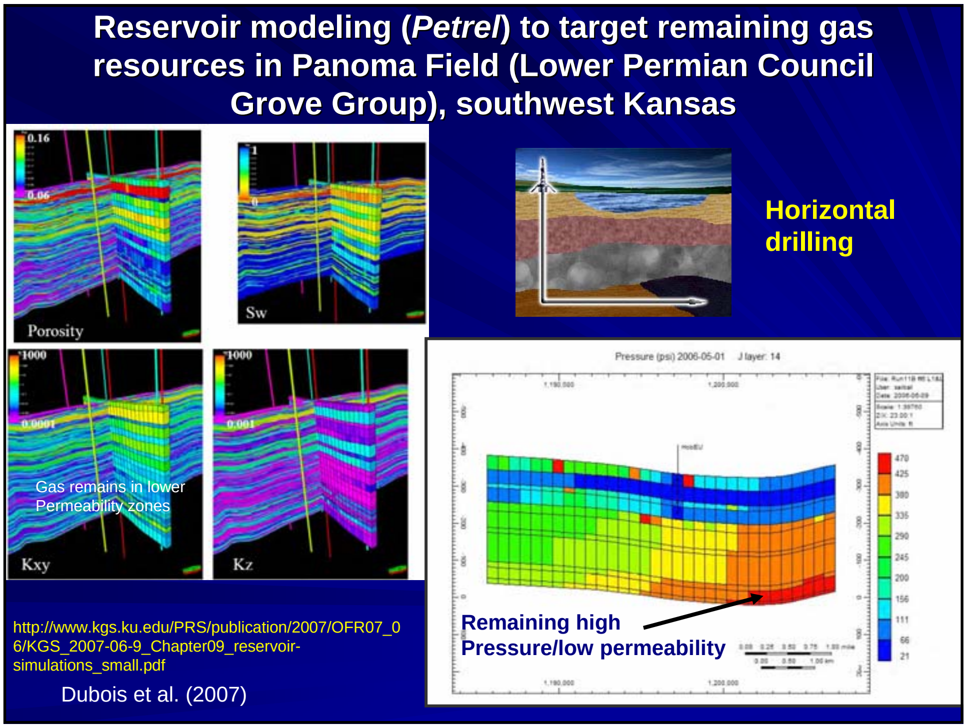


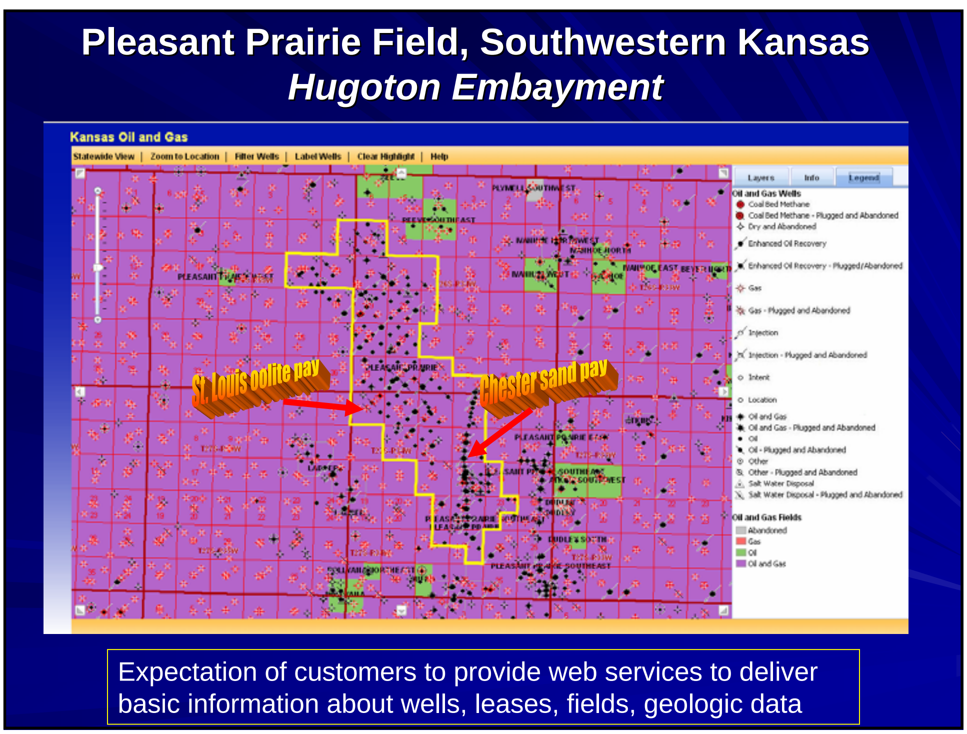


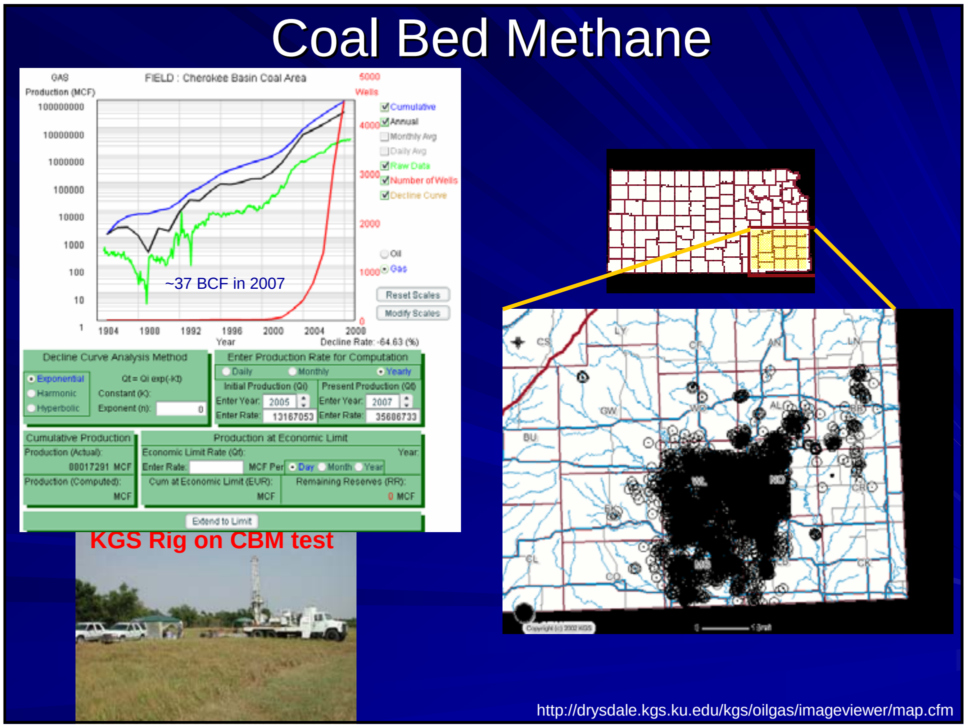
Giant gas field

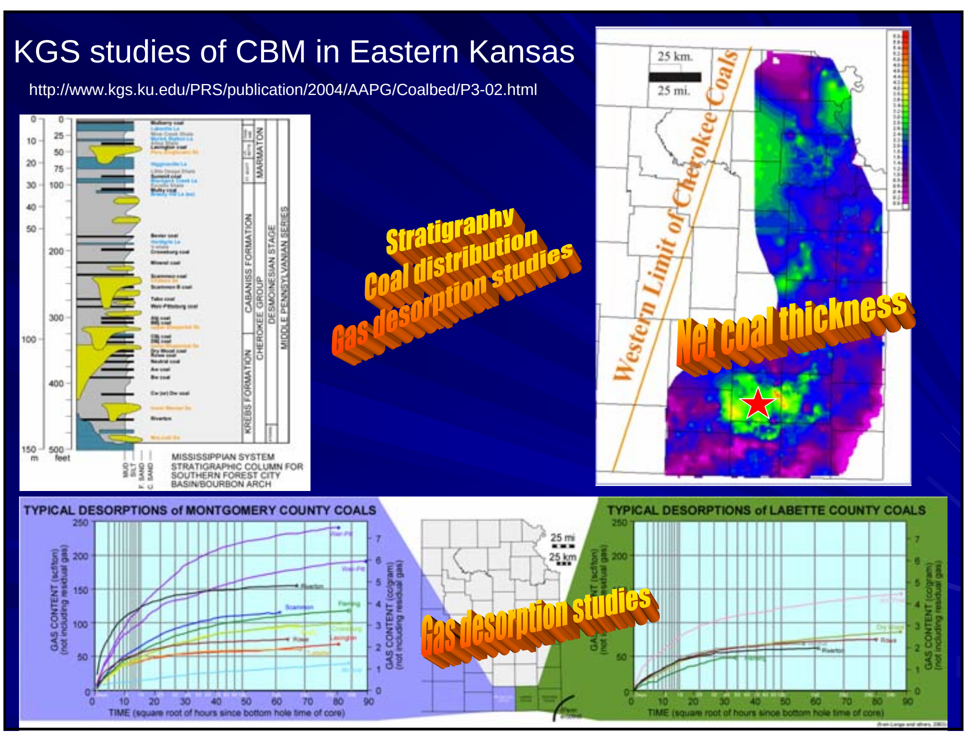
- Mature gas asset
- Enhance gas recovery options
- Reservoir modeling → forecasting response to technology and reducing risk



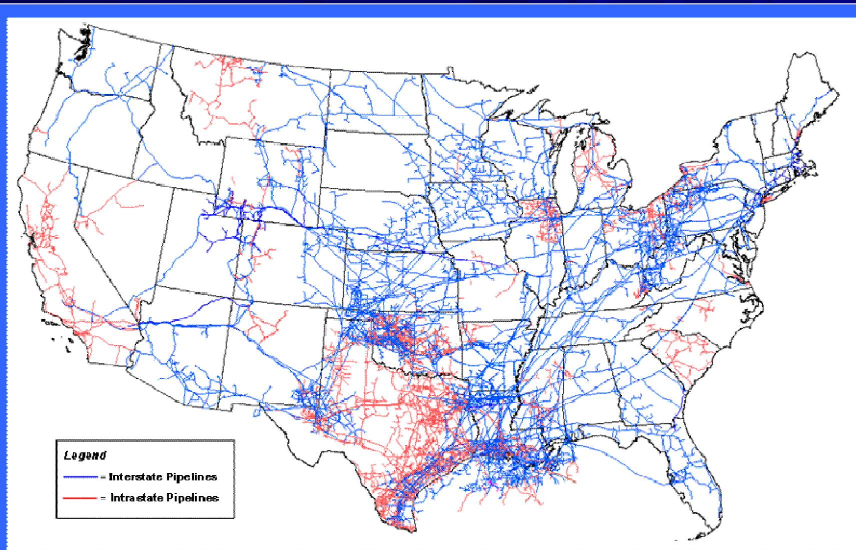

Reservoir modeling (*Petrel*) to target remaining gas resources in Panoma Field (Lower Permian Council Grove Group), southwest Kansas
Porosity
Sw
Horizontal drilling
Kxy
Kz
Gas remains in lower Permeability zones
Pressure (psi) 2006-05-01 J layer: 14
Remaining high Pressure/low permeability
http://www.kgs.ku.edu/PRS/publication/2007/OFR07_06/KGS_2007-06-9_Chapter09_reservoir-simulations_small.pdf
Dubois et al. (2007)


Pleasant Prairie Field, Southwestern Kansas
Hugoton Embayment
Kansas Oil and Gas
Statewide View | Zoom to Location | Filter Wells | Label Wells | Clear Highlight | Help
St. Louis oolite pay
Chester sand pay
Layers
Info
Legend
Oil and Gas Wells
Oil and Gas Fields
Expectation of customers to provide web services to deliver basic information about wells, leases, fields, geologic data


Coal Bed Methane
FIELD : Cherokee Basin Coal Area
~37 BCF in 2007
KGS Rig on CBM test
http://drysdale.kgs.ku.edu/kgs/oilgas/imageviewer/map.cfm

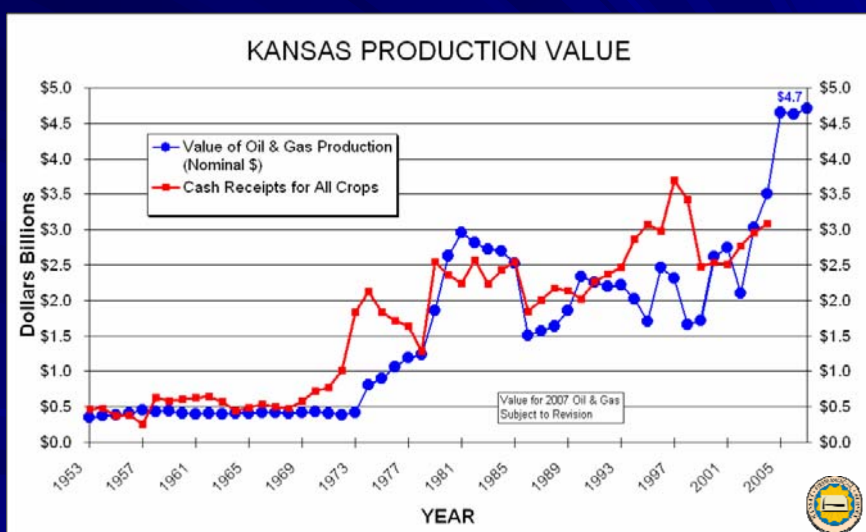

KGS studies of CBM in Eastern Kansas
http://www.kgs.ku.edu/PRS/publication/2004/AAPG/Coalbed/P3-02.html
Stratigraphy
Coal distribution
Gas desorption studies
Western Limit of Cherokee Coals
Net coal thickness
TYPICAL DESORPTIONS of MONTGOMERY COUNTY COALS
TYPICAL DESORPTIONS of LABETTE COUNTY COALS
Gas desorption studies

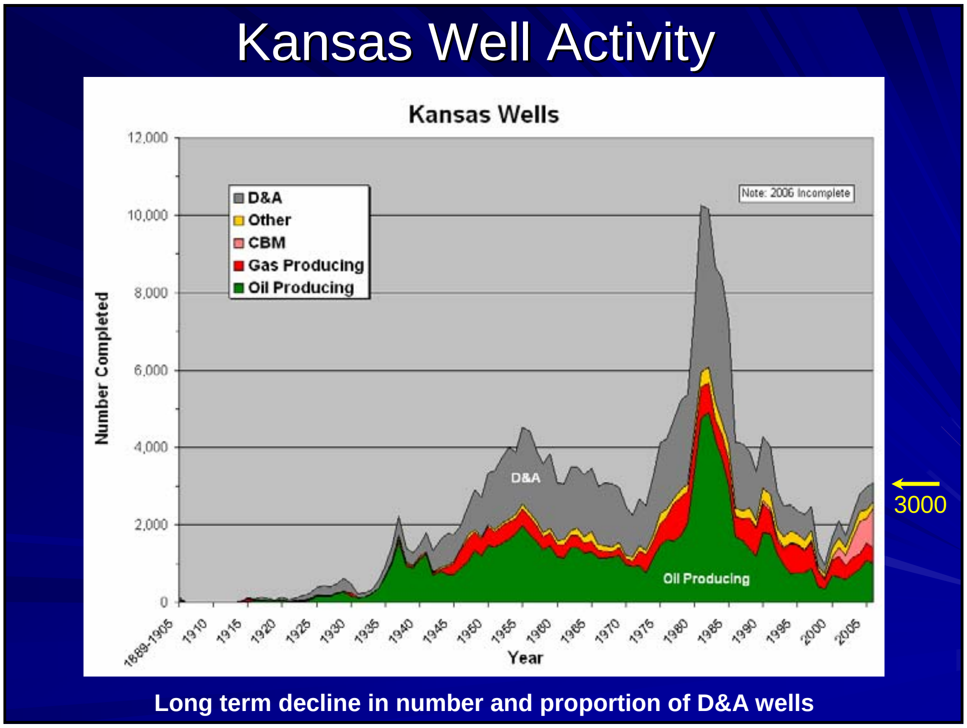
Natural gas infrastructure

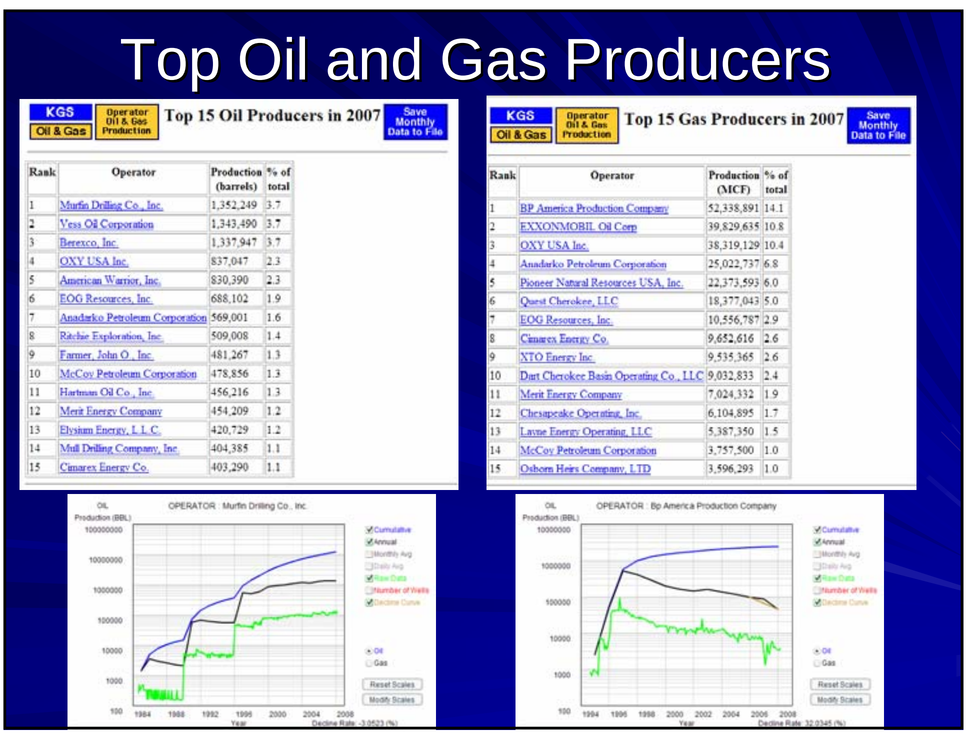


Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

Value of Oil & Gas







Top 15 Oil Producers in 2007

Rank	Operator	Production (barrels)	% of total
1	Murfin Drilling Co., Inc.	1,352,249	3.7
2	Vess Oil Corporation	1,343,490	3.7
3	Berexco, Inc.	1,337,947	3.7
4	OXY USA Inc.	837,047	2.3
5	American Warrior, Inc.	830,390	2.3
6	EOG Resources, Inc.	688,102	1.9
7	Anadarko Petroleum Corporation	569,001	1.6
8	Ritchie Exploration, Inc.	509,008	1.4
9	Farmer, John O., Inc.	481,267	1.3
10	McCoy Petroleum Corporation	478,856	1.3
11	Hartman Oil Co., Inc.	456,216	1.3
12	Merit Energy Company	454,209	1.2
13	Elysium Energy, L.L.C.	420,729	1.2
14	Mull Drilling Company, Inc.	404,385	1.1
15	Cimarex Energy Co.	403,290	1.1

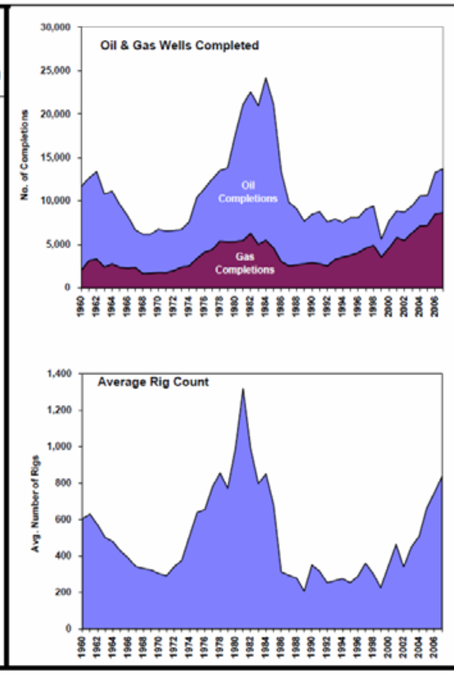
Top 15 Gas Producers in 2007

Rank	Operator	Production (MCF)	% of total
1	BP America Production Company	52,338,891	14.1
2	EXXONMOBIL Oil Corp	39,829,635	10.8
3	OXY USA Inc.	38,319,129	10.4
4	Anadarko Petroleum Corporation	25,022,737	6.8
5	Pioneer Natural Resources USA, Inc.	22,373,593	6.0
6	Quest Cherokee, LLC	18,377,043	5.0
7	EOG Resources, Inc.	10,556,787	2.9
8	Cimarex Energy Co.	9,652,616	2.6
9	XTO Energy Inc.	9,535,365	2.6
10	Dart Cherokee Basin Operating Co., LLC	9,032,833	2.4
11	Merit Energy Company	7,024,332	1.9
12	Chesapeake Operating, Inc.	6,104,895	1.7
13	Layne Energy Operating, LLC	5,387,350	1.5
14	McCoy Petroleum Corporation	3,757,500	1.0
15	Osborn Heirs Company, LTD	3,596,293	1.0

Texas Drilling Statistics

Year	Drilling Permits Issued	Oil Wells Completed	Gas Wells Completed	Total Holes Drilled*	Total Holes Plugged	Average Rotary Rig Count
1960	15,601	9,666	2,011	17,342	8,889	604
1965	14,227	7,207	2,383	14,433	8,836	425
1970	11,034	4,987	1,796	9,438	8,310	302
1975	20,293	7,004	3,396	14,393	10,960	638
1976	22,693	7,348	4,108	15,378	8,232	653
1977	25,189	8,121	4,399	16,577	8,129	778
1978	26,050	8,132	5,383	17,189	7,396	855
1979	29,241	8,487	5,319	17,509	6,658	770
1980	39,442	12,322	5,331	21,427	6,673	989
1981	47,940	15,627	5,454	26,209	9,054	1,318
1982	41,224	16,296	6,273	27,648	10,435	990
1983	45,550	15,941	5,027	26,882	11,661	796
1984	37,507	18,716	5,489	30,898	13,393	849
1985	30,878	16,543	4,605	27,124	14,479	677
1986	15,894	10,373	3,034	18,707	15,451	311
1987	15,297	7,327	2,542	13,121	13,186	293
1988	13,493	6,441	2,665	12,261	12,566	277
1989	12,756	4,914	2,760	10,054	11,229	206
1990	14,033	5,593	2,894	11,231	10,290	348
1991	12,494	6,025	2,755	11,295	13,089	315
1992	12,089	5,031	2,537	9,498	11,423	251
1993	11,612	4,646	3,295	9,969	11,552	263
1994	11,248	3,962	3,553	9,299	13,657	274
1995	11,244	4,334	3,778	9,785	11,081	251
1996	12,669	4,061	4,060	9,747	10,901	283
1997	13,933	4,482	4,594	10,778	9,336	358
1998	9,385	4,509	4,907	11,057	8,951	302
1999	8,430	2,049	3,566	6,658	7,011	226
2000	12,021	3,111	4,580	8,854	7,219	343
2001	12,227	3,082	5,787	10,005	8,023	462
2002	9,716	3,268	5,474	9,877	8,343	338
2003	12,664	3,111	6,336	10,420	8,720	448
2004	14,700	3,446	7,118	11,587	8,391	506
2005	16,914	3,454	7,197	12,664	7,191	662
2006	18,952	4,761	8,534	13,854	7,504	746
2007	19,994	5,084	8,643	20,619	6,892	834

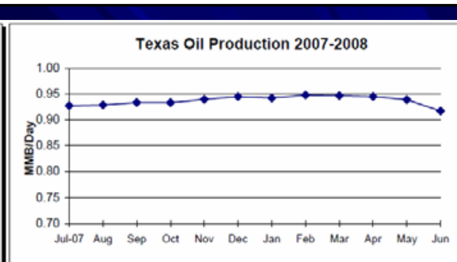
*includes oil & gas wells & dry holes; does not include service wells.

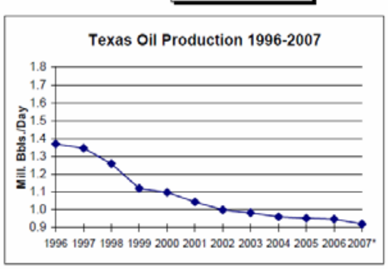


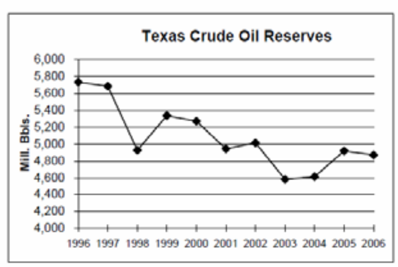
http://www.rrc.state.tx.us/data/drilling/txdrillingstat.pdf

Jul-07	28.74	0.927
Aug	28.78	0.928
Sep	28.00	0.933
Oct	28.92	0.933
Nov	28.18	0.939
Dec	29.28	0.945
Jan	29.20	0.942
Feb	27.48	0.948
Mar	29.34	0.946
Apr	28.34	0.945
May	29.10	0.939
Jun	27.50	0.917
Jul*	29.45	0.950

Note: The most recent 12 months of production data is preliminary and subject to revision. The most recent month of data is incomplete and may underestimate the final and complete total; a production adjustment factor of 1.0714 has been applied to reported June crude oil production to obtain an estimate of final crude oil production.







Source: U.S. Energy Information Administration (EIA). Reserve estimates for 1985 and after exclude federal offshore.
* Source: Railroad Commission of Texas, December Active Oil Well Counts
** Source: Texas Comptroller of Public Accounts. Wellhead price is average net taxable price ($/bbl.) and excludes federal offshore production. Source for 2001 and after is (EIA) and wellhead price is West Texas Intermediate spot average.

http://www.rrc.state.tx.us/data/petrofacts/2008/petro1008.pdf

Permian Basin cumulative oil production discovered by year

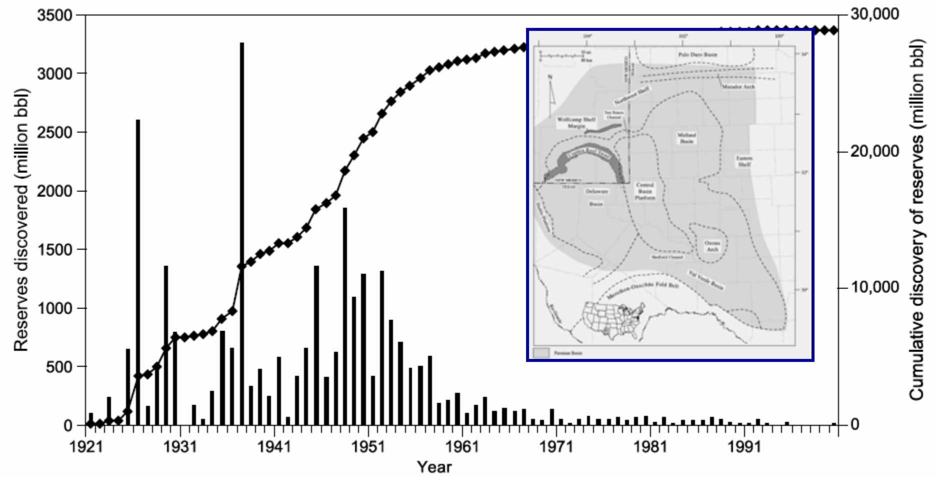


Figure 9. Permian basin cumulative oil production discovered by year. Bars show years in which reservoirs were discovered, with the height of bar indicating volume of oil produced by those reservoirs through 2000. Data are for the significant-sized reservoirs having cumulative production of greater than 1 million bbl (1.59 × 10^5 m^3) through 2000.

(Dutton et al., 2005)

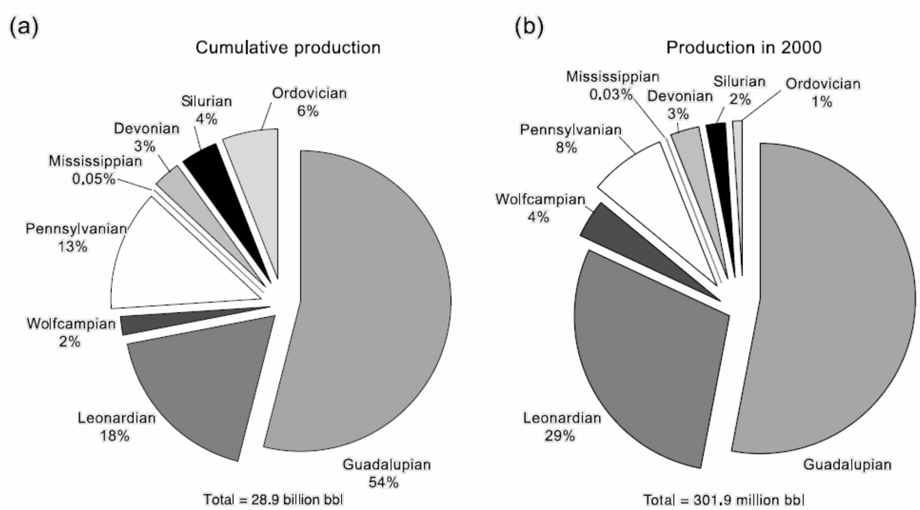
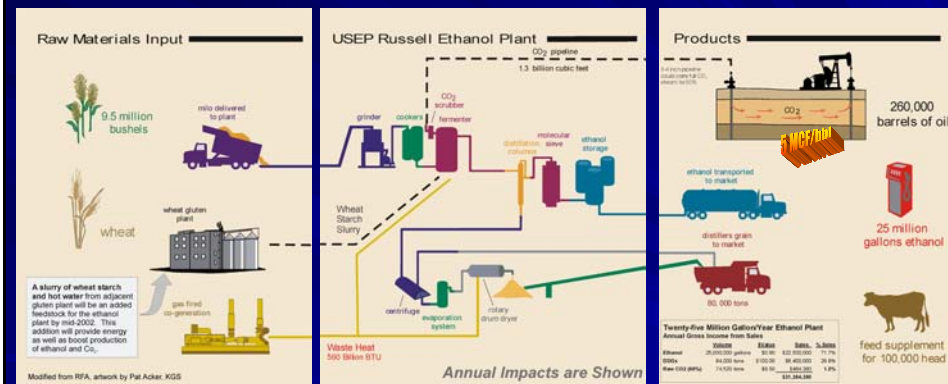


Figure 10. Permian basin production by geologic age: (a) cumulative production through 2000; (b) production in 2000.

DUTTON ET AL. 571

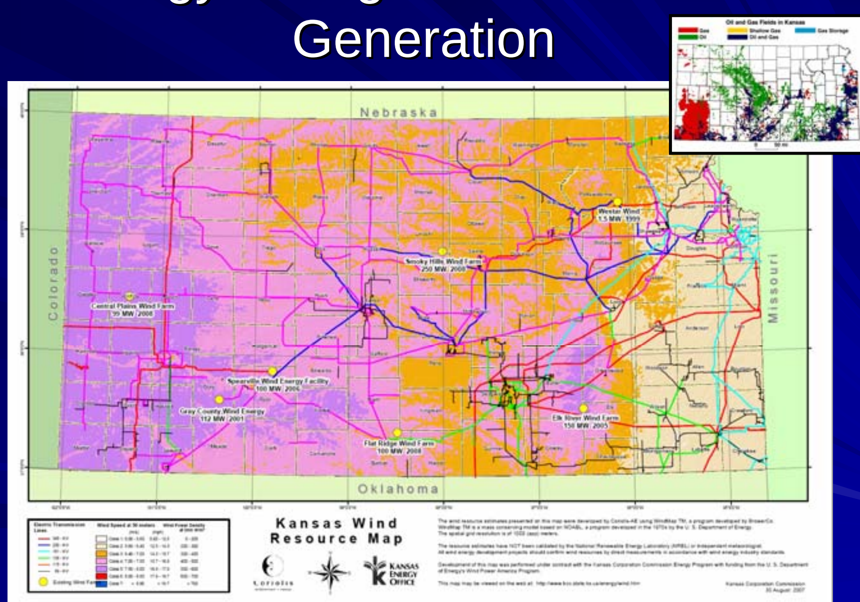
Remaining oil reserves in the Permian Basin that will be produced through 2015 is estimated at 3.25 billion bbls (Dutton et al., 2005).

Co-generation, Ethanol Production and CO2 Enhanced Oil Recovery Model for Environmentally and Economically Sound *Linked Energy Systems*



Dubois, White, Carr (2002)

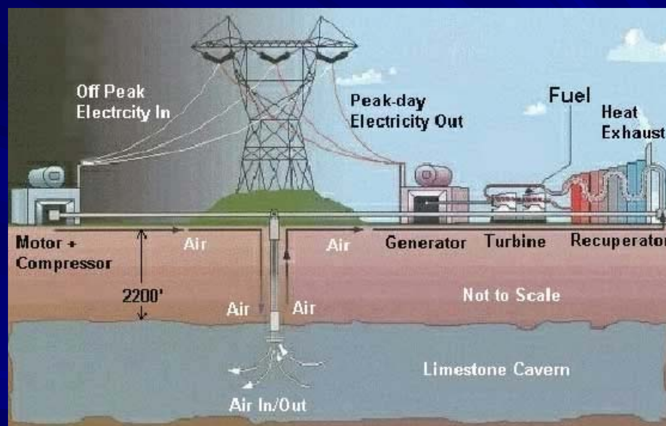
Energy storage for Wind Power Generation



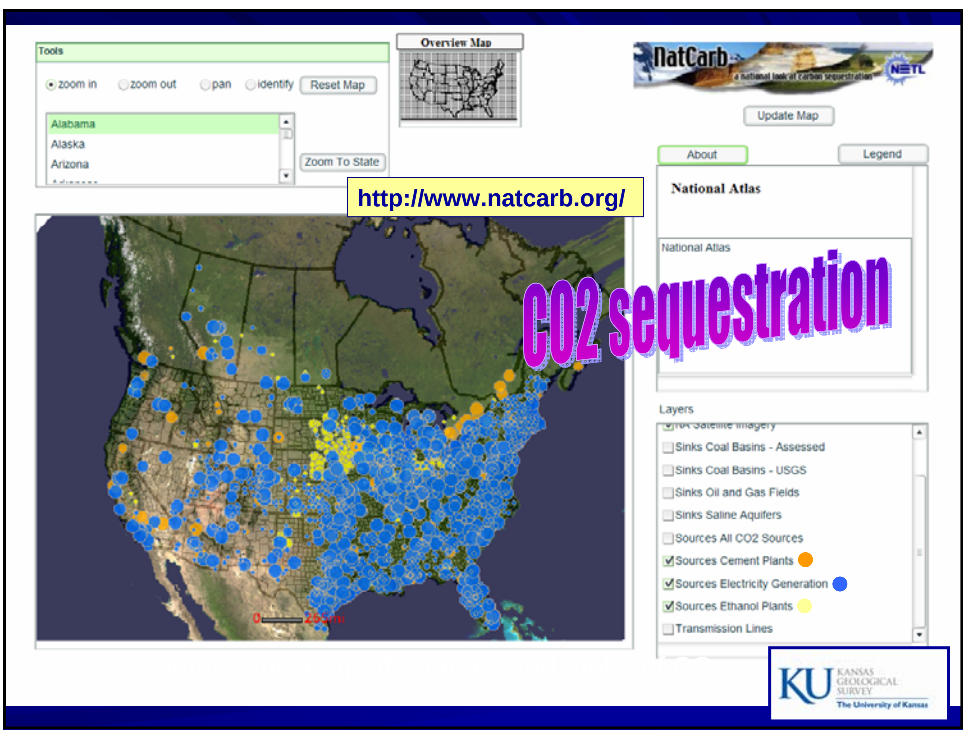
As of August 2007

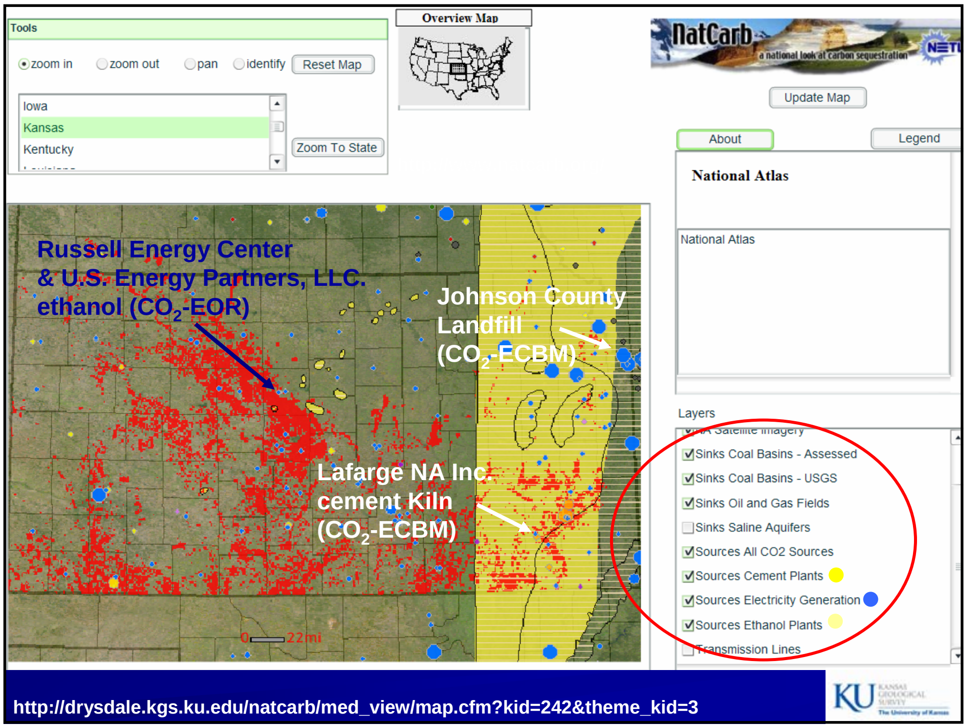
http://www.kcc.state.ks.us/energy/wind.htm

Compressed Air Storage for Suited for Wind Power Generation

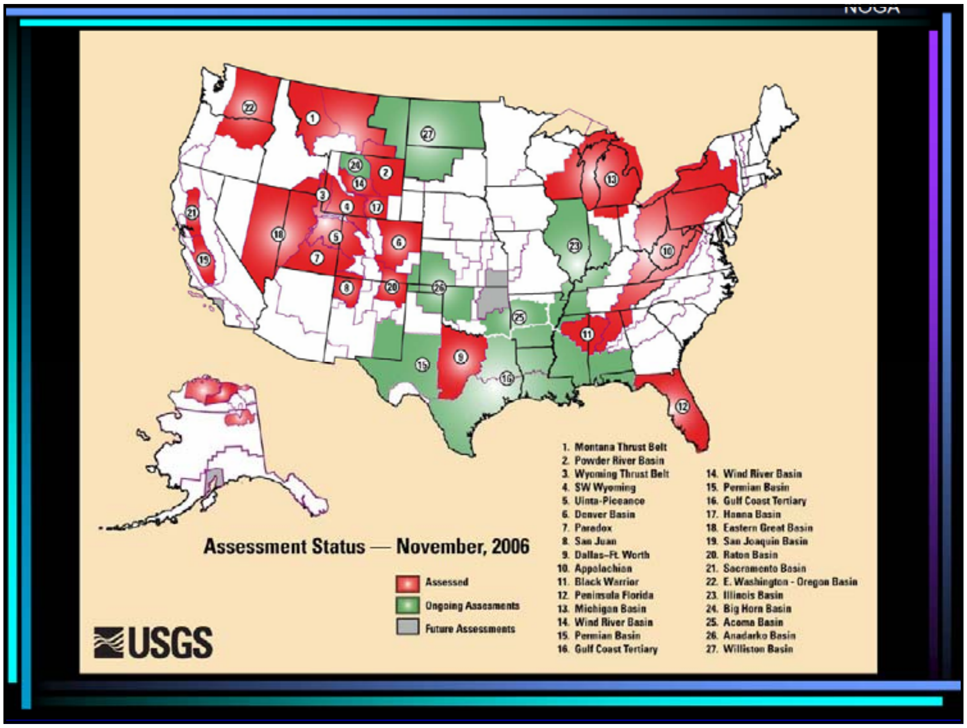


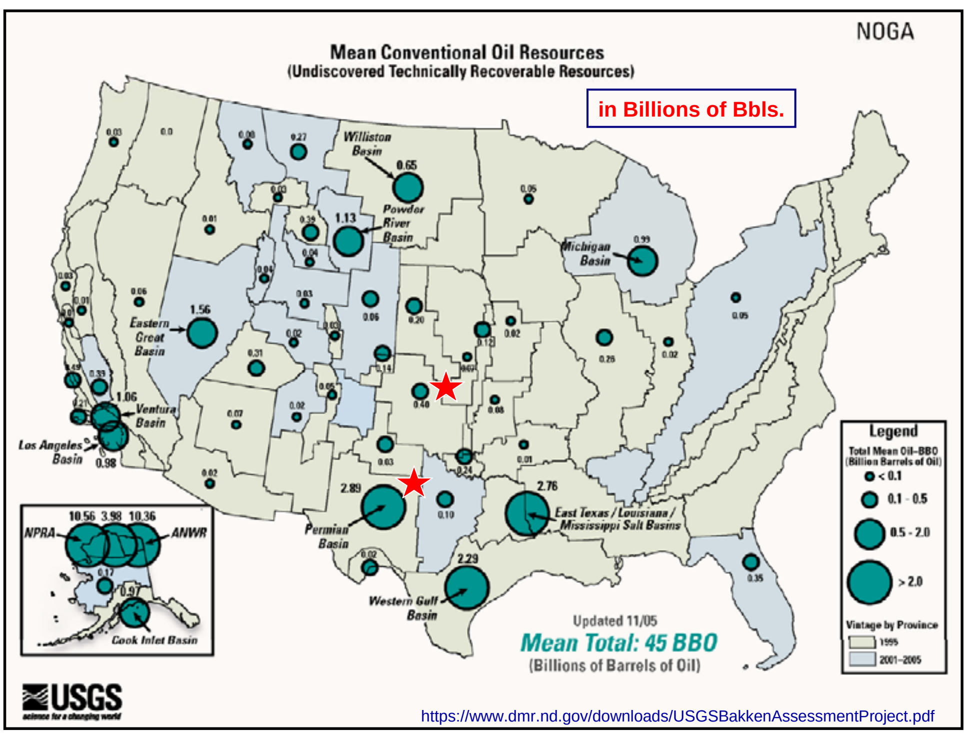
http://www.seco.cpa.state.tx.us/re_wind-reserve.htm

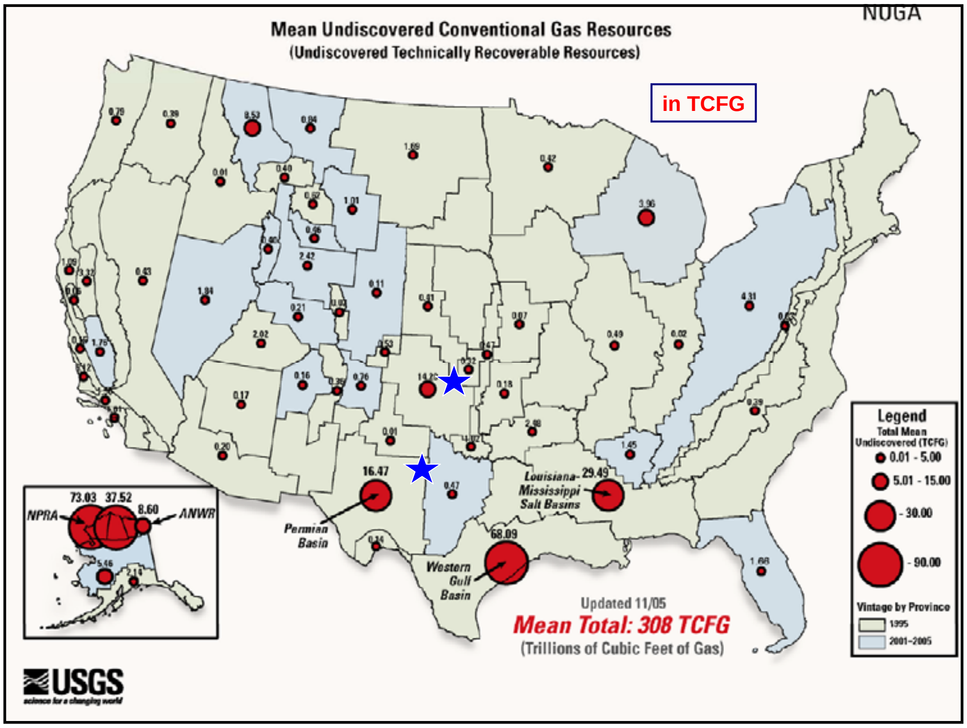


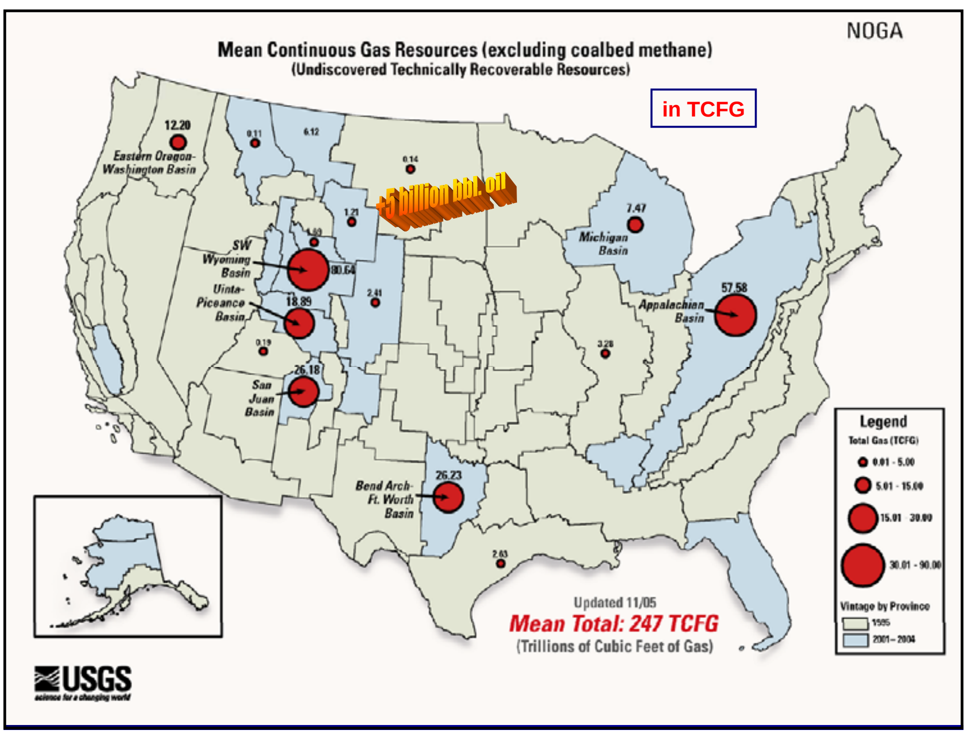

Tools
zoom in
zoom out
pan
identify
Reset Map
Iowa
Kansas
Kentucky
Zoom To State
Overview Map
NatCarb
a national look at carbon sequestration
Update Map
About
Legend
National Atlas
National Atlas
Russell Energy Center
& U.S. Energy Partners, LLC.
ethanol (CO_2-EOR)
Johnson County
Landfill
(CO_2-ECBM)
Lafarge NA Inc.
cement Kiln
(CO_2-ECBM)
Layers
Sinks Coal Basins - Assessed
Sinks Coal Basins - USGS
Sinks Oil and Gas Fields
Sinks Saline Aquifers
Sources All CO2 Sources
Sources Cement Plants
Sources Electricity Generation
Sources Ethanol Plants
Transmission Lines
http://drysdale.kgs.ku.edu/natcarb/med_view/map.cfm?kid=242&theme_kid=3


USGS
science for a changing world
National Assessment of Oil and Gas Fact Sheet
Assessment of Undiscovered Oil and Gas Resources of the Bend Arch-Fort Worth Basin Province of North-Central Texas and Southwestern Oklahoma, 2003


NOGA
Assessment Status — November, 2006
Assessed
Ongoing Assessments
Future Assessments
USGS
1. Montana Thrust Belt
2. Powder River Basin
3. Wyoming Thrust Belt
4. SW Wyoming
5. Uinta-Piceance
6. Denver Basin
7. Paradox
8. San Juan
9. Dallas–Ft. Worth
10. Appalachian
11. Black Warrior
12. Peninsula Florida
13. Michigan Basin
14. Wind River Basin
15. Permian Basin
16. Gulf Coast Tertiary
14. Wind River Basin
15. Permian Basin
16. Gulf Coast Tertiary
17. Hanna Basin
18. Eastern Great Basin
19. San Joaquin Basin
20. Raton Basin
21. Sacramento Basin
22. E. Washington - Oregon Basin
23. Illinois Basin
24. Big Horn Basin
25. Acoma Basin
26. Anadarko Basin
27. Williston Basin


NOGA
Mean Conventional Oil Resources
(Undiscovered Technically Recoverable Resources)
in Billions of Bbls.
Williston Basin
0.65
Powder River Basin
1.13
Michigan Basin
Eastern Great Basin
1.56
1.06
Ventura Basin
Los Angeles Basin
0.98
2.89
Permian Basin
2.76
East Texas / Louisiana / Mississippi Salt Basins
2.29
Western Gulf Basin
10.56 3.98 10.36
NPRA
ANWR
Cook Inlet Basin
Legend
Total Mean Oil–BBO (Billion Barrels of Oil)
< 0.1
0.1 - 0.5
0.5 - 2.0
> 2.0
Vintage by Province
1995
2001–2005
Updated 11/05
Mean Total: 45 BBO
(Billions of Barrels of Oil)
USGS
science for a changing world
https://www.dmr.nd.gov/downloads/USGSBakkenAssessmentProject.pdf


NOGA
Mean Undiscovered Conventional Gas Resources
(Undiscovered Technically Recoverable Resources)
in TCFG
16.47
Permian Basin
Louisiana-Mississippi Salt Basins
29.49
68.09
Western Gulf Basin
NPRA
73.03
37.52
8.60
ANWR
Legend
Total Mean Undiscovered (TCFG)
0.01 - 5.00
5.01 - 15.00
- 30.00
- 90.00
Vintage by Province
1995
2001–2005
Updated 11/05
Mean Total: 308 TCFG
(Trillions of Cubic Feet of Gas)
USGS


NOGA
Mean Continuous Gas Resources (excluding coalbed methane)
(Undiscovered Technically Recoverable Resources)
in TCFG
12.20
Eastern Oregon-Washington Basin
SW Wyoming Basin
80.64
Uinta-Piceance Basin
18.89
26.18
San Juan Basin
7.47
Michigan Basin
57.58
Appalachian Basin
26.23
Bend Arch-Ft. Worth Basin
Legend
Total Gas (TCFG)
Vintage by Province
Updated 11/05
Mean Total: 247 TCFG
(Trillions of Cubic Feet of Gas)
USGS

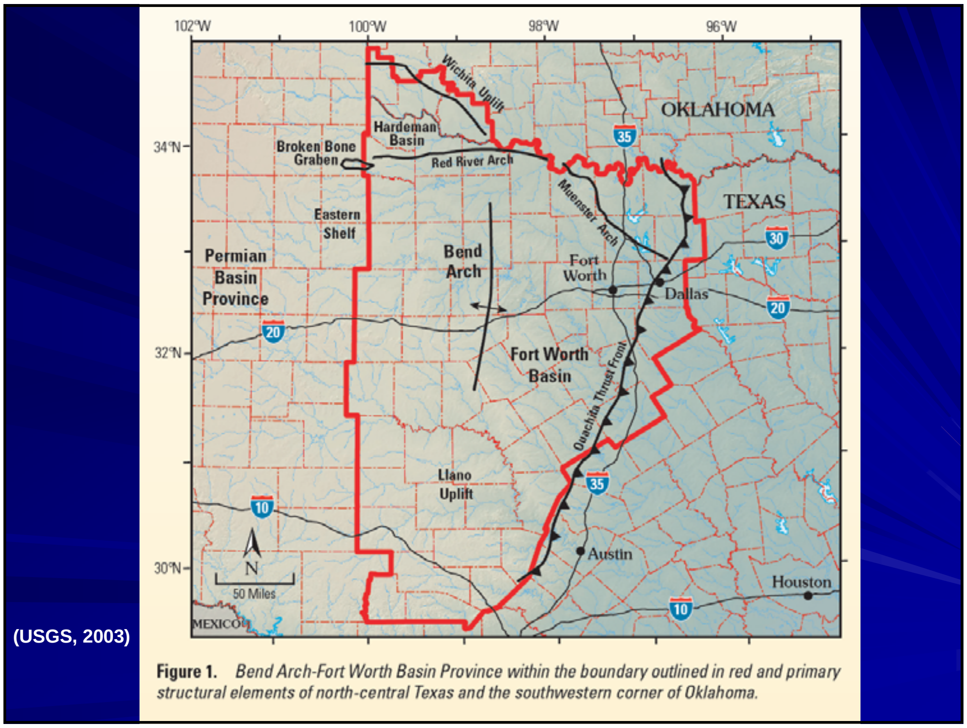


Figure 1. *Bend Arch-Fort Worth Basin Province within the boundary outlined in red and primary structural elements of north-central Texas and the southwestern corner of Oklahoma.*

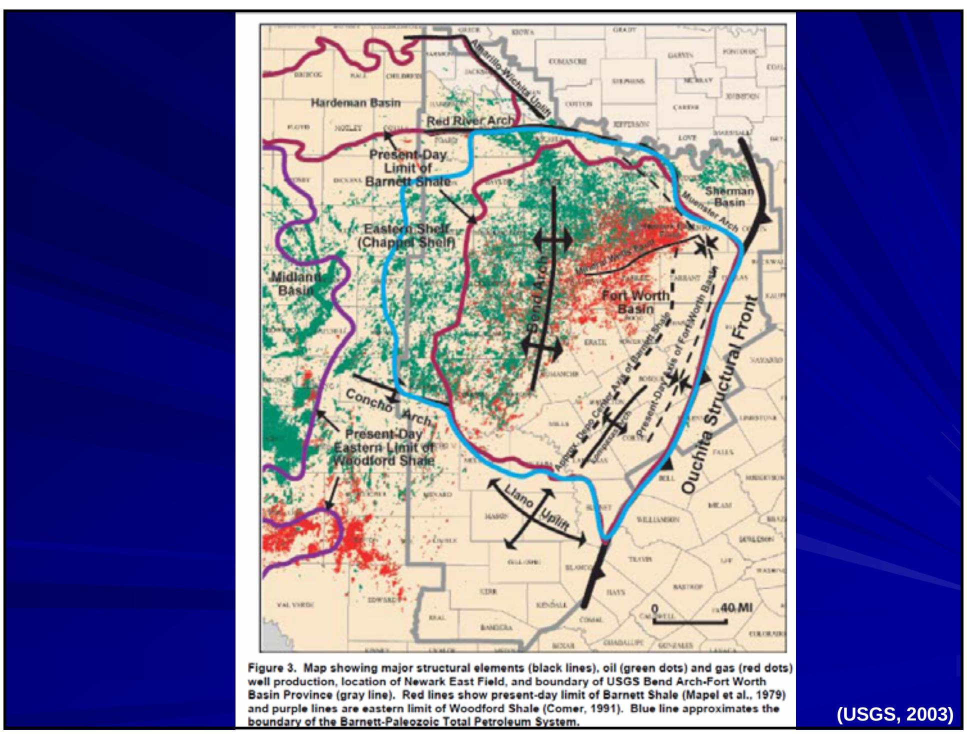


Figure 3. Map showing major structural elements (black lines), oil (green dots) and gas (red dots) well production, location of Newark East Field, and boundary of USGS Bend Arch-Fort Worth Basin Province (gray line). Red lines show present-day limit of Barnett Shale (Mapel et al., 1979) and purple lines are eastern limit of Woodford Shale (Comer, 1991). Blue line approximates the boundary of the Barnett-Paleozoic Total Petroleum System.

Table 1. *Bend Arch-Fort Worth Basin Province Assessment Results.*

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 denotes a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS is Total Petroleum System. AU is Assessment Unit. CBG is coalbed gas. Gray shading indicates not applicable]

	Total Petroleum Systems (TPS) and Assessment Units (AU)	Field Type	Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional Oil and Gas Resources	**Barnett-Paleozoic TPS**													
	Paleozoic Shelf and Bank Carbonates AU ★	Oil	7.69	19.85	38.90	21.21	11.30	30.96	66.52	33.92	0.63	1.81	4.22	2.03
		Gas					46.10	116.83	219.03	123.15	1.70	4.53	9.42	4.92
	Mississippian Chappel Pinnacle Reefs AU ★	Oil	2.52	5.39	9.89	5.70	2.52	5.83	11.52	6.27	0.11	0.28	0.61	0.31
		Gas					17.35	44.02	90.63	47.81	0.95	2.57	5.79	2.87
	Pennsylvanian/Permian Fluvial-Deltaic Sandstone and Conglomerate AU ★	Oil	11.58	35.76	69.80	37.66	16.23	51.87	111.71	56.44	1.06	3.53	8.26	3.95
		Gas					42.39	134.76	262.21	141.59	1.98	6.55	14.04	7.08
	Barnett-Hardeman Basin TPS													
	Mississippian Chappel Waulsortian Mounds AU ★	Oil	7.54	21.08	39.88	22.17	2.19	6.25	12.35	6.65	0.24	0.68	1.39	0.73
	Paleozoic Clastics and Carbonates AU	Oil	1.63	7.01	17.13	7.89	0.26	1.11	2.77	1.26	0.03	0.12	0.31	0.14
	Pennsylvanian Bend-Broken Bone Graben TPS													
	Fluvial Sandstone-Carbonate Bank AU	Oil	1.37	3.42	7.73	3.83	1.20	3.34	8.10	3.83	0.05	0.13	0.33	0.15
		Gas					15.02	42.23	89.50	46.00	0.53	1.51	3.30	1.66
	Total Conventional Resources		32.33	92.51	183.33	98.46	154.56	437.20	874.34	466.92	7.28	21.71	47.67	23.84
Continuous Oil and Gas Resources	**Barnett-Paleozoic TPS**													
	Greater Newark East Frac-Barrier Continuous Barnett Shale Gas AU	Gas					13,410.69	14,638.36	15,978.42	14,659.13	406.84	573.70	809.00	586.37
	Extended Continuous Barnett Shale Gas AU ★	Gas					8,305.14	11,361.66	15,543.04	11,569.73	282.01	445.28	703.09	462.79
	Hypothetical Basin-Arch Barnett Shale Oil AU	Oil	Not quantitatively assessed											
	Barnett-Hardeman Basin TPS													
	Hypothetical Continuous Fractured Barnett Shale Oil AU	Oil	Not quantitatively assessed											
	Pennsylvanian-Lower Permian Coal-Bed Gas TPS													
	Hypothetical Pennsylvanian-Lower Permian Coal-Bed Gas AU	CBG	Not quantitatively assessed											
	Total Continuous Resources						21,715.83	26,000.02	31,521.46	26,228.86	688.85	1,018.98	1,512.09	1,049.16
	TOTAL UNDISCOVERED OIL AND GAS RESOURCES		32.33	92.51	183.33	98.46	21,870.39	26,437.22	32,395.80	26,695.78	696.13	1,040.69	1,559.76	1,074.00

(USGS, 2003)

Assessment of Undiscovered Oil and Gas Resources of the Permian Basin Province

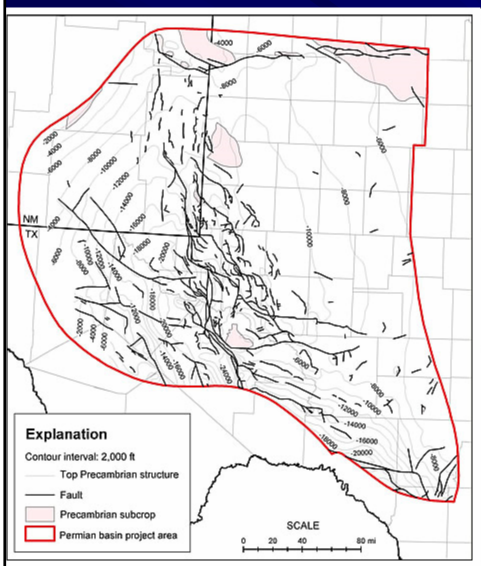
Fact Sheet 2007-3115

(USGS, 2007)

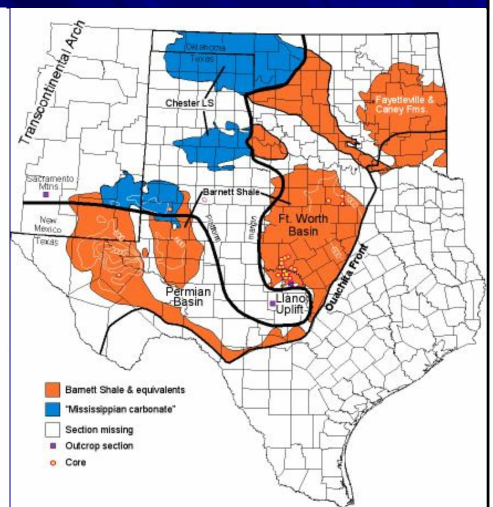
Examples cited in short Course

Total Petroleum System (TPS) and Assessment Unit (AU)	Field Type	Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Paleozoic Composite TPS													
Ellenberger Group Karst and Dolomite AU	Oil	12	40	83	43	12	40	90	44	1	3	8	4
	Gas					147	475	924	498	3	11	24	12
Simpson Group Sandstones AU	Oil	1	3	6	3	2	6	14	7	0	0	1	0
	Gas					22	63	123	66	1	2	5	2
Pre-Pennsylvanian Ramp and Platform Carbonates AU	Oil	15	48	95	51	17	58	122	61	1	4	10	5
	Gas					91	323	664	343	3	12	28	14
★ Devonian Thirtyone Formation Chert and Carbonate AU	Oil	7	22	45	24	23	79	178	87	2	8	19	9
	Gas					91	321	665	344	5	17	38	19
Lower Pennsylvanian (Morrow/Atoka) Shelf Sandstone and Carbonate AU	Oil	0	0	0	0	0	0	0	0	0	0	0	0
	Gas					238	780	1,485	812	3	9	19	10
Pennsylvanian–Lower Permian (Wolfcamp) Northwest Shelf Carbonate AU	Oil	8	27	56	29	21	72	161	79	1	5	11	5
	Gas					43	148	308	158	1	4	9	4
★ Pennsylvanian–Lower Permian (Wolfcamp) Central Basin Platform and Shelf Carbonate AU	Oil	12	40	79	42	43	150	330	164	3	10	24	11
	Gas					57	183	355	192	3	9	18	9
★ Pennsylvanian–Lower Permian (Wolfcamp) Horseshoe Platform and Eastern Shelf Carbonate and Sandstone AU	Oil	28	93	175	96	42	143	299	154	5	17	38	18
	Gas					15	38	69	40	0	1	3	1
Pennsylvanian–Lower Permian (Wolfcamp) Val Verde Slope and Basinal Sandstone and Carbonate AU	Oil	3	9	22	10	16	56	139	64	1	3	9	4
	Gas					183	702	1,517	758	8	31	74	35
Pennsylvanian–Lower Permian (Wolfcamp) Slope and Basinal Carbonates AU	Oil	3	12	27	13	9	32	83	37	0	2	5	2
	Gas					62	222	481	241	2	9	20	10
Abo Fluvial Sandstones AU	Oil	0	0	0	0	0	0	0	0	0	0	0	0
	Gas					0	0	23	8	0	0	0	0
Abo Shelf and Shelf Edge Carbonates AU	Oil	11	39	83	42	23	83	194	93	2	6	15	7
	Gas					25	65	123	69	1	2	5	3
Leonardian NW and E Shelf Restricted Platform Carbonates AU	Oil	22	74	146	78	16	57	125	62	1	4	10	5
	Gas					0	0	0	0	0	0	0	0
Leonardian Central Basin Platform Restricted Carbonates AU	Oil	10	31	61	33	29	96	209	105	2	7	16	8
	Gas					13	33	62	35	1	1	3	2
Leonardian Midland Basin Carbonate Sediment Gravity Flow Reservoirs AU	Oil	28	93	185	98	47	161	355	176	3	10	25	12
	Gas					0	0	0	0	0	0	0	0
Bone Spring Slope and Basin Reservoirs AU	Oil	15	50	100	53	55	192	423	210	2	9	21	10
	Gas					0	0	0	0	0	0	0	0
Spraberry Conventional Sandstones AU	Oil	5	18	42	20	4	14	38	16	0	1	4	2
	Gas					0	0	0	0	0	0	0	0
★ San Andres NW Shelf Platform Carbonates AU	Oil	2	5	8	5	2	4	8	4	0	0	1	0
	Gas					0	0	0	0	0	0	0	0
San Andres Eastern Shelf Platform Carbonates AU	Oil	0	0	3	1	0	0	1	0	0	0	0	0
	Gas					0	0	0	0	0	0	0	0

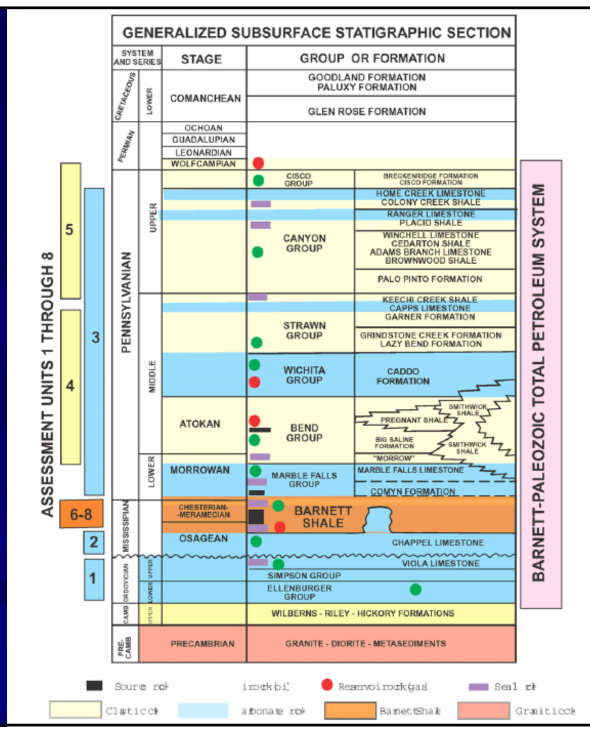
Permian Basin faults



Paleozoic Basins



http://www.netl.doe.gov/technologies/oil-gas/Petroleum/projects/EP/ResChar/15509.htm



Barnett-Paleozoic Total Petroleum System in Bend Arch-Fort Worth Basin Province

Pollastro et al. (1997)

Events chart for Miss-Penn Barnett-Paleozoic Total Petroleum System

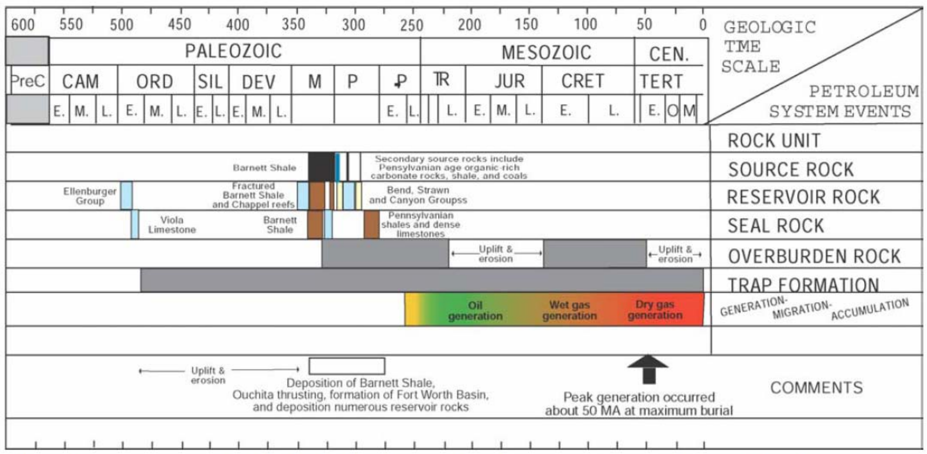


Figure 5. Events chart for Mississippian-Pennsylvanian Barnett-Paleozoic Total Petroleum System (TPS) of the Bend Arch-Fort Worth Basin Province, Texas, showing TPS elements and timing of trap formation and hydrocarbon generation. Also see stratigraphic chart of Figure 4. Hydrocarbon generation models were summarized and modified from Jarvie et al. (2001).

(Palastro, 2003)

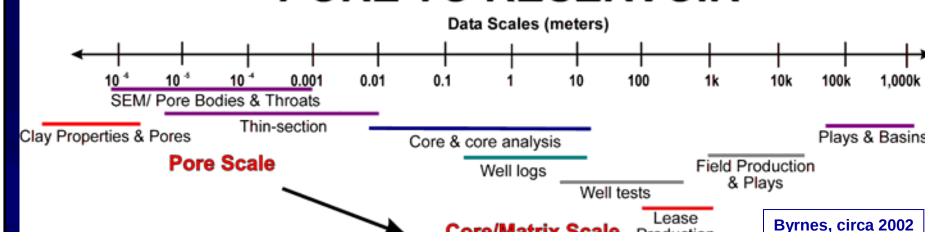
Evolving Concepts of Oil and Gas Reservoir Characterization

- Increasingly quantitative, refined, integrated and multidisciplinary, 3D to find subtle accumulations of remaining oil and gas in our mature areas
- Increasingly more quantitative information and software to process it – new Kansas rule enacted to require copies of electronic logs (image and LAS) to be submitted to the state (*industry driven*)
- Stratigraphic classification
  - Lithology and lithofacies
  - Petrofacies
  - Mechanical stratigraphy
  - Seismic signature/attributes
  - Genetic units and sequence stratigraphy
- Sequence stratigraphy and reservoir continuity and conformance
- Scalable depositional sequences (Possamentier) -- sequence boundaries, flooding surfaces, and maximum flooding surfaces
- Key to defining, correlating, and mapping fundamental temporally distinct units and to develop high-resolution paleogeography.
- When have topography in subsurface units (such as along shelf margins, depositional topography, or erosional relief), filling and progradation of units is not a simple matter to resolve.

Petroleum Reservoir Characterization

- **Definition**
  - **Reservoir characterization** is the broad discipline of the process of describing and distributing properties of pores and fluids that comprise a petroleum reservoir, a geomodel, that is used for efficient exploitation of the oil and gas resources.
  - Modern reservoir characterization is multidisciplinary.
  - *Geologists* develop geomodels expressed as maps, cross sections, and now increasingly 3D models to capture structure, lithofacies, seismic attributes, statistical properties of reservoir.
  - *Engineers/geoscientists* integrate fluid data to refine the geomodel and possibly build a reservoir simulation.
  - *Geophysicists* ascertain interwell-scale reservoir geometries and use seismic to empirically interpolate reservoir properties (attribute mapping).

RESERVOIR ANALYSIS TOOLS
PORE TO RESERVOIR



Problem or Opportunity

- ***12+ orders of scales*** **in reservoir characterization**
- **Appropriate application of new technologies to suite reservoir complexity**
- **"Devil is in details": solution beyond beyond rules of thumb, thickness, and structure**
- **Risk management and rapid, but measured/calculated response to:**
  - *** changing economic conditions and opportunities, e.g., gas price**
  - *** advent of new technologies**

Petroleum Reservoir Characterization

- ***Geological Analysis*** -- Geological analysis is derived from data obtained from wells that are drilled to tap oil and gas.
- Data types -- sample cuttings, cores, wireline logs, fluid tests and analyses acquired during drilling. Well logs, calibrated with rock properties.

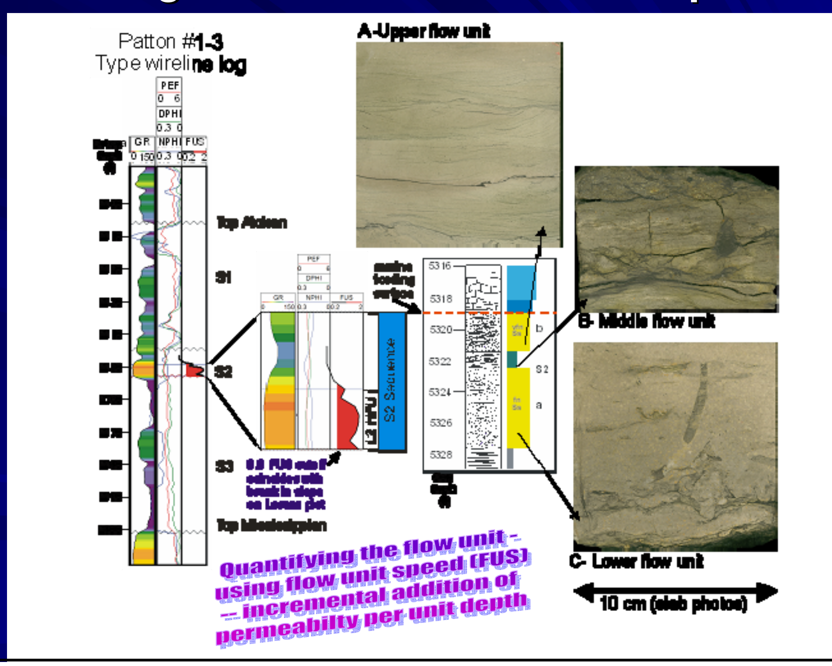
Reservoir Flow Units

- **Reservoir flow units** are the primary elements of the reservoir that have sufficient pore space (porosity) to store hydrocarbon and ability to transmit hydrocarbon (permeability).
- Defining flow units and correlating them between wells is accomplished using geological, geophysical, and engineering data, which becomes the essence of a successful geomodel and an important objective of reservoir characterization.
- Related "net pay" is an economic and technical definition applied to flow units as *cut-offs of key properties*, e.g., defining cutoffs of Vsh, phi, k, BVW, Sw.

Reservoir flow units (continued)

- The *measured parameters and rock descriptions* are observed in depth profiles in each well; Used to classify and subdivide the reservoir interval.
- The *stratigraphic divisions* that delineate discrete episodes of deposition are important in recognizing potential flow units.
- *Lithofacies, pore types, and core analysis* further aid in defining and characterizing flow units.
- Flow units reflect *modification of depositional fabrics* by diagenetic overprinting and structural deformation.
- Flow unit definition is *verified* by well test, production, volumetrics, material balance, and simulation.
- Flow unit definition is refined through time with need (cost/benefit).

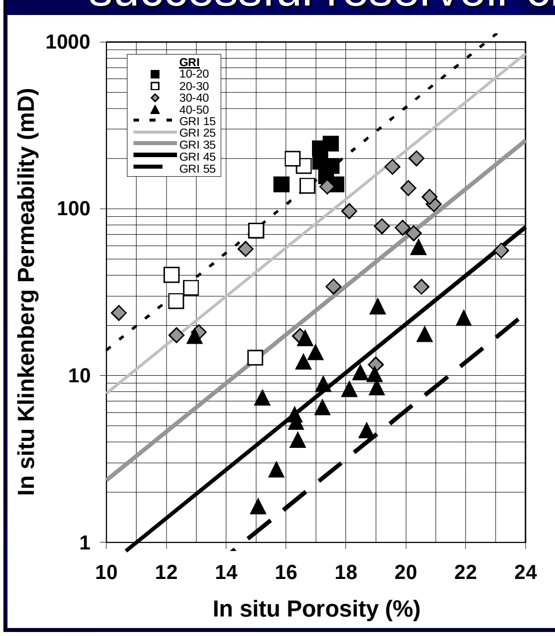
Refining flow units is an iterative process



Reservoir flow units (continued)

- *Well-log and core data* are fundamental for defining flow units, but well tests and production data and, more recently, *seismic attributes* are included.
- Digital log, core, test, and seismic data are ideally used in software to integrate and quantitatively analyze them.
- *Lithofacies* represent a combination of rock texture, dominant constituent particles, and pore space.
- *Petrofacies* extends the lithofacies definition to include pore type and quantitative attributes/parameters used to establish uniqueness.
- *Petrofacies classification* aids in systematizing and classifying flow units and making results more robust.

Petrofacies is a key ingredient to successful reservoir characterization.



- Cross plot of porosity vs. permeability for the sandstone interval in earlier figure.
- As porosity increases permeability generally increases, but scatter in this correlation is roughly three orders of magnitude.
- Scatter is this example is closely related to shale context, i.e., a change in lithofacies, as indicated here by the magnitude of the natural gamma ray (GR).
- When sample shaliness is considered the correlation between porosity and permeability greatly improves (Bhattacharya et al., 2008).
- Petrofacies – using lithofacies to classify pore type and physical properties, e.g., log response and Ø-k.

Pore types in vuggy carbonates

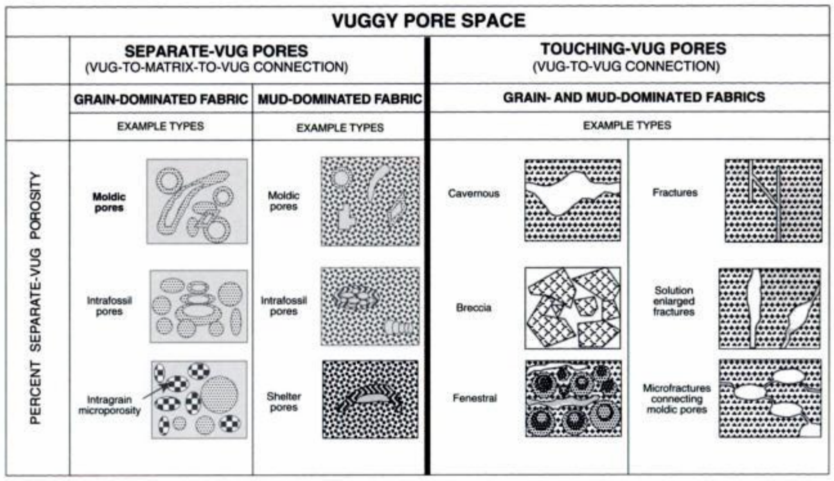
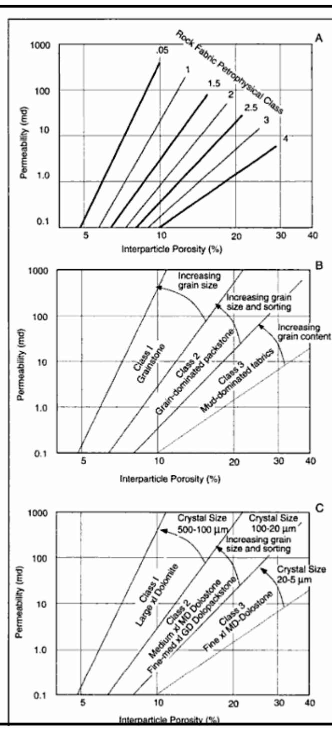


Fig. 7. Geological/petrophysical classification of vuggy pore space based on vug interconnection. The volume of separate-vug pore space is important for characterizing the pore-size distribution

Carbonate Reservoir Characterization
By F. Jerry Lucia (1999)

Fig. 15. Continuum of rock fabrics and associated porosity-permeability transforms. **A** Class fabrics ranging from 0.5 – 4 defined by class-average and class-boundary porosity-permeability transforms. **B** Fabric continuum in nonvuggy limestone. **C** Fabric continuum in nonvuggy dolostone

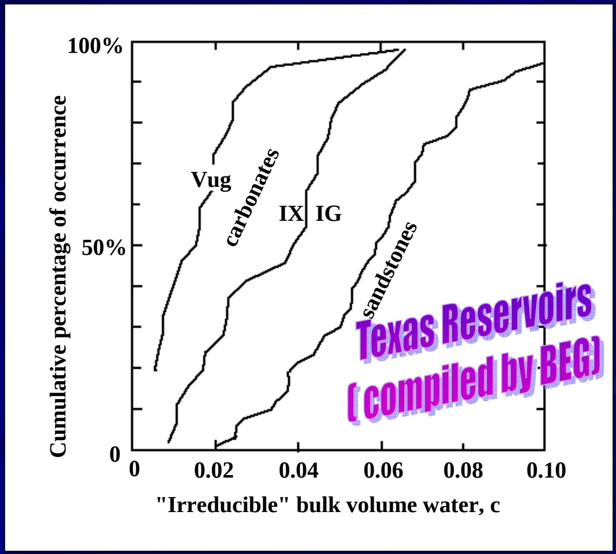


Rock fabrics and permeability in carbonates

where k is proportional to crystal and grain size, grain sorting, and extent that vugs are touching

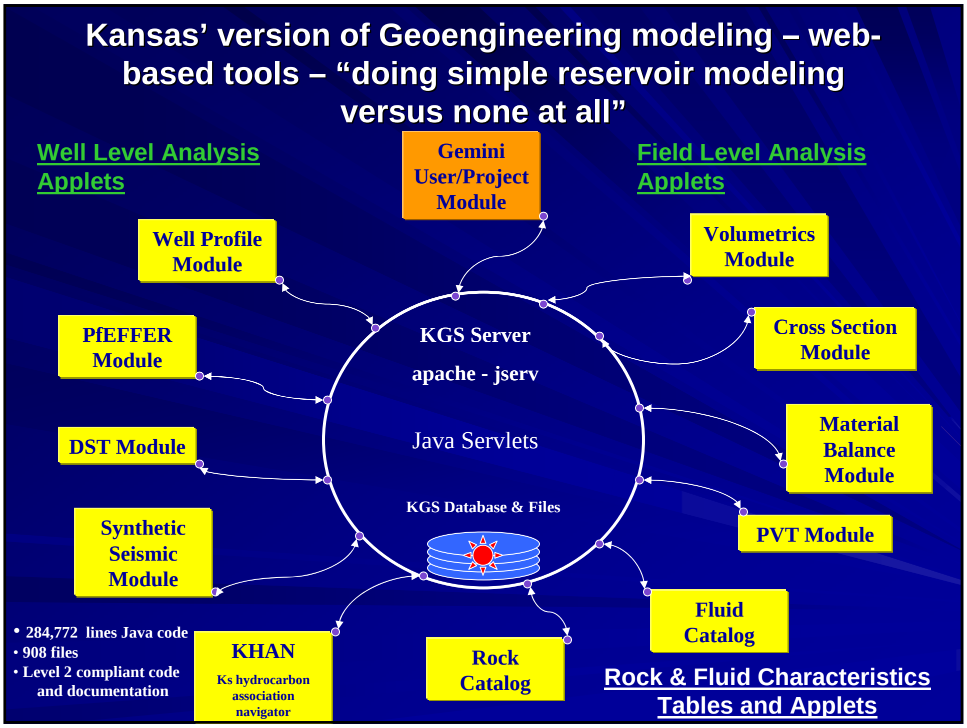
Carbonate Reservoir Characterization
By F. Jerry Lucia (1999)

Cumulative frequency plots of c (BVWi)



Geomodeling

- Maps are used to depict the structural elevation, thicknesses and reservoir properties and are the fundamental basis for a geomodel.
- Geomodels are increasingly being refined by continued improvements in well logging tools (formation imaging, NMR) and 3D seismic.
- Computer hardware and software are increasingly user-friendly with interoperability to facilitate distributing reservoir properties into a 3D volumes.
- Integration with engineering is facilitated – material balance, volumetrics, test, and performance used to validate and refine the model.
- A refined and validated reservoir model is then suited for use in targeting additional oil and gas recovery.
- Geomodels are as good as geological framework and concepts employed in them.


Kansas' version of Geoengineering modeling – web-based tools – "doing simple reservoir modeling versus none at all"
Well Level Analysis Applets
Gemini User/Project Module
Field Level Analysis Applets
Well Profile Module
Volumetrics Module
PfEFFER Module
KGS Server
apache - jserv
Cross Section Module
DST Module
Java Servlets
Material Balance Module
KGS Database & Files
PVT Module
Synthetic Seismic Module
Fluid Catalog
• 284,772 lines Java code
• 908 files
• Level 2 compliant code and documentation
KHAN
Ks hydrocarbon association navigator
Rock Catalog
Rock & Fluid Characteristics Tables and Applets