

Sequence Stratigraphy of the Bakken and Three Forks Formations, Williston Basin, USA*

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Search and Discovery Article #10990 (2017)**

Posted September 11, 2017

*Adapted from oral presentation given at AAPG Rocky Mountain Section Annual Meeting, Billings, Montana, June 25-28, 2017

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Abstract

The Williston Basin Bakken petroleum system is a giant continuous accumulation. The petroleum system consists of source beds in the upper and lower Bakken shales and reservoirs in the middle, and upper Three Forks, Pronghorn Member of the Bakken and the Middle Bakken. The Petroleum System is characterized by low-porosity and permeability reservoirs, organic-rich source rocks, and regional hydrocarbon charge. USGS (2013) mean technologically recoverable resource estimates for the Bakken Petroleum System is 7.375 billion barrels oil, 6.7 TCF gas, and 527 million barrels of natural gas liquids. The Three Forks is a silty dolostone throughout much of its stratigraphic interval. The Three Forks ranges in thickness from less than 25 feet to over 250 feet in the mapped area. Thickness patterns are controlled by paleostructural features such as the Poplar Dome, Nesson, Antelope, Cedar Creek, and Bottineau anticlines. Thinning and/or truncation occurs over the crest of the highs and thickening of strata occurs on the flanks of the highs.

The Three Forks can be subdivided into three units (up to six by some authors). Most of the development activity in the Three Forks targets the upper Three Forks. The Three Forks consists of at least five system tracts: a lowstand system tract consisting of the lower continental to supratidal sediments (overlies marine Birdbear carbonates and evaporites); overlain by a transgressive system tract of subtidal dolostone; overlain by a highstand systems tract of the middle Three Forks consisting mainly of peritidal sediments; in turn overlain by a transgressive system tract representing subtidal dolostones; which in turn is overlain by highstand systems tract of the upper Three Forks consisting of peritidal dolostones. A major unconformity separates the Three

Forks from the Bakken Formation, probably representing tectonic movement from the Acadian/Antler orogenies. The unconformity is complex in that it probably represents both a lowstand surface of erosion and a transgressive surface of erosion.

The Bakken Formation regionally in the Williston Basin consists of four members: upper and lower organic-rich black shale; a middle member (silty dolostone or limestone to sandstone lithology); a basal member (dolostone, limestone, and siltstone) recently named the Pronghorn. The Bakken Formation ranges in thickness from a wedge edge to over 140 feet with the thickest area in the Bakken located in northwest North Dakota, east of the Nesson Anticline. The Bakken in the U.S. Williston Basin consists of five system tracts: the Pronghorn Member represents a lowstand to transgressive system tract (proximal and distal members); a lower transgressive system tract consisting of the Lower Bakken Shale; a highstand systems tract consisting of the lower Middle Member; a falling stage to lowstand systems tract consisting of the oolitic, bioclastic, sandy Middle Member; overlain by a transgressive system tract consisting of the upper Middle Bakken and the Upper Bakken Shale. The Upper Bakken Shale is overlain sharply by the Lodgepole Formation which represents a highstand systems tract. Sharp downlap surfaces are noted at the base of the Middle Bakken and the base of the Lodgepole. The downlap surfaces represent the transition from transgressive system tracts to highstand system tracts. Maximum flooding surfaces are found in the middle and upper portions of the upper and lower Bakken shales. Relative sea level changes occur in the Bakken and Three Forks intervals related to both tectonics and glaciation. These changes result in the numerous system tracts identified in this study.

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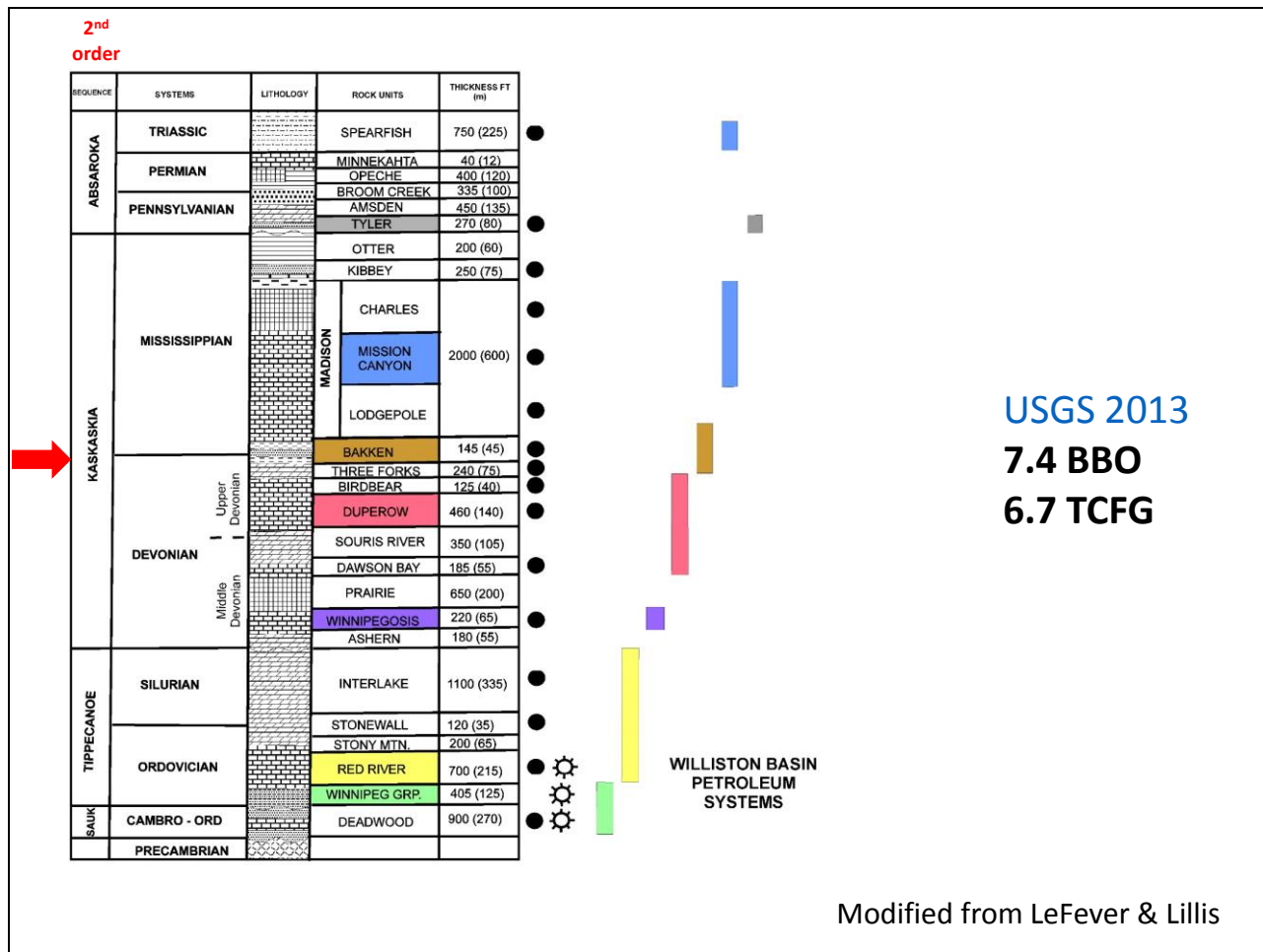
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Sequence Stratigraphy of the Bakken and Three Forks, Williston Basin, USA

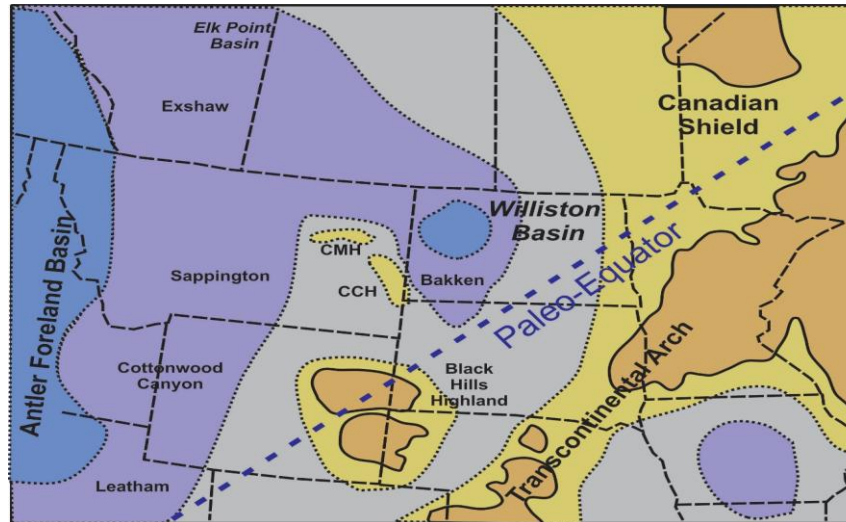
Dr. Steve Sonnenberg
Colorado School of Mines



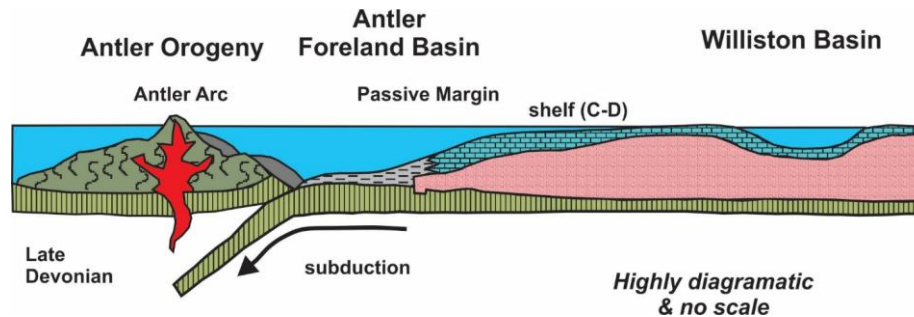
Presenter's notes: This paper presents a new look at the sequence stratigraphy of the Bakken and Three Forks in the Williston Basin.



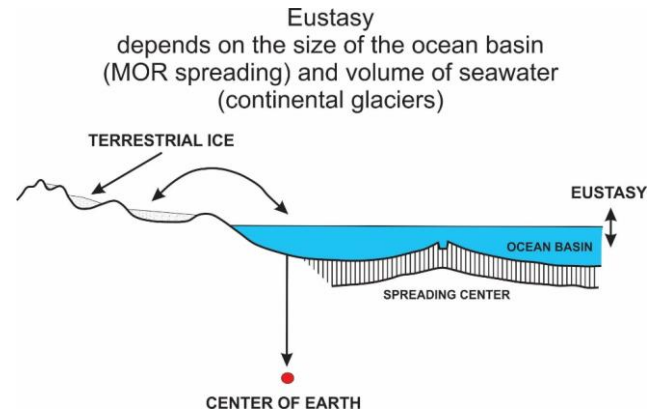
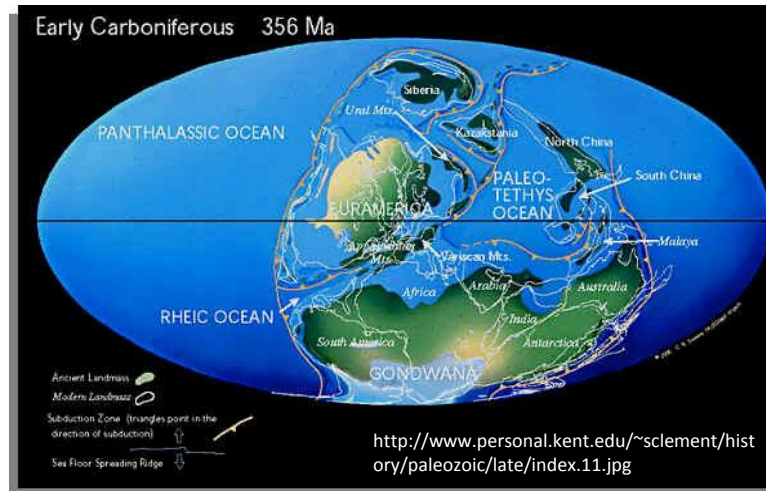
Presenter's notes: Stratigraphic column for Paleozoic producing units in the Williston Basin. Producing units shown by oil and gas symbols. The Bakken Petroleum system consists of source beds in the Bakken and reservoirs in the lower Lodgepole, Bakken, and upper Three Forks. The upper Three Forks is the main producer in the Antelope Field. Sedimentary sequences following Sloss (1963) are indicated. Thickness of stratigraphic units indicated in the column to the right (ft/m). Oil and gas symbols indicate producing formations. Modified from LeFever, 1992. Petroleum systems are modified from Lillis (2013).



Paleogeography "Bakken Time"



Presenter's notes: North America paleogeography and black shale deposits for Late Devonian, 360 Ma (modified from Blakey, 2005). Structural features: Canadian Shield; Transcontinental Arch; Black Hills Highland; Cedar Creek High (CCH); Central Montana High (CMH). Position of equator marked by dashed line (Paleo-Equator).

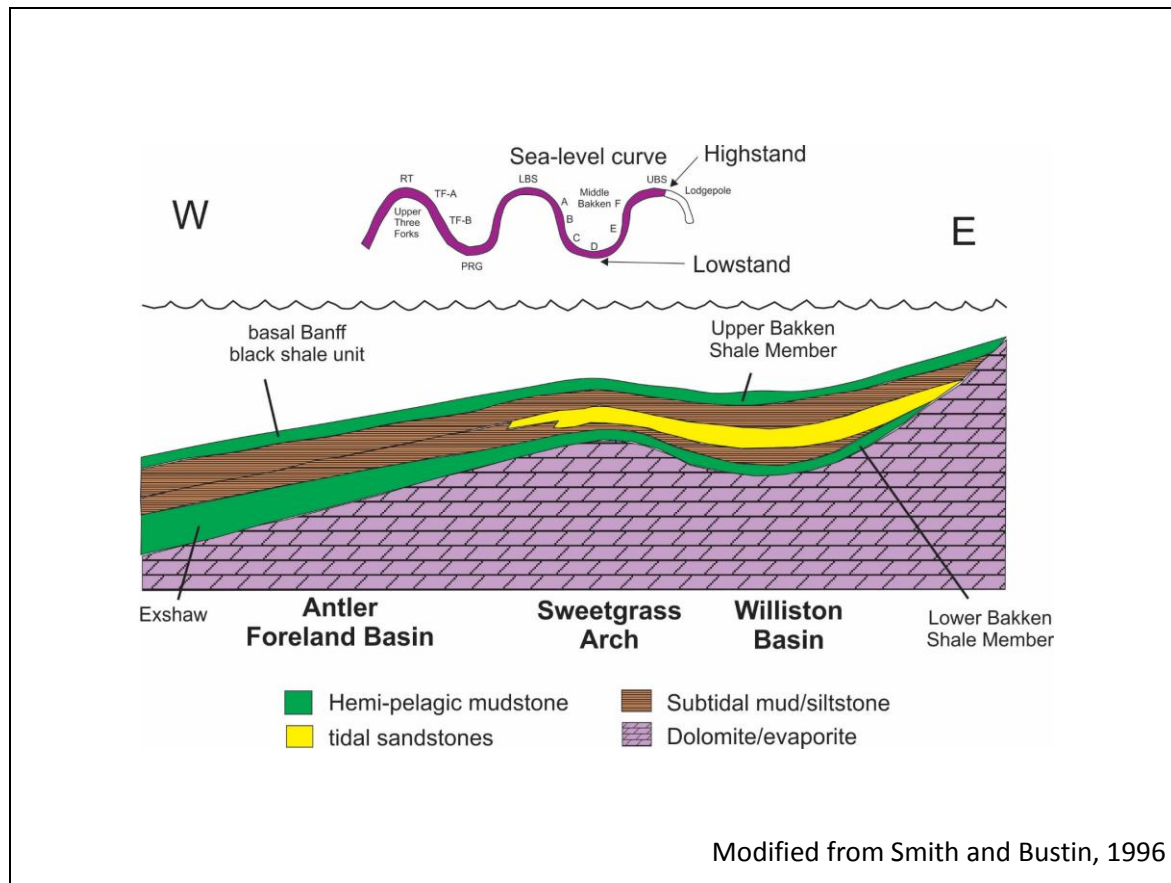


Presenter's notes: Sea level changes affect Bakken and Three Forks deposition and also cause cyclic sedimentation. Drivers for sea level changes in Bakken time are glaciation and tectonics.

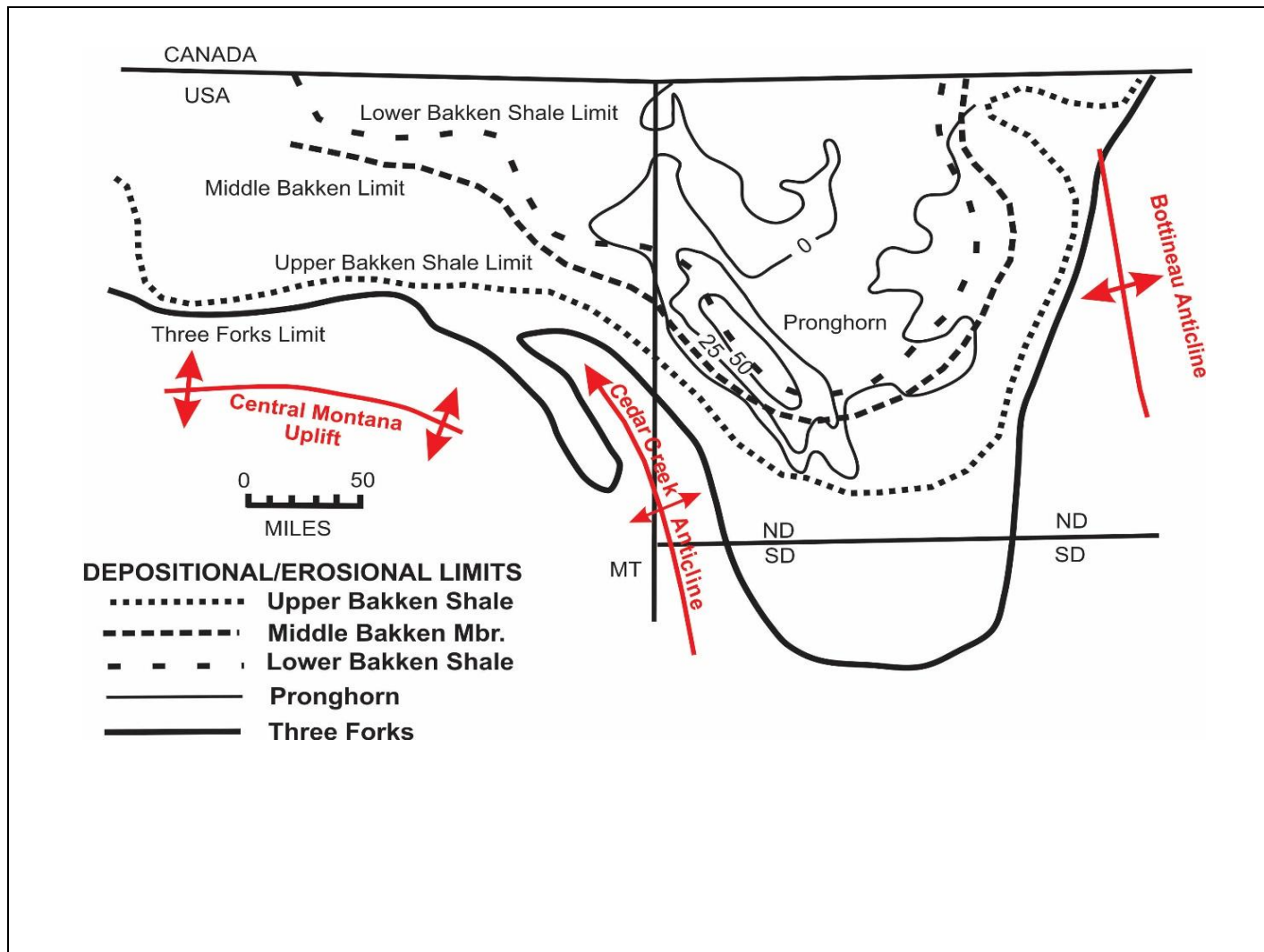
SERIES	STAGE	Conodont Zones	Ma	Stratigraphy	
				Central Montana	North Dakota
EARLY MISS.	KINDERHOOKIAN	crenulata	356?	Lodgepole	Lodgepole
		sandbergi		Cottonwood Canyon	U. Bakken Sh
		duplicata			?
		sulcata			? ?
LATE DEVONIAN	FAMENNIAN	praesulcata	361	Sappington	Middle Bakken
		expansa	365		
		postera	366.5	L. Sh	L. Bakken Sh
		trachytera	367.5		Pronghorn/Sanish
		marginifera	368.5	Trident	
		rhomboidea	370	Logan Gulch	Three Forks
		crepida	370.5		
		triangularis	372.5		
			376		
		linguiformis	376.5		
	FRASNIAN	rhenana	379	Birdbear Mbr. Of Jefferson Fm.	Birdbear Mbr. Of Jefferson Fm.

modified from Sandberg et al., 1988; Hartel et al., 2012

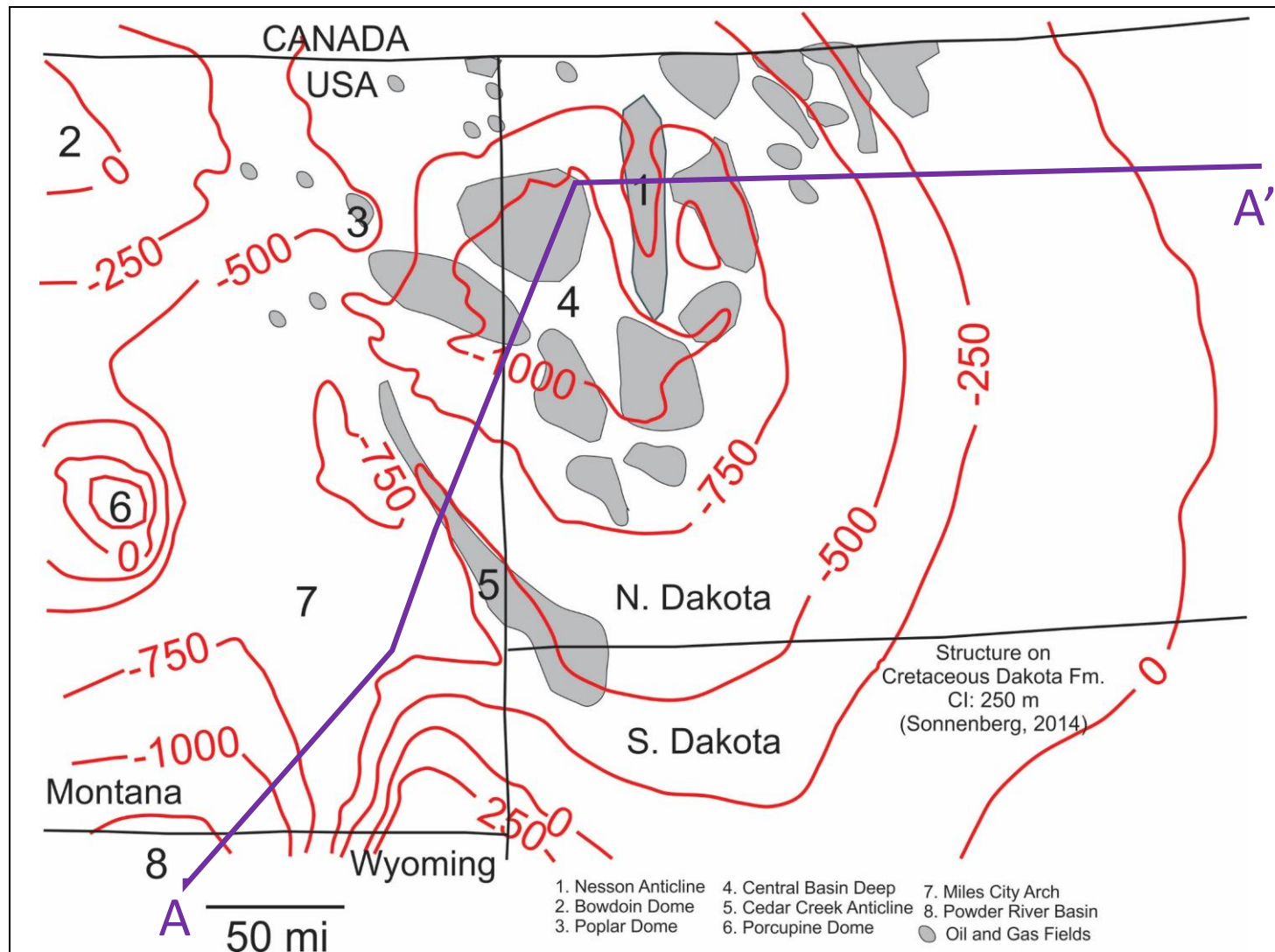
Presenter's notes: Conodont zones for the Late Devonian and early Mississippian (from Sandberg et al., 1988.



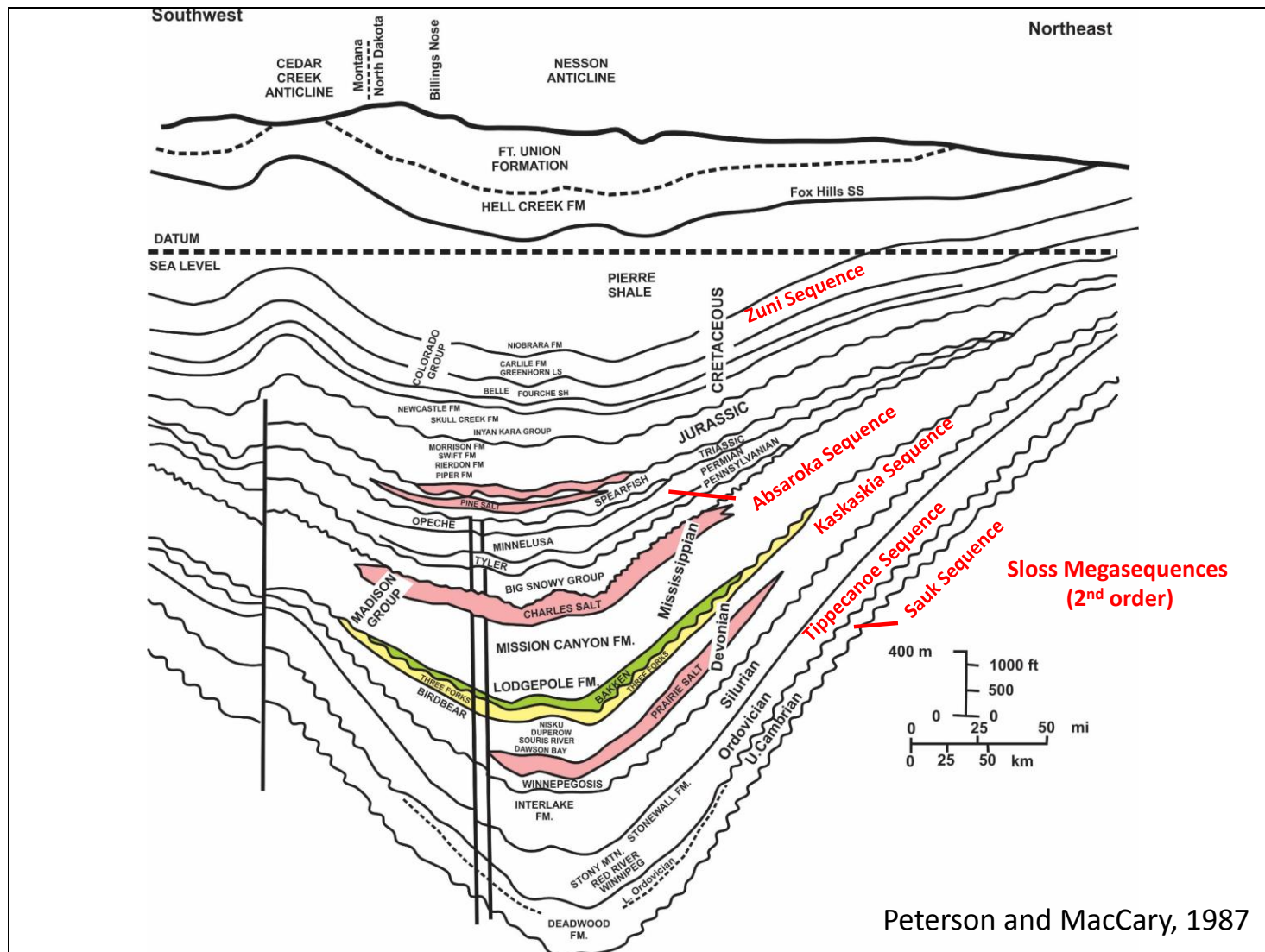
Presenter's notes: Deposition of Upper Three Forks is followed by a regional erosional event and sea level drop followed by deposition of the Pronghorn member (PR-A, PR-B, PR-C) of the Bakken as part of the lowstand to transgressive system tract. This is followed by continued transgression and water deepening which results in Lower Bakken Shale deposition. Deposition of the lower Middle Bakken occurs during the highstand to falling stage systems tract (facies A-C). The tidal sandstones in the Middle Bakken (facies D) represent the lowstand systems tract which then is followed by deposition of the upper Middle Bakken (facies E-F) transgressive system tract. This is followed by continued transgression and deposition of the Upper Bakken mudrocks as part of the transgressive system tract. The upper shale is sharply overlain by highstand deposits of the Longpole formation. Maximum flooding surfaces occur in the upper parts of the Lower and Upper Bakken shales.



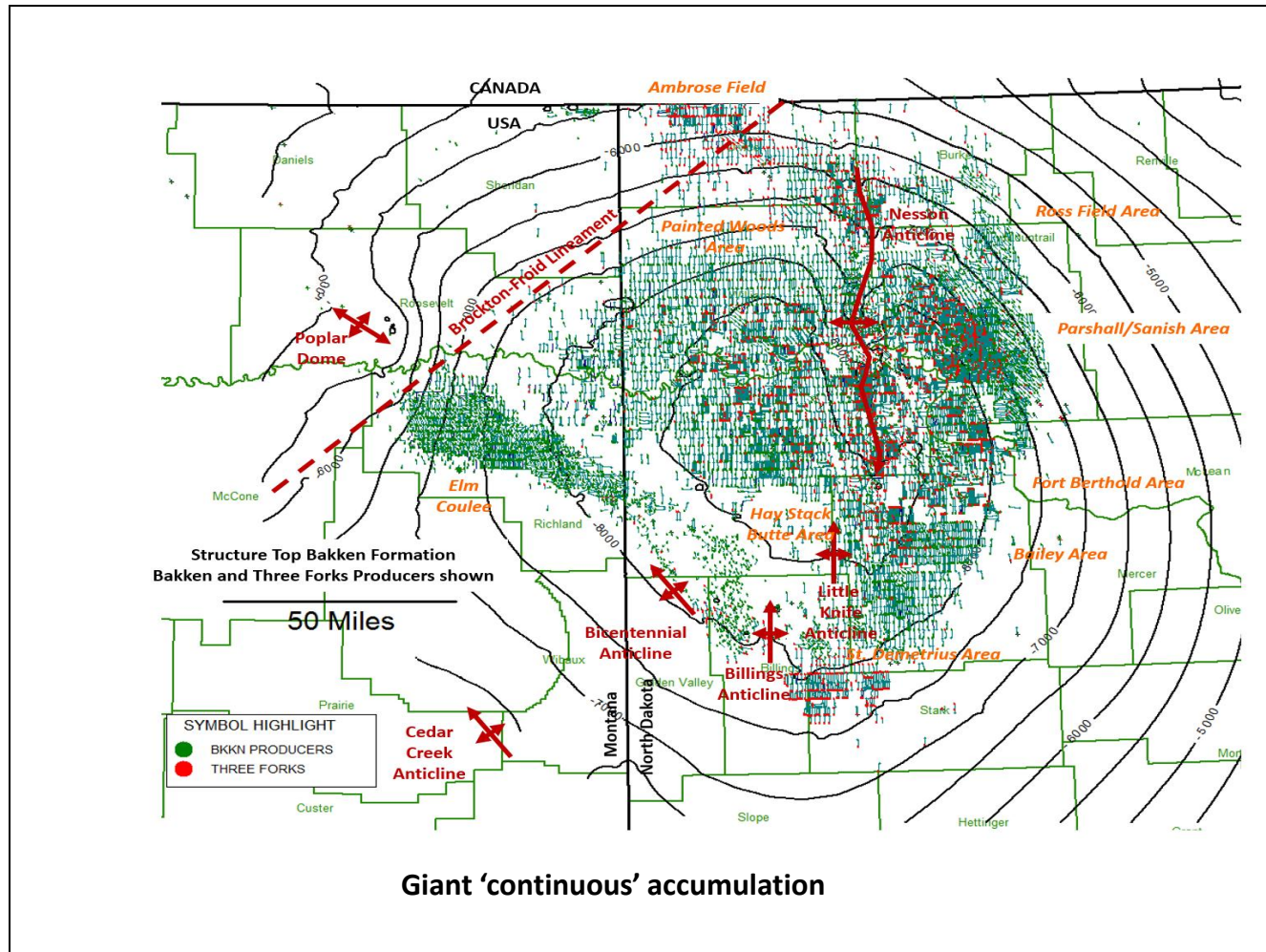
Presenter's notes: Depositional and erosional limits of the Bakken Formation members and the Three Forks Formation (modified from Theloy, 2014; after Meissner, 1978; Pronghorn limits from LeFever et al., 2011).



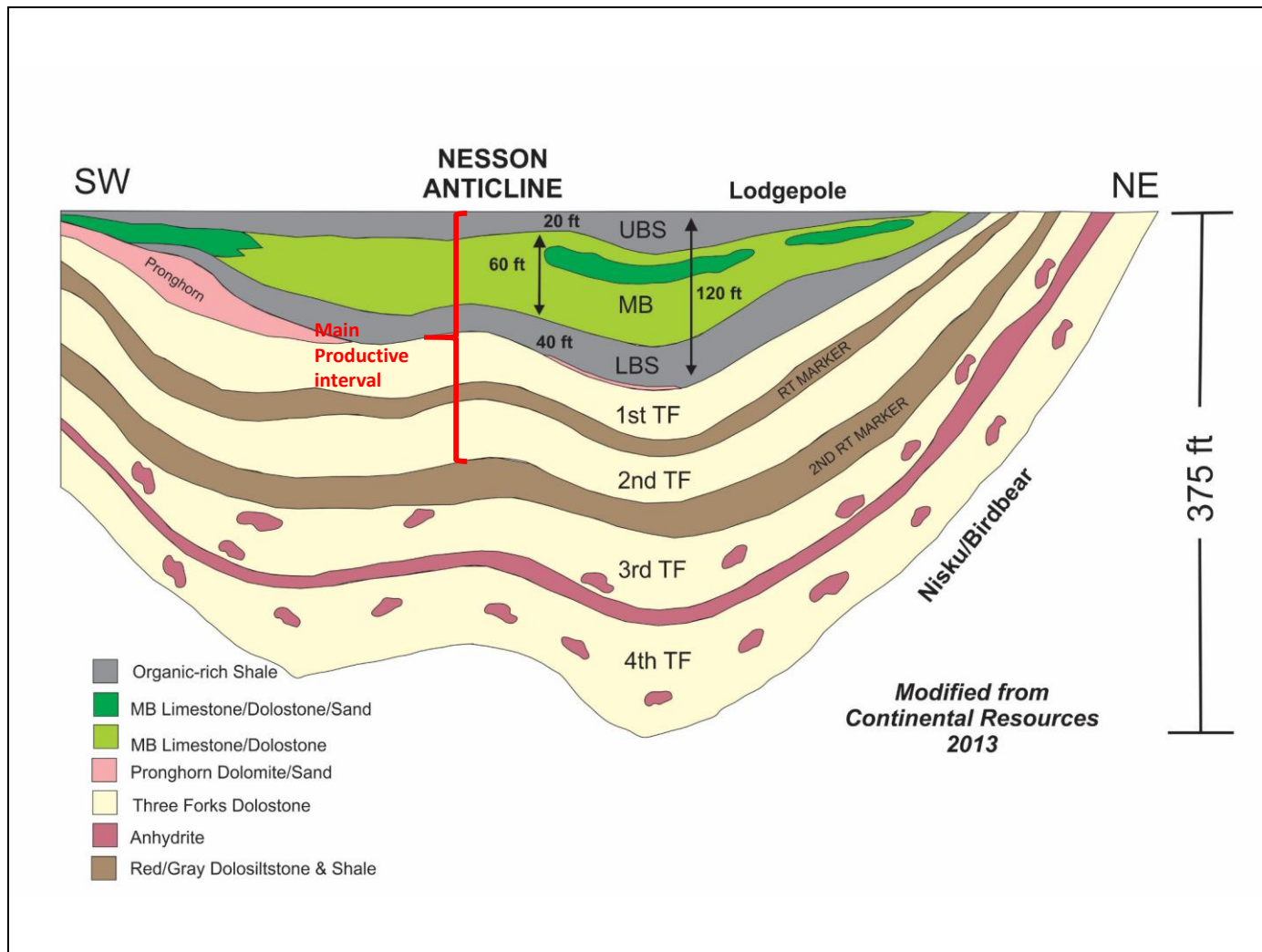
Presenter's notes: Structure map top Dakota illustrating prominent structures and location of important producing fields.



Presenter's notes: Cross section A-A' illustrating the stratigraphy of the Williston Basin and also important unconformities.



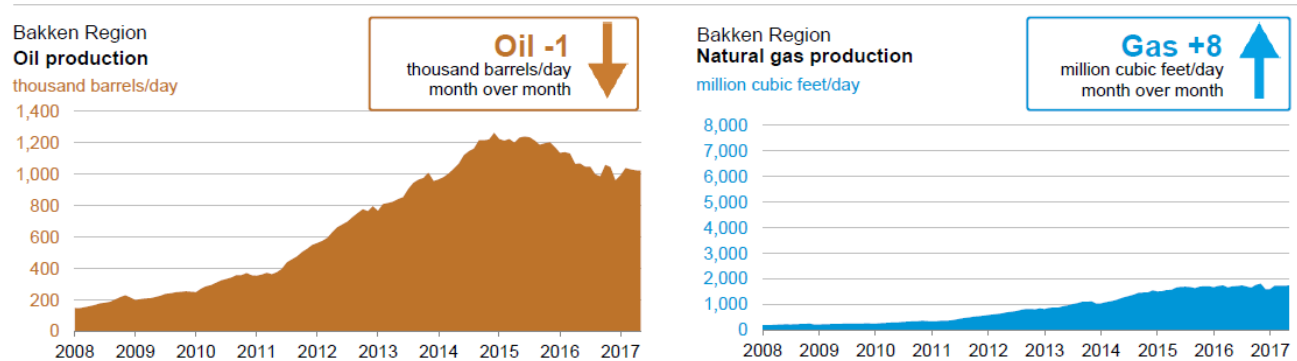
Presenter's notes: Structure map on top of Bakken. Contour interval is 500 ft. Prominent structural features in the Williston Basin include the Poplar, Cedar Creek, Billings, Bicentennial, Little Knife, and Nesson anticlines. The Nesson, Billings, and Little Knife anticlines trend north-south which is most likely related to the Precambrian geology. All the major structural features show evidence of recurrent structural movement during the Phanerozoic.



Presenter's notes: Schematic cross section showing the Bakken Petroleum System. Source beds are the lower and upper Bakken shales. Reservoirs are the Middle Bakken and upper and middle Three Forks.

Note anhydrites in the lower Three Forks.

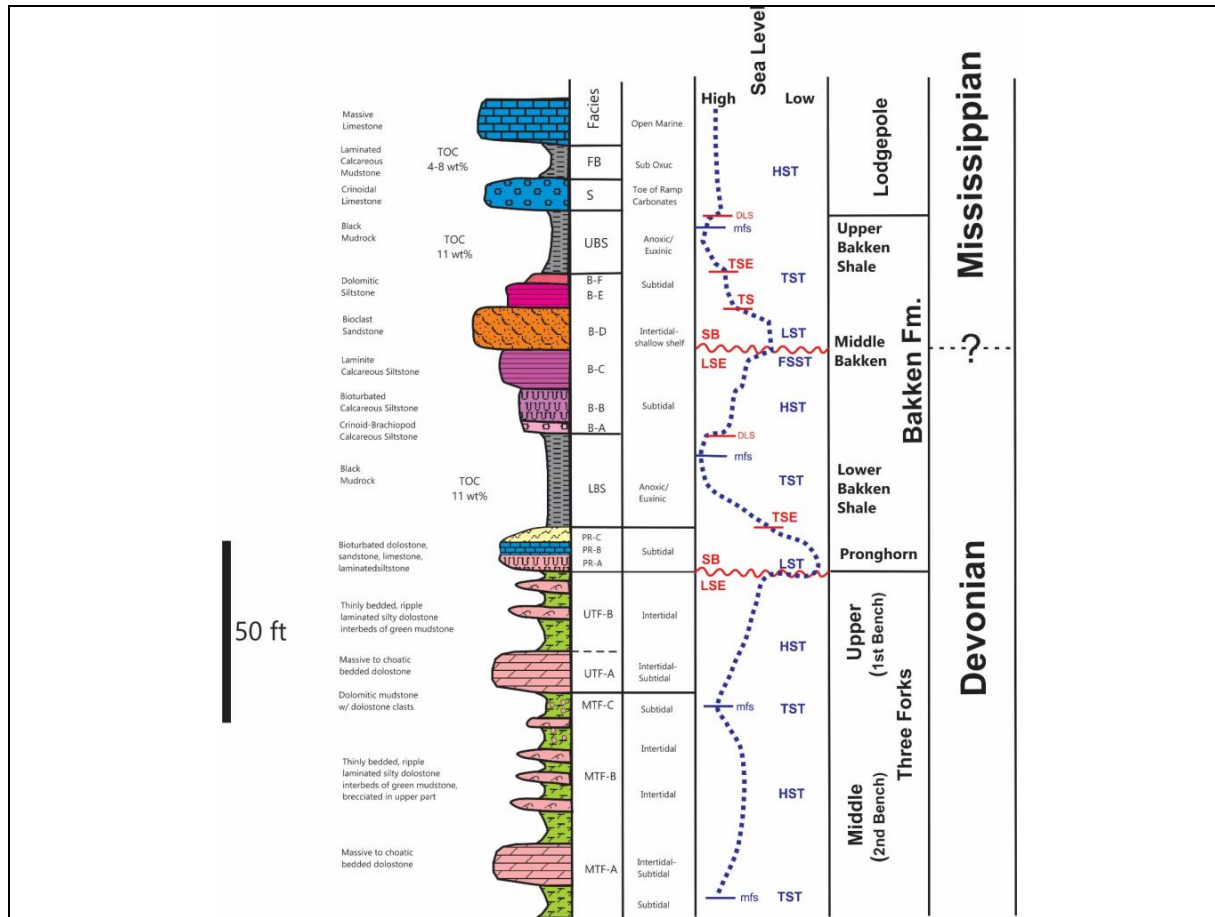
US Bakken Production EIA, 2017



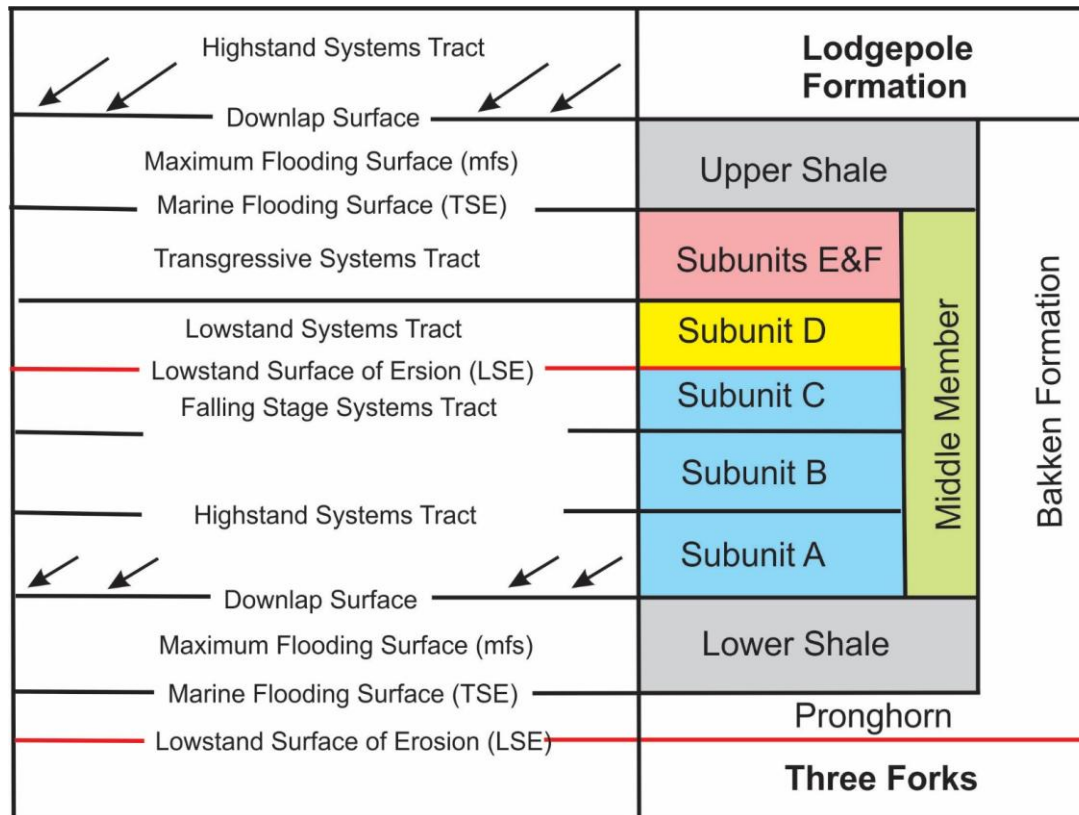
Presenter's notes: Diagram which illustrates US Bakken oil and gas production. Current oil production is over 1 million Barrels per day.

Key Surfaces in Sequence Stratigraphy

1. Erosional unconformities that form with a relative lowering of sea level (sequence boundary: lowstand surface of erosion—LSE)
2. Drowning surfaces (transgressive surface of erosion—TSE, ravinement surfaces)
3. Condensed sections (maximum flooding surface, maximum transgression)

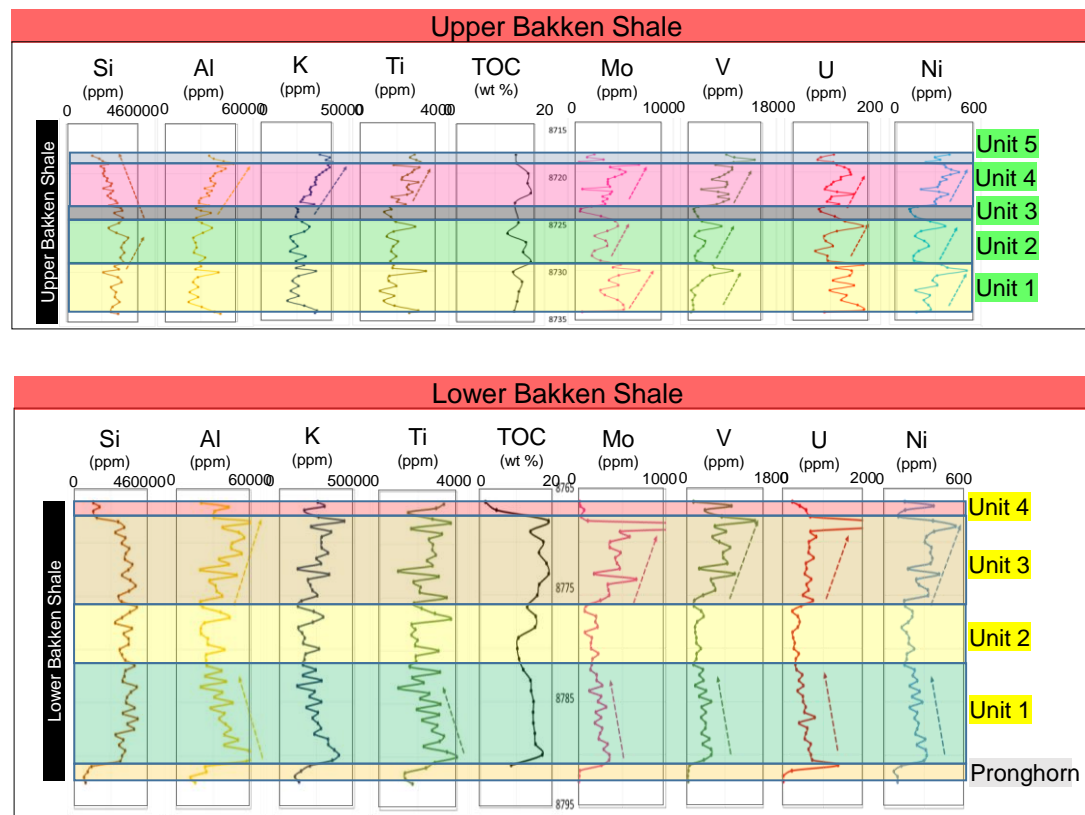


Presenter's notes: Stratigraphic column for Paleozoic producing units in the Williston Basin. Producing units shown by oil and gas symbols. The Bakken Petroleum system consists of source beds in the Bakken and reservoirs in the lower Lodgepole, Bakken, and upper Three Forks. The upper Three Forks is the main producer in the Antelope Field. Sedimentary sequences following Sloss (1963) are indicated. Thickness of stratigraphic units indicated in the column to the right (ft/m). Oil and gas symbols indicate producing formations. Modified from LeFever, 1992. Petroleum systems are modified from Lillis (2013).



Presenter's notes: Sequence stratigraphic diagram for the Bakken Petroleum System.

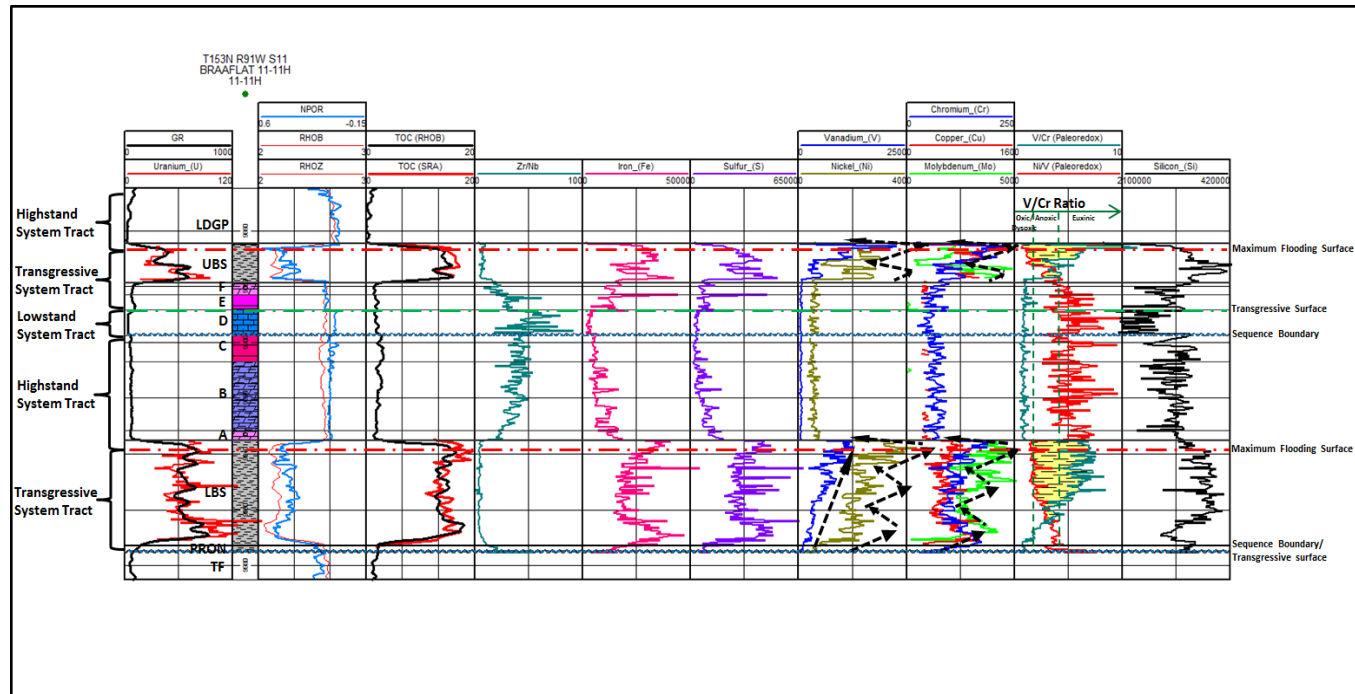
Sidonia 1-6H
6-T158N-R90W



Nandy, 2014

Presenter's notes: XRF data for the Upper and Lower Bakken Shales. Highest V, Mo, and U in the upper parts suggesting anoxic to euxinic conditions and position of the maximum flooding surface in the upper parts of the shales.

System tract identification



Jin, 2012

Presenter's notes: The most reducing sections are identified in Bakken shales, so the maximum flooding surface can further be inferred.

(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

During the deposition of Bakken shales, an overall transgression occurred in the basin as sea level rose. A stratified water column was formed with reducing conditions prevailing on the bottom surface. As progressive flooding, deeper parts of the basin would become more and more reducing, because of limited water and oxygen circulation in the restricted and stagnant central basin.

So, the timing of most reducing conditions can correspond to the timing of maximum flooding in the basin. Based on this hypothesis, the maximum flooding surface may be located in shale section with maximum V and Ni enrichments, which is near the top contact of the shale sections.

So, the sequence stratigraphic model for the Bakken Formation was then established.

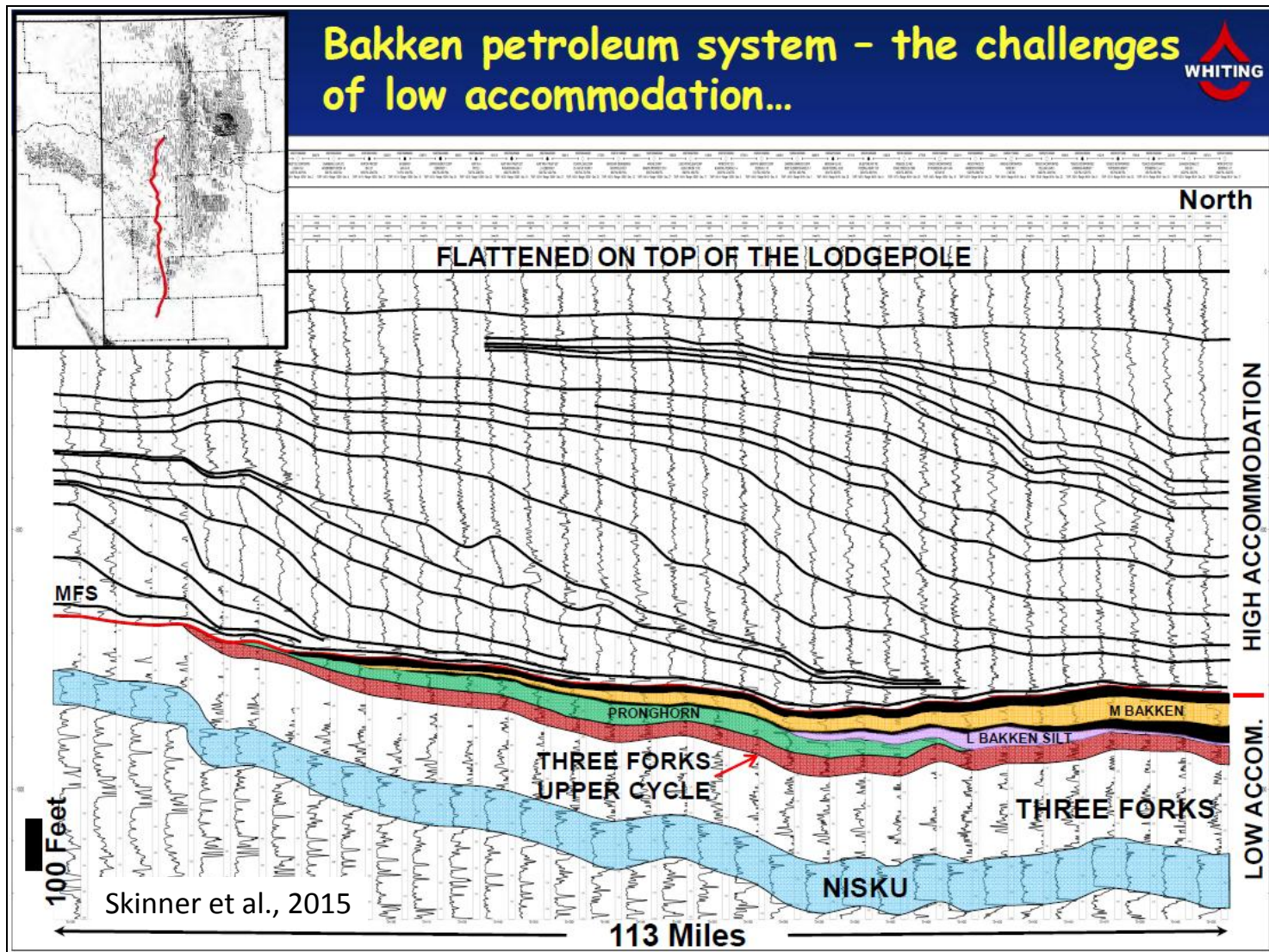
The basal surface of Bakken Formation is an amalgamated surface, consisting of the Acadian unconformity and the transgressive surface. So, the majority of lower Bakken shale below the maximum flooding surface belong to the transgressive system tract (TST).

After the maximum flooding event, the sea level was slowly falling from its highstand level, and the water chemistry of the basin changed from the euxinic/anoxic back to oxic conditions. Simultaneously, more terrigenous sediments were transported into the basin. As a result, the coarsening-upward A, B, and C middle Bakken facies were deposited as relative sea level falls, and they belong to the highstand system tract (HST).

At the end of the C facies deposition, sea level probably dropped to its minimum level and an erosion surface was induced on the top of C facies. The coarsest D facies in the middle Bakken was deposited during the maximum regression of sea level. So, the middle Bakken D facies can be considered as the lowstand system tract (LST).

After the deposition of D facies, the sea level rose again, fining upward middle Bakken E and F facies were deposited in the basin. The rising of sea level continued during upper Bakken time, and the maximum flooding event probably occur near the end of the upper Bakken shale deposition. So, the middle Bakken E, F facies and most of upper Bakken shale are regarded as the second transgressive system tract (TST).

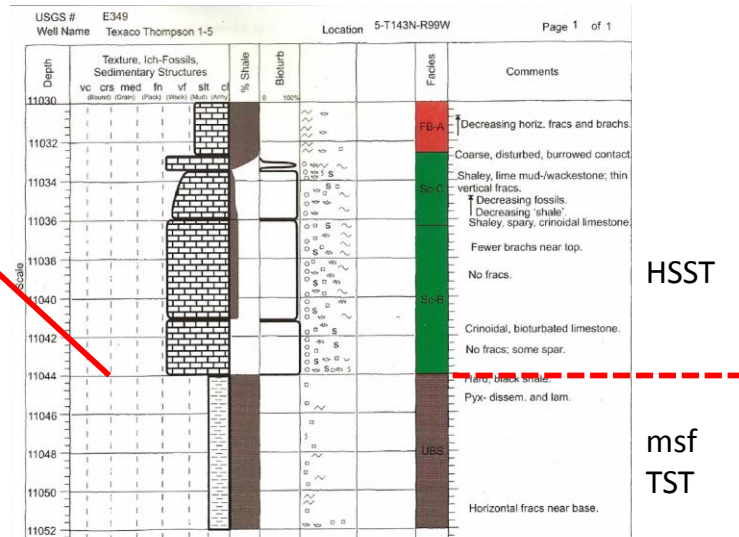
The overlying Lodgepole Formation was deposited during the highstand of sea level and considered as the highstand system tract.



Presenter's notes: Progradation sequences within the Lodgepole Formation and also downlapping that occurs on top of Upper Bakken Shale.

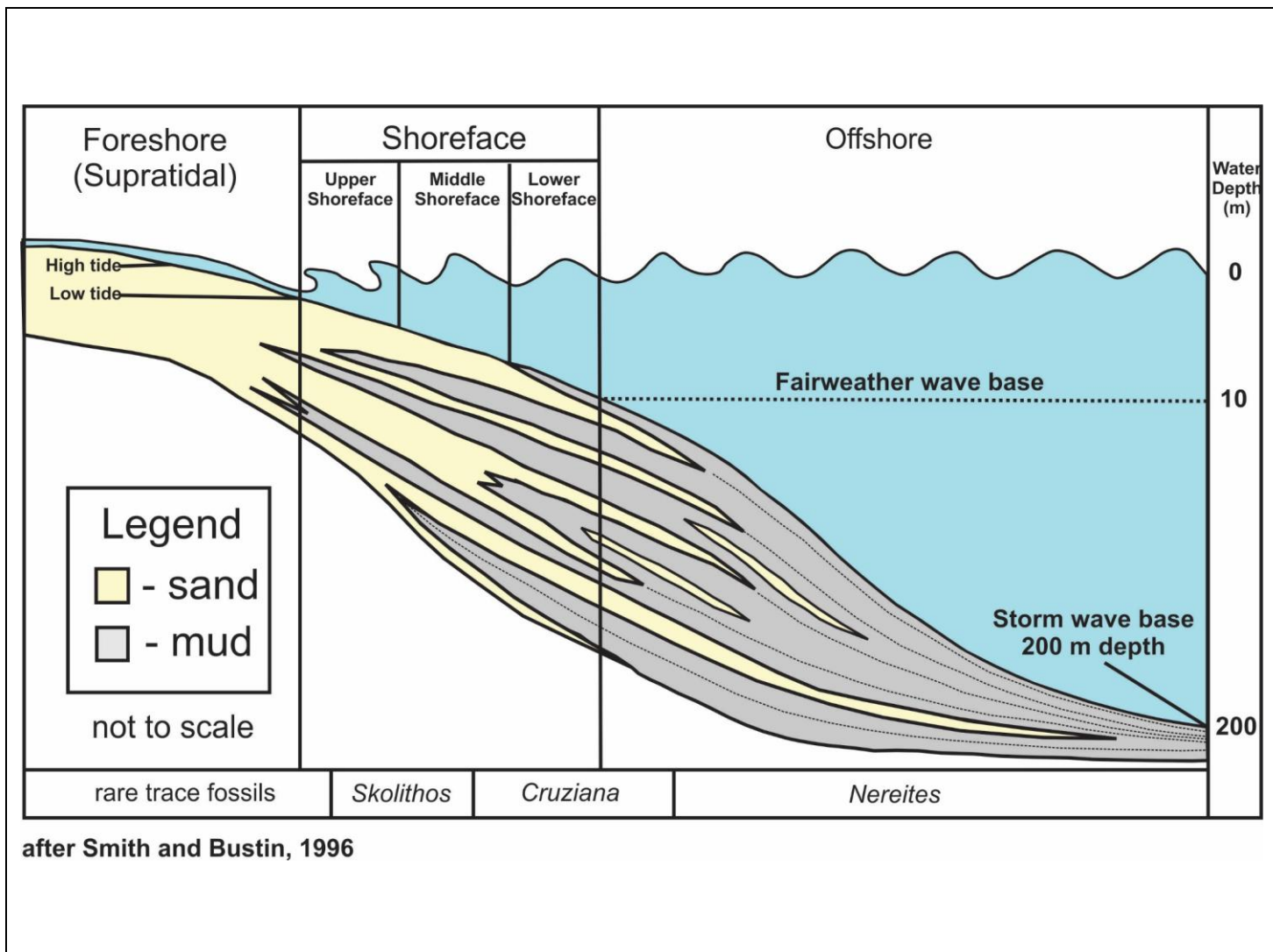


“Downlap surface”

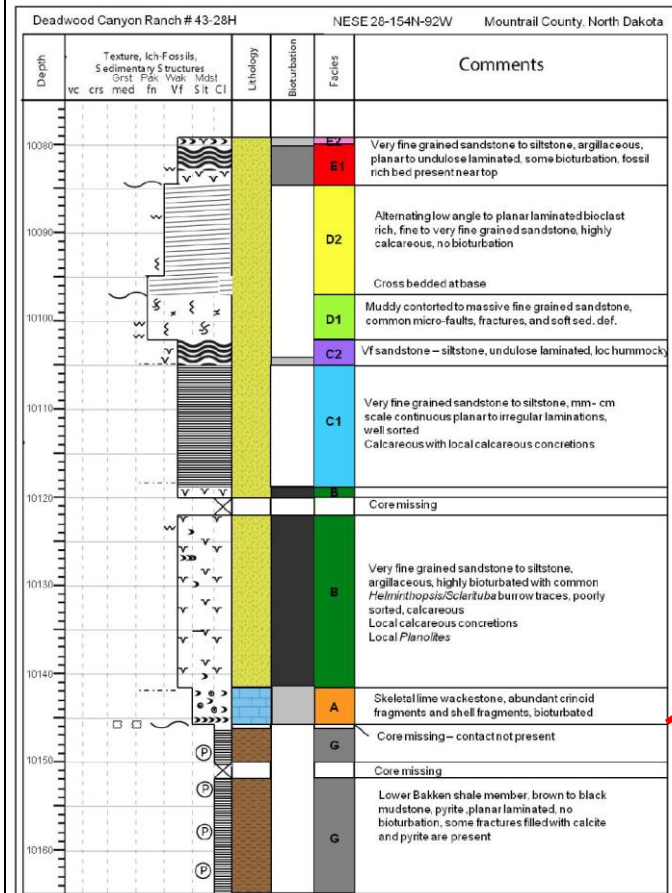


Stroud, 2010

Presenter’s notes: Core photos of sharp surface between the Upper Bakken Shale and overlying Lodgepole formation. The surface is thought by me to represent a downlap surface separating the transgressive system tract from the overlying high stand systems tract.

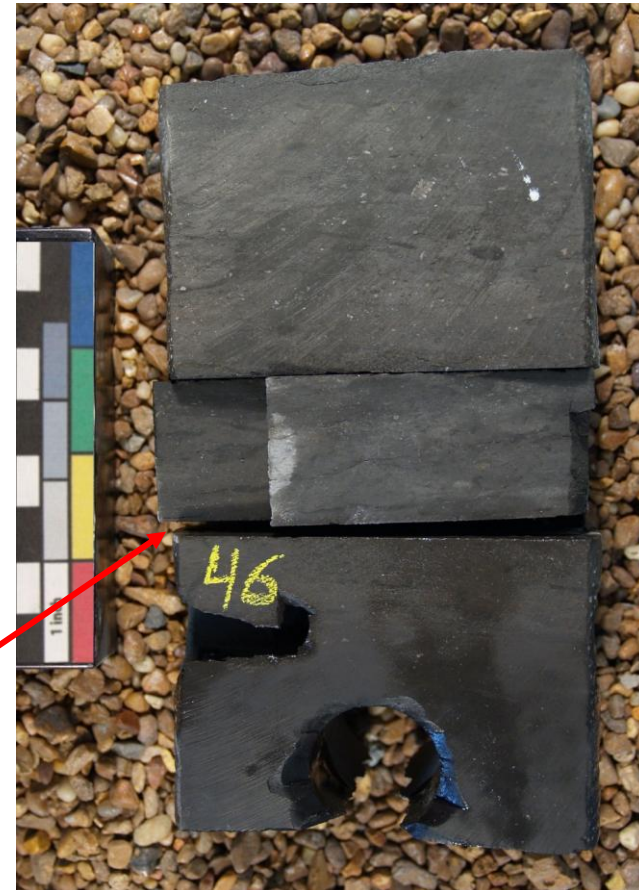


Presenter's notes: Middle Bakken schematic from Smith and Bustin, 1996. This diagram illustrating progradation and downlap onto the Lower Bakken Shale.



Kowalski, 2010

down lap surface



Presenter's notes: Sharp contact between the Lower Bakken Shale and the Middle Bakken. This zone is interpreted as a downlap surface.

Facies	Grain Size	Depth	Lithology	Bioturbation	Remarks
	ve, crs, med, fn, vf, silt, cl				
Upper Bakken Shale		-9860			upper Bakken shale - dark brown organic rich laminated mudstone. Concentrated pyrite as nodules and along bedding planes. Local silty calcitic lamina and kerogen blobs.
		-9870			
		-9880			F - dolo-lime wackestone with fossils
		-9890			E - thin-bedded dolomitic mud/wackestone. Disturbed bedding near the bottom.
		-9900			D - laminated lime grainstone/sandstone. Coarsest grained = highest energy.
Middle Bakken		-9910			C - laminated sandstone/siltstone. Some hummocks and wave ripples. Calcite cement and filled vertical fracture ~9 cm.
		-9920			B - bioturbated, argillaceous siltstone/sandstone. <i>Helminthopsis/scalarituba</i> burrows throughout and the occasional brachiopod.
		-9930			A - Skeletal lime wackestone
Lower Bakken Shale		-9940			lower Bakken shale - dark brown organic rich laminated mudstone. Concentrated areas of pyrite (nodules and along bedding planes). Organic rich material forms as 'blobs'. Local silty calcitic laminae. Occasional tygmatic fracture.
		-9950			
		-9960			

Kowalski, 2010

Braaflat 11-11

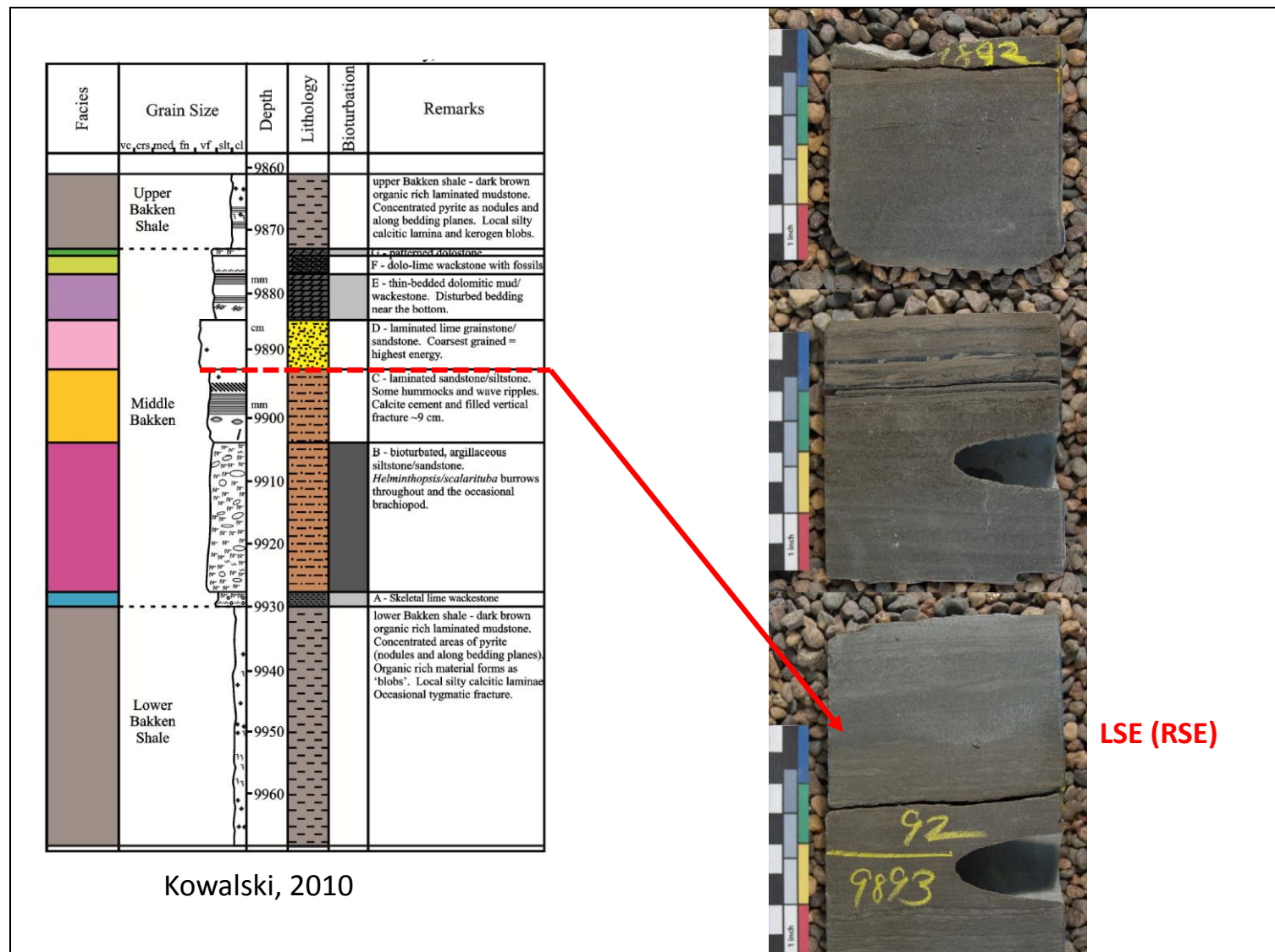


HSST

TST

"down lap Surface"

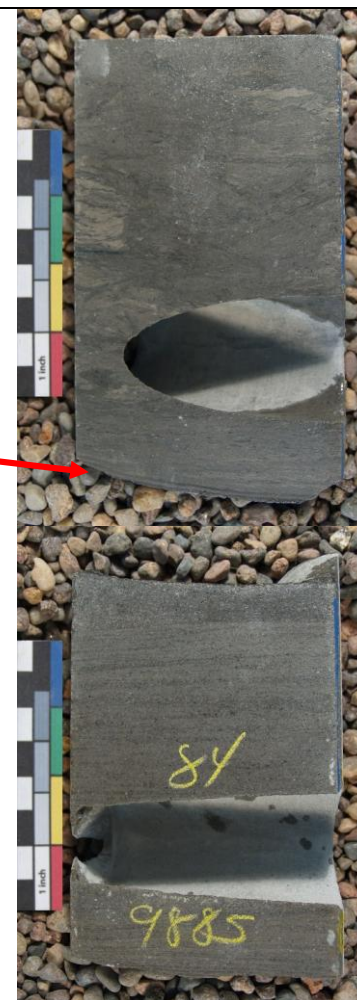
Presenter's notes: Sharp contact between the Lower Bakken Shale and the Middle Bakken. This zone is interpreted as a downlap surface.



Presenter's notes: Lowstand surface of erosion found in the Middle Bakken. This unconformity truncates in C facies in places in the Williston Basin.

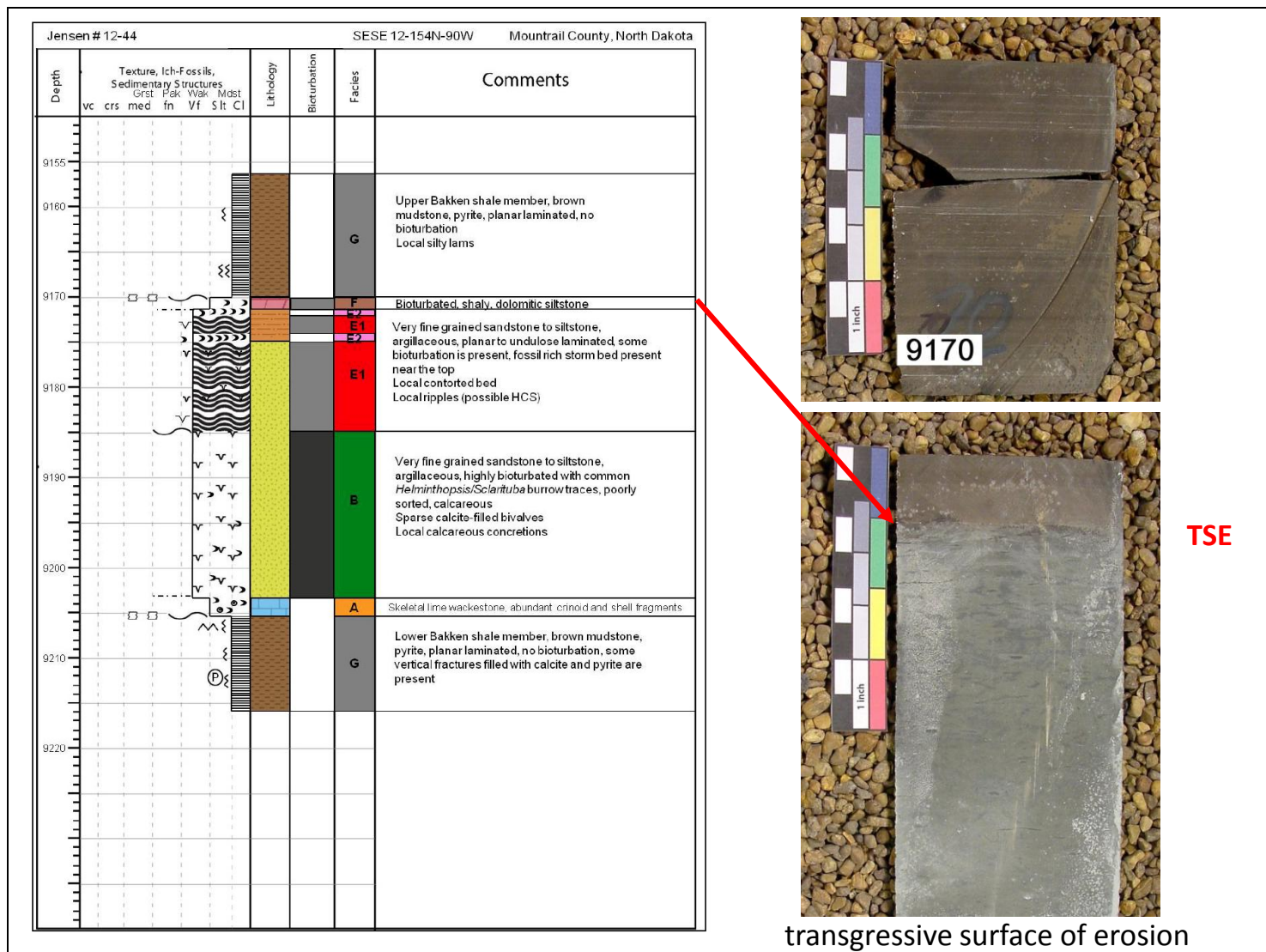
Facies	Grain Size	Depth	Lithology	Bioturbation	Remarks
	vc, crs, med, fn, vf, silt, cl				
Upper Bakken Shale		-9860			upper Bakken shale - dark brown organic rich laminated mudstone. Concentrated pyrite as nodules and along bedding planes. Local silty calcitic lamina and kerogen blobs.
		-9870			
		-9880			F - dolomite wackestone with fossils E - thin-bedded dolomitic mud/wackestone. Disturbed bedding near the bottom.
		-9890			D - laminated lime grainstone/sandstone. Coarsest grained = highest energy.
Middle Bakken		-9900			C - laminated sandstone/siltstone. Some hummocks and wave ripples. Calcite cement and filled vertical fracture ~9 cm.
		-9910			B - bioturbated, argillaceous siltstone/sandstone. <i>Helminthopsis/scalarituba</i> burrows throughout and the occasional brachiopod.
		-9920			
		-9930			A - Skeletal lime wackestone
Lower Bakken Shale		-9940			lower Bakken shale - dark brown organic rich laminated mudstone. Concentrated areas of pyrite (nodules and along bedding planes). Organic rich material forms as 'blobs'. Local silty calcitic laminae. Occasional tygmatic fracture.
		-9950			
		-9960			

Kowalski, 2010

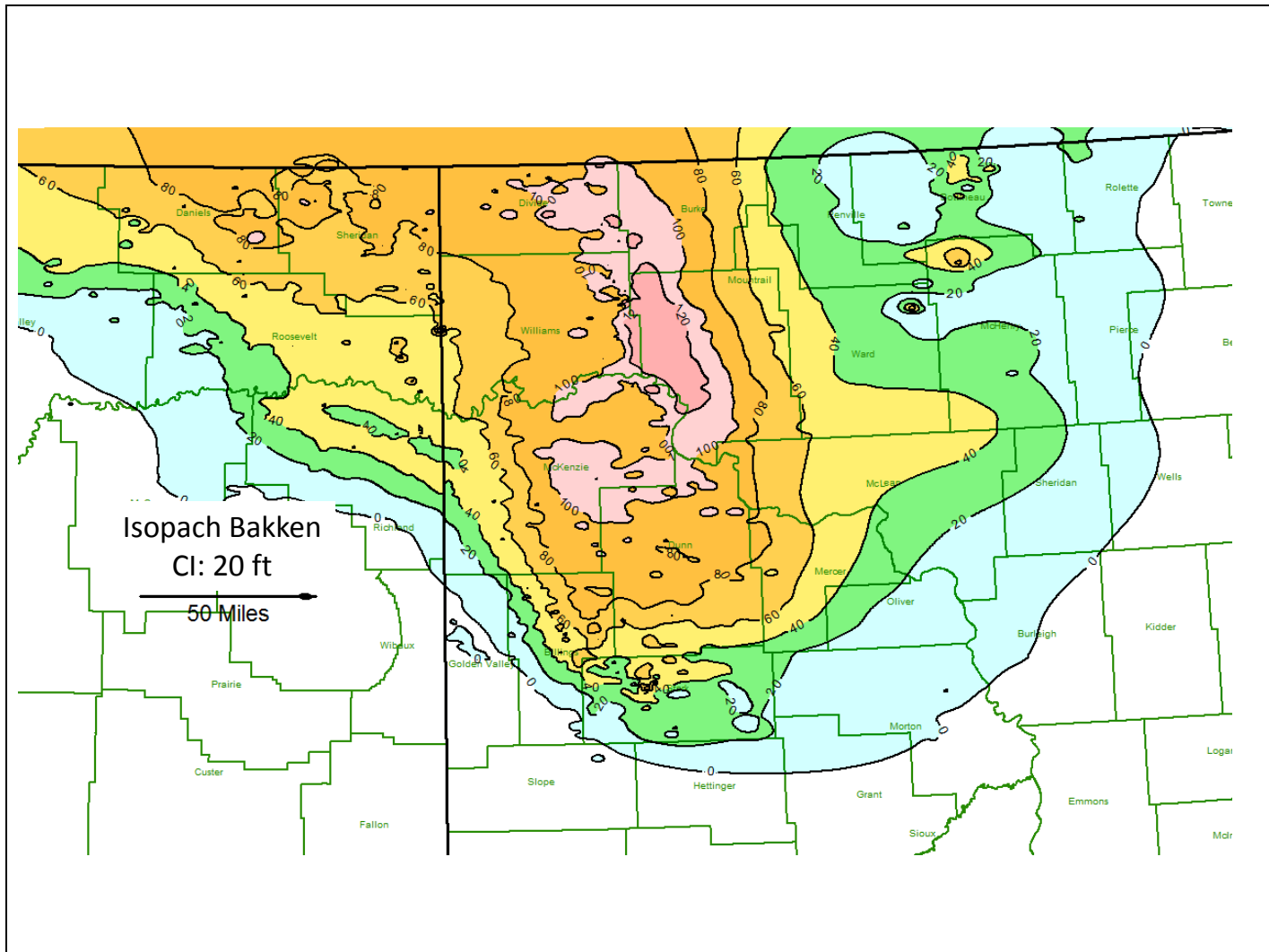


transgressive surface of erosion

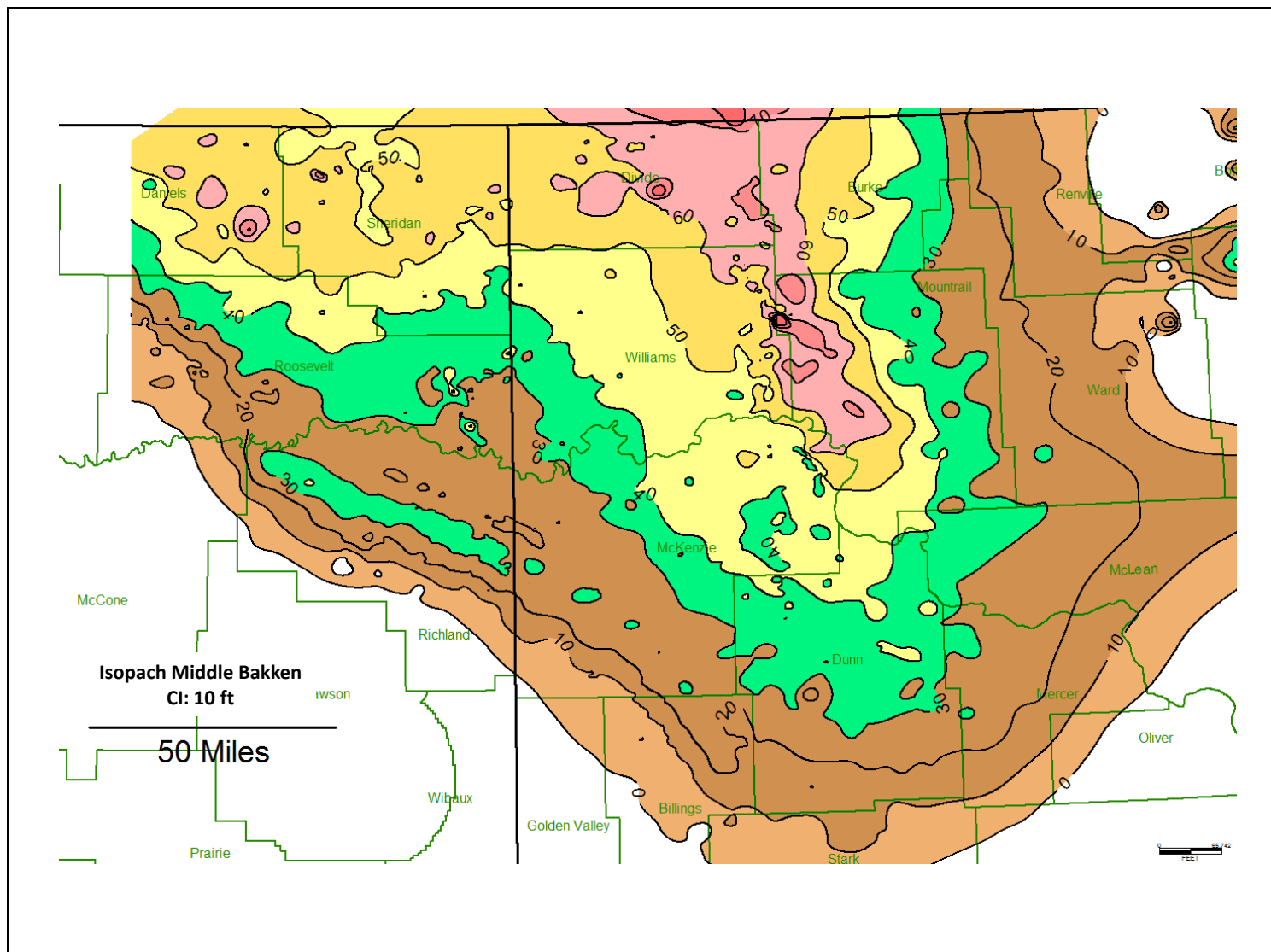
Presenter's notes: Surface which represents the beginning of the transgressive system tract of the upper Middle Bakken and the Upper Bakken Shale.



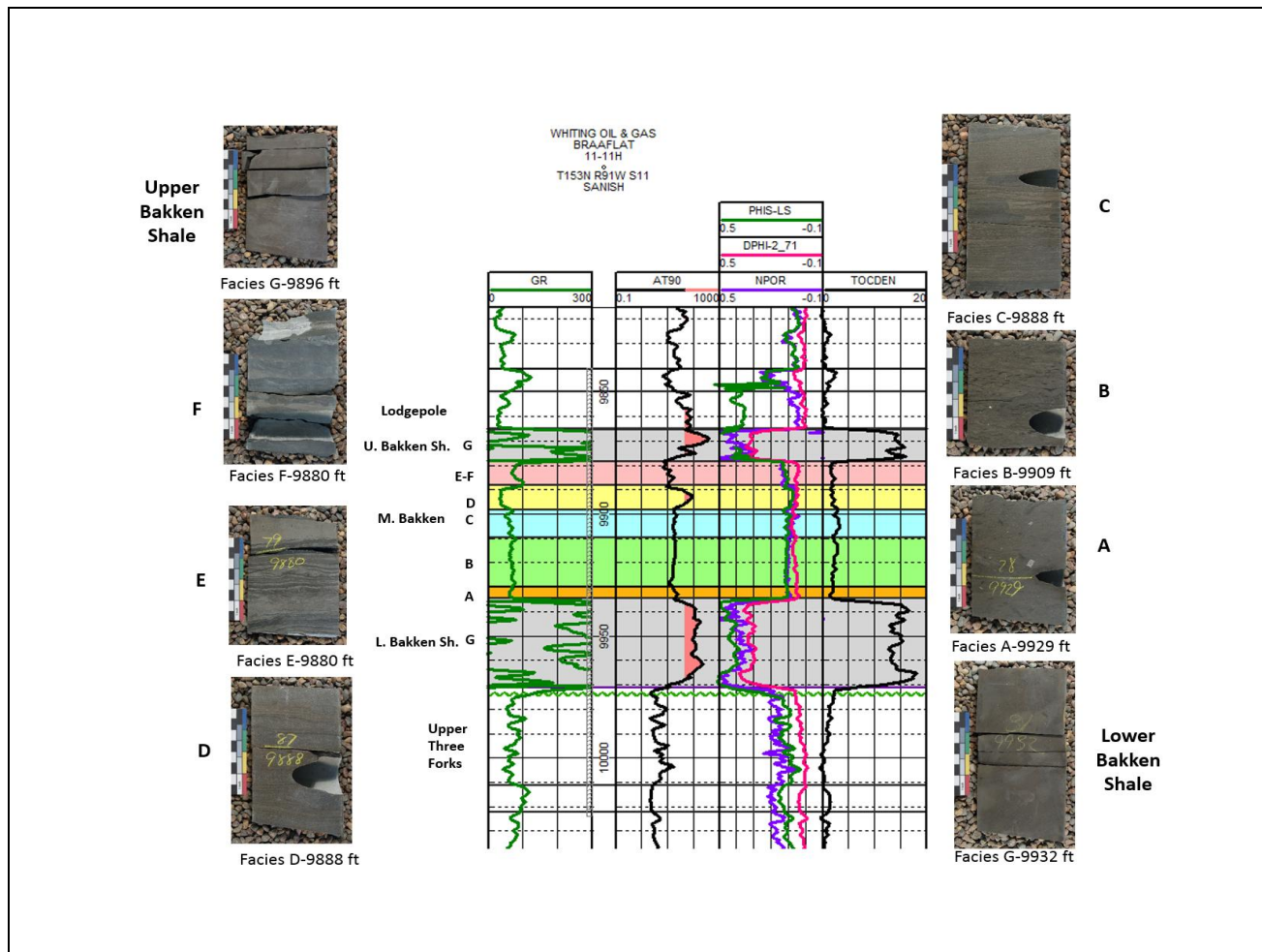
Presenter's notes: The transgressive surface of erosion located on the top of the Middle Bakken and Upper Bakken Shale contact.



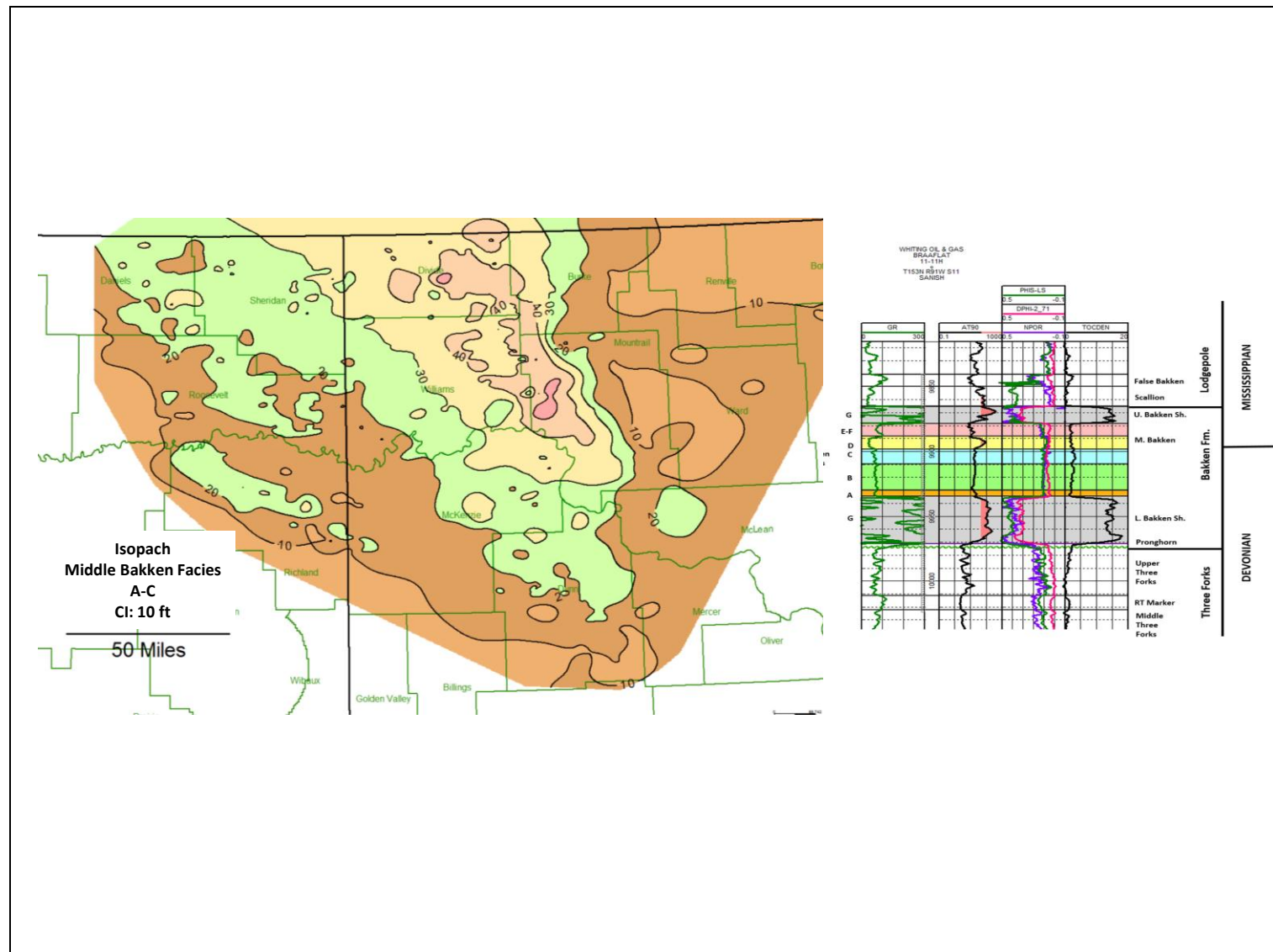
Presenter's notes: Isopach map of Bakken Formation. The Bakken ranges in thickness from a wedge-edge to over 140 ft. The thickest area is just east of the Nesson Anticline in Mountrail County.



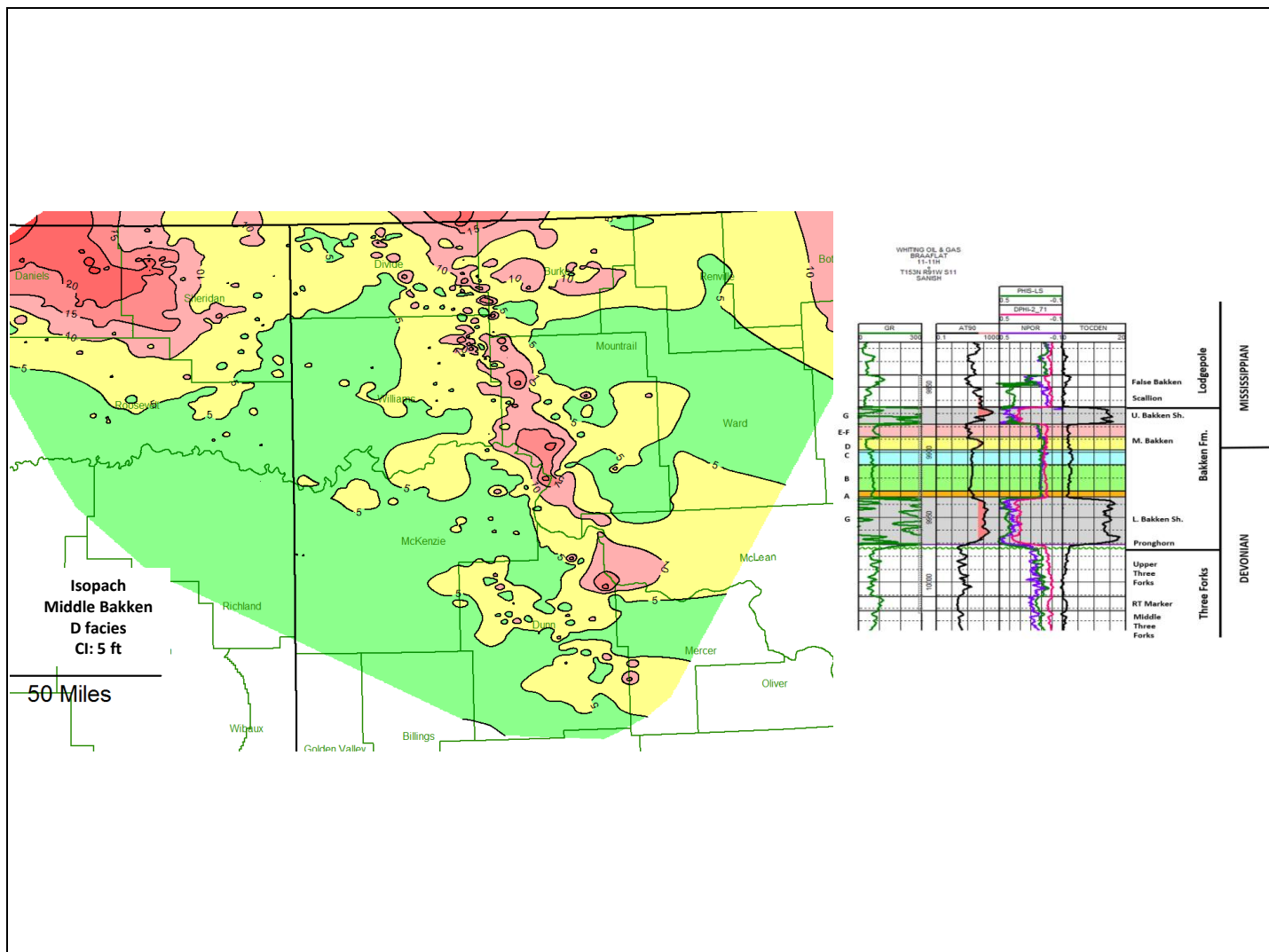
Presenter's notes: Isopach map of Middle Bakken. Contour interval equals 10 ft. The Middle Bakken ranges in thickness from a wedge-edge to over 70 ft.



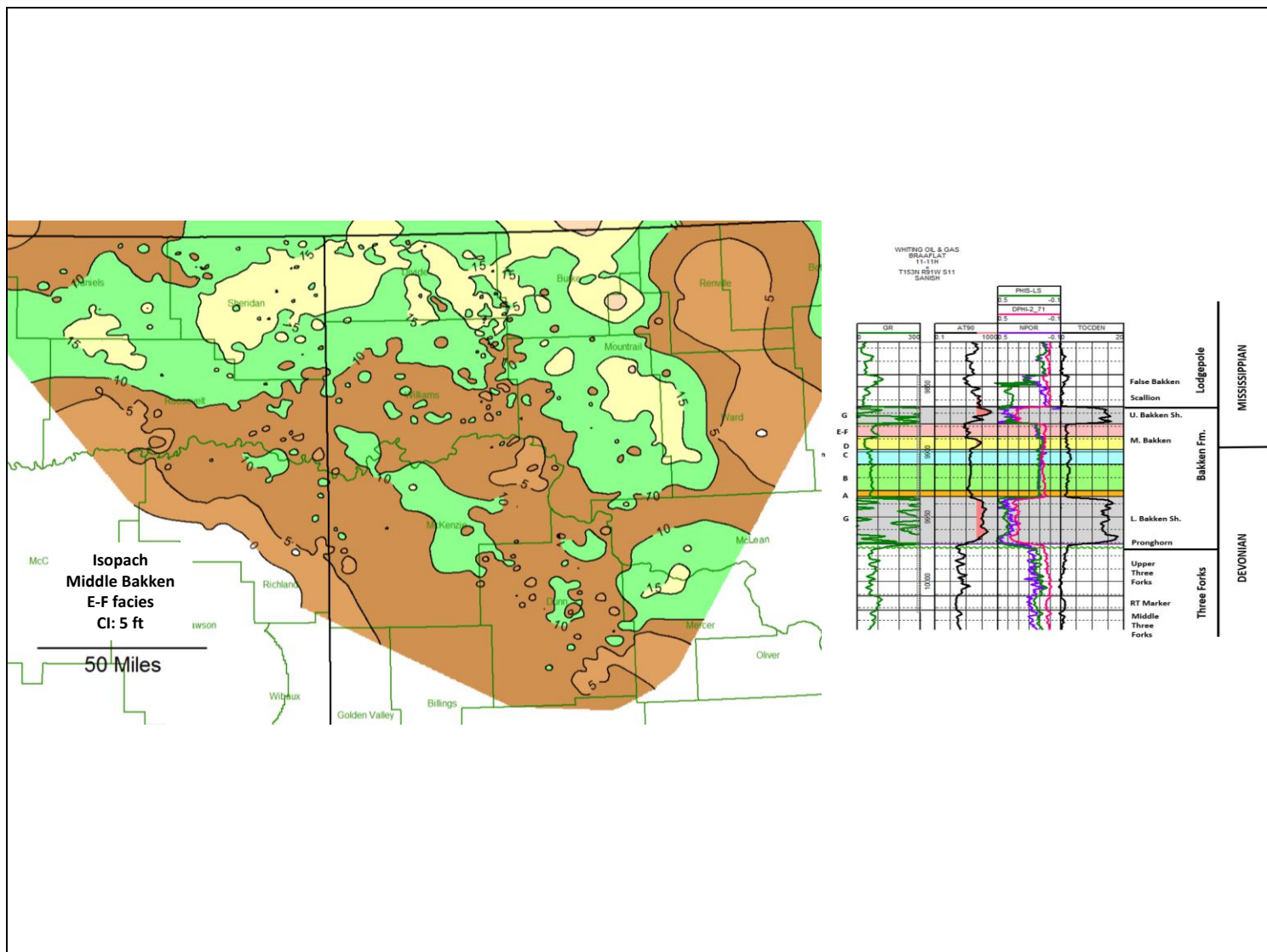
Presenter's notes: Well log display of the Bakken and upper Three Forks from the Whiting Oil and Gas Braaflat 11-11H (Sec. 11, T153N, R91W). Upper and lower Bakken shales have very high GR readings (>200 API). Middle Bakken and Three Forks have low porosities (<10%). Middle Bakken can be subdivided into facies A-F. Headings: GR –gamma ray; AT90 resistivity curves; PHIS-sonic porosity; DPHI-density porosity; NPOR-neutron porosity; TOCDEN-calculated TOC from density log. Resistivity greater than 50 ohm-m shaded pink.



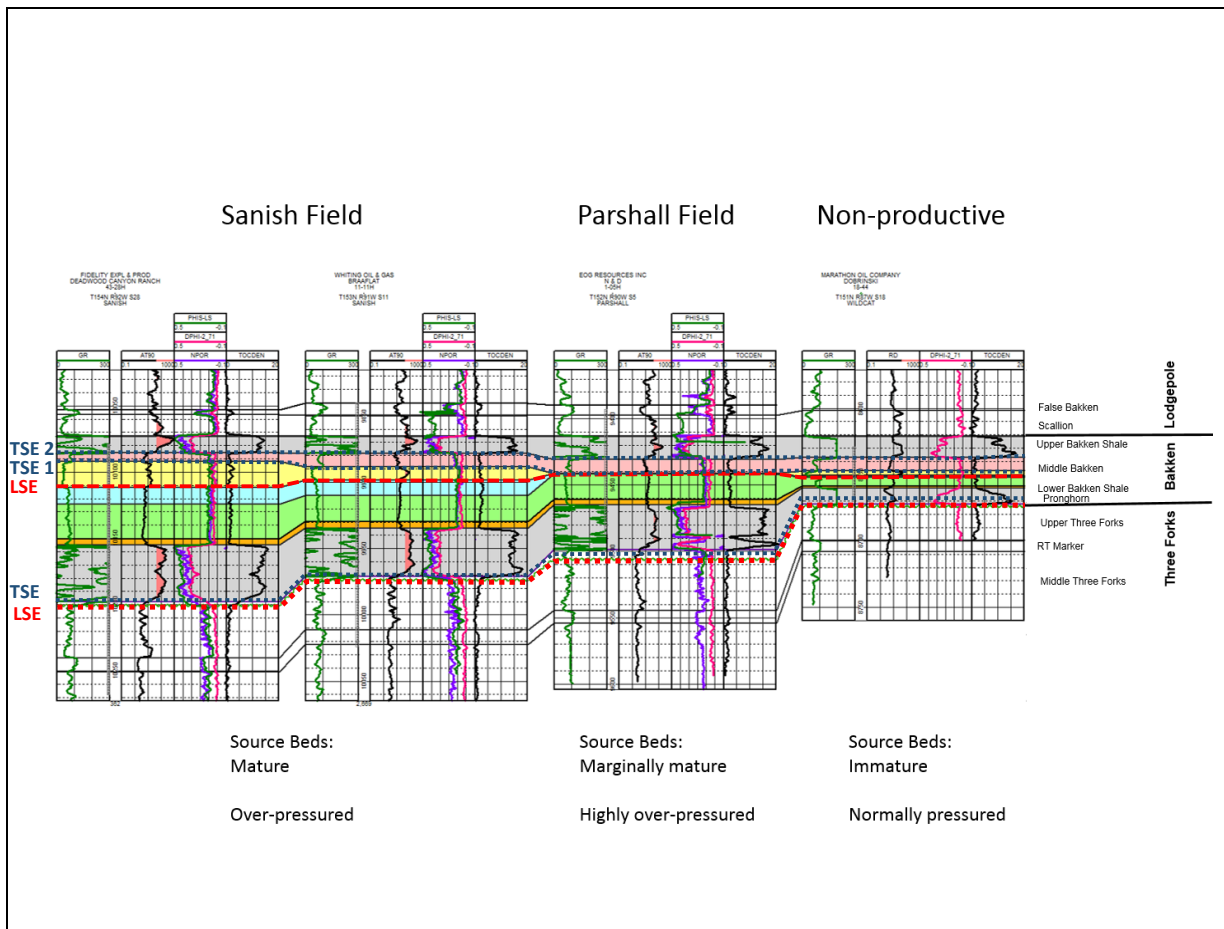
Presenter's notes: Isopach Middle Bakken facies A-C. The unit ranges in thickness from less than 10 ft to over 50 ft.



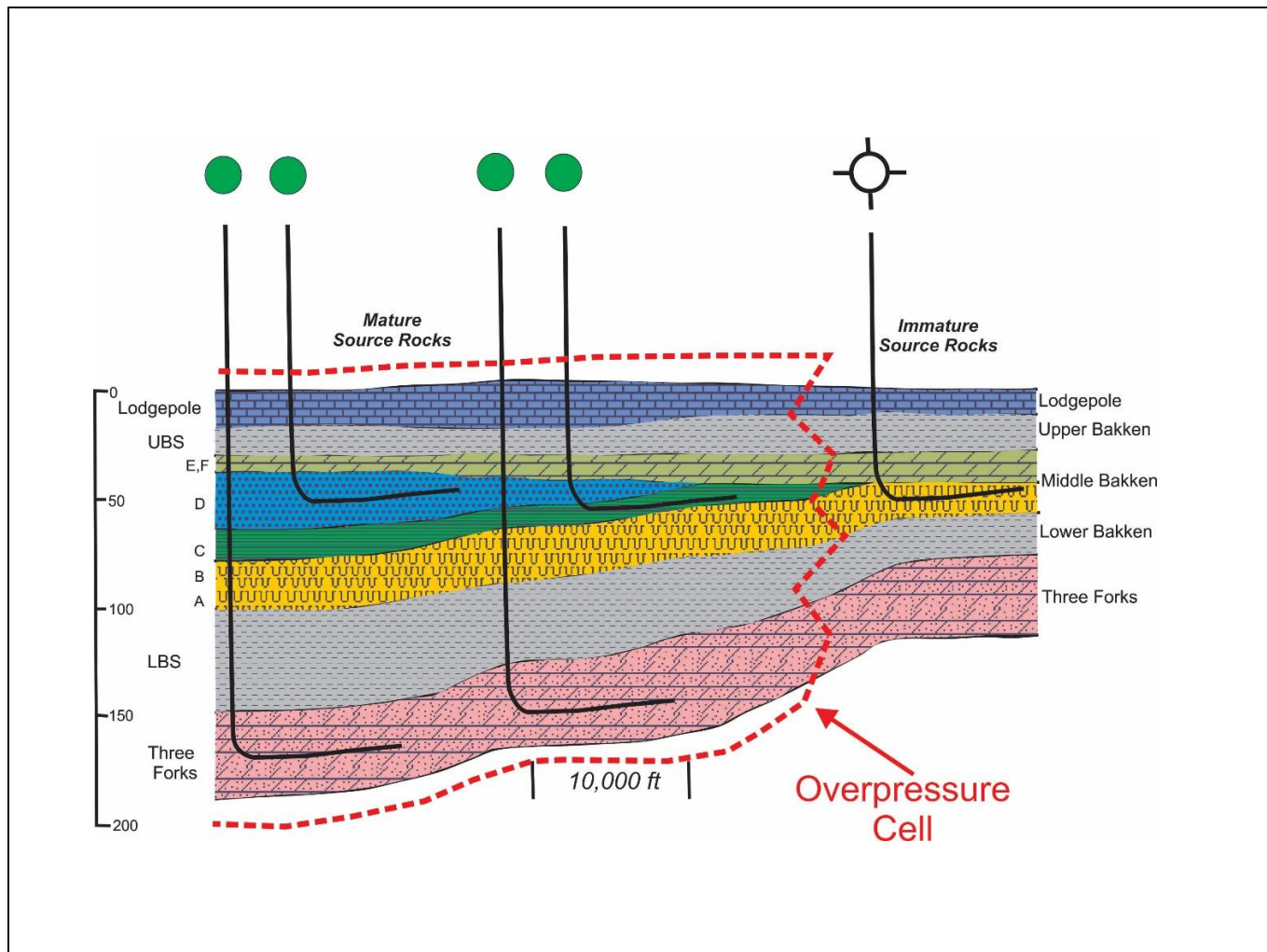
Presenter's notes: Isopach Middle Bakken facies D. The unit ranges in thickness from less than 0 ft to over 20 ft.



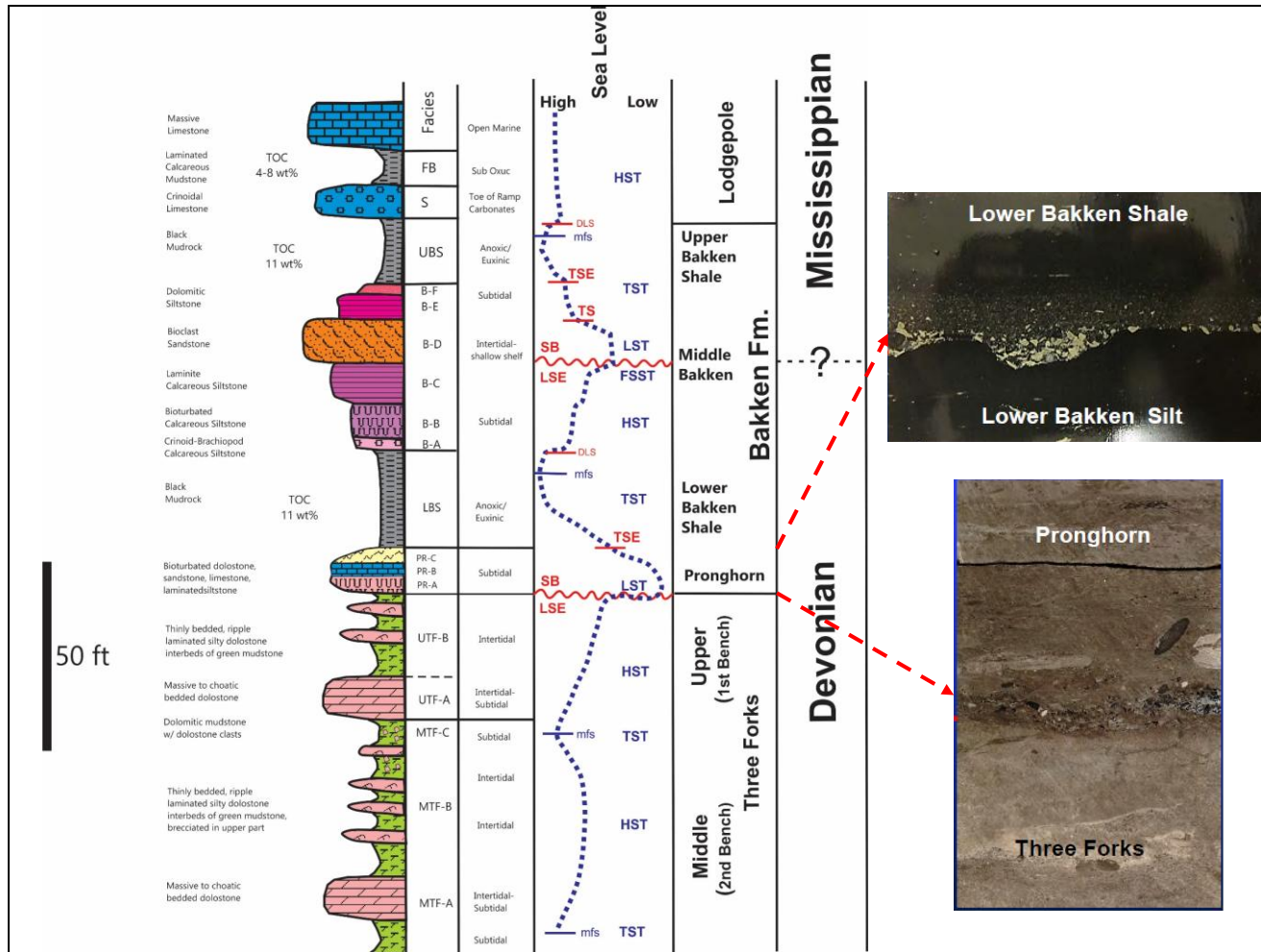
Presenter's notes: Isopach Middle Bakken facies E-F. The unit ranges in thickness from less than 0 ft to over 20 ft.



Presenter's notes: Four well cross-section Sanish to Parshall Fields (W-E). Upper and lower Bakken shales (facies G) have very high GR readings (>200 API). Middle Bakken and Three Forks have low porosities ($<10\%$). Middle Bakken can be subdivided into facies A-F. Headings: GR –gamma ray; AT90 deep resistivity curves; PHIS-sonic porosity; DPHI-density porosity; NPOR-neutron porosity; TOCDEN-calculated TOC from density log. Resistivity greater than 50 ohm-m shaded pink. Note decrease in resistivity to the east (decrease in thermal maturity). Note pinching out of facies C and D to the east. Horizontal wells were drilled from these pilot wells. Deadwood Canyon well completed for 362 BOPD & 364 MCFD; Braafat well completed for 2669 BOPD & 1968 MCFD; N&D well completed for 1285 BOPD & 404 MCFD.

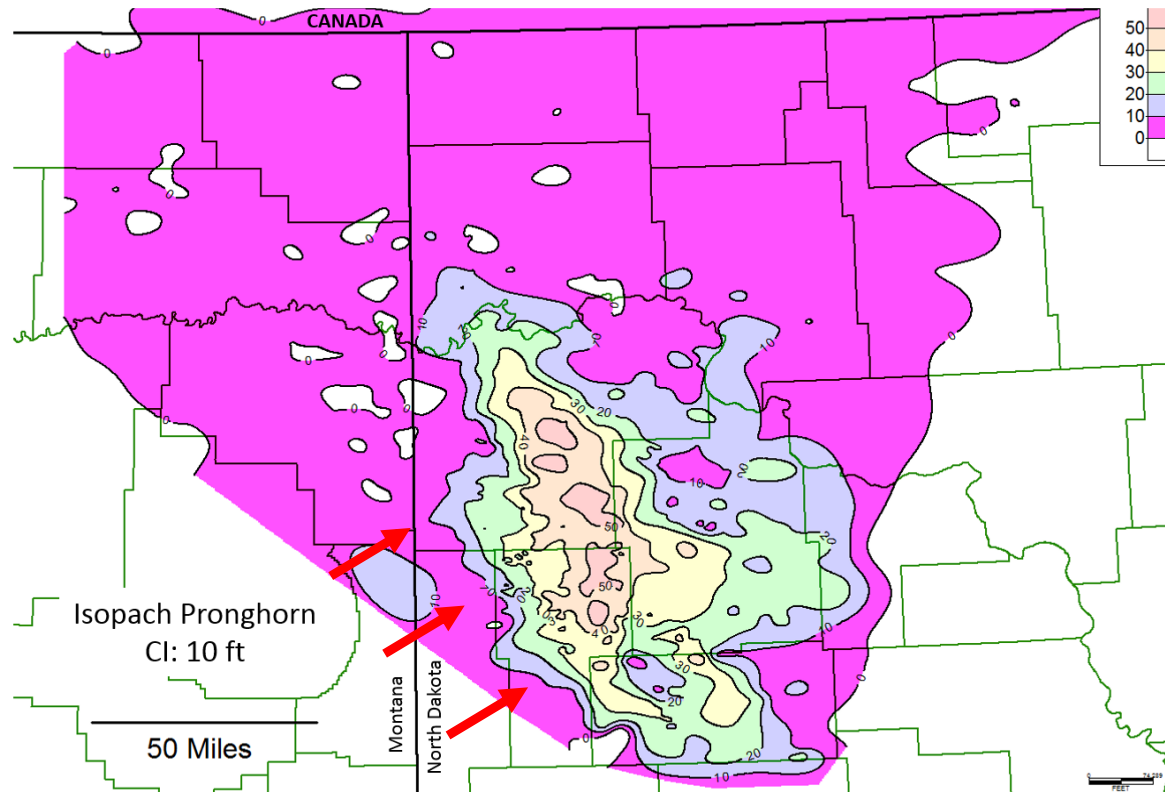


Presenter's notes: Schematic which shows both Bakken and Three Forks production in the Parshall and Sanish field areas. The trap on the east side is interpreted as the result of facies changes in the Middle Bakken and maturity changes in the Upper and Lower Bakken shales. The maturity creates an overpressured compartment in the Bakken and Three Forks.

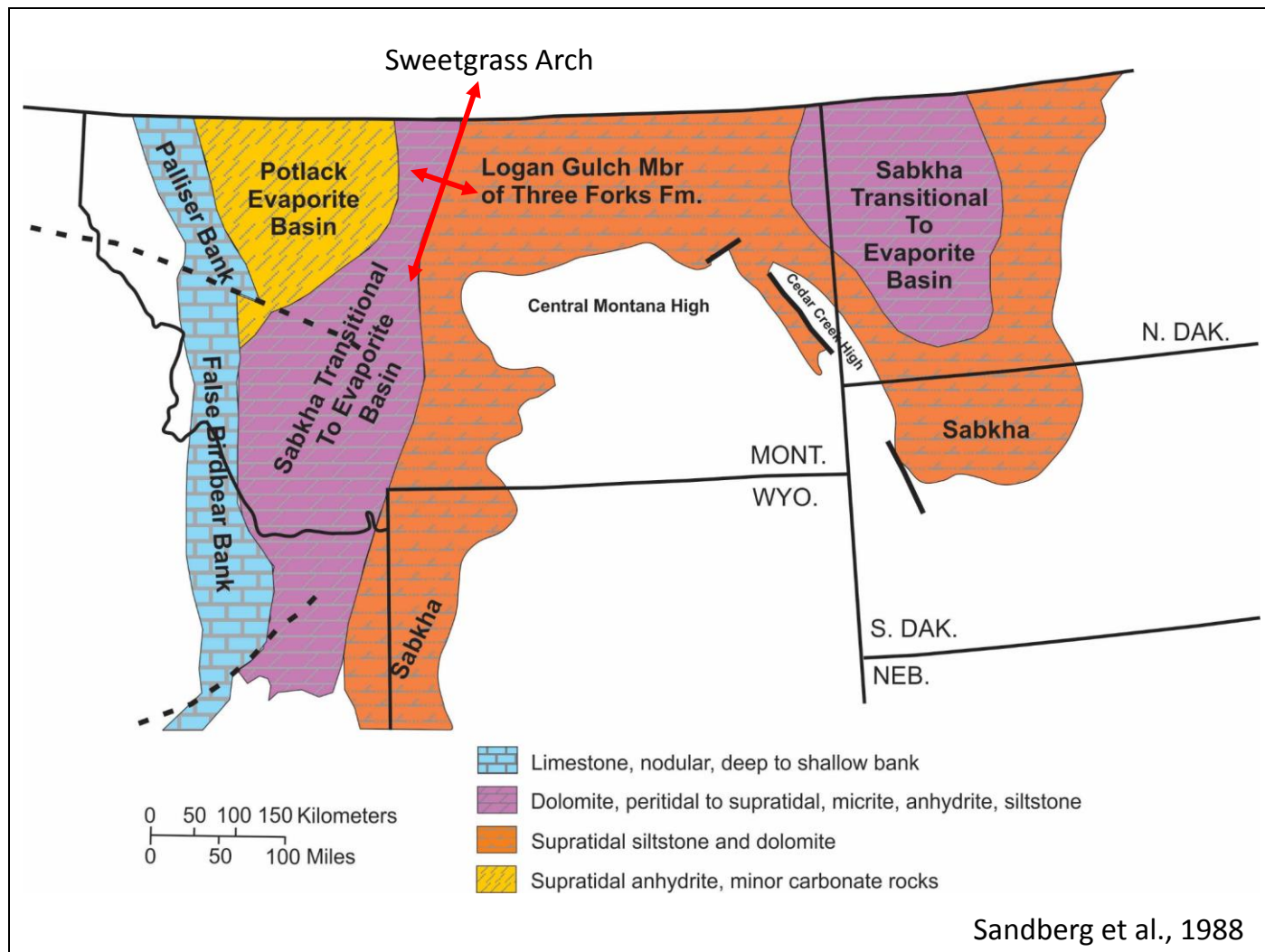


Presenter's notes: Diagram illustrating members of the Bakken Petroleum System. Source beds are the Lower and Upper Bakken shales and the False Bakken member of the Lodgepole. Reservoirs are the middle and upper Three Forks, Middle Member of the Bakken, and the Scallion member of the Lodgepole. Sequence stratigraphy for the Bakken and Upper Three Forks is also shown.

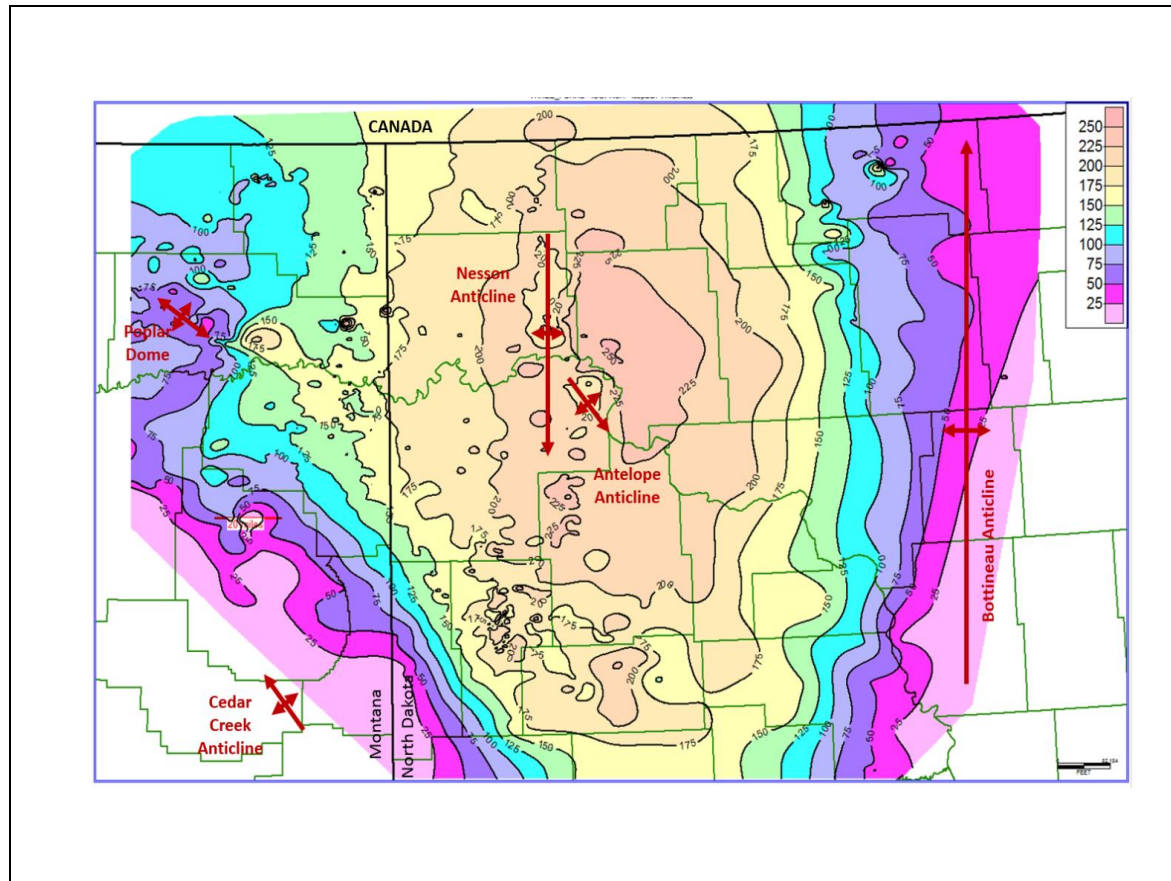
Pronghorn



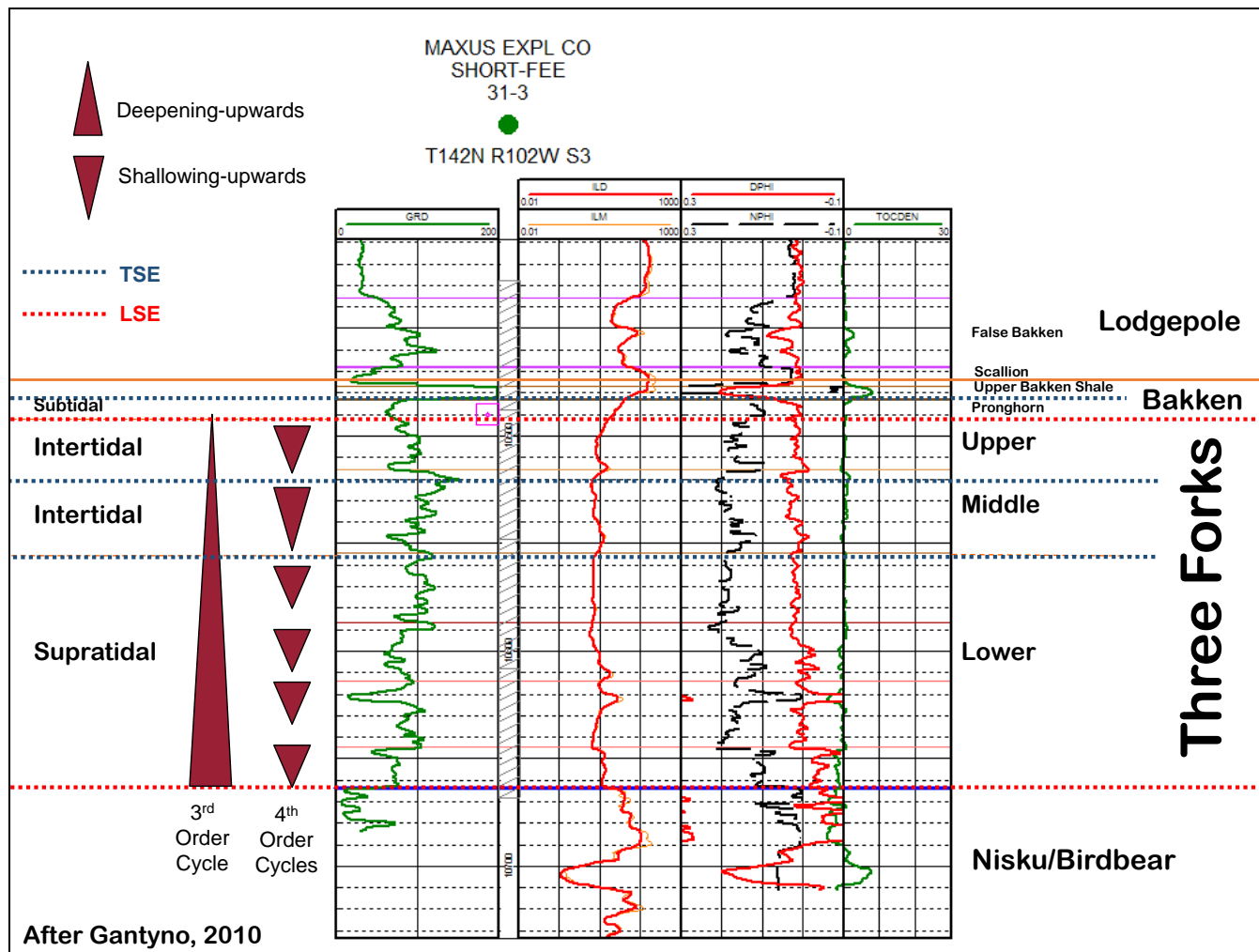
Presenter's notes: Isopach map of Pronghorn interval. The thickness ranges from a wedge-edge to over 50 ft. This largely dolomitic interval may largely be derived from erosion of Paleozoic units on the Cedar Creek Anticline



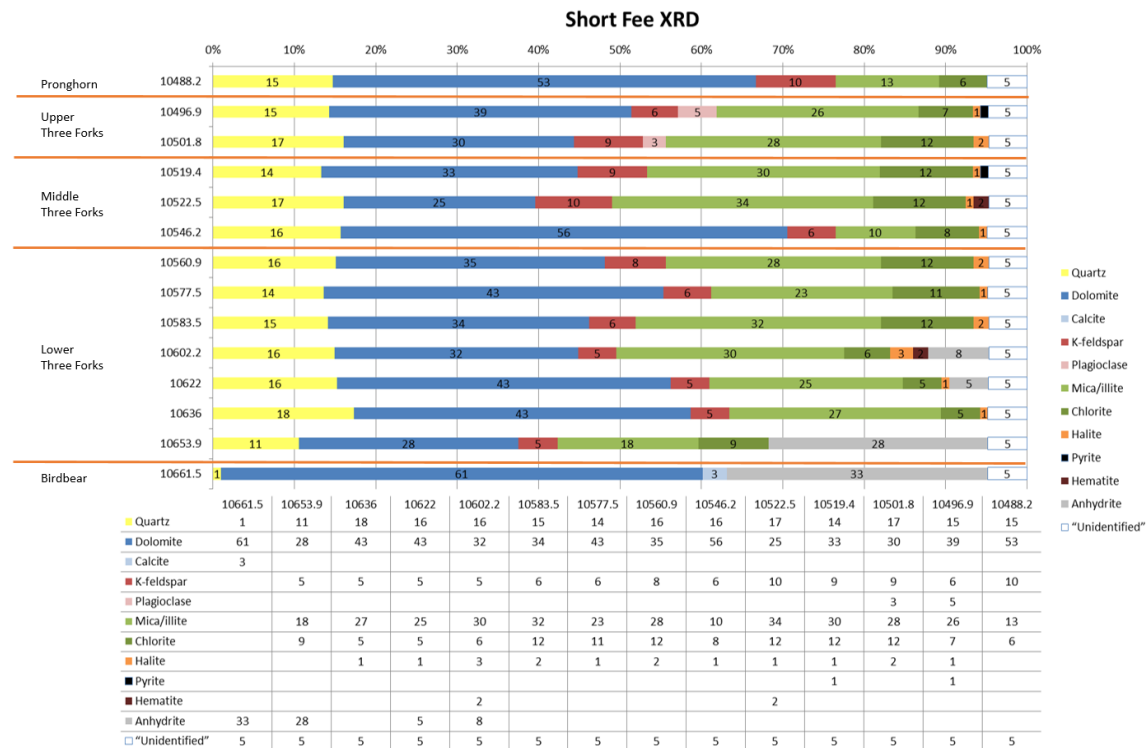
Presenter's notes: Devonian paleogeography from Sandberg 1988. The Williston Basin is a highly restricted basin during Three Forks time. The Sweet Grass Arch may be a barrier that isolates the basin from the open seaway to the west.



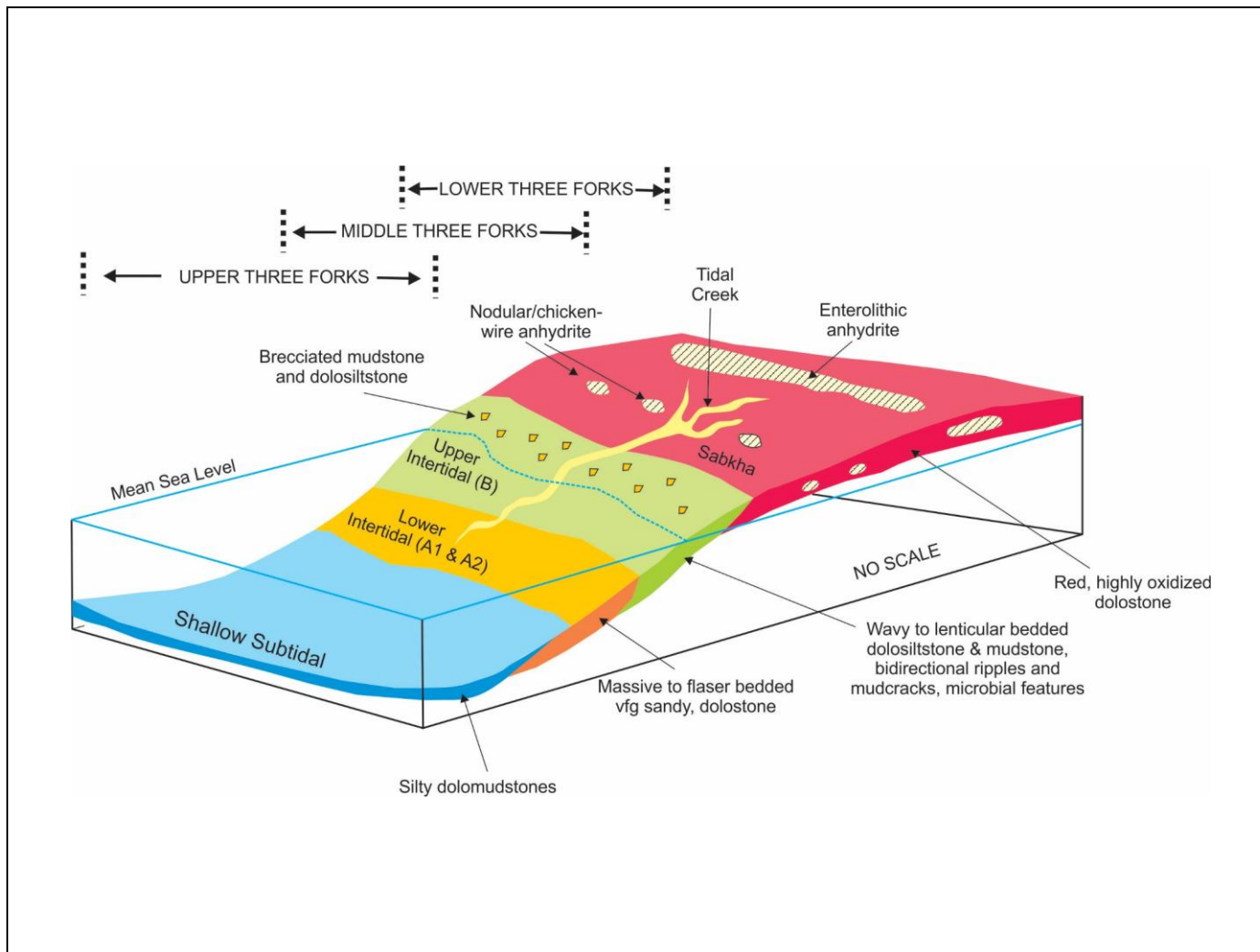
Presenter's notes: Deposition of Upper Three Forks is followed by a regional erosional event and sea level drop followed by deposition of the Pronghorn member (PR-A, PR-B, PR-C) of the Bakken as part of the lowstand to transgressive system tract. This is followed by continued transgression and water deepening which results in Lower Bakken Shale deposition. Deposition of the lower Middle Bakken occurs during the highstand to falling stage systems tract (facies A-C). The tidal sandstones in the Middle Bakken (facies D) represent the lowstand systems tract which then is followed by deposition of the upper Middle Bakken (facies E-F) transgressive system tract. This is followed by continued transgression and deposition of the Upper Bakken mudrocks as part of the transgressive system tract. The upper shale is sharply overlain by highstand deposits of the Longpole formation. Maximum flooding surfaces occur in the upper parts of the Lower and Upper Bakken shales.



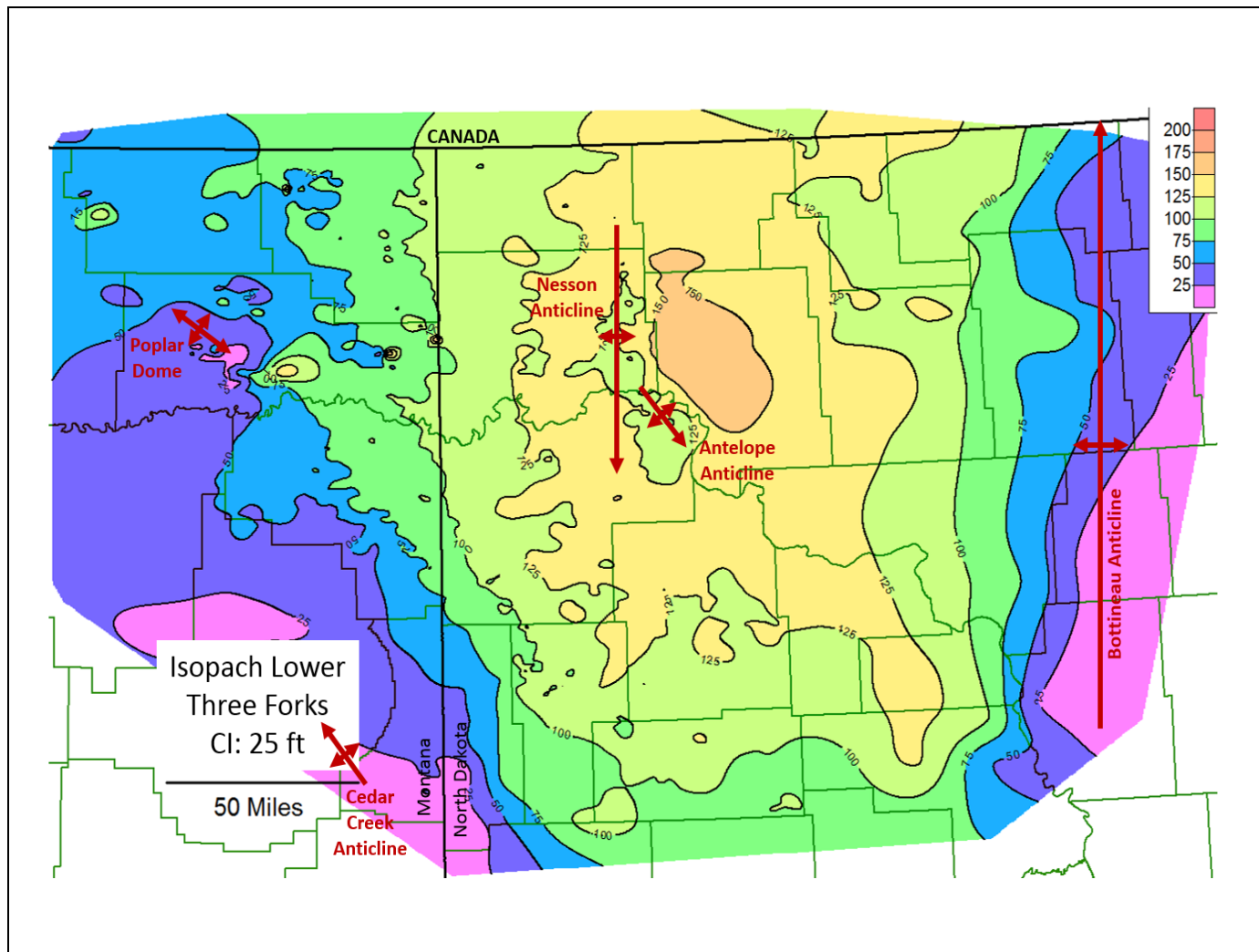
Presenter's notes: Well log display of the Bakken and Three Forks from the Maxus Short-Fee 31-3 (Sec. 3, T142N, R102W). Headings: GRD –gamma ray; ILD and ILM resistivity curves; NPHI-porosity; DPHI-density porosity; TOCDEN-calculated TOC from density log. Modified from Gantyno, 2010.



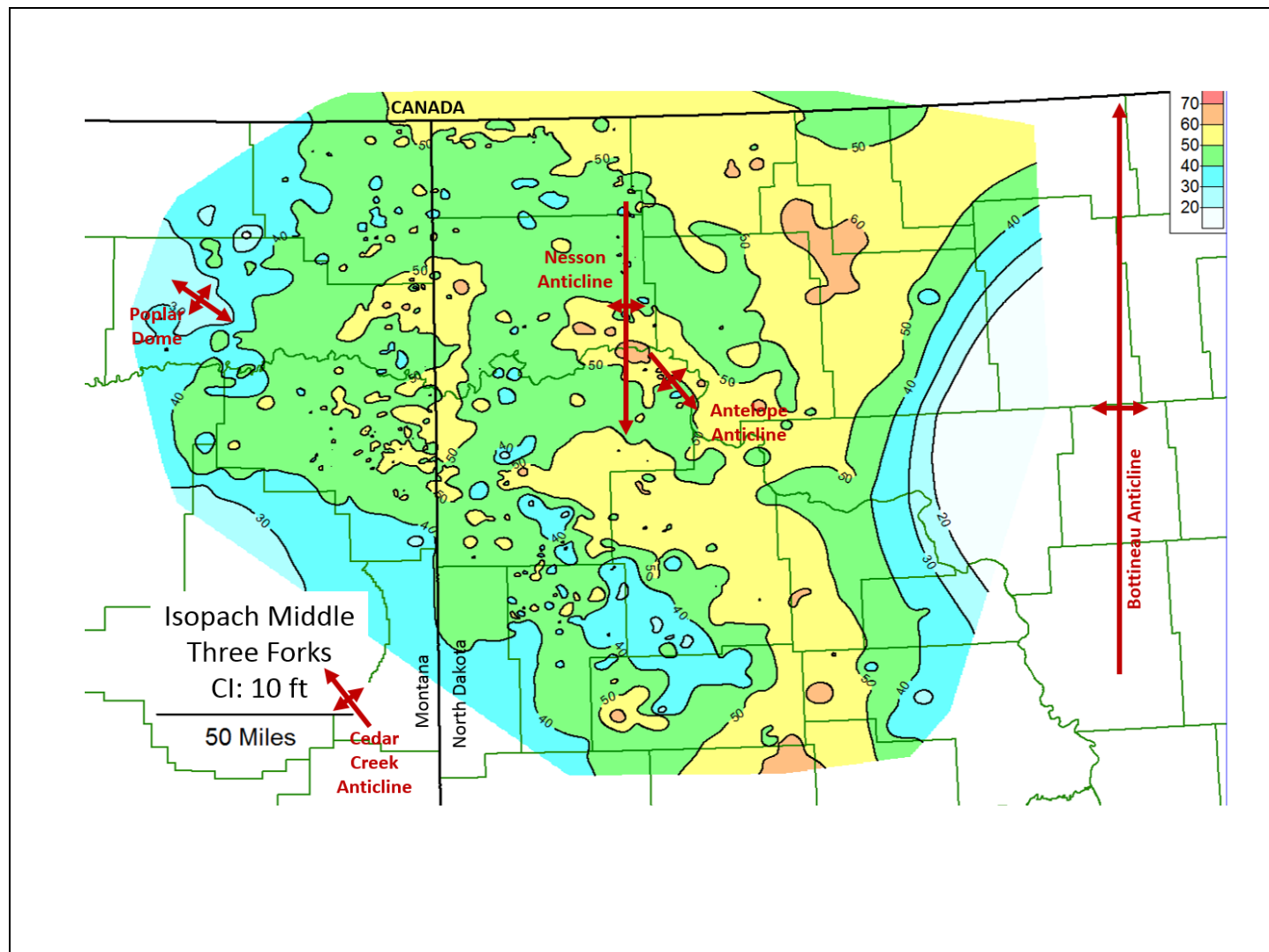
Presenter's notes: X-ray diffraction data (XRD) for the Three Forks Formation from the Maxus Short-Fee 31-3 (Sec. 3, T142N, R102W) well. Uppermost data is from the Pronghorn interval and lowermost data is from the Birdbear. Note the presence of dolomite, illite, and chlorite throughout the Three Forks. Note also the presence of evaporites (anhydrite and halite) in the Three Forks interval.



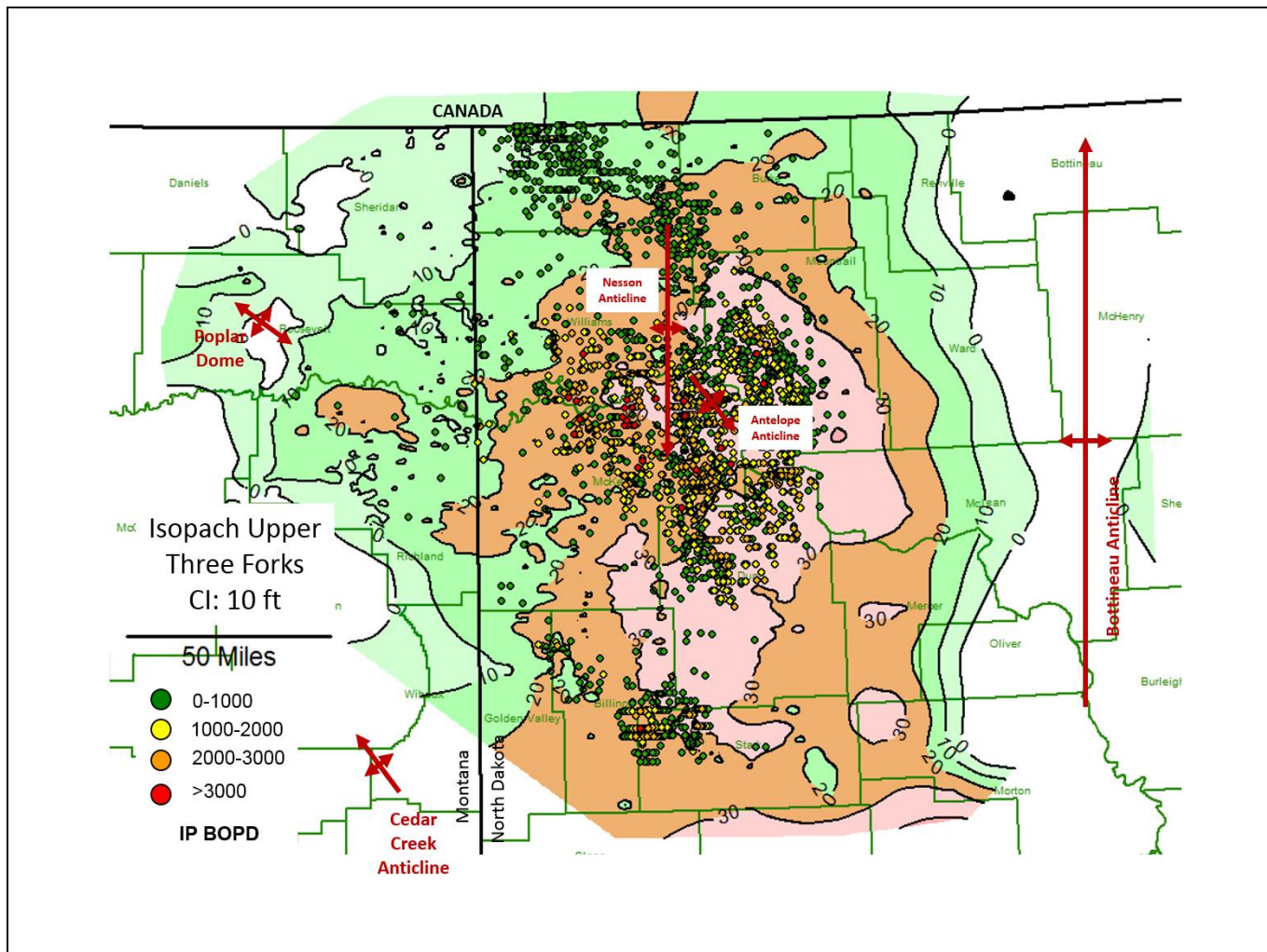
Presenter's notes: Three Forks schematic depositional model. Approximate settings for lower, middle, and upper Three Forks shown. Anhydrites mainly found in lower Three Forks. Modified from Berwick (2008), Gantyno (2010), and Franklin and Sonnenberg (2012)



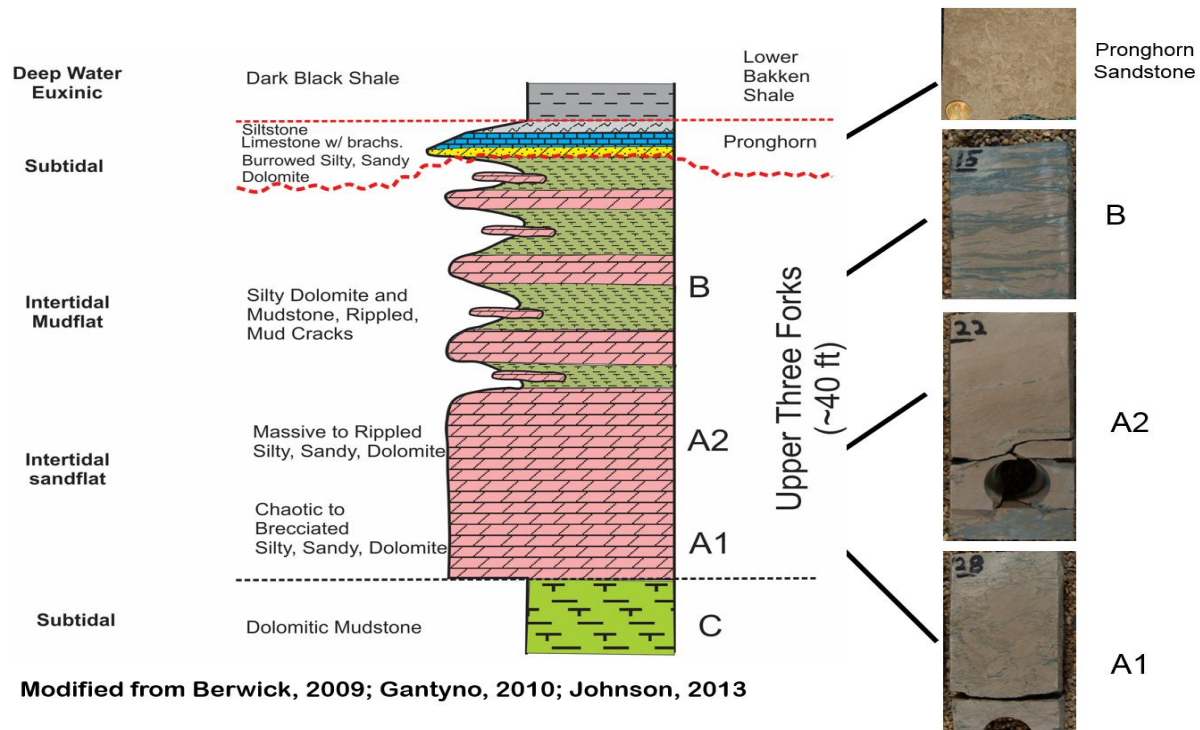
Presenter's notes: Isopach lower Three Forks. Thickness ranges from less than 25 ft to over 150 ft in mapped area. Thickest area is east of Nesson Anticline. Thinning occurs on Poplar, Nesson, Cedar Creek, and Boutineau anticlines.



Presenter's notes: Isopach map of middle Three Forks. Thickness ranges from less than 20 ft to over 60 ft in mapped area.



Presenter's notes: Isopach map upper Three Forks. Thickness ranges from a wedge-edge to over 30 ft. Thinning occurs towards Poplar Dome and the Cedar Creek Anticline. The vast majority of Three Forks wells are drilled in this interval. The colored dots indicate Three Forks initial production (see legend).



Presenter's notes: Schematic of upper Three Forks showing facies, core photographs, and interpreted depositional environment. Tidal environments dominate the upper Three Forks. Modified from Berwick, 2009 and Gantyno, 2010.

Summary thoughts:

- Three Forks & Bakken: ~ 20 my
- LSE surfaces: top Three Forks, base Middle Bakken D facies
- TSE surfaces: top Pronghorn, top Middle Bakken D facies, top Middle Bakken
- mfs: upper LBS, upper UBS
- downlap surfaces: base Middle Bakken, base Lodgepole
- Important unconformities: LSE's and TSE's