Chester Incised Valley System, Haskell and Seward Counties, Kansas

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Presented at the Kansas Geological Society

IHR Improved Hydrocarbon Recovery LLC

Ihr-llc.com

SUNFLOWER ENERGY LLC

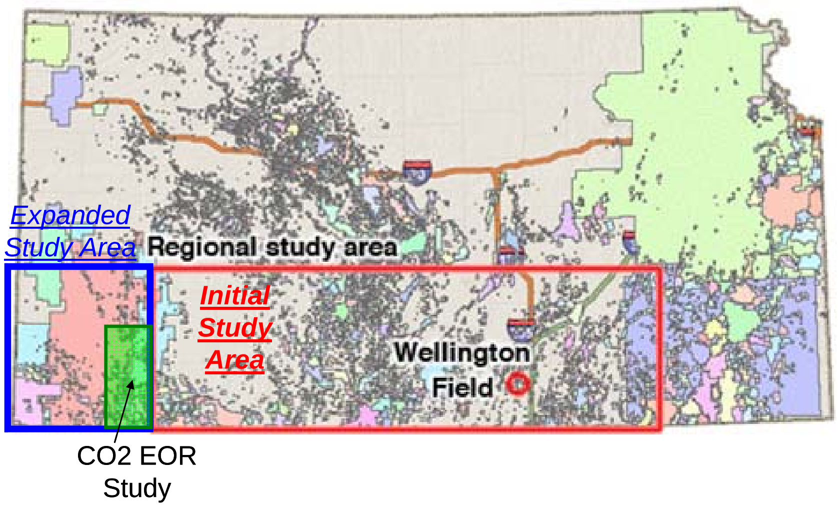
HEDKE-SAENGER GEOSCIENCE, LTD

WILLIAMS PETROLEUM CONSULTING

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

Southwest Kansas CO2 EOR Initiative Chester and Morrow Reservoirs

Western Annex to Regional CO2 Sequestration Project (DE-FE0002056) run by the Kansas Geological Survey



Six Industry partners:

- Anadarko Petroleum Corp.
- Berexco LLC
- Cimarex Energy Company
- Glori Oil Limited
- Elm III, LLC
- Merit Energy Company

Support by:

Sunflower Electric Power Corp.

The SW Kansas part of project

- CO2 EOR technical feasibility study – Chester IVF and Morrow
- Part of larger KGS-industry CCS and EOR study
- Will not inject CO2 – paper study only
- Get fields in study "CO2-ready"

Technical Team:

	Project Role	Company
Martin Dubois	Team Lead, geo-model	Consultant - IHR LLC
John Youle	Core & depo-models	Consultant - Sunflower
Ray Sorenson	Data sleuth & advisor	Consultant
Eugene Williams	Reservoir engineering	Williams Petrol. Consultants
Dennis Hedke	3D Seismic	Consultant - Hedke & Sanger
Peter Senior	Reservoir modeling	MS student
Ken Stalder	Geotech	IHR, LLC
Susan Nissen	3D Seismic	Consultant
Lynn Watney	Project PI	KGS
Jason Rush	Project PI	KGS
John Doveton	Log Petrophysics	KGS
Paul Gerlach	Data support	Consultant - Charter

Modeling Status and Outline

Current project status (April, 2013) by field:

Pleasant Prairie South	3D geomodel and flow simulation complete
Eubank North Unit	3D geomodel and flow simulation underway
Shuck	3D geomodel under construction

Outline

Introduction

- Stratigraphic and geologic setting
- Fields' statistics and histories

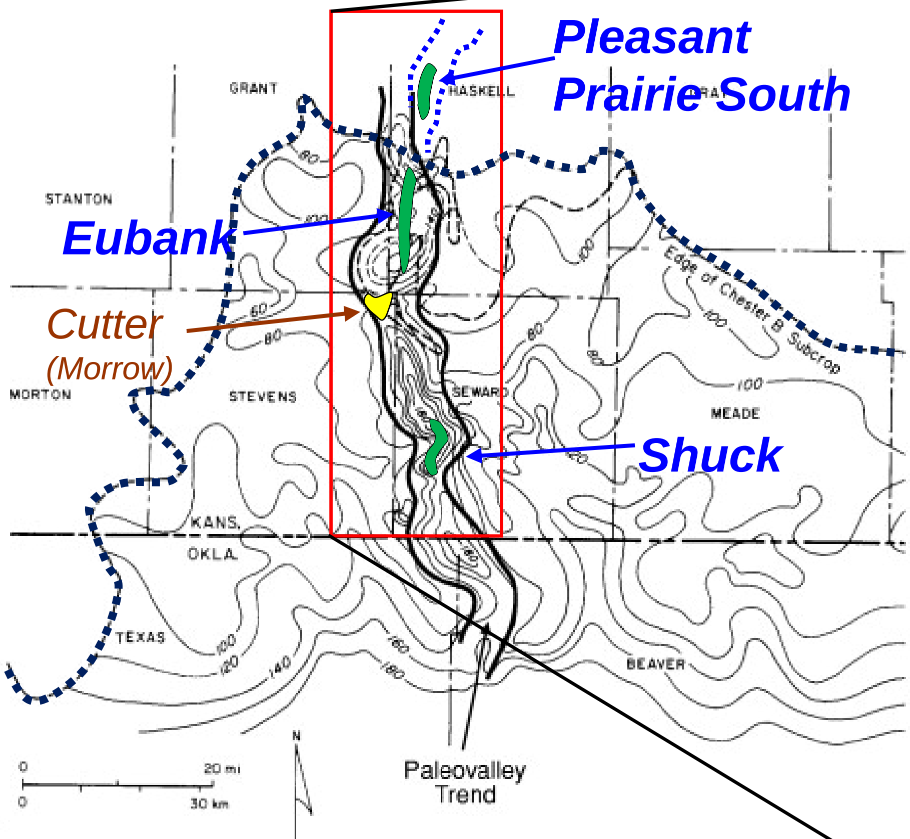
Geology

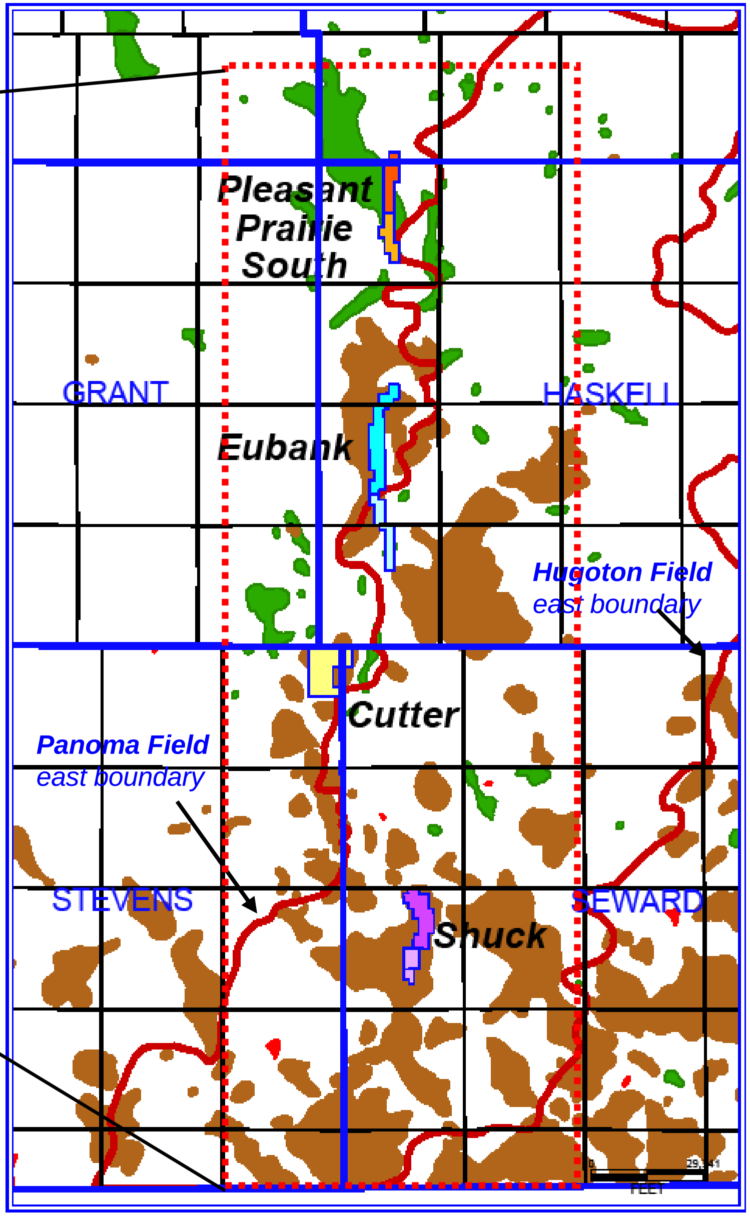
- Evolution of Chester incision
- Valley fill and sequence stratigraphy

Modeling and Simulation

- Workflow
- Static 3D modeling
- Flow simulation

Fields in study in relation to Chester Incised Valley

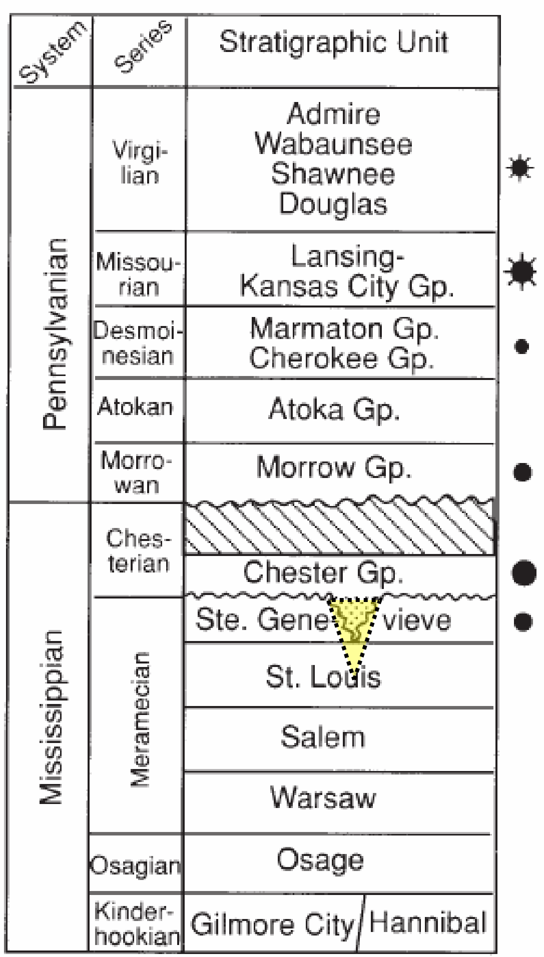




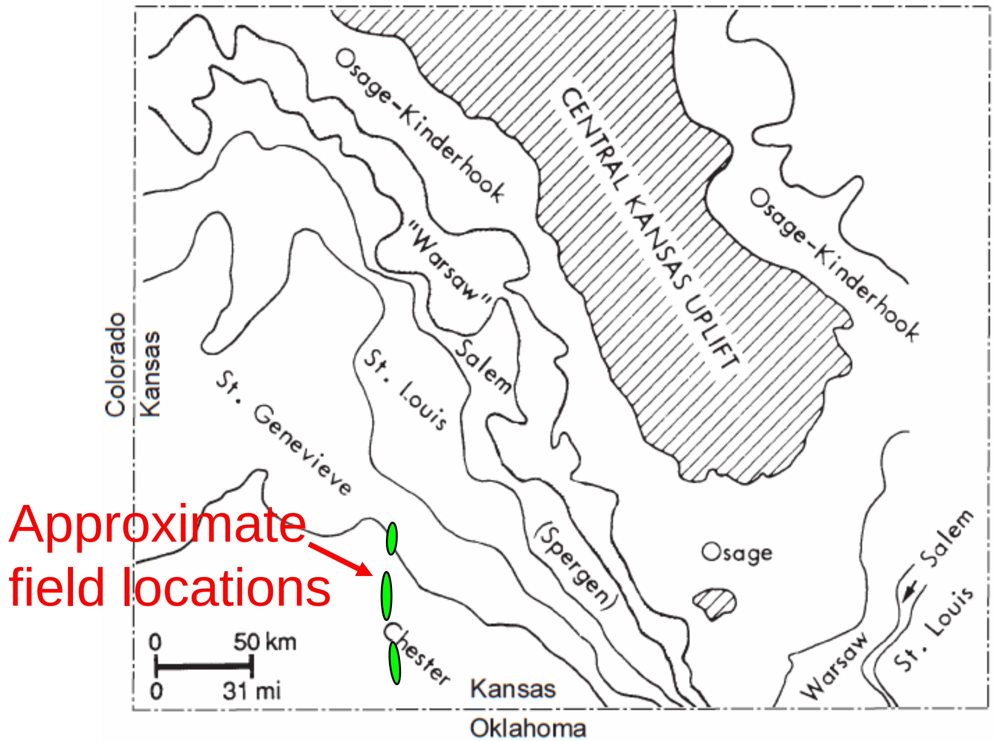
(Above) Regional isopach of lowermost Chesterian incised valley fill (*Montgomery & Morrison, 2008)*

(Right) Four fields in study. Green – Oil; Brown – Oil and Gas. Grid is Township-scale (6 mi.).

Stratigraphic setting



Generalized stratigraphic column (Montgomery and Morrison, 1999).



Subcrop pattern for Mississippian strata, western Kansas (Ebanks, 1991).

Valley incision took place during exposure of the Meramecian. Subsequent Chesterian transgression, punctuated by still-stands filled the narrow, nearly linear valley with fine-grained reservoir sand.

Field statistics and histories

	Discovered by	Disc. Year	Development (pre-3D)	3D shot	Post 3D drilling	Water flood start	Injectors	Oil Wells	Current Status	EUR - P&S (mbo)
Pleasant Prairie So	Helmrich & Payne	1990	Only 2 wells added pre-3D	1998	19 wells	2002	9	13	near end of waterflood	**4,600**
Eubank North	Anadarko Petroleum	1959	5 total by 1965; 9 total pre-3D	1995	26 wells	2004	11	24	downslope waterflood	**7,500** est. from
Shuck	Anadarko Petroleum	1978	have not reviewed history	~1995	few	1989	~13	~22	waterflood end ~2000	**7,900**

Oil Volumes

Recovery Factor (% OOIP)

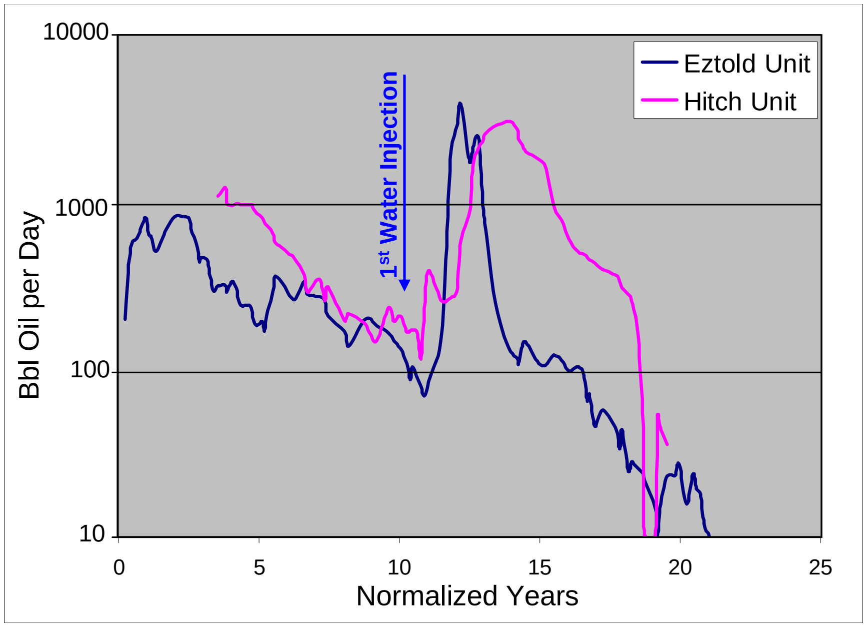
	Study	OOIP (mbo)	Primary (mbo)	Second. (mbo)	Ultimate	Primary	Secondary	EUR - P&S
Pleasant Prairie South	SW Ks CO2 project	14,641	2,320	2,320	4,640	**15.8%**	**15.8%**	**31.7%**
Eubank North	Anadarko	21,177	3,484	4,035	7,519	**16.5%**	**19.1%**	**35.5%**
	SW Ks CO2 project	25,261	3,484	2,416	(thru 2012)	**13.8%**		**TBD**
Shuck	Anadarko actual history	23,542	3,546	4,352	7,898	**15.1%**	**18.5%**	**33.5%**

Eubank North Unit Geomodel OOIP is based on a seismic-defined valley that is slightly wider than that in Anadarko waterflood study

Shuck Field, Hitch and Etzold Units

<u>Shuck Waterflood Units Unit</u>

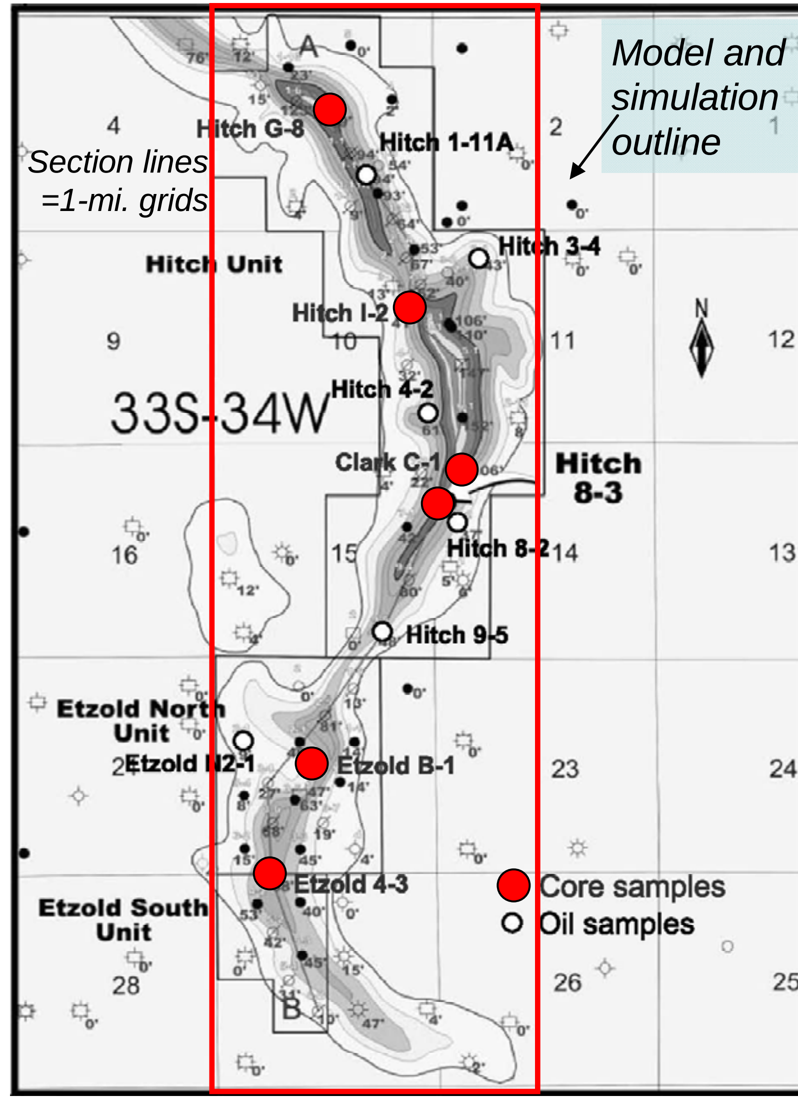
Discovered:	**1978**
Waterflood:	**1989**
Pre-WF:	3.53 mmbo
Since WF:	4.28 mmbo
Cumulative:	**7.81 mmbo**



(Above) Production plots for Hitch and Etzold waterflood units in Shuck Field, normalized to waterflood initiation.

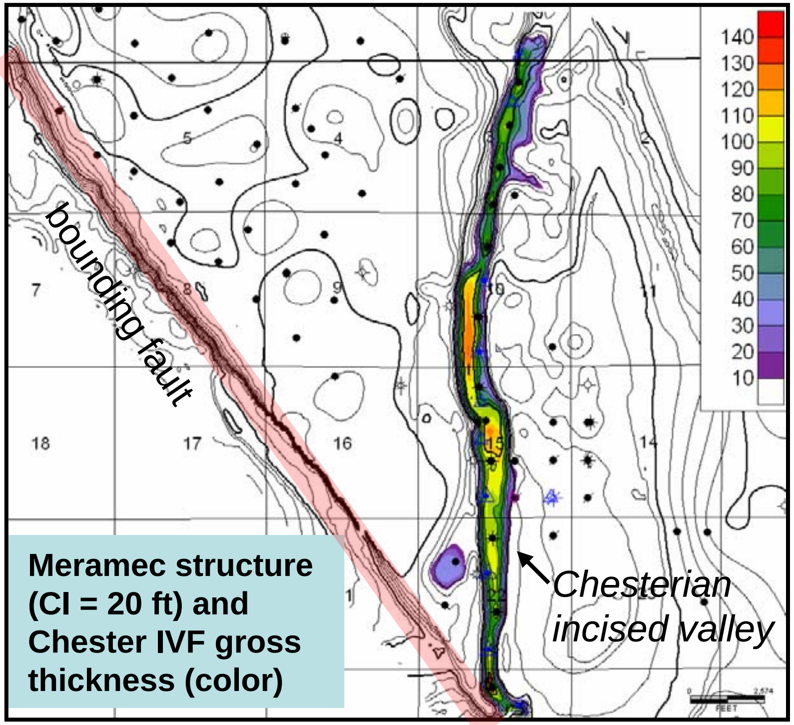
(Right) Isopach map of the net basal Chester sandstone, >8% porosity, contour interval 20 ft.

Planned

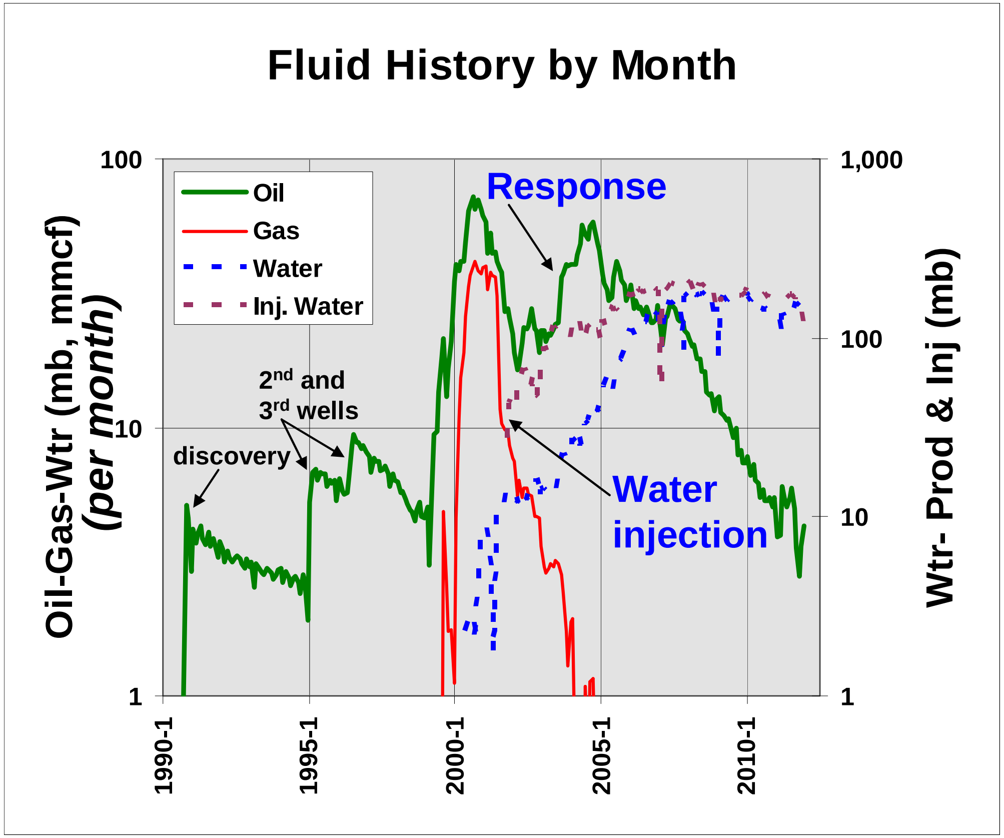


(from Kim, Philip, and Sorenson, 2010).

Pleasant Prairie South Field Summary

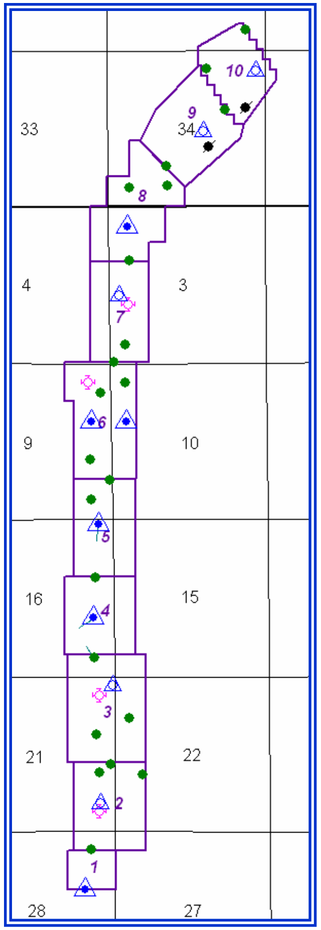


Chester IV (Pleasant Prairie South) cuts through Pleasant Prairie, a faulted anticline producing from the St. Louis (34 mmbo).

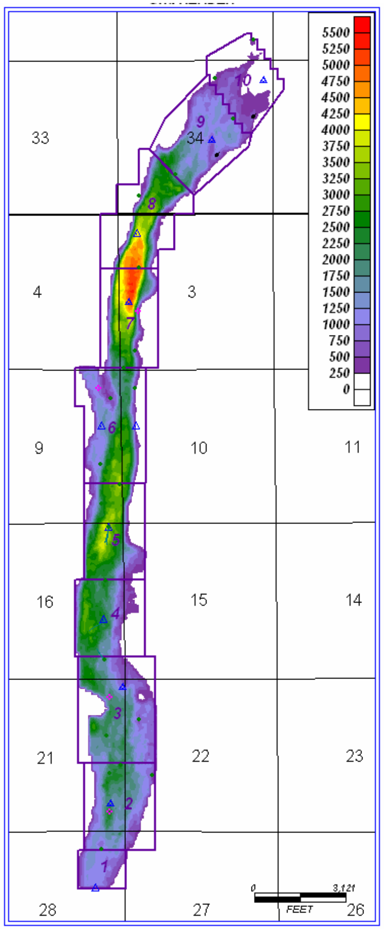


Producing zone	Miss. Chester	**WF recovery**	Appx 50% of cum.
Discovered	1990	**Oil wells total**	18*
Waterflood	2002	**Current oil wells**	13
Cumulative Oil	4.4 mmbo	**Current wtr inj wells**	9
Cumulative Gas	0.7 BCF	**5 oil converted to injectors*	

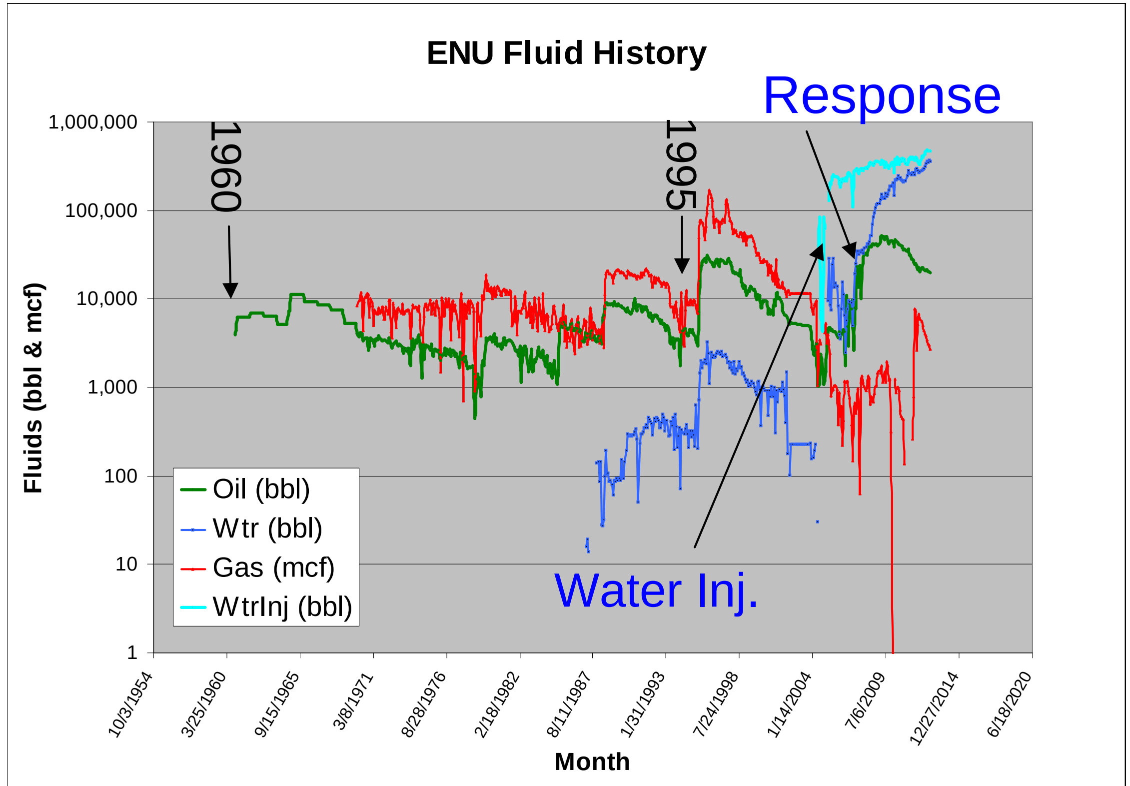
North Eubank Unit

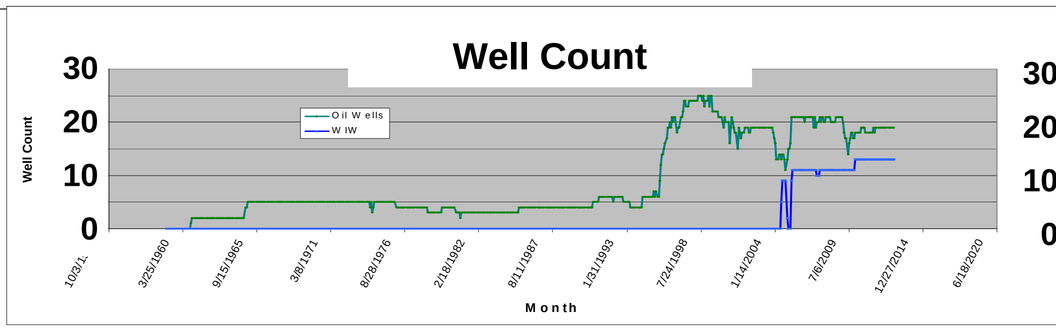


39 wells in 2004



OOIP STB/10 ac





Discovered	**1960**	**Primary**	3,484 mbo
Developed	post 1995 3D	**Secondary**	TBD
Waterflood	2004	**Oil wells total**	24
Cumulative Oil	5.9 mmbo	**Current oil wells**	19
Cumulative Gas	7.7 BCF	**Current wtr inj wells**	11

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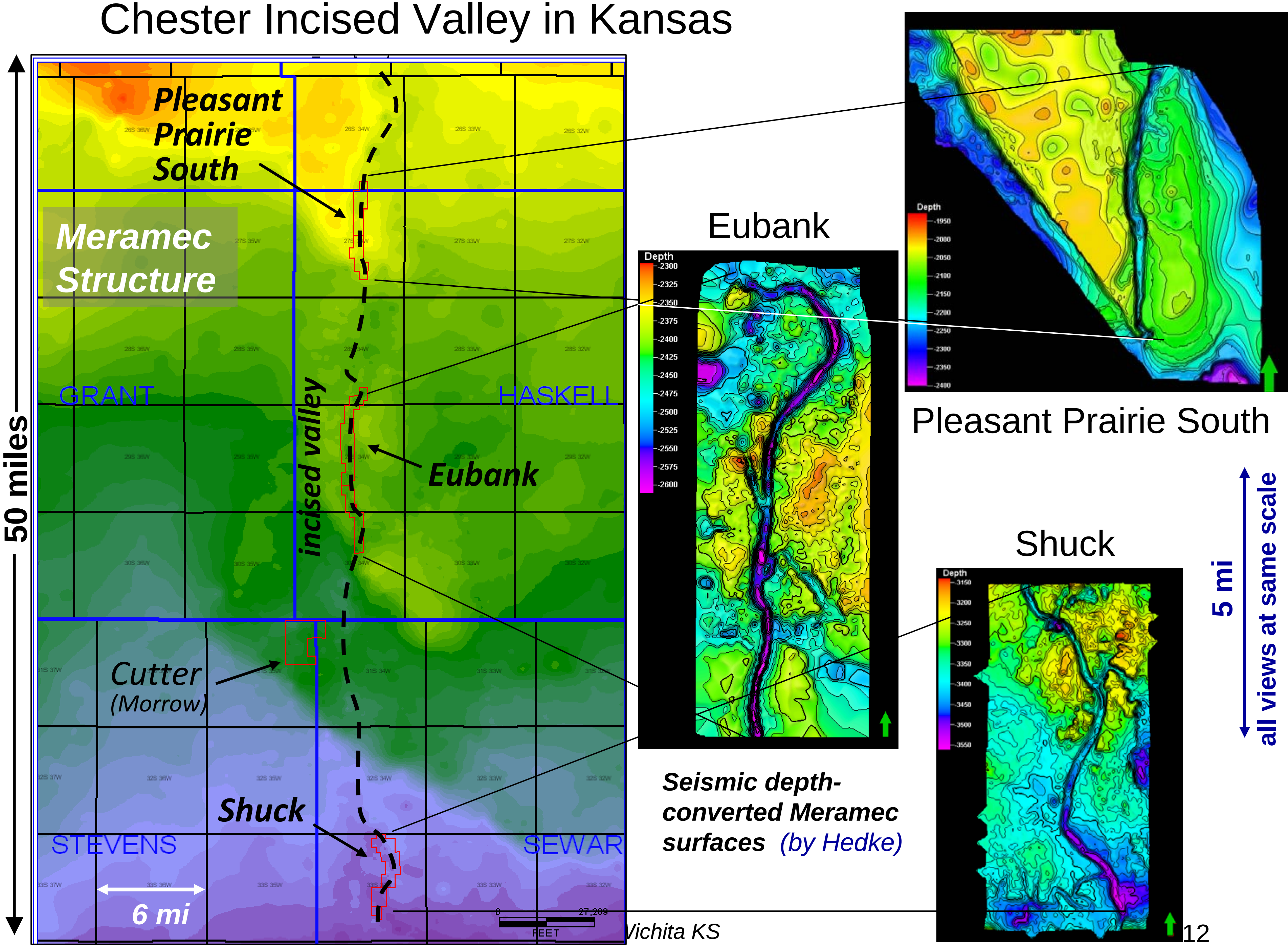
Evolution of Chester Incision and Fill

Exposure and incision

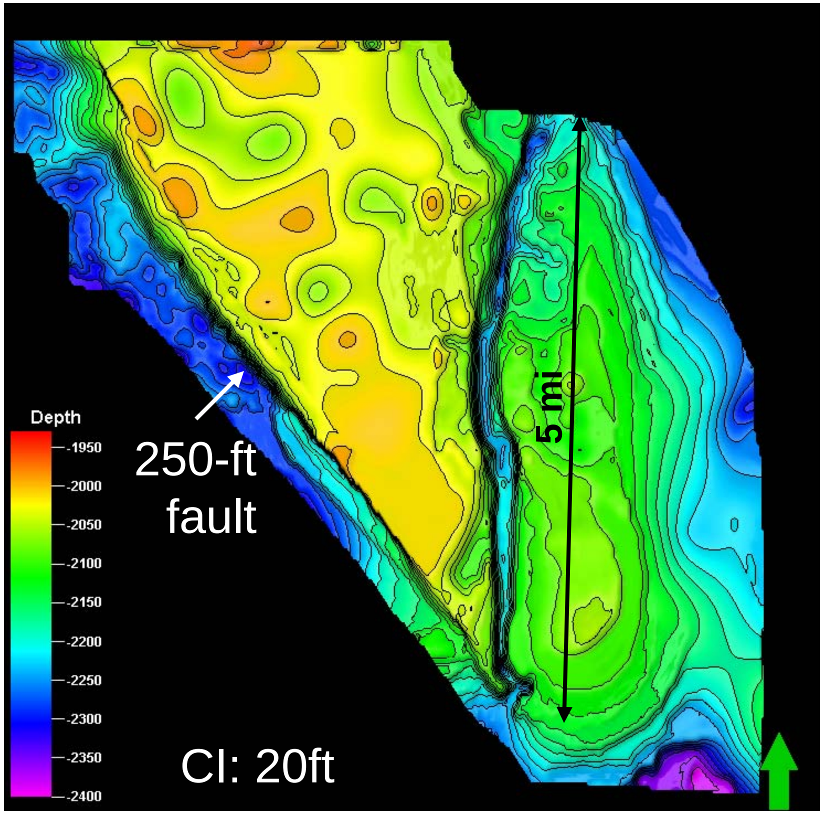
- Mississippian carbonate rocks deposited on a broad relatively **shallow platform through Meramec**
- Widespread post-Meramecian **subareal exposure**
- **Deep fluvial incision** formed a nearly linear, narrow, deep valley in the Meramecian surface.
- Location of incision in places appears to have been **related to reactivated basement fractures and faults** and associated karst in the Mississippian and as deep as the Arbuckle
- Incised valley **may be more linear** over present day major positive structural features

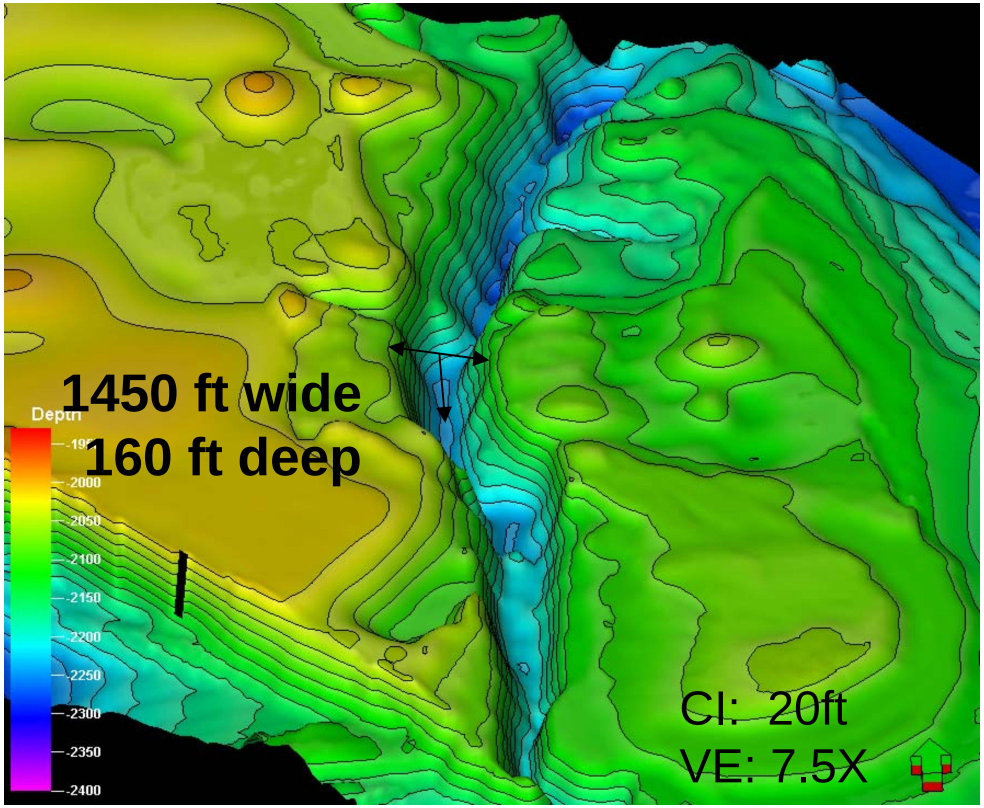
Chester Incised Valley in Kansas



Seismic depth-converted Meramec surfaces (by Hedke)

Peasant Prairie South

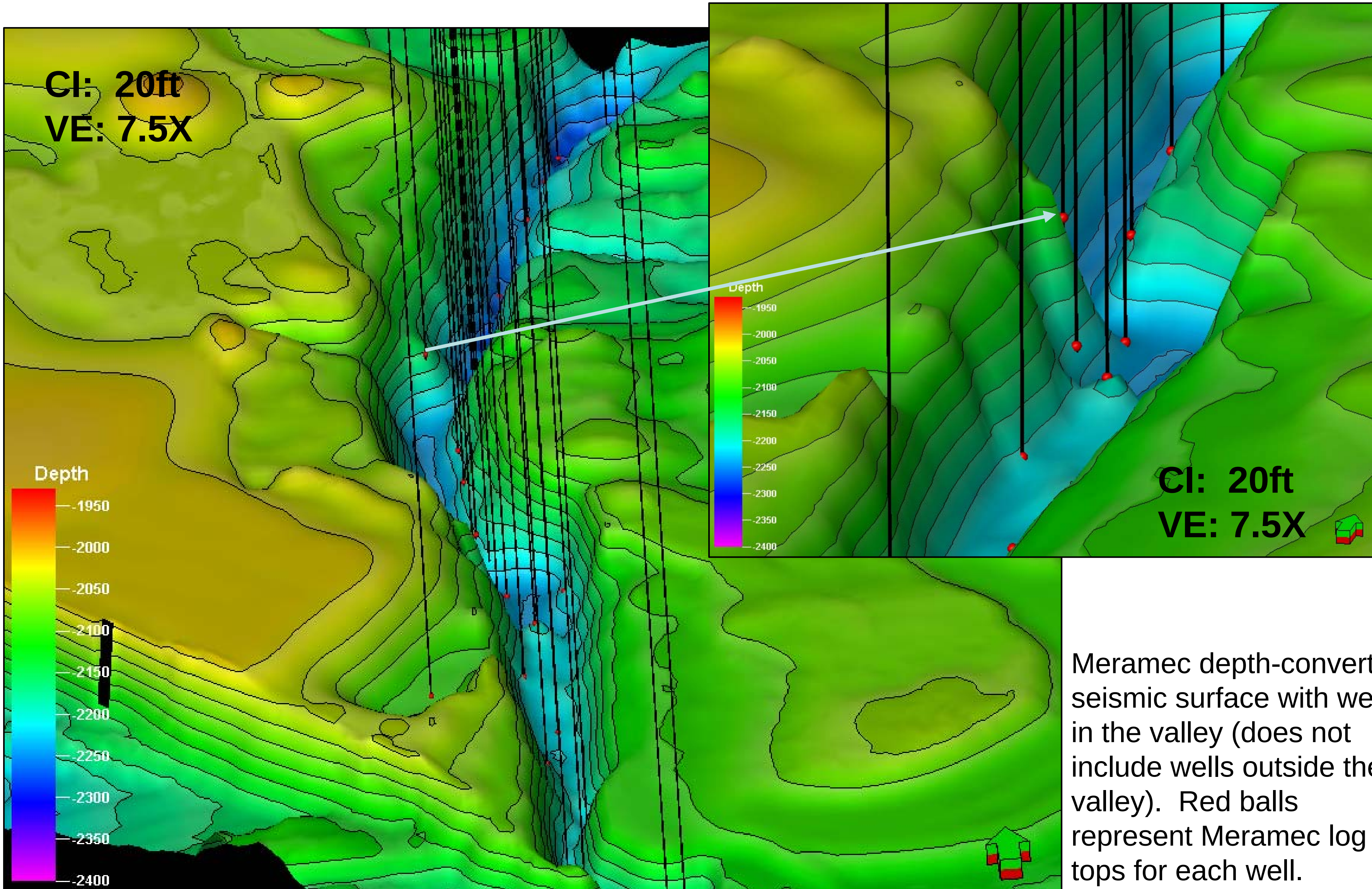




Pleasant Prairie faulted anticline has produced 39 mbo primarily from the St. Louis. Pleasant Prairie South Chester IVF reservoirs have yielded 4.4 mbo.

Seismic depth-converted Meramec surface (*smoothed*). 1450 ft maximum width at top of valley.
Seismic interpretation by Hedke

Other Pleasant Prairie views with IVF wells

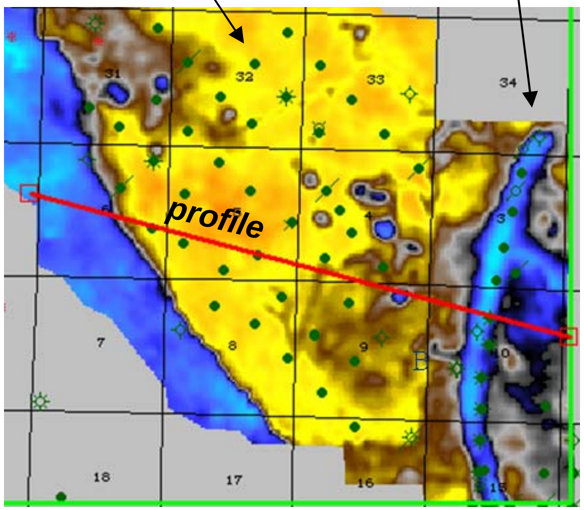


Meramec depth-converted seismic surface with wells in the valley (does not include wells outside the valley). Red balls represent Meramec log tops for each well.

Pleasant Prairie IV related to deeper, older structure

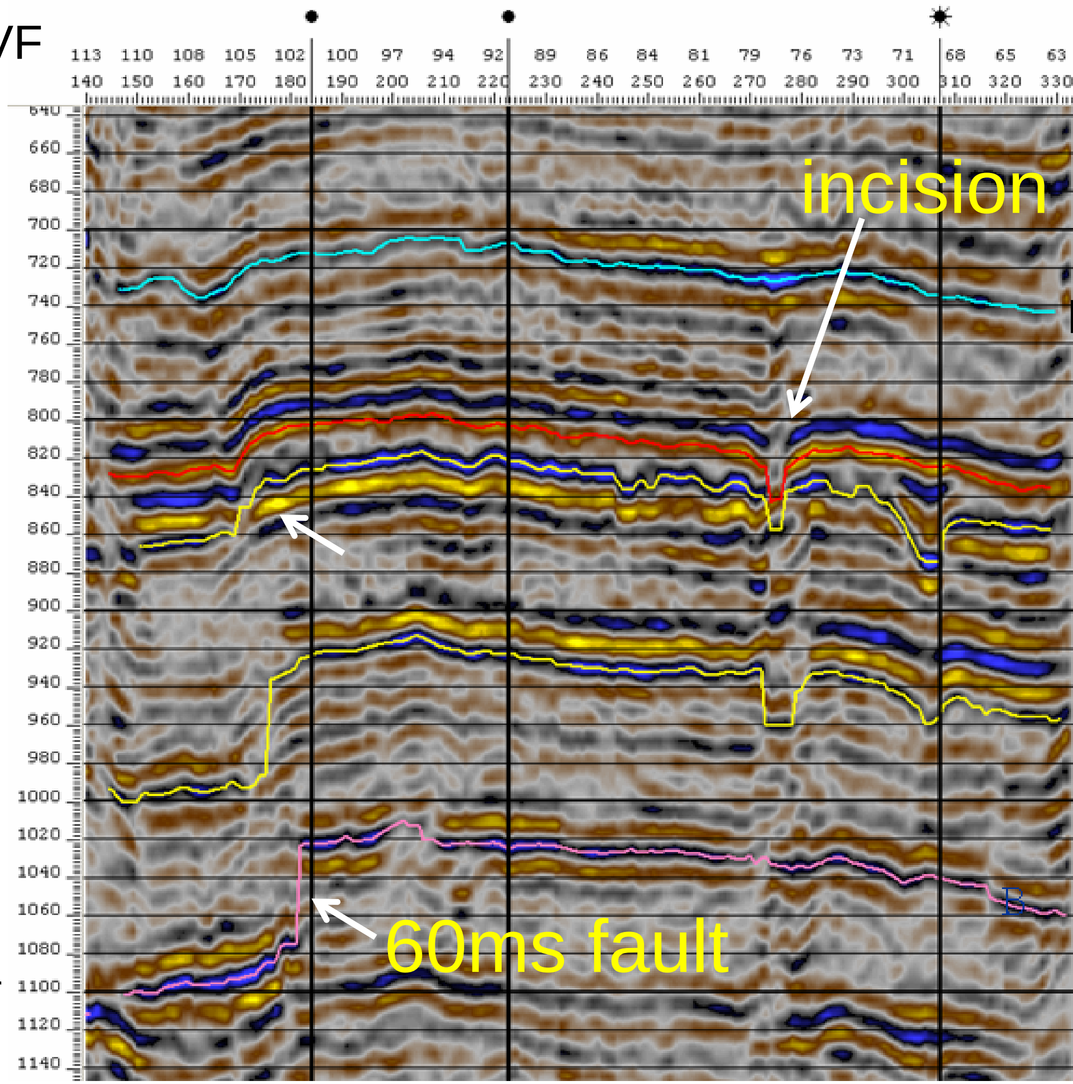
St Louis wells

Chester IVF



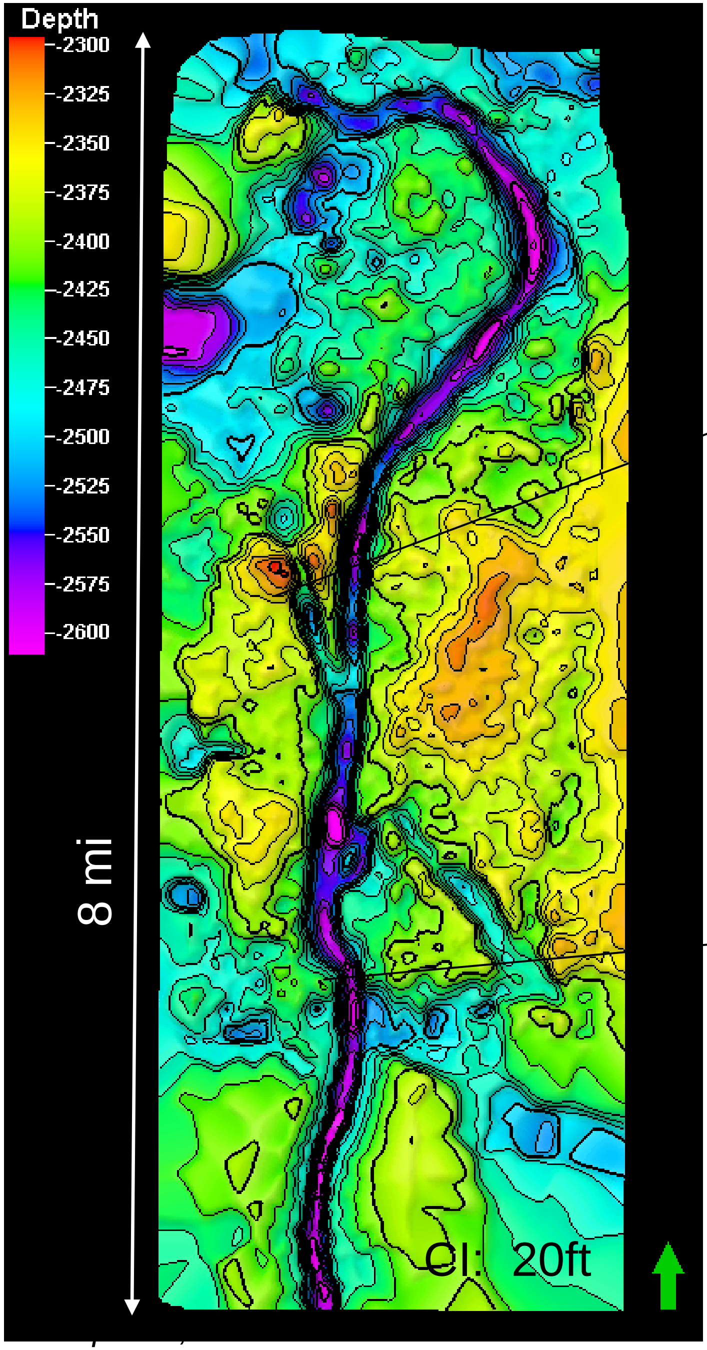
Meramec Time Structure

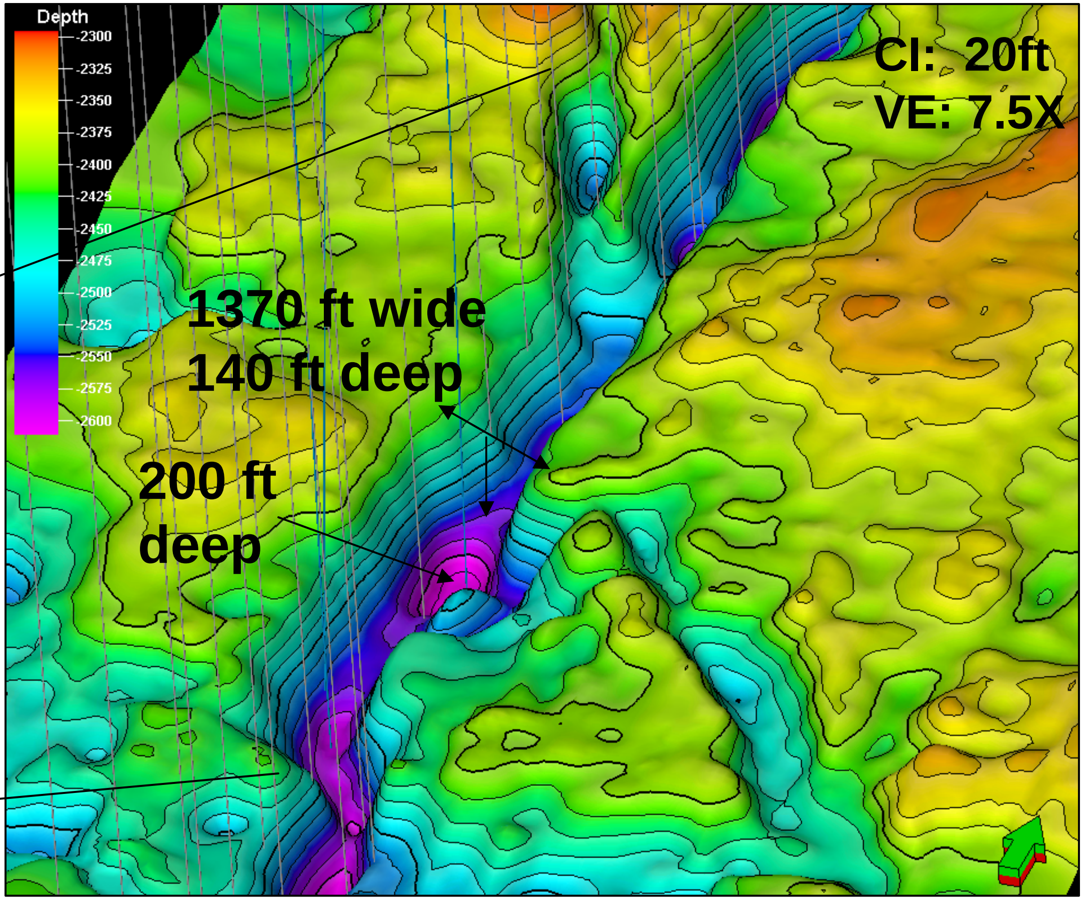
- Down-to-west bounding fault with 60ms throw on Precambrian and Arbuckle. Possibly less throw at Meramec (if not accounted for by erosion/removal)
- Incised valley may be associated with basement fracture and deeper karst in Arbuckle
- Karsted Meramec surface evident in time structure



Interpretation work by Dennis Hedke

Eubank

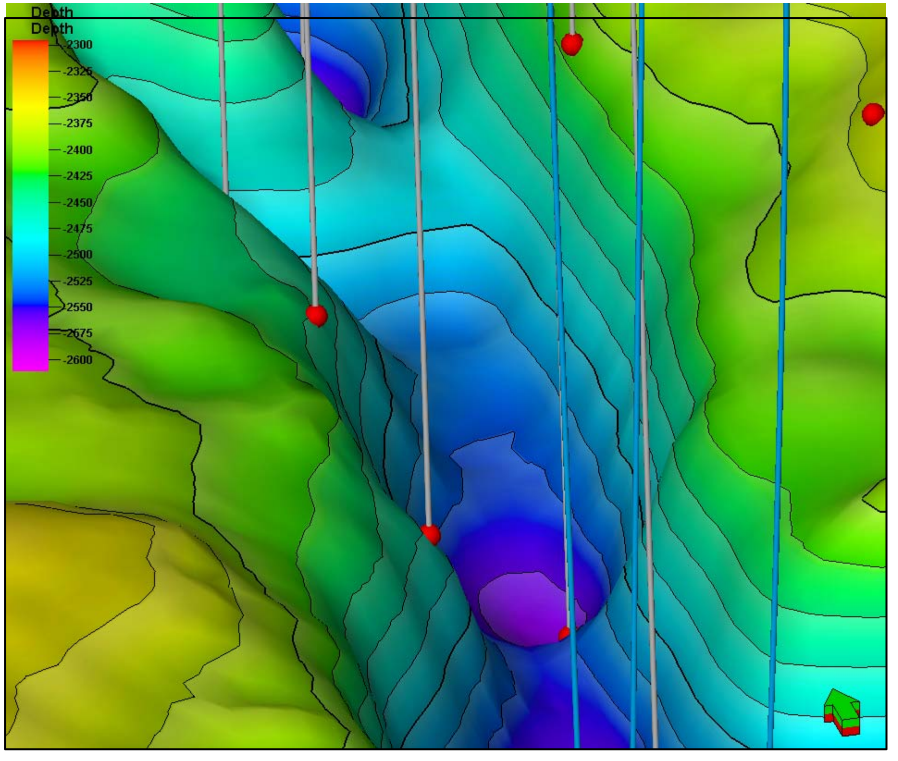


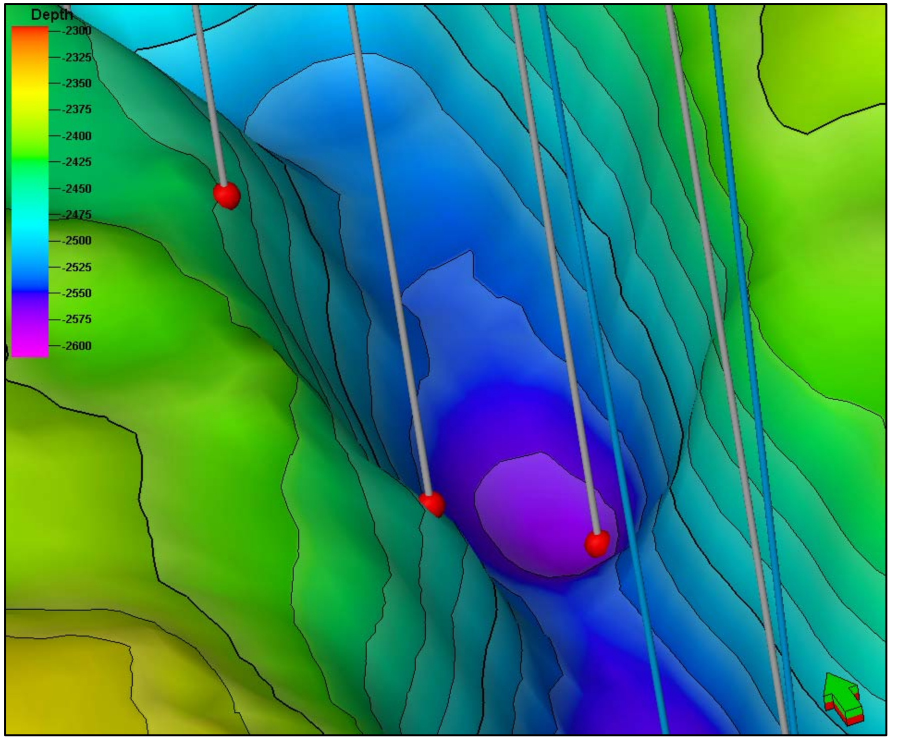


Seismic depth-converted Meramec surfaces

Seismic interpretation by Hedke

Eubank – depth ties



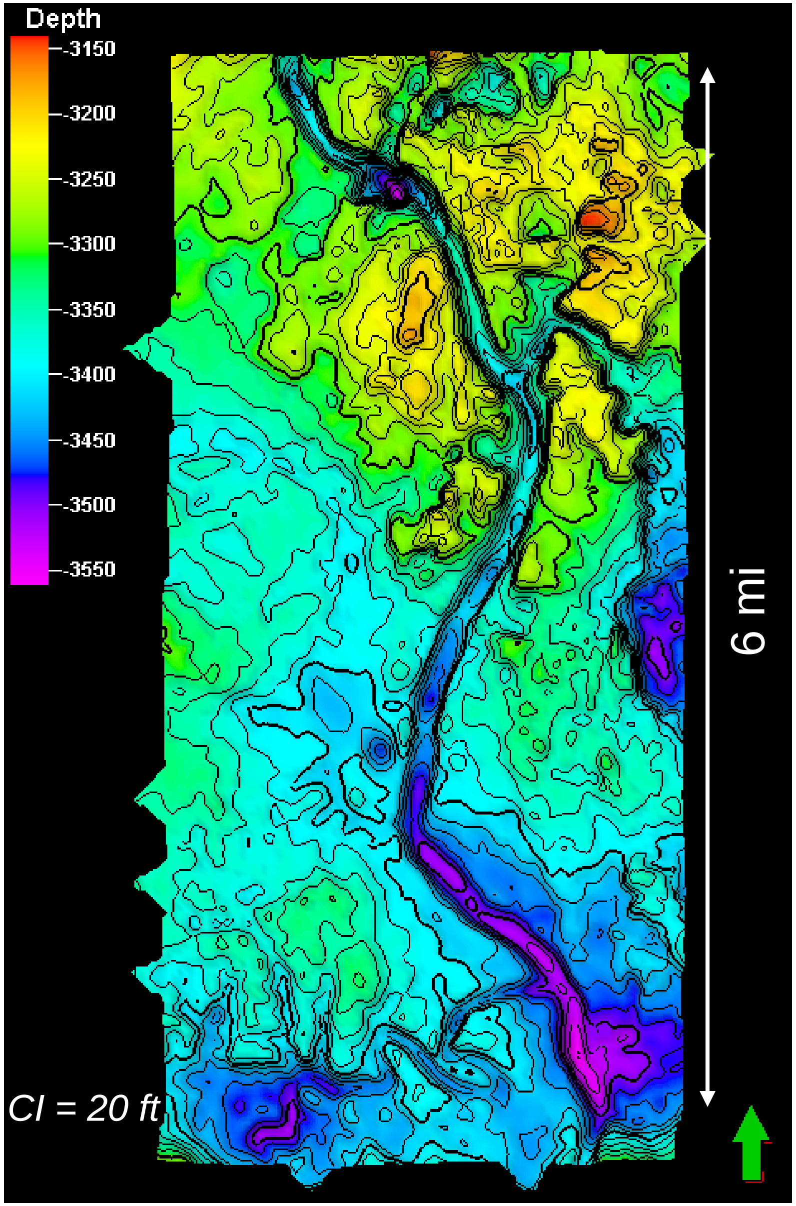


Valley walls and irregular floor tied to well measured tops – same view, different perspective. Red dots are Meramec tops intersected by the depth-converted Meramec seismic surface. Isolated lows in valley floor, confirmed by well penetration, may be karst-related sink holes.

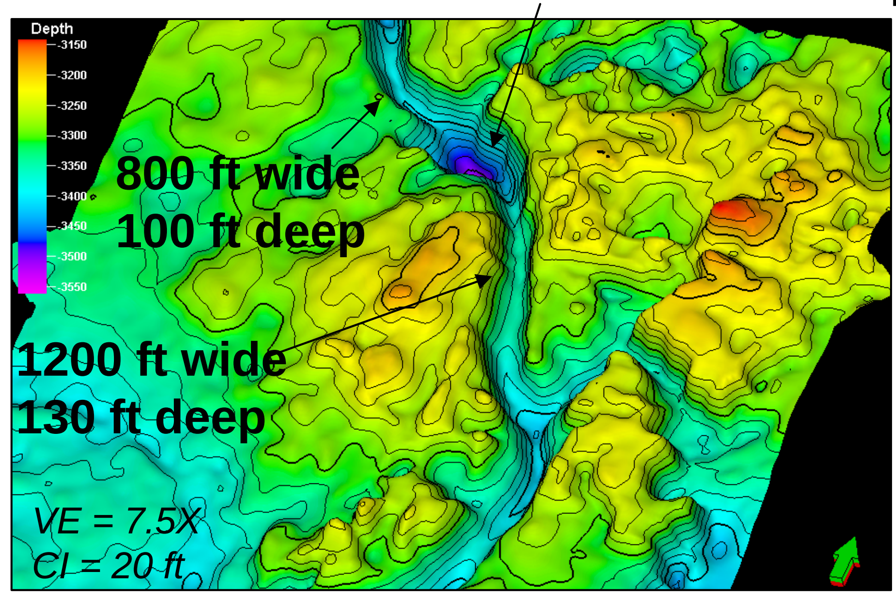
Shuck

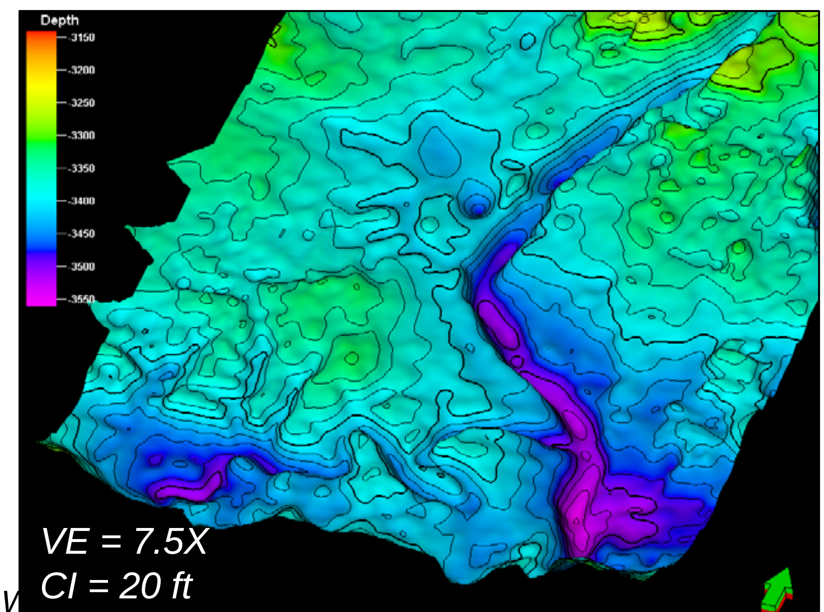
Seismic depth-converted Meramec surface

Seismic interpretation by Hedke



Post-Chester sinkhole forms trap





KGS, V

Chester Incised Valley Fill

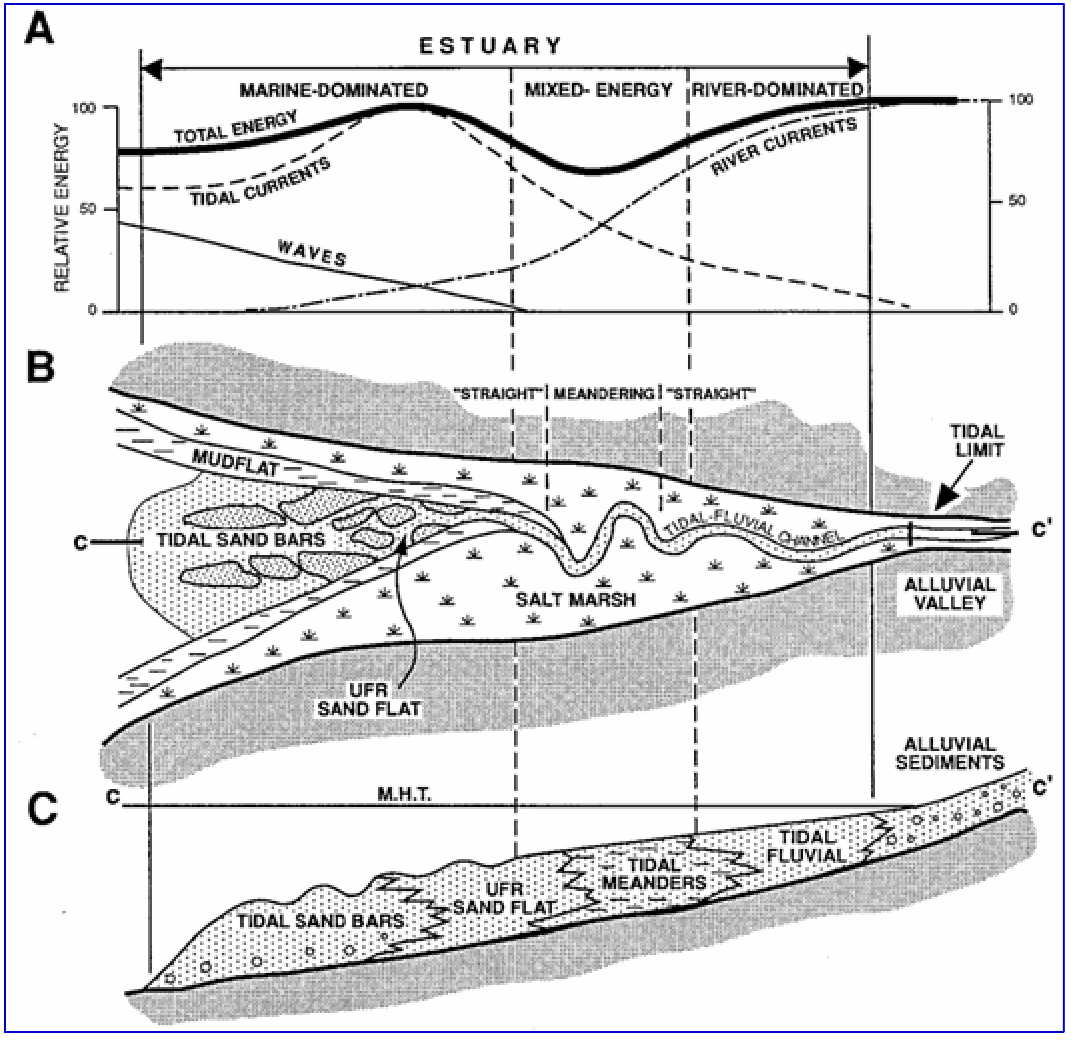
Valley fill *(based on work by Youle and Senior, project technical team members)*

- As Chesterian seas onlapped the exposed Meramecian surface the valley was **filled by a fluvial-estuarine system** from south to north
- Incision still may have been occurring north of the Chester shoreline during fill south of the shoreline
- **Oldest Chester fill is to the south**, youngest is to the north.
- Depositional environments are more **marine and tidal-influenced to the south.** More **fluvial influence to the north.**

IVF Depositional Environment

Shuck and Eubank valley-fill sediments are primarily tidal-dominated estuarine-type deposits, although some are more related to Dalrymple et al's (1992) wave-dominated estuary system (Youle).

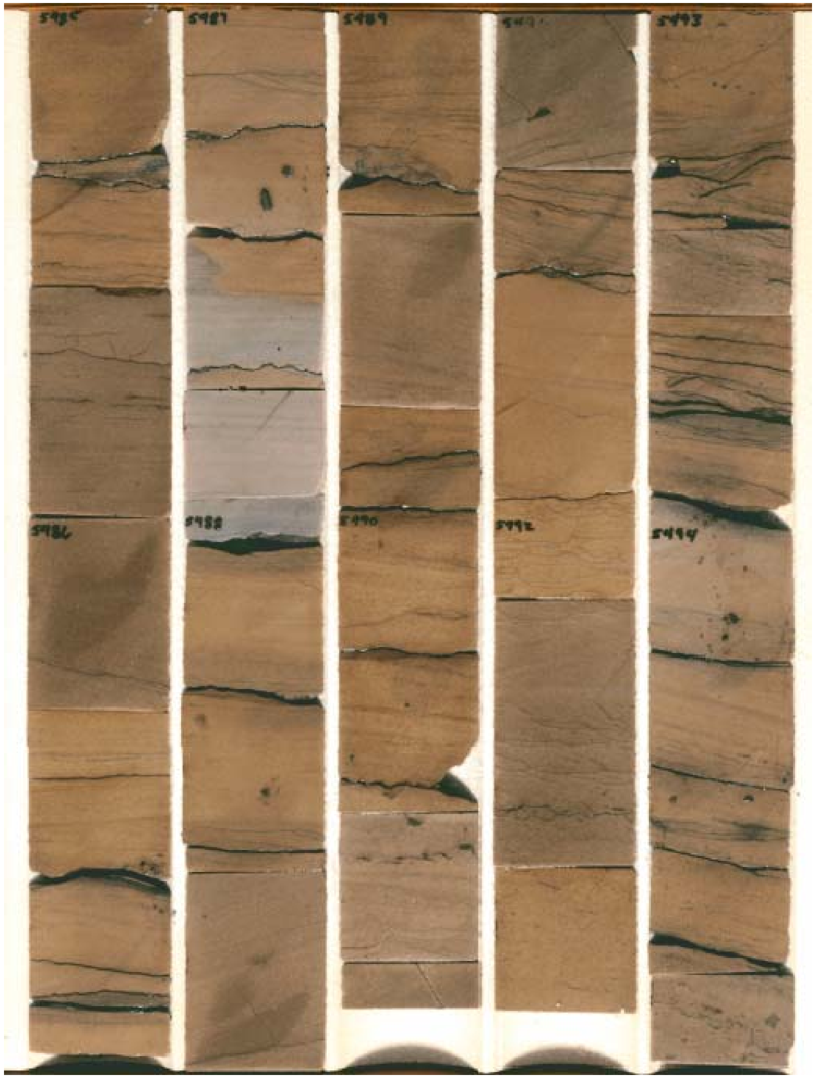
Pleasant Prairie South has more fluvial influence but still some tidal influence (Senior).



Dalrymple et al (1992) tide-dominated estuary model

Eubank – Depositional Facies and Petrofacies

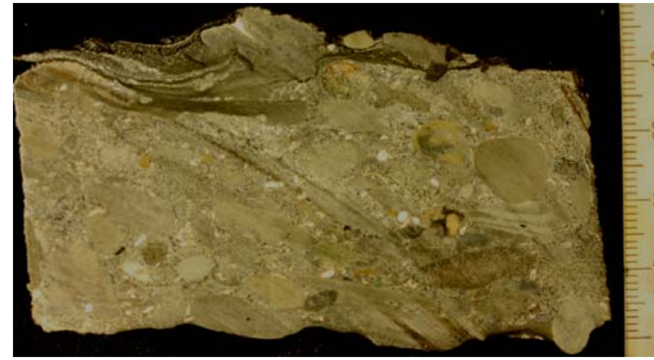
- **Depositional facies** are lithofacies defined in core deposited in a similar depositional environment
- **Petrofacies** are lithofacies identifiable on wireline logs. Multiple depositional facies may be in same petrofacies class
- **Youle defined five petrofacies** in Eubank and Shuck that can be defined by log signatures



Petrofacies 5 (main pay lithofacies) Figure 24. Estuary Bar sandstone depositional facies, very-fine to fine-grained sandstone lithofacies. Owens 3A core (MD 5465-5475).

Eubank Facies continued

Petrofacies 4 (below left)
Estuary Bar facies sandstones (Petrofacies 5) interbedded with shalier Estuary Bar Margin depositional facies, slightly shaley fine-grained sandstone lithofacies (Petrofacies 4). Facies are depositionally linked - deposited in immediately adjacent settings. (Hugoton Energy Black 4-3 core 5481-5491)



Petrofacies 3 (above)
Marine Transgressive Conglomerate lag depositonal facies, conglomerate lithofacies, lies on top of parasequence boundary FS P4. Lithoclasts of limestone, sandstone and shale in sandy bioclastic packstone. Grades upward into the Marine Shale facies **(Petrofacies 1).** (Hugoton Energy Black 4-3 core 5422.8)

Petrofacies 2 (left)
"Salt Marsh" facies depositional facies, sandy shale lithofacies**.** Soft sediment deformation and root traces noted. (APC Owens 3A 5595-5601)

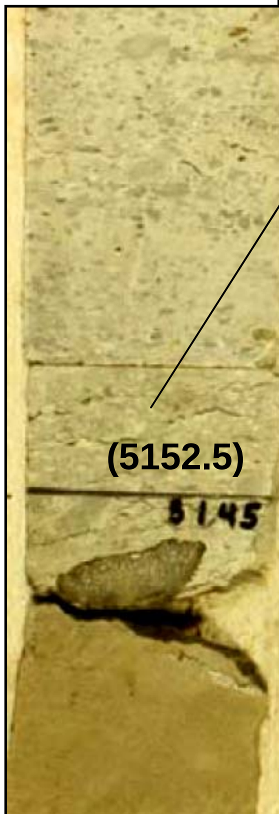
Petrofacies 1
Marine shale – not identified in core but recognizable on logs

Pleasant Prairie So. Lithofacies in core and e-logs (Senior)

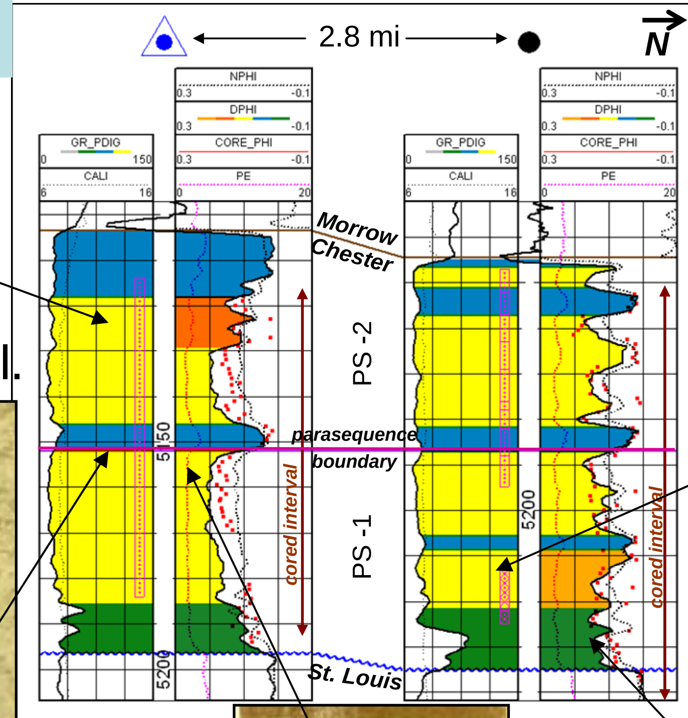
(log depth in parenthesis)

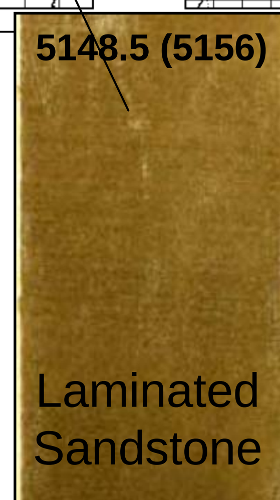
Pebbly Sandstone

Limey Congl.



Color fill Model lithofacies on left, Core on right

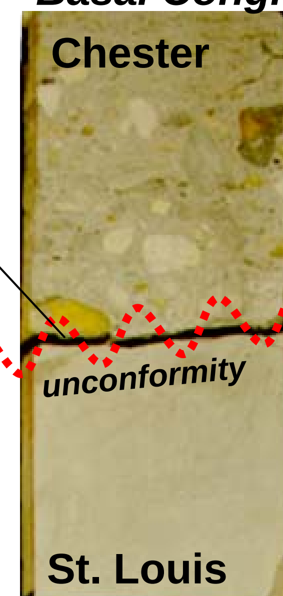




5218.5 (5213.5)

X-bedded Sandstone

Basal Congl.



5240.5 (5235.5)

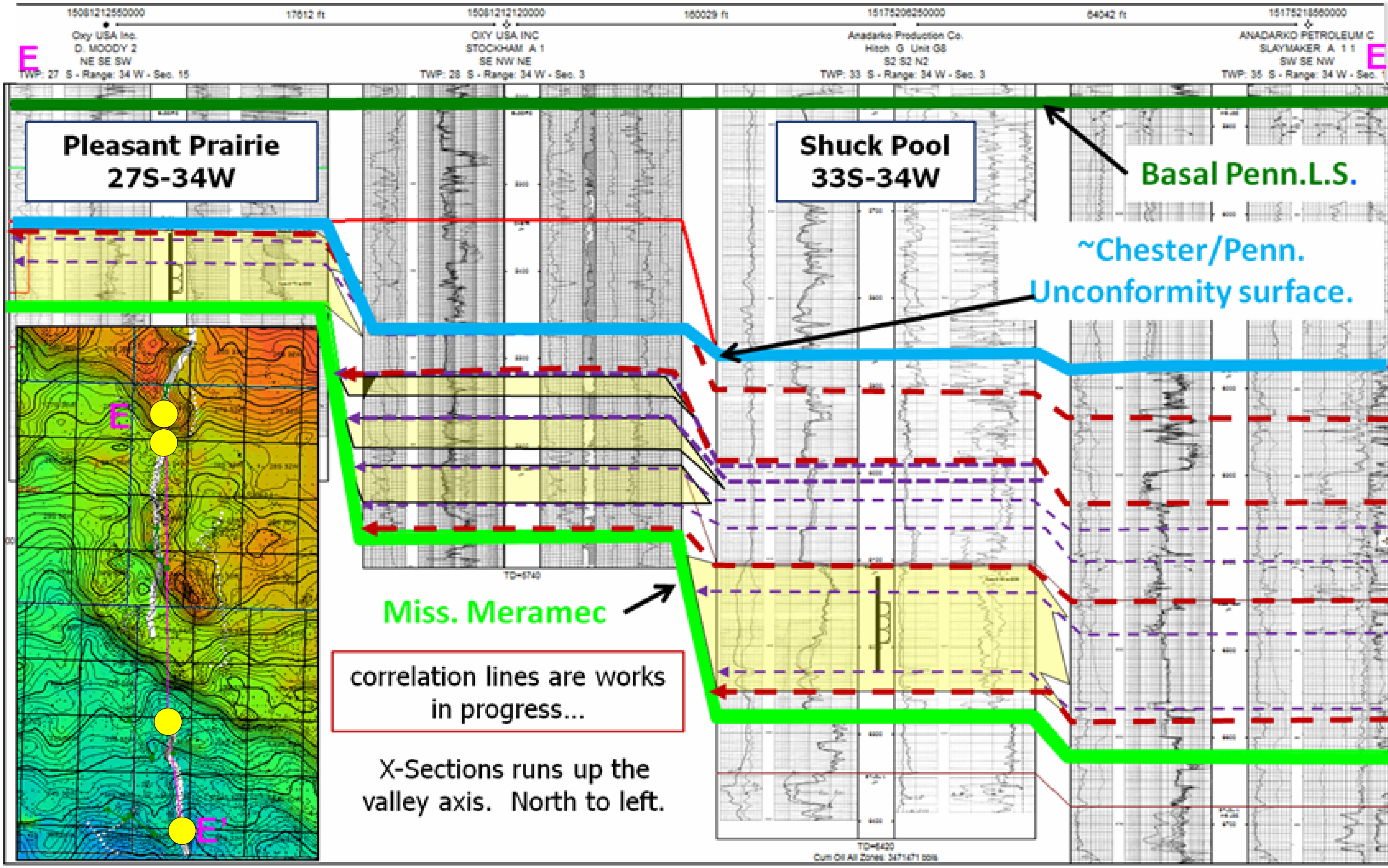
Main Lithofacies

Model	Core
3 limey congl	limey congl
4 reservoir ss	wkly strat/lam ss
	pebbly ss
	x-bedded ss
1 shale	shale
2 basal congl	basal congl

Not all core lithofacies are recognizable on logs and lumping was required.

North Chester Sequence Stratigraphy

work by John Youle



The cyclic retrogradational nature of Chester shoreline advances into Kansas are interpreted to have filled incised valleys with a series of 'back-stepping' stacked estuarine sandstone reservoirs. Red dashed lines are postulated sequence boundaries, and purple lines are possible parasequences. *(Youle)*

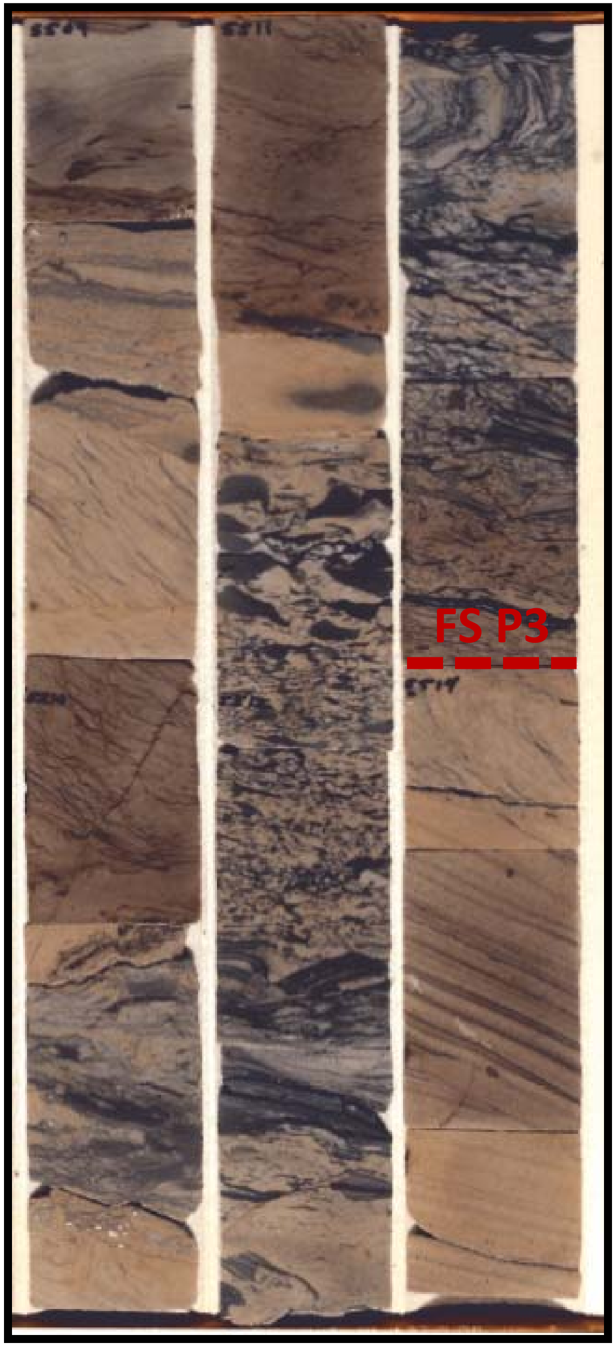
Parasequence Boundaries recognized in core

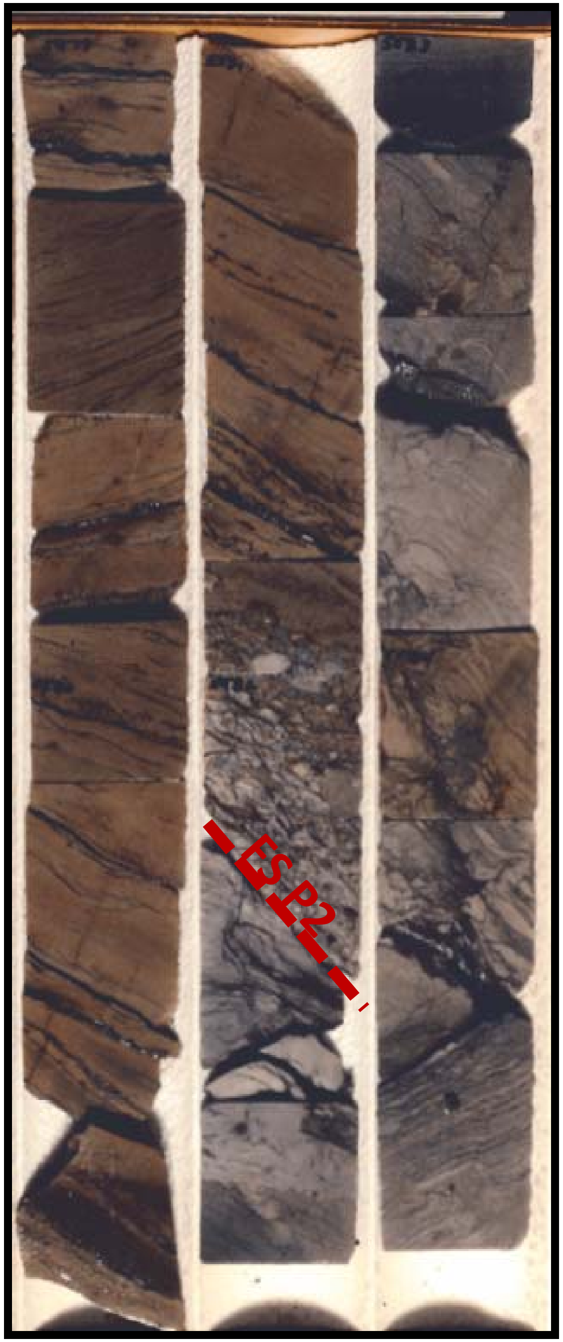
Key parasequence boundaries marking acceleration in Chester sea onlap are recognized in core and correlated with wireline logs in wells without core.

(Left) **Flooding Surface for PS3 at 5514.** Maximum flooding surface for PS3 is appx. 10 ft above this surface. (core 5509-5515)

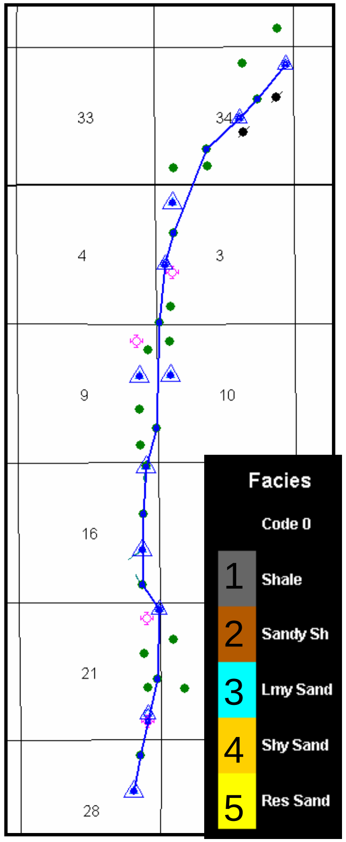
(Right) **PS2 Flooding surface at 5581.5**, Estuary Bar and Bar Margin facies of PS 2 lying sharply above intertidal to supratidal "Salt Marsh" facies. (core 5579-5586)

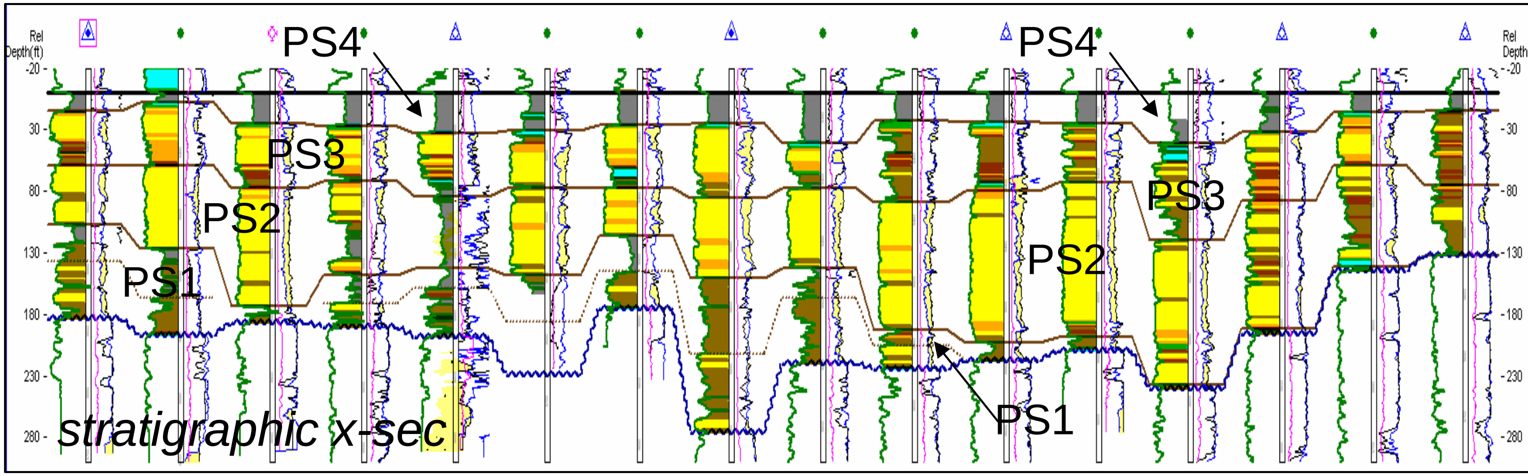
(work by Youle)

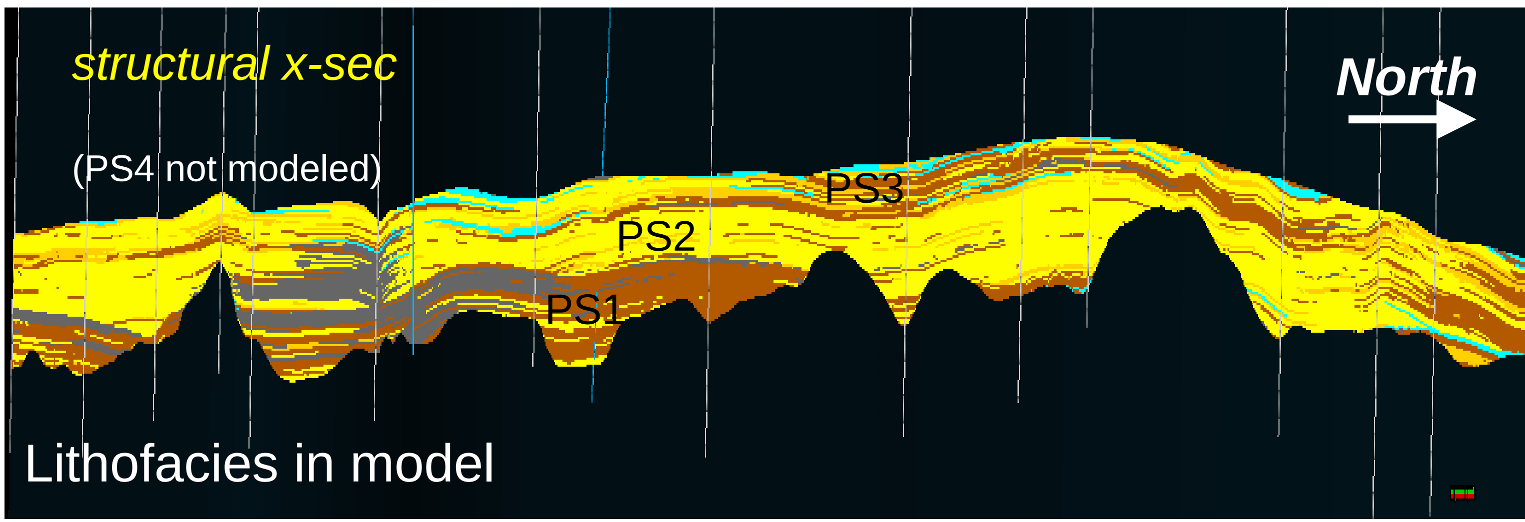




Eubank North, Parasequences in logs and model



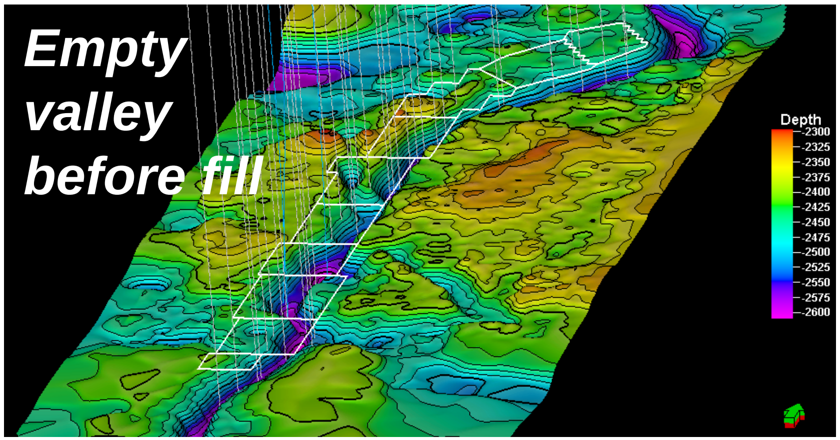


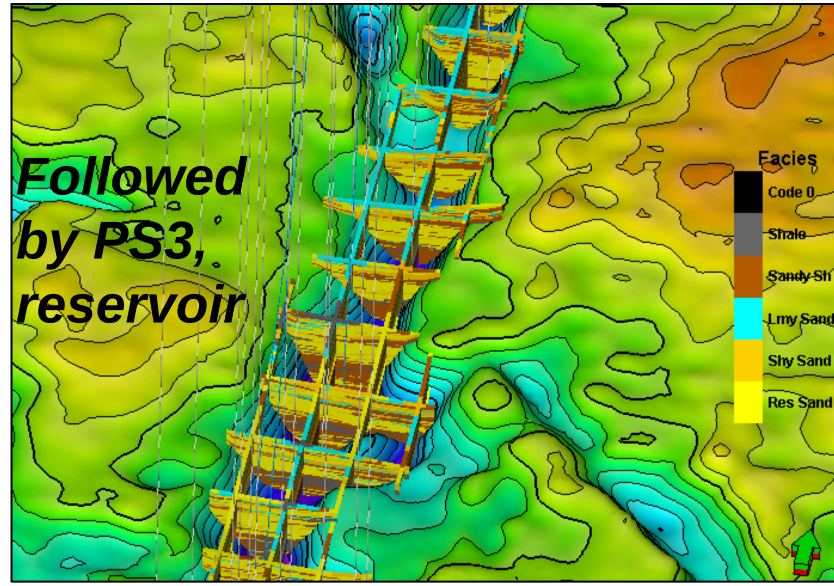


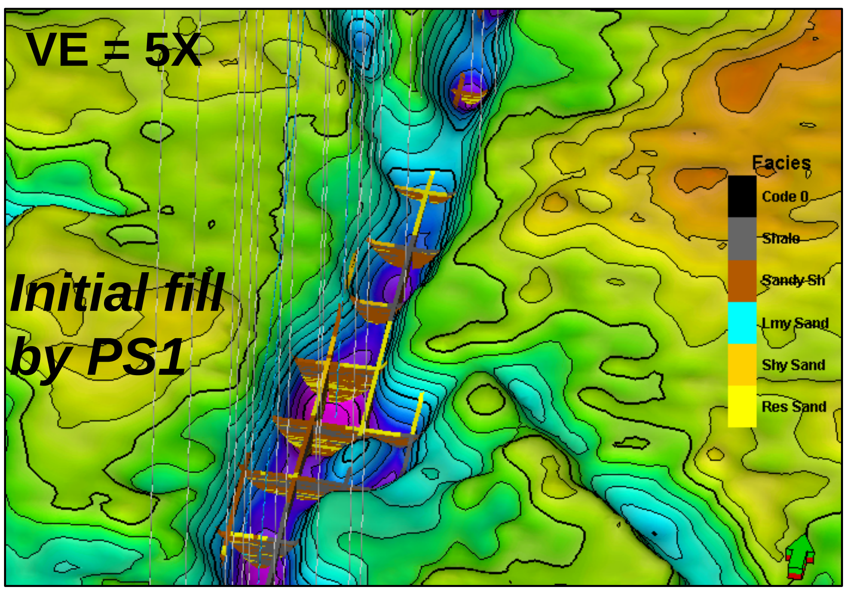
Four parasequences in North Eubank unit area. Wireline x-sec is not to scale. Model x-sec has true horizontal scale along similar path, but crosses “bumps” in straight line between wells rather than center of valley.

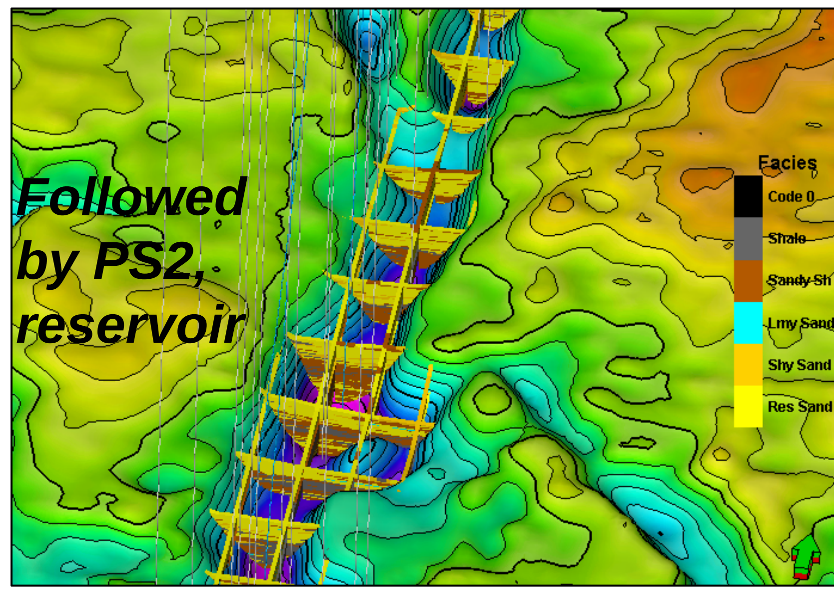
North Eubank Valley fill

Fence diagrams show lithofacies during valley fill stages (parasequences)



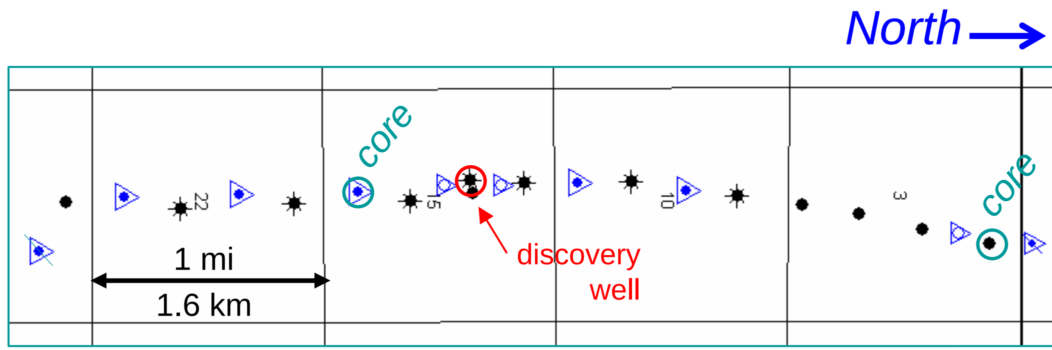


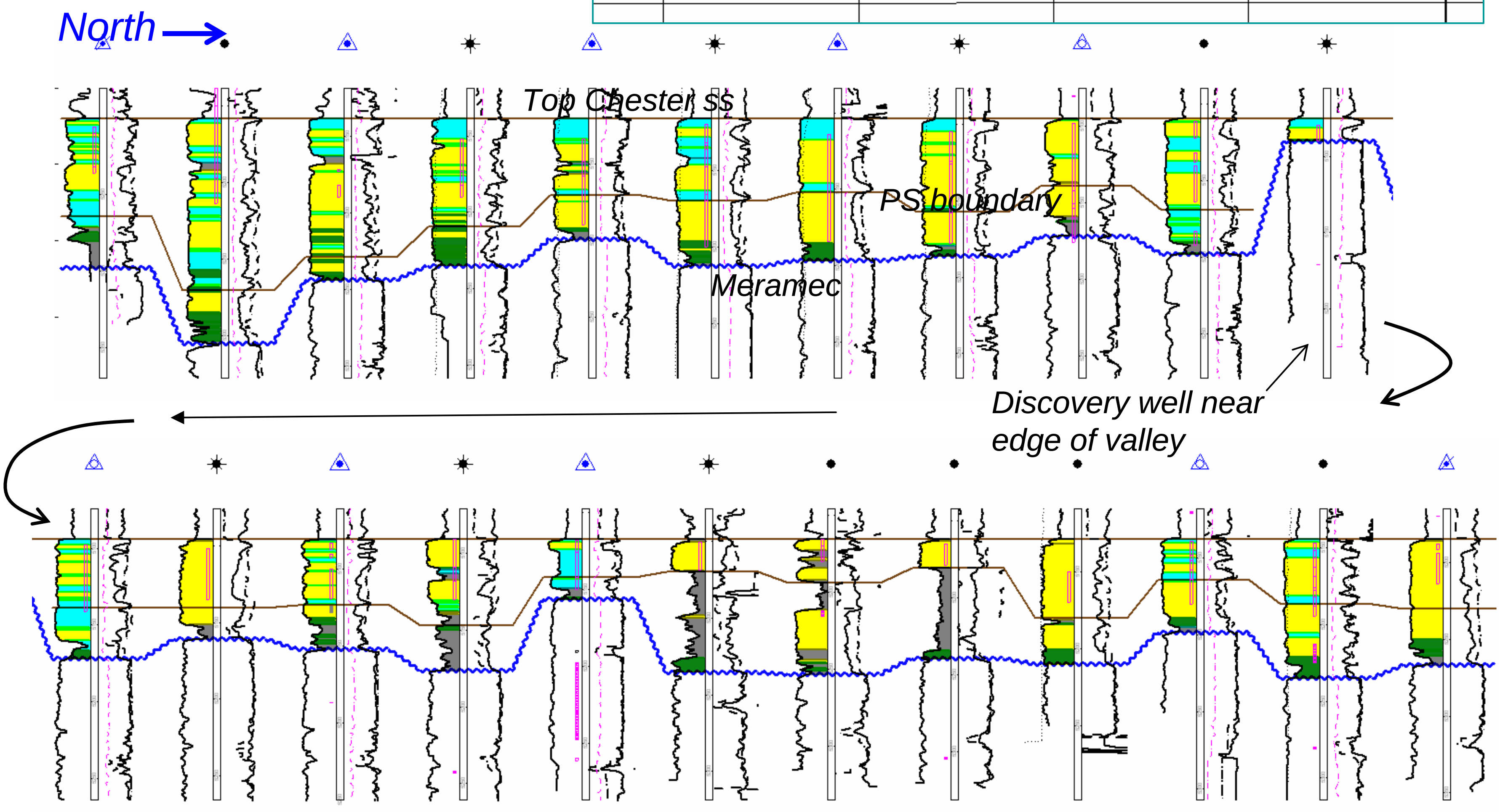




Pleasant Prairie South sequence stratigraphy

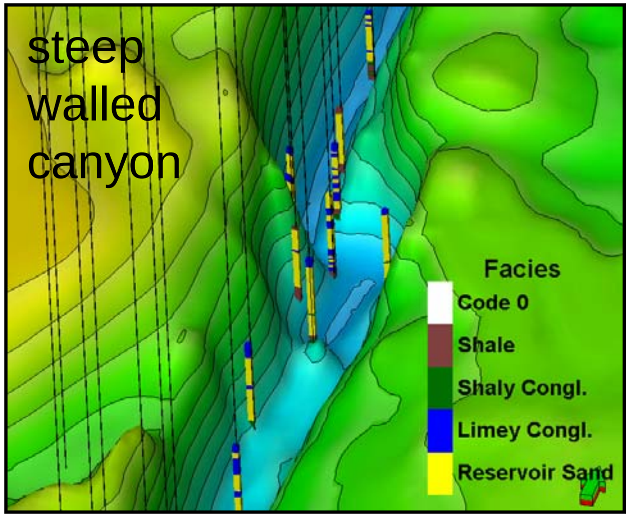
Two parasequences. Four lithofacies (color key slide 23)



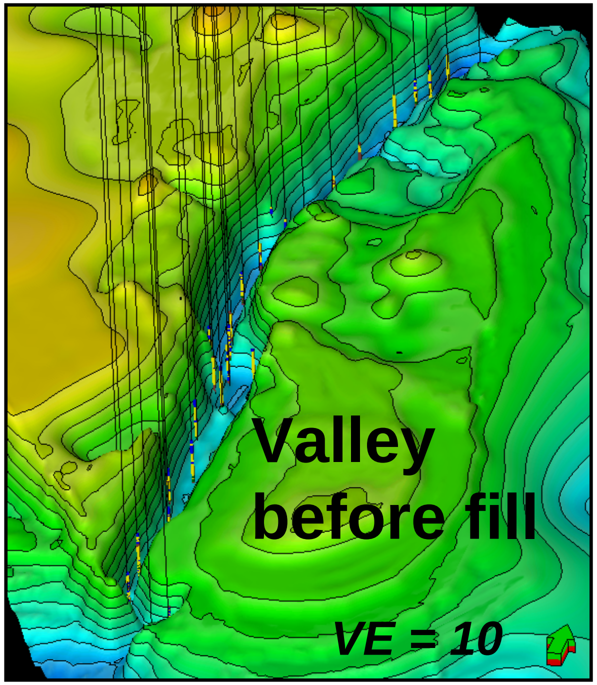


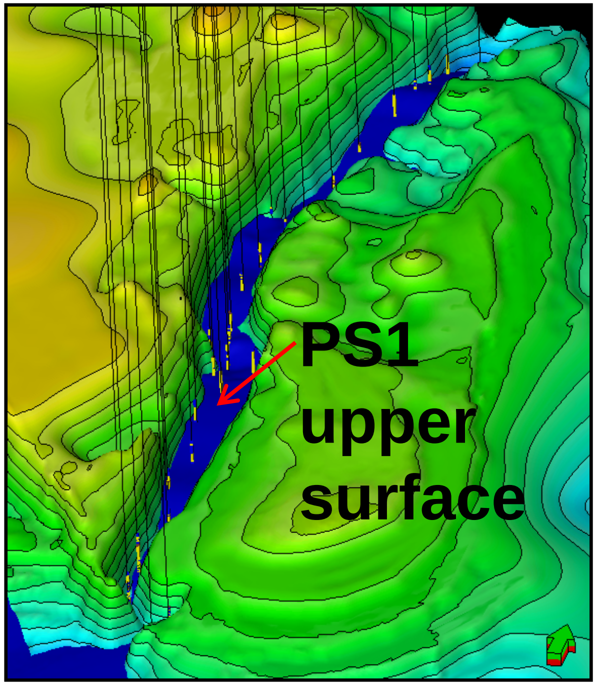
Pleasant Prairie South Model framework

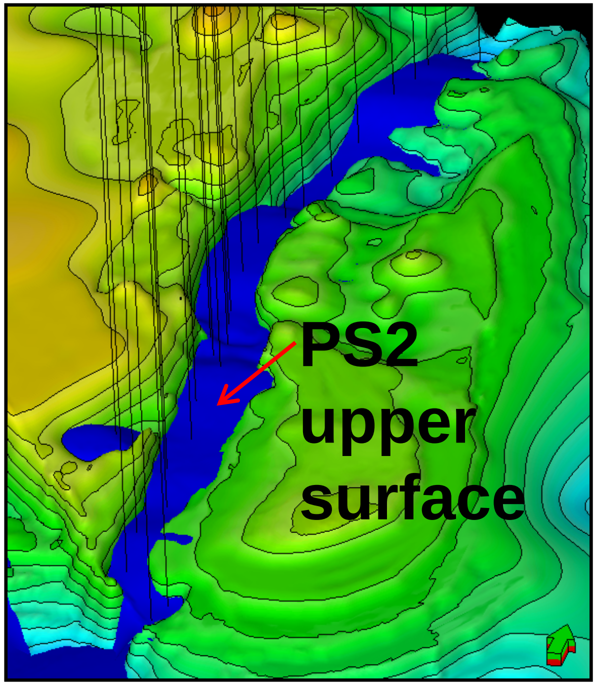
1. **Incised valley** cuts through Meramec and into St. Louis during post-Meramec exposure
2. **Two distinct sedimentary cycles (PS1 and PS2)** are recognizable in core and correlated in on wireline logs
3. **Chester sediments are absent from highlands**



Initial modeling work by Peter Senior.
Geomod2 by Dubois.







Traps and Hydrocarbon Fill

Trapping mechanism

- Sandstone reservoir filling incised valley appear to be connected.
- Barriers to northward, updip flow **(traps) are structural in nature**.
- **Pleasant Prairie and Eubank IVF traps** occur where the valley “crosses” post-Chesterian faulted structures related to the Ouchita Orogeny and the development of the Anadarko Basin.
- Northern closure to the **Shuck field appears to be due to a very localized karst** (Sorenson, personal communication)

Hydrocarbon migration and fill

- Oil along the length of the valley are very similar and are **primarily of Woodford origin** (Anadarko Basin), but with a minor component being of Ordovician age (Kim et al, 2010)
- The Chester IVF system may have been a **primary route for the Woodford oil charging the reservoirs in the much of western Kansas** (Sorenson, personal communication)

Outline

Introduction

- Stratigraphic and geologic setting
- Fields' statistics and histories

Geology

- Evolution of Chester incision
- Valley fill and sequence stratigraphy

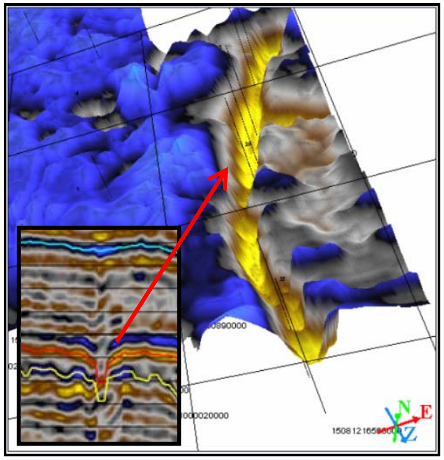
Modeling and Simulation

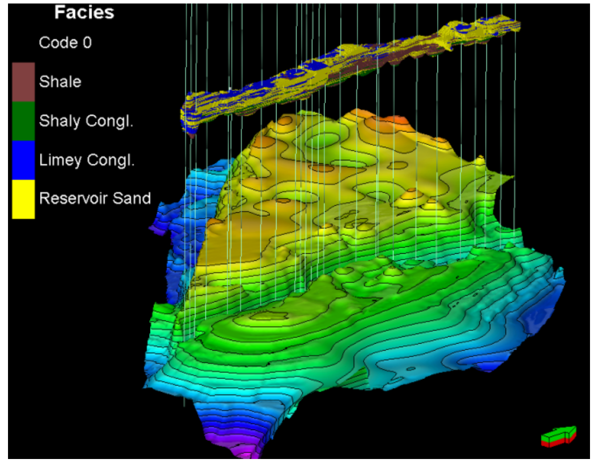
- Workflow
- Static 3D modeling
- Flow simulation

Integrated Multi-Discipline Project

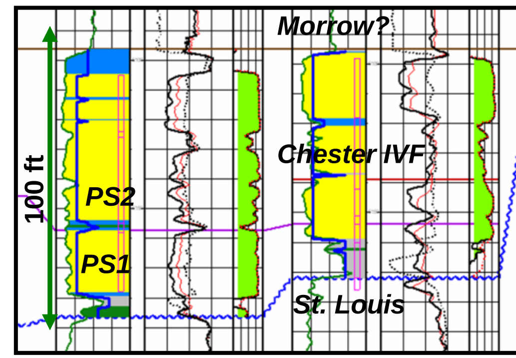
Static Model

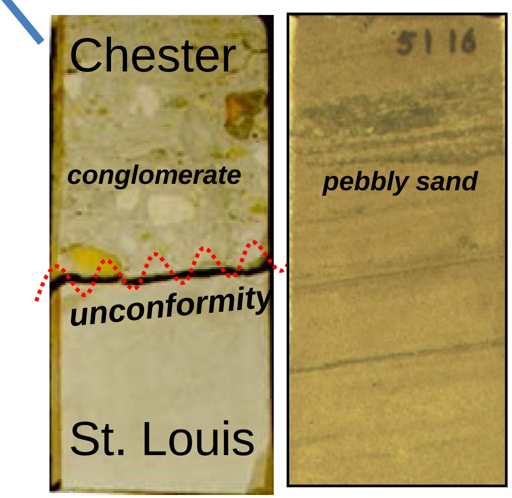
Geophysics:
structure, attributes, faults



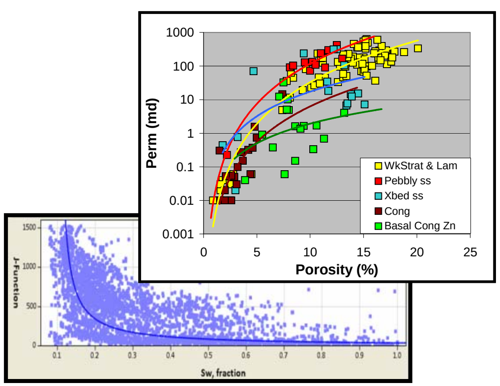


Geology:
Formation tops, sequence stratigraphy, core lithofacies, lithofacies prediction (NNet)



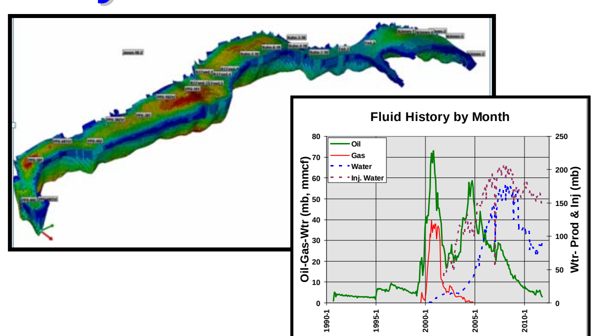


Petrophysics:
Core K-Phi, corrected porosity, free water level, J-function



Engineering:
PVT and fluid analysis, recurrent histories, dynamic modeling

Dynamic Model



Basic Workflow (Pleasant Prairie South)

Inputs

Framework data:

- Formation tops
- Sequence stratigraphy
- Depth-converted seismic structural surfaces
- Seismic attributes

Well-scale data

- Lithofacies (by NNet)
- Core data
- Porosity (corrected)
- Water saturation (Archies)

Sw solution

- Oil/water contacts and free water level
- Sw by Leverett J-function

Static Model

Structural wire frame model

- Incised valley by seismic and well tops
- Two parasequences
- 0-249 layers
- Cells: XY=55 ft, Z=2ft
- 700,000 active cells

Fine- grid cellular property model

- Lithofacies
- Porosity
- Permeability (XY)
- Water saturation
- OOIP

Dynamic Model

Upscale model

- Phi, K, Sw
- 0-25 layers
- Cells: XY=55 ft, Z=10 ft
- 65,000 active cells

Equation of State from PVT and fluid composition

Recurrent well history

- Mechanical
- Fluids produced and injected

✓ **History matched primary and secondary** black oil simulation

✓ **Forecast CO2 EOR** compositional simulation

Lithofacies in core and wireline logs

Two cores of Chester IVF

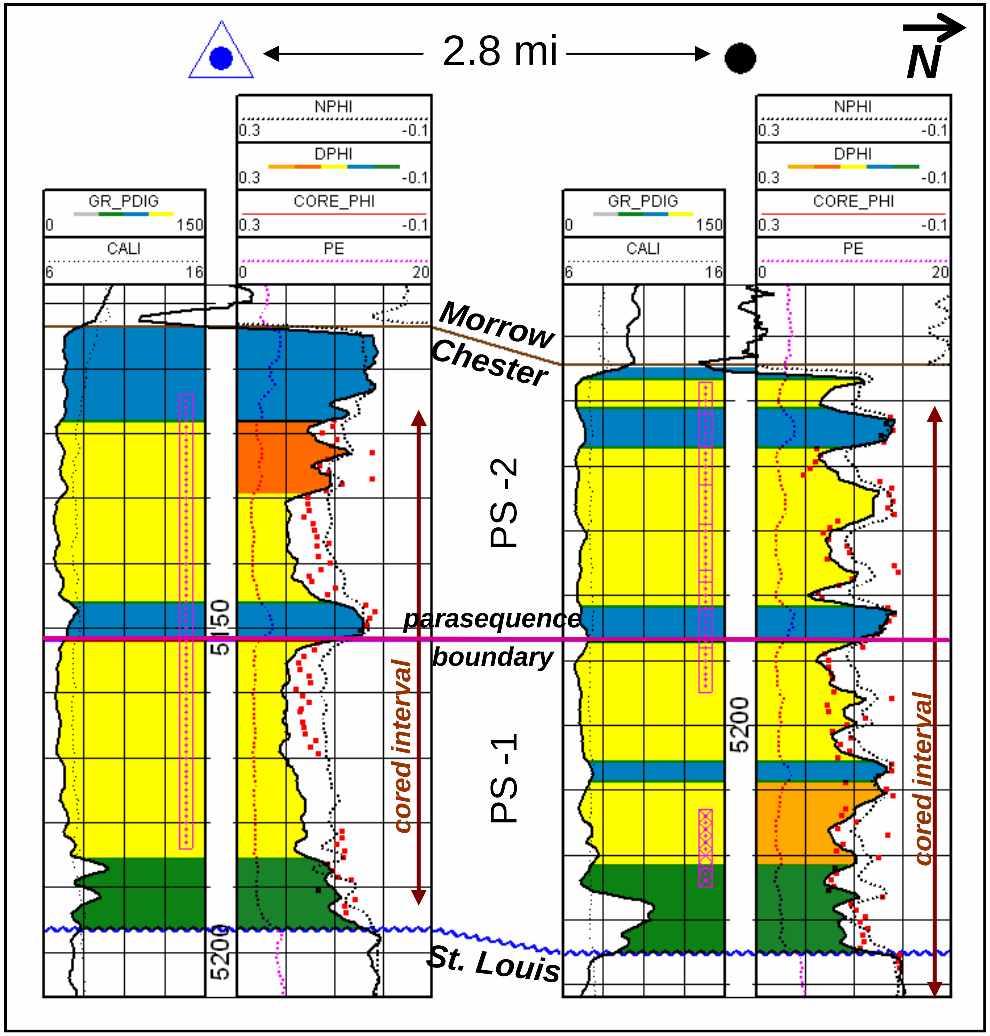
- Lithofacies
- Petrophysics

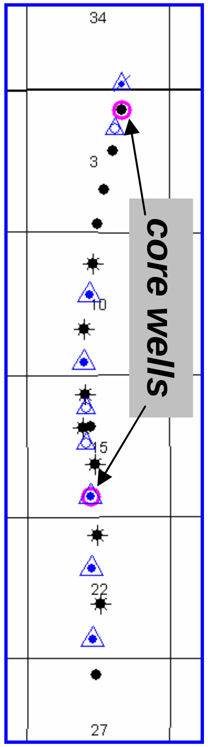
Defined lithofacies

- Trained Neural Network on core
- Predict litofacies in wells without core

Main Lithofacies

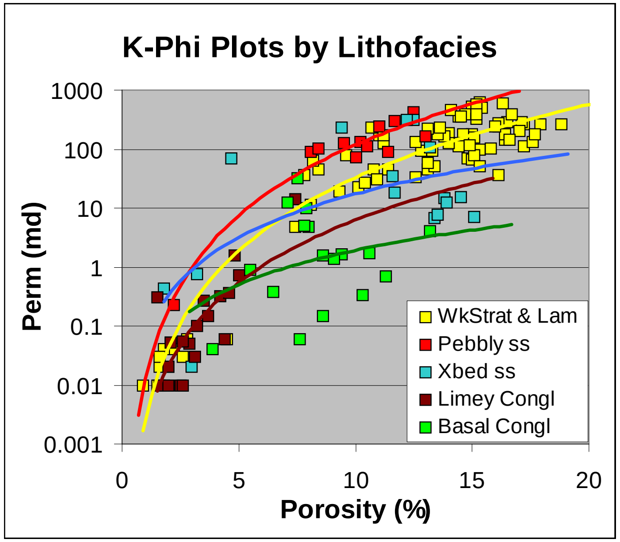
Model		Core
3	limey congl	limey congl
4	reservoir ss	wkly strat/lam ss
		pebbly ss
		x-bedded ss
1	shale	shale
2	basal congl	basal congl

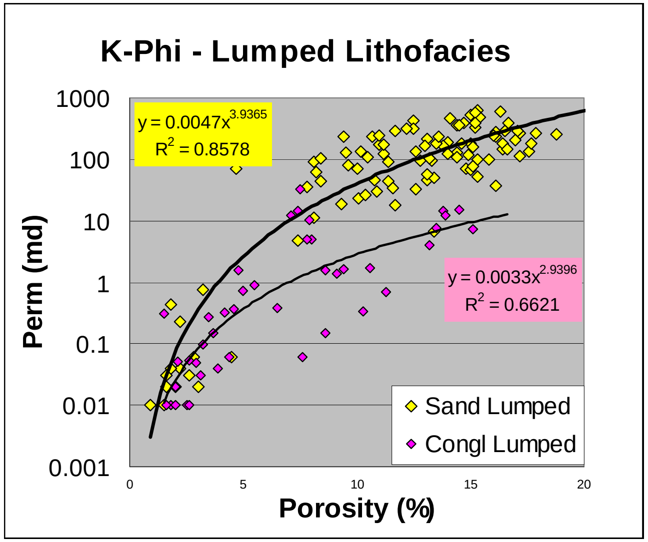




Pore throats, permeability, Sw are dependent on lithofacies

Pleasant Prairie South





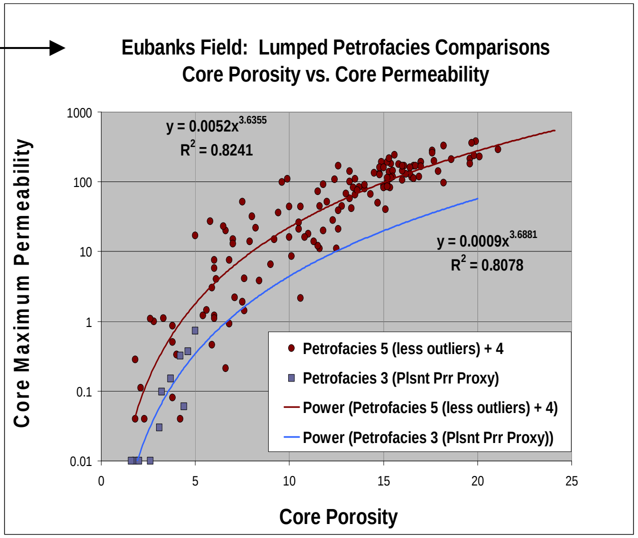
Pleasant Prairie

- Five core lithofacies have somewhat distinctive K-Phi trends (left), but are not all distinguishable on logs
- Lumped into two lithofacies, Sandstone and Conglomerate (right)

Pore throats, hence permeability and capillary pressure (and Sw) are a function of lithofacies. Thus it is important to distinguish lithofacies in the characterization and modeling process

Eubank

- Lumped lithofacies in Eubank have very similar K-Phi relationships as Pleasant Prairie
- Eubank sandstone has very slightly lower permeability for a given porosity



Pleasant Prairie South Static Model Properties

Inputs: 25 valley wells with ***Phi*, *Lithofacies* and *Sw***

Import LAS curves at half-foot sample rate

Upscale to layer scale (2-ft)

Model Lithofacies

- Data analysis and variograms
- Sequential indicator simulation

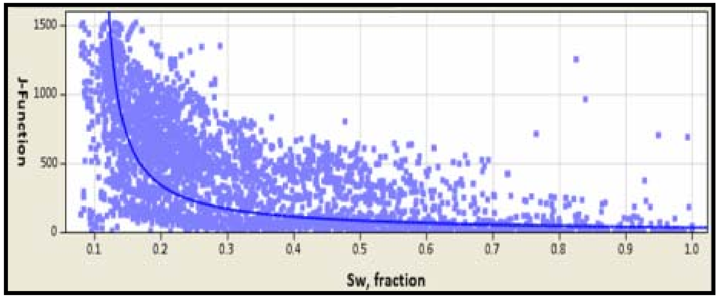
Model Porosity

- Data analysis and variograms by lithofacies
- Sequential Gaussian simulation by lithofacies

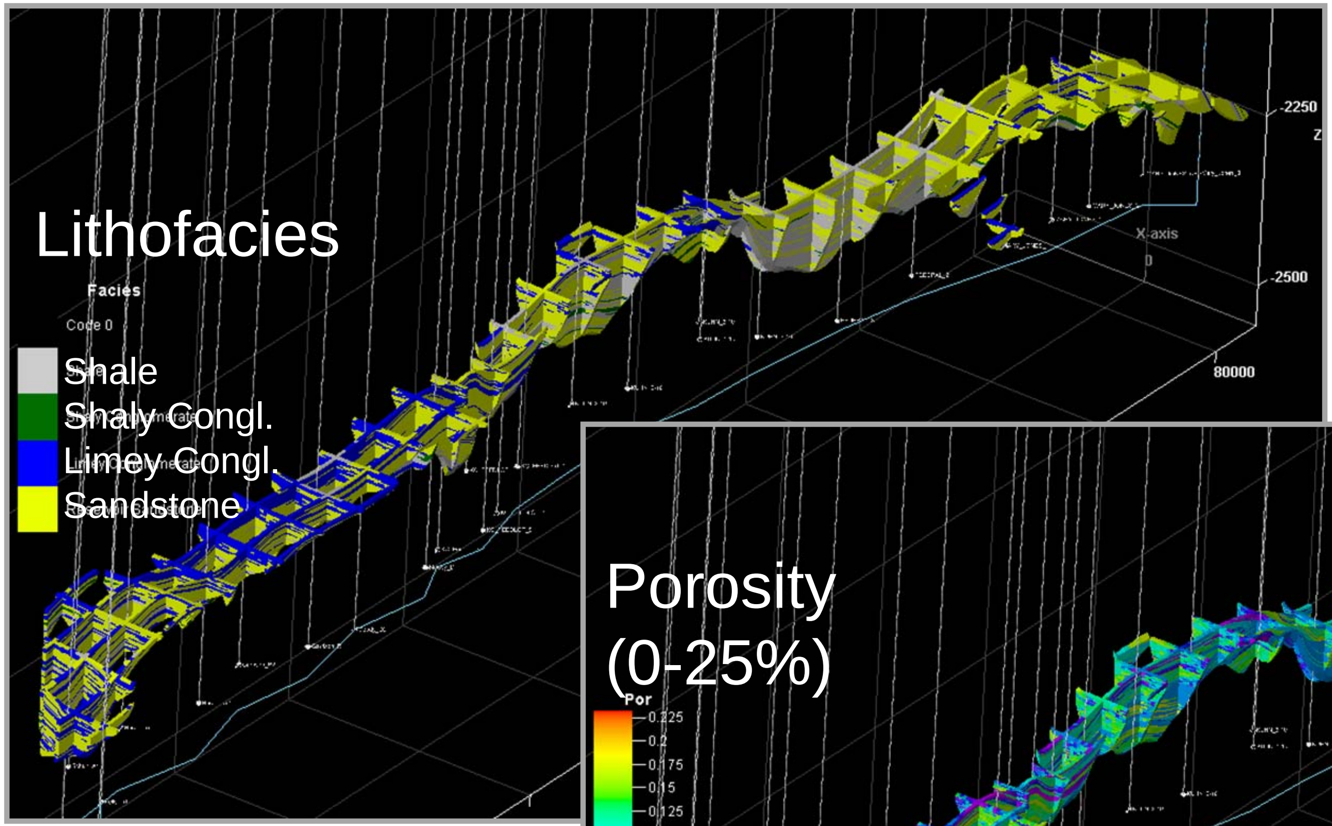
Calculate Kxy by lithofacies

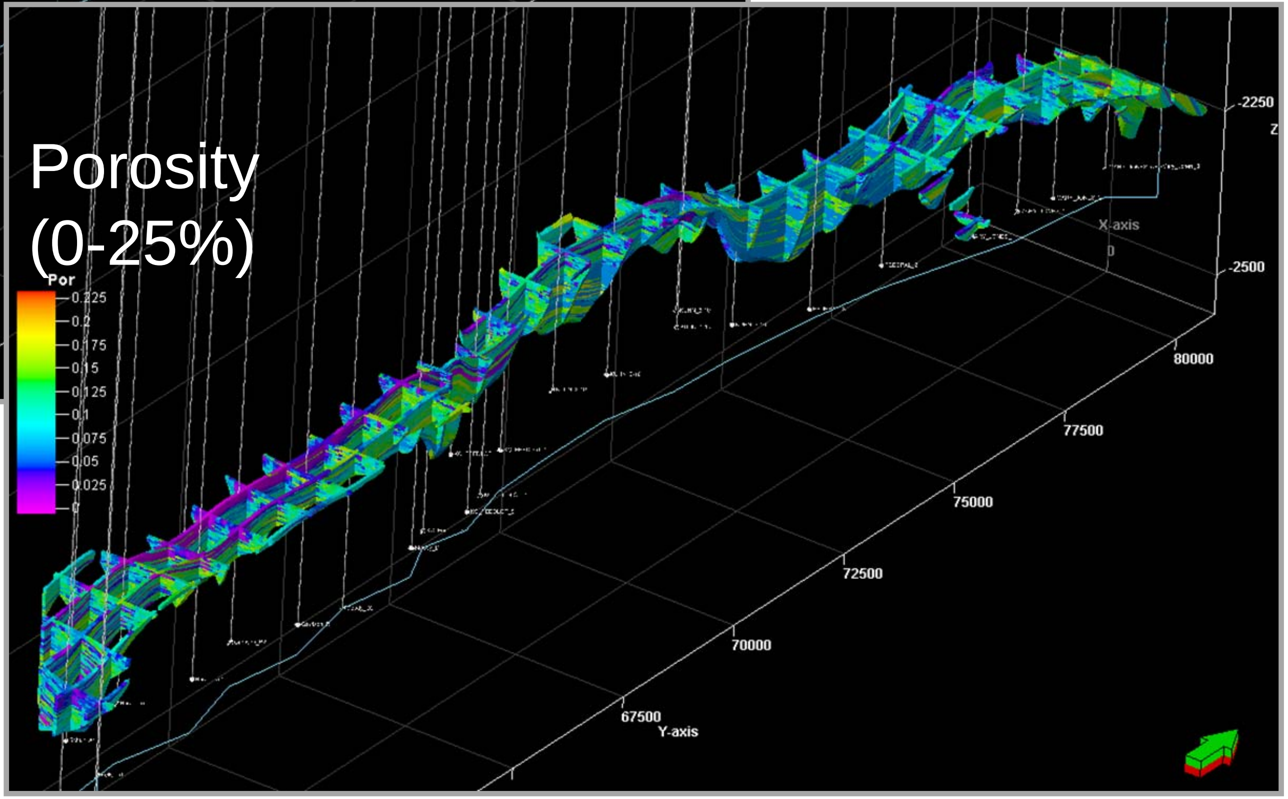
Sandstone	K(md)= 0.0047*PHI^3.9365
Conglomerate	K(md)= 0.0033*PHI^2.9396
Shale	K(md)= 0.01

Estimate Sw by J-Function

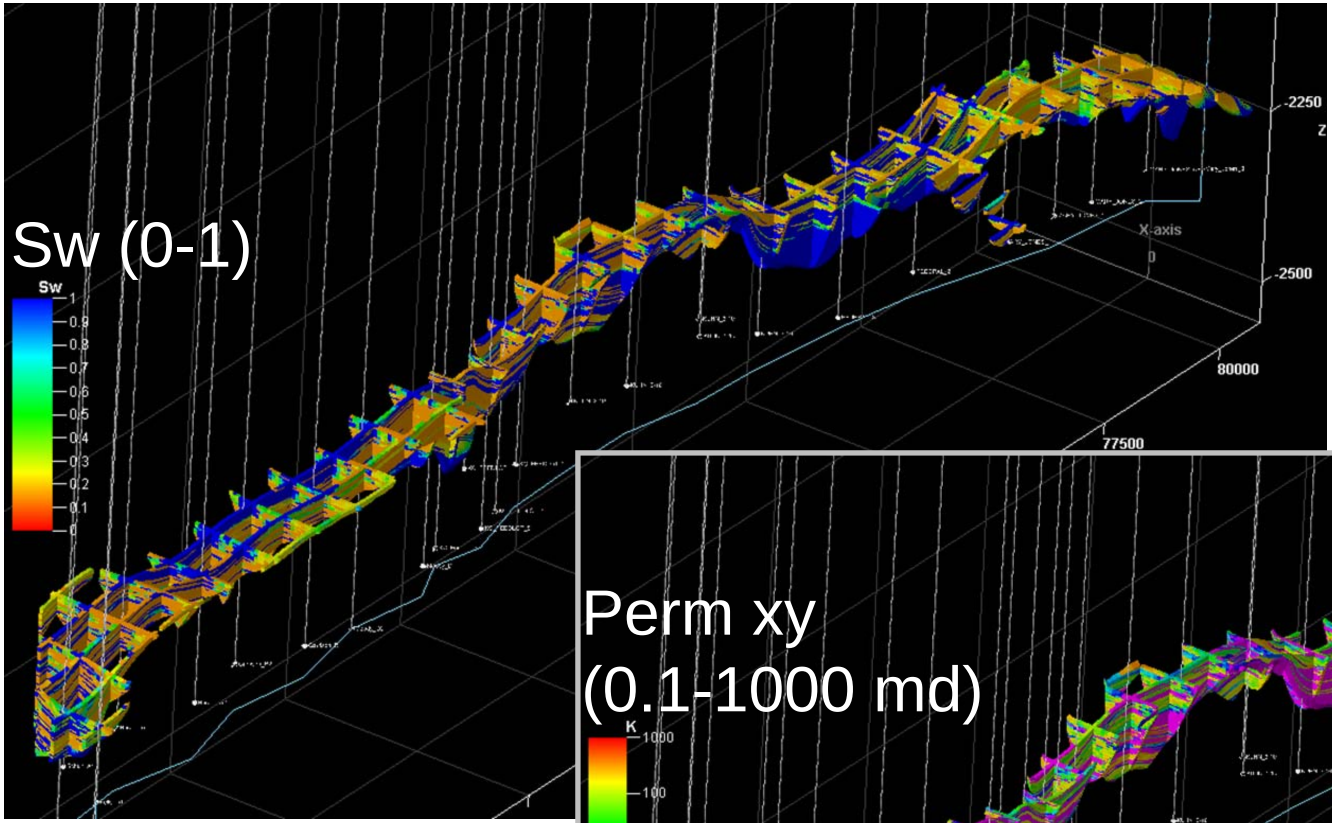


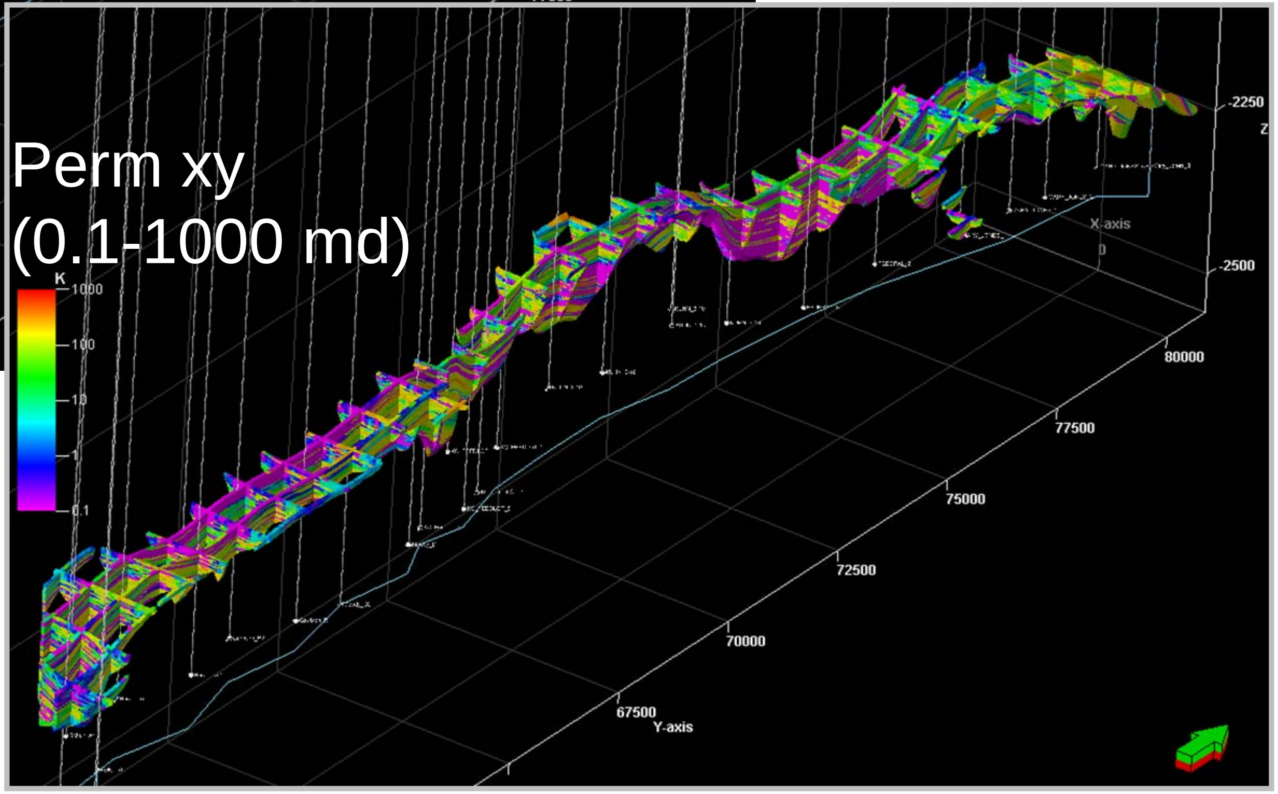
Lithofacies and Porosity





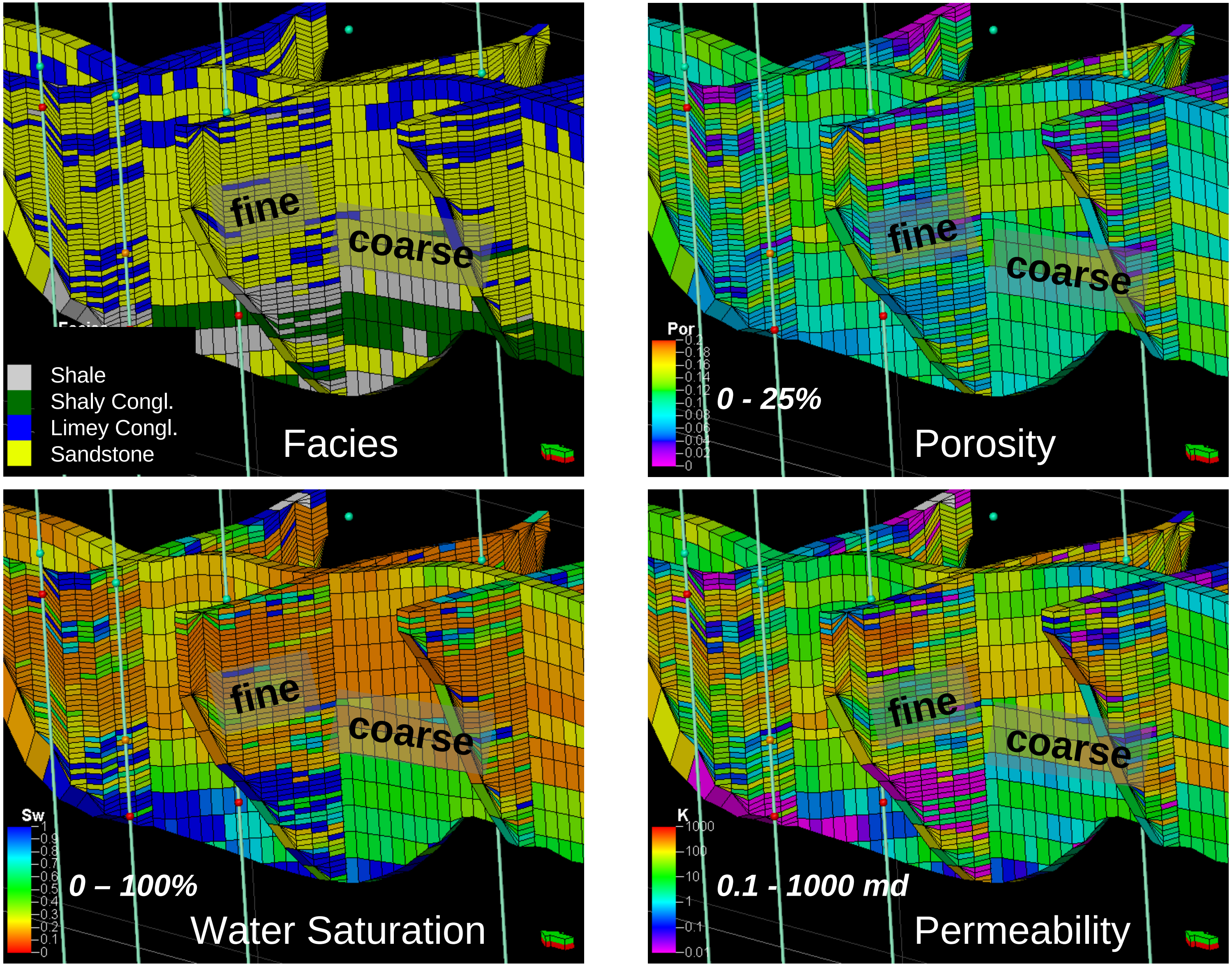
Water Saturation and Permeability





Upscale to coarse grid and export for simulation

Fine-grid static model 2-ft *h* cells were upscaled to 10-ft *h* cells for simulation.



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Dynamic Model

- ✓ **History matched primary and secondary** black oil simulation
- ✓ **Forecast CO2 EOR** compositional simulation

Equation of State from PVT and fluid composition

Recurrent well history
- Mechanical
- Fluids produced and injected

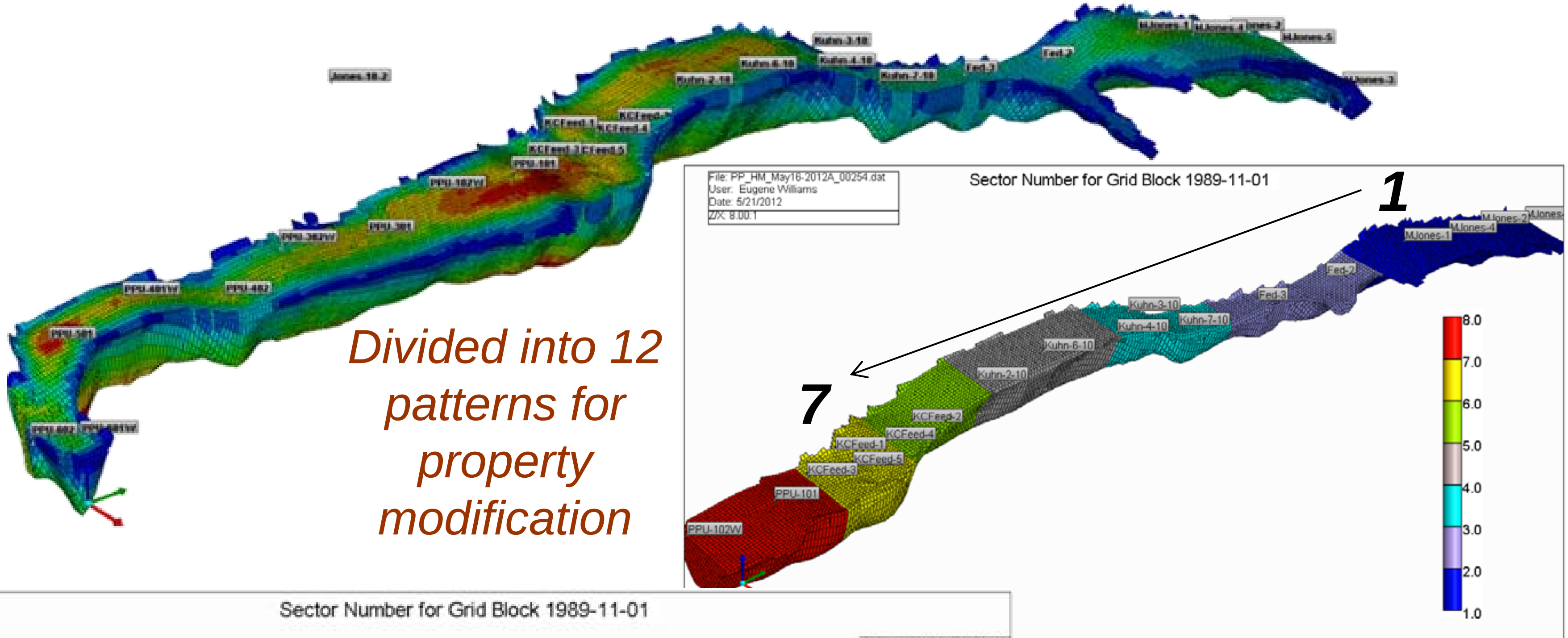
Black Oil Simulation

Reservoir simulation work by Eugene Williams

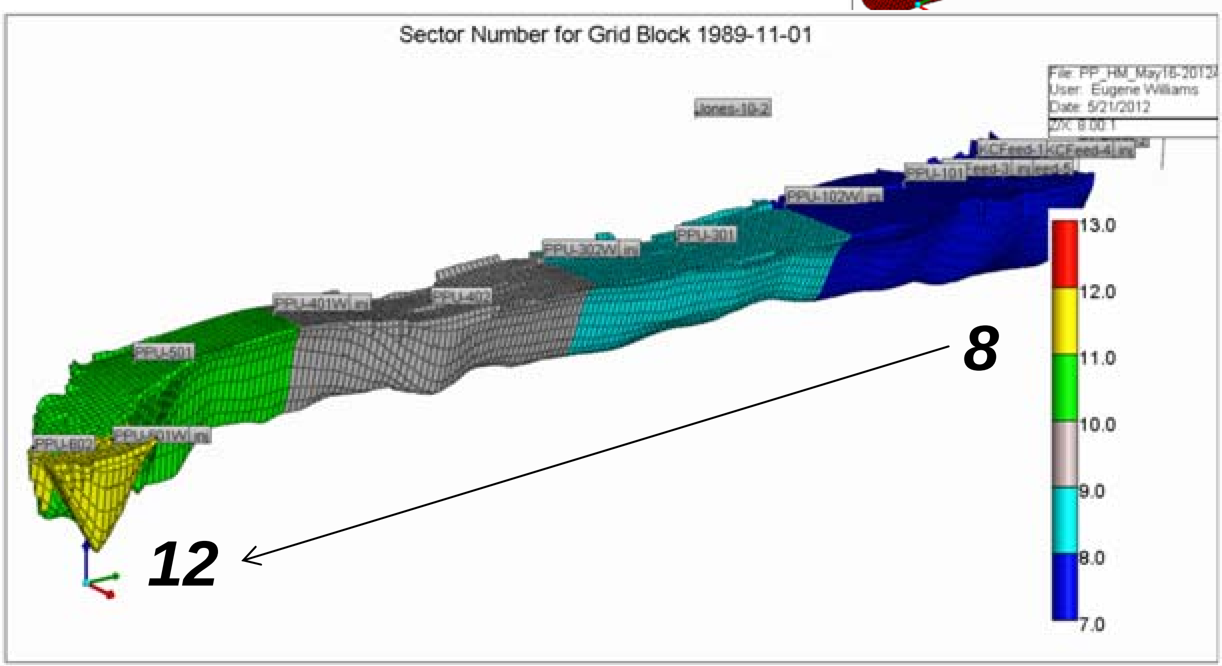
General workflow

1. Match fluid & pressure histories (1990-2011)
2. Define 12 patterns (polygons)
3. Modify properties to attain match
    - Pore volume modifiers by polygon
    - I-Permeability modifiers by polygon
    - I and J Transmissibility modifiers (by polygon)
    - Relative permeability
        - Psuedo-functions – Rocktype, VE, Stratified – by polygon
        - End points (SWCR, SOWR, KRW) by region
4. CMOST automation to run hundreds of iterations to get close
5. QC and manual inputs for final

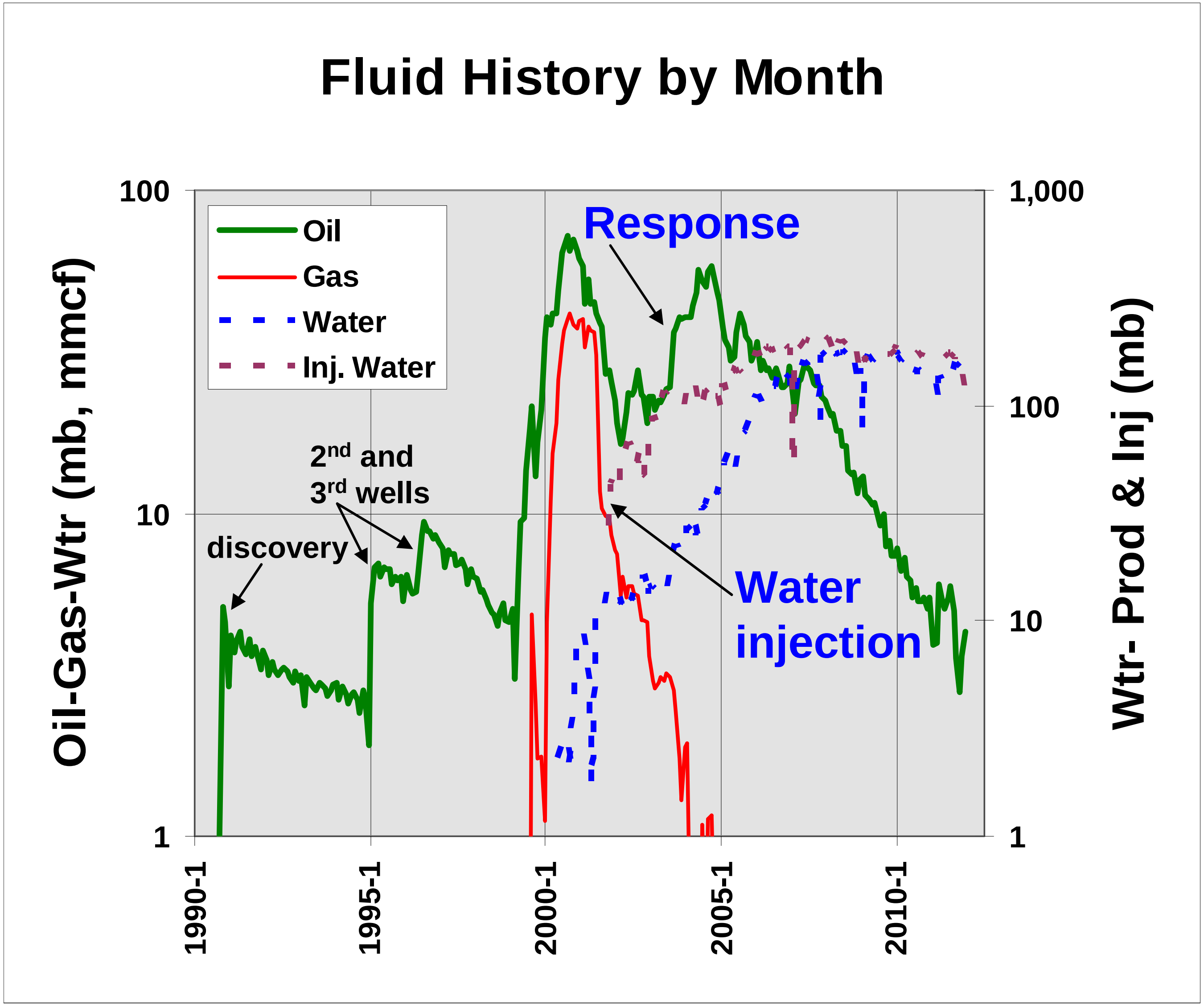
Simulation model views



Divided into 12 patterns for property modification

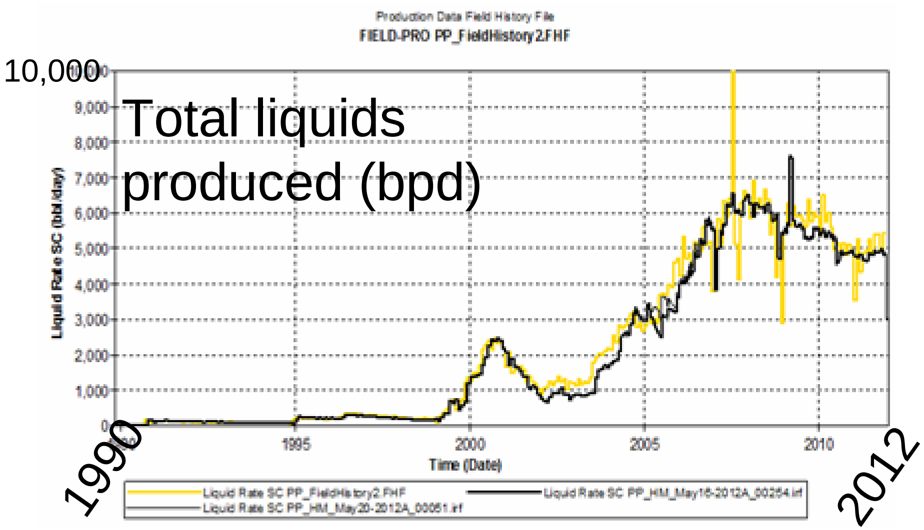


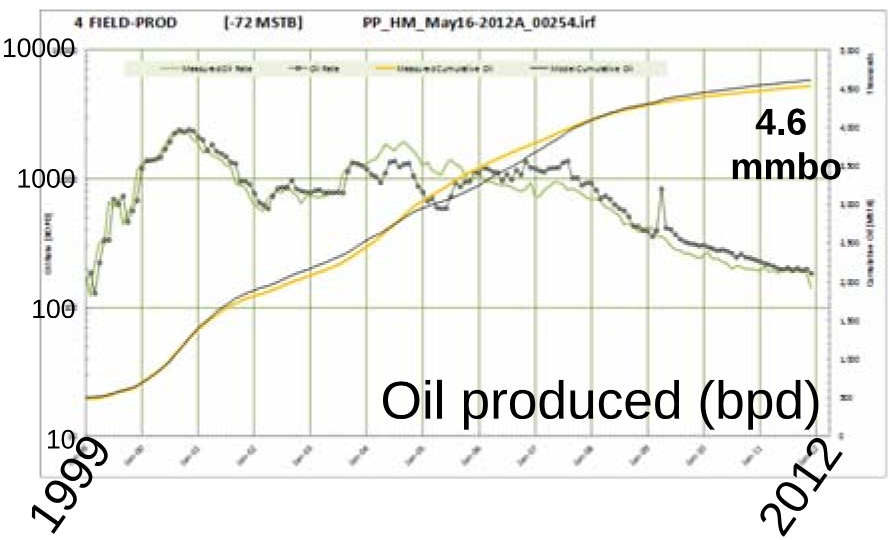
Field History - review

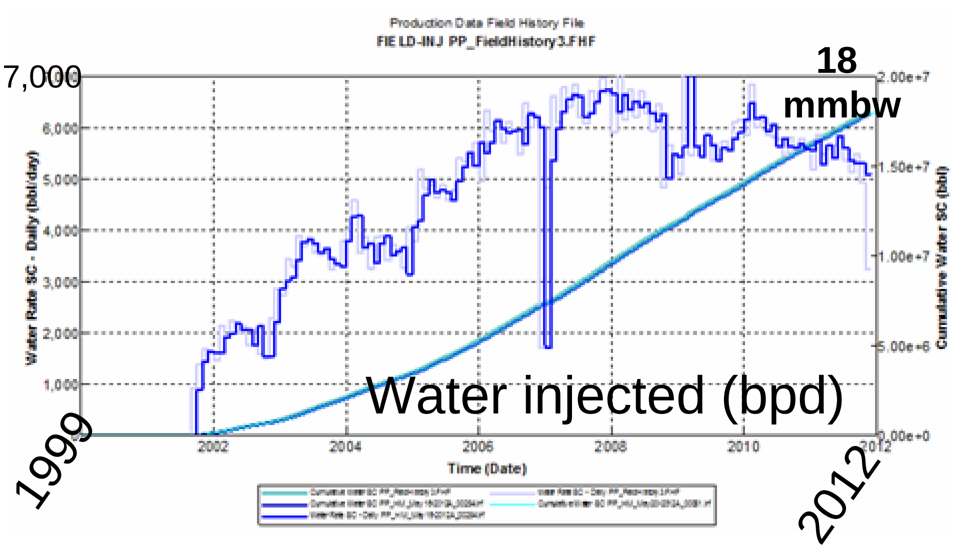


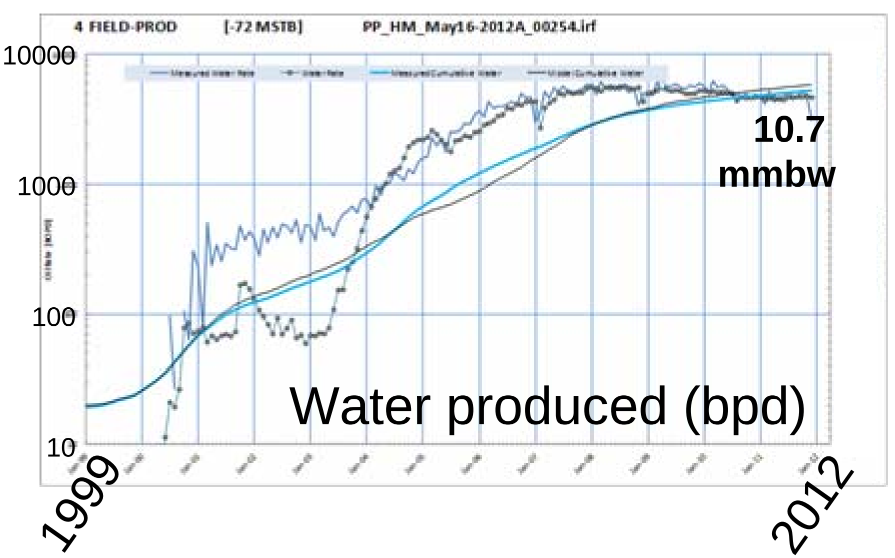
Field-scale matches (through waterflood)

Lighter colored are actual, darker are modeled





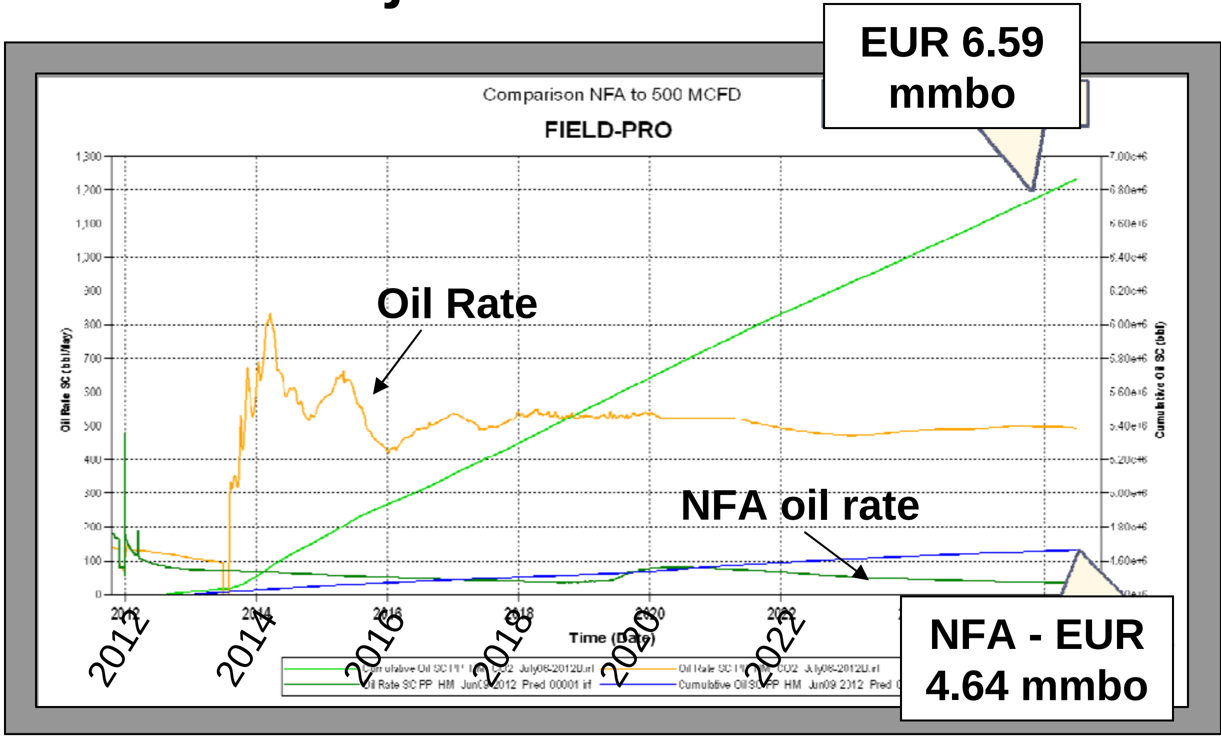




CO2 EOR Projections

Assumptions:

1. Convert WIW to CO2 IW
2. Oil wells as is
3. Inject 5 mmcfd CO2, not exceeding bhp 2600 psi
4. Continuous CO2, no WAG
5. Injection = production
6. No optimization



13 years injection

Projections:

OIL (mmbo)		
Cumulative 2011	4.48	
NFA cum. 2026	4.64	
CO2 case cum.	6.59	
Increment. CO2	1.95	
Cum. 2012-2026	2.11	
CO2		*mm tons*
CO2 injected (mmcf)	23.7	1.38
CO2 produced (mmcf)	13.2	0.77
CO2 sequestered (mmcf)	10.5	0.61
Gross utilization (mcf/bo)	11.2	
Net utilization (mcf/bo)	5.0	

assume 56%
CO2 is recycled

RF as *f* (OOIP)

Primary	15.8%
Secondary	15.8%
CO2	13.3%
	45.0%

Pleasant Prairie South Simulation

Detailed report available online: Appendix A of quarterly DOE report, p 50-143: http://www.kgs.ku.edu/PRS/Ozark/Reports/2012/Q11_2012_v2.pdf

The purpose of the simulation model is to demonstrate incremental volume of oil that might be generated with CO2 injection and to determine the volume of CO2 that might be sequestered.

There is room for improvement in the static model and justification for further dynamic modeling, but the current models are sufficient to demonstrate with confidence that substantial volumes of CO2 can be injected and sequestered and a significant volume of oil recovered in the process.

Dynamic flow modeling required a pore volume reduction to a volume-weighted average of 79% of static model pore volume for the best history match of primary and secondary production. This could indicate that 21% of the reservoir is excess volume, or 21% of the modeled reservoir was not in communication with the wellbores.

The volume of potential oil recovered might be significantly less if residual oil to miscible CO2 is greater than the zero value assumed in these model predictions.

Summary

1. Generous operator contributions of data has allowed comprehensive study of Chester IVF system
2. Post-Meramec incision was filled by tidally dominated estuarine sediments to south and more fluvial to the north
3. Trapping mechanism is structural in nature for the three fields studied
4. Shuck, Eubank North Unit, and Pleasant Prairie South were prolific in primary and water flood phases.
5. Based on relatively simple modeling and simulation, the fields should be good CO_2 flood candidates provided a source of CO_2 can be found
6. Substantial model and flow simulation improvements are advisable prior to implementing CO_2 floods based on these studies

Acknowledgments

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Anadarko Petroleum Corp.
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Glori Oil Limited
Elm III Operating, LLC
Merit Energy Company

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