The Devonian-Mississippian Sappington Formation in the Bridger Range, Montana: An Outcrop-based Unconventional Reservoir Prediction for the Bakken Formation in the Williston Basin*

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Search and Discovery Article #80474 (2015)**
Posted September 21, 2015

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

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Abstract

Deposition of the Devonian-Mississippian Sappington Formation is contemporaneous with the Bakken Formation in the Williston Basin. Despite good drilling success rates, hydrocarbon production rates across the Williston Basin are highly variable and at present, many of the geologic controls behind this heterogeneity are poorly understood. The Sappington Formation in the Bridger Range (BR), Montana offers an opportunity to study the architecture and facies heterogeneity of Bakken-equivalent strata at the surface. Here we present results from an outcrop study along a 17 km transect in the BR to discern the lateral lithologic heterogeneity and architecture on the reservoir and field scale. The Sappington Formation is divided into three members: the lower and upper organic-rich shale members and a middle calcareous, siltstone to very fine-grained sandstone member. Facies in the lower and upper shale members include: organic-rich mudstones; muddy, organic-rich siltstones; and silty, bioturbated, organic-rich mudstones. These members are interpreted as being deposited in a dysoxic (anoxic?), semi-restricted offshore environment. Middle Sappington member facies include cross-stratified and rippled sandstones, and bioturbated sandstones and siltstones. Normal-marine assemblages of Cruziana ichnofauna and cross- and ripple-stratification suggest deposition in a normal-marine shoreface environment. The Sappington Formation thickens from 16 m in the south to 23 m in the northern BR. Lithofacies relationships change laterally across the BR and contribute to a complex stratigraphic architecture. The middle member of the Sappington Formation in the southern BR displays more proximal facies with larger, planar, and high angle cross-stratified bedforms and the highest abundance of the coarsest grained sand in the system. In the

northern BR, facies of the middle Sappington member contain smaller ripple lamination and are more heavily bioturbated. Conversely, the upper and lower shales thin in a southerly direction and spectral GR data suggests a lower organic content in the southern locations. The facies distribution and thickening trends, combined with paleoflow analysis, suggest Sappington Formation shoreface deposition in the BR, with sediment transport directed in a northerly direction. Heterogeneity of facies and architecture of sedimentary elements observed along this depositional dip section provide insight into the geologic controls of reservoirs and the fate of preserved organic carbon on a development scale.

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The Devonian-Mississippian Sappington Formation in the Bridger Range, Montana: An outcrop-based unconventional reservoir prediction for the Bakken Formation in the Williston Basin

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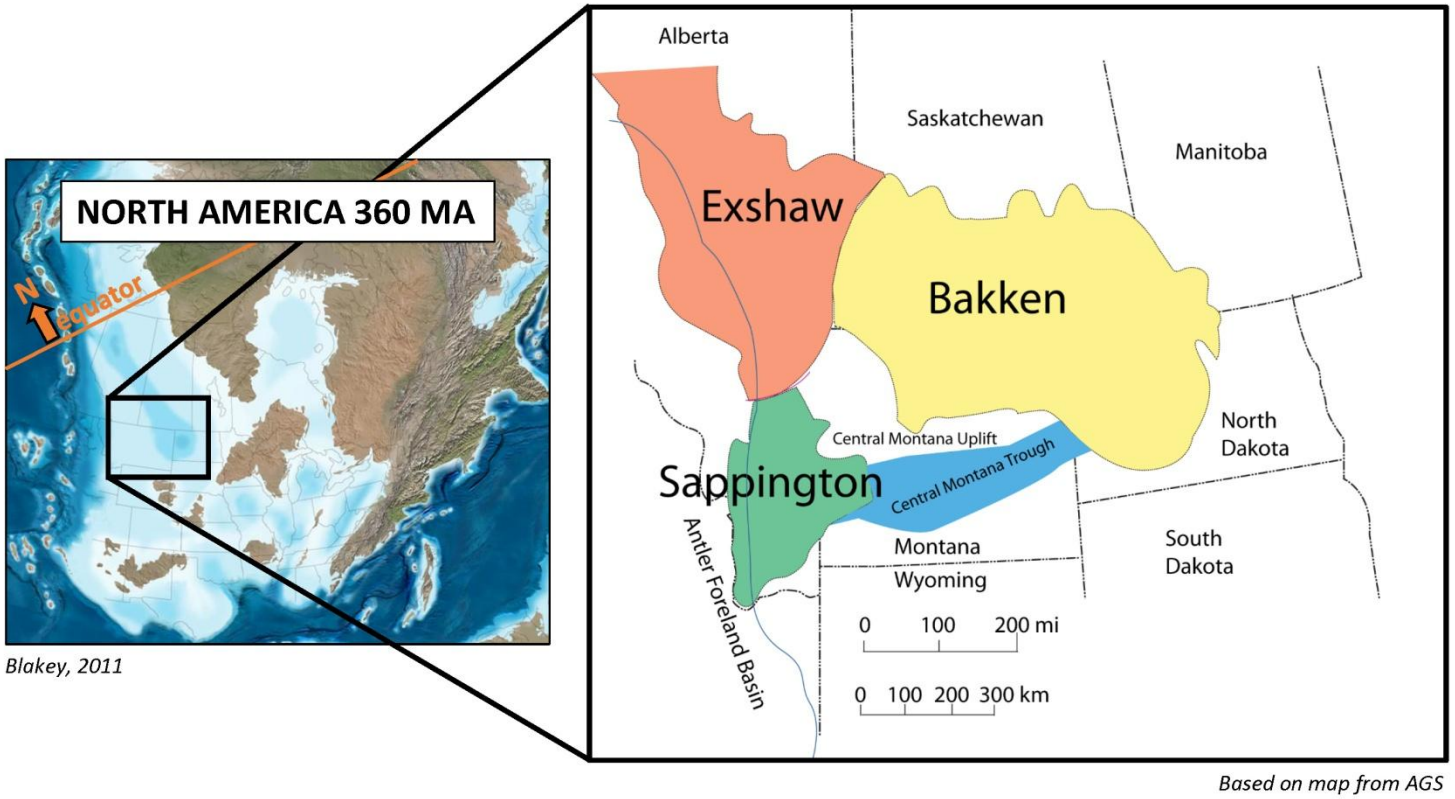
UNIVERSITY OF MONTANA

Presenter's notes: My Master's research is on the Devonian/Mississippian Bakken-equivalent Sappington Formation in the Bridger Range and here is a view looking north across the Bridge Range from the summit of Hardscrabble Peak. This photo shows a wide range of strata exposed from Paleozoic to Mesozoic strata.

Outline

- Regional Setting
- Sappington Formation Correlation to the Bakken Formation
- Study Area
- Source and Reservoir Facies
- Field Architecture
- Reservoir Architecture
- Implications for Production of the Bakken Formation
- Conclusions

Late Devonian Paleogeography



Presenter's notes: During the Late Devonian, western North America was located near the equator and was covered in a shallow, epicontinental sea, dominated by siliciclastic sedimentation. On the left is a paleogeographic reconstruction of North American at 360 MA with a blowup inset of Montana, North Dakota and southern Canada. Highlighted in green is the Sappington depositional basin,
(Presenter's notes continued on next page)

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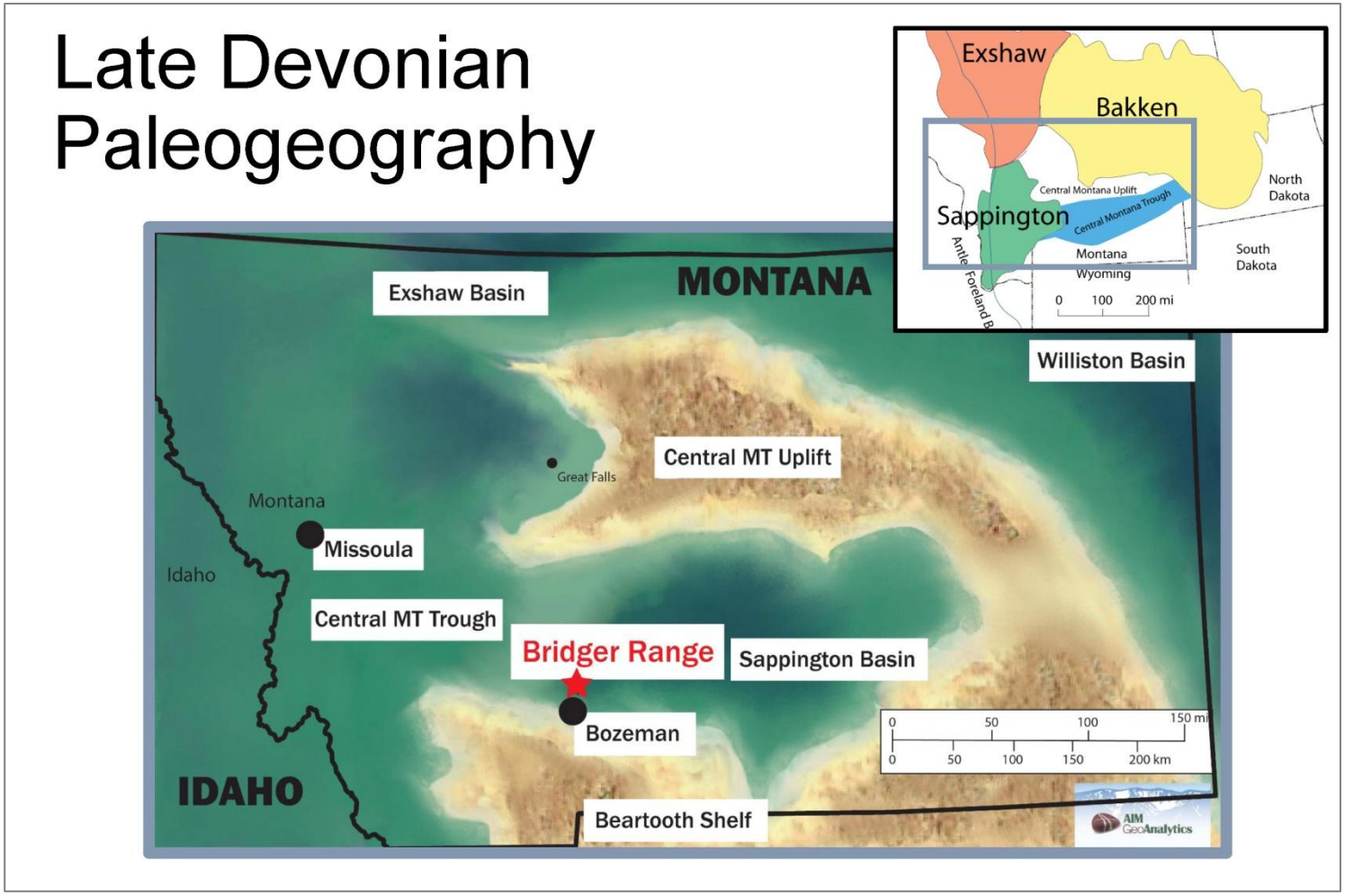
several hundred kilometers to the southwest of the Bakken depositional basin – the Williston Basin. The Sappington depositional basin is separated from the Williston by the Central Montana Uplift but may be intermittently connected with the Williston through the Central Montana Trough. The map on the right will be shown as a reference map in the following slides. Let’s take a look at the Sappington depositional basin.



Presenter's notes: The Sappington was deposited in isolated subbasin in Montana. Here is the outline of the state of Montana and Bozeman and Missoula for reference. The Sappington Basin is bound to the north by the Central Montana Uplift, and to the south by the Beartooth Shelf. Sappington outcrops shown in this study are in the Bridger Range, just north of Bozeman Montana, highlighted in red here. Although the Antler Orogeny was emergent to the west after the Middle Devonian, the Central Montana Trough was

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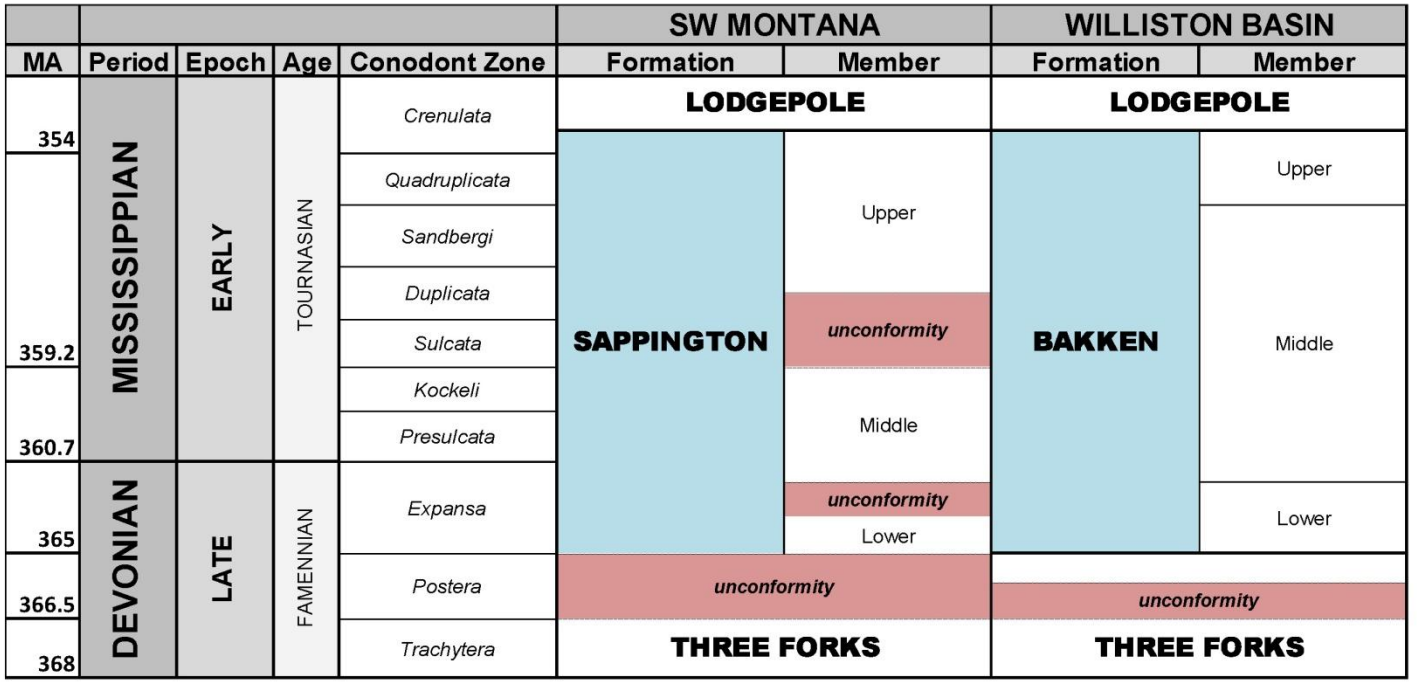
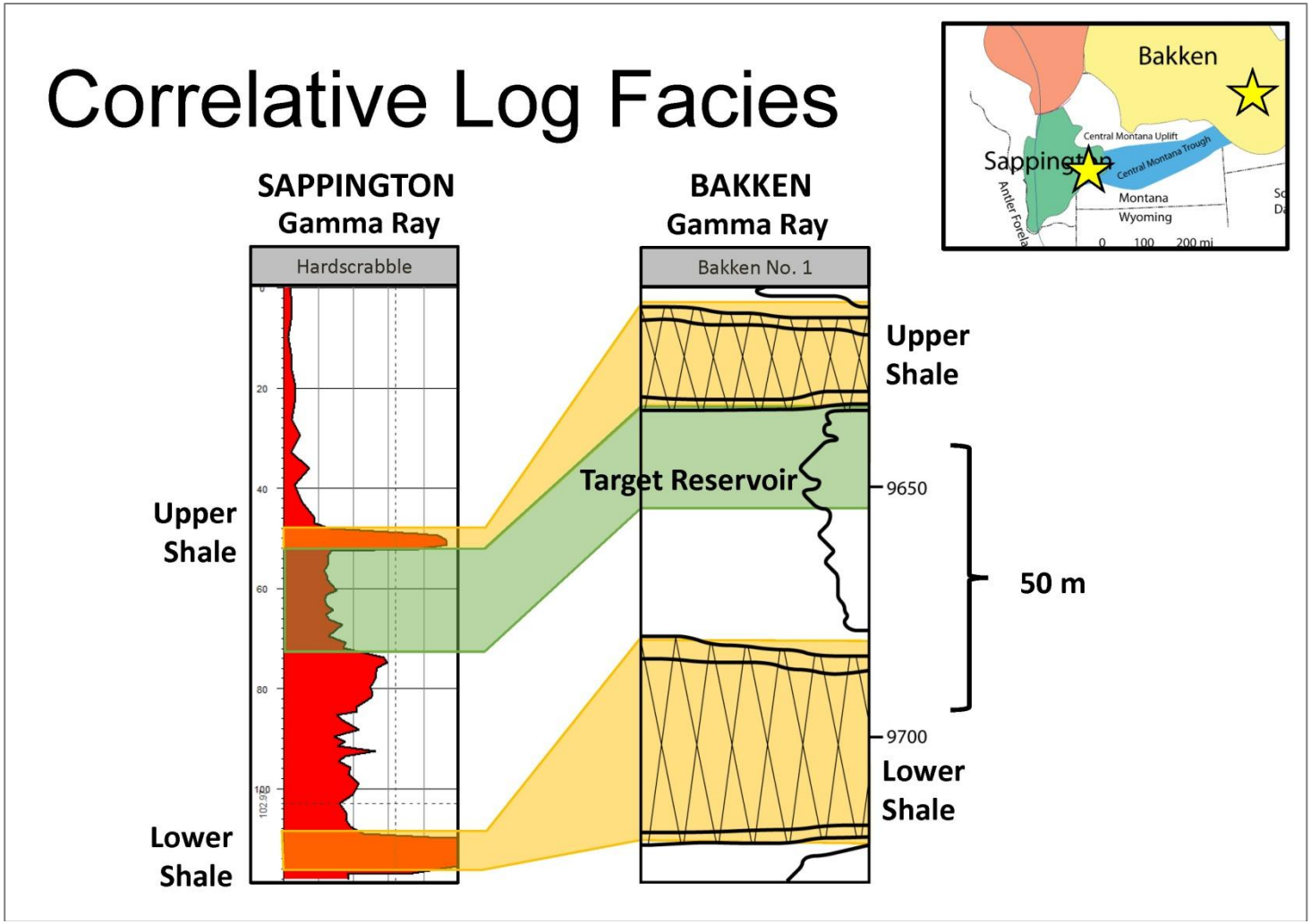
separated by the Antler foredeep from any major siliciclastic input from the west. Based on my outcrop work in the Bridger Range, the primary sediment source for the Sappington Formation in the Beartooth Shelf to the south.

Stratigraphy and Biostratigraphy



Compiled from: Klapper (1996), Huber (1983), Hayes (1985), Karma (1990), Savoy and Harris (1993), Kaufman (2006), Johnston et al. (2010), Nagase et al. (2014).

Presenter's notes: The Sappington Formation unconformably overlies the Late Devonian Three Forks Formation and is overlain by the Lodgepole Formation of the Mississippian Madison Group. Conodont recovery is the primary biostratigraphic control for age of the Sappington and Bakken Formations. This chart show the stratigraphic and biostratigraphic correlations of the two formations. Similar to the Bakken Formation, the Sappington is made up of three members: the lower organic-rich mudstone member, the middle dolomitic siltstone member, and the upper organic-rich mudstone member.



Presenter's notes: Sappington Formation spectral gamma ray data has been correlated to wireline gamma ray logs for the Bakken in the Williston Basin. Here are two gamma ray logs showing an example of that correlation. On the left is a gamma ray log for Hardscrabble Peak in the Bridger Range in southwestern Montana highlighted by this yellow star on the map and on the right is a

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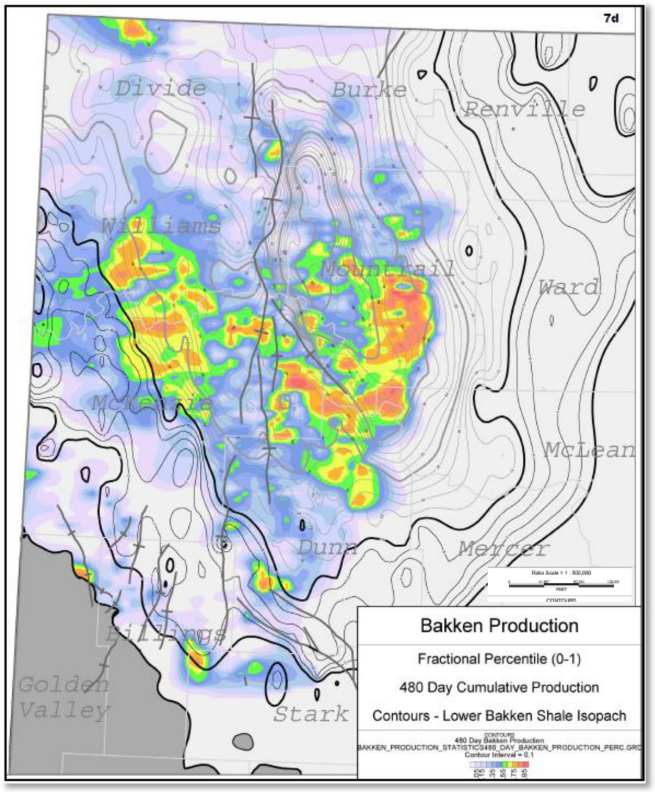
gamma ray log for the Bakken No 1 well in the Williston Basin also shown as a yellow star. The Upper and Lower Sappington mudstone members show an abrupt kick in GR and very high values which correlate across to the Upper Bakken Shale and Lower Bakken Shale in the Bakken No 1 well. The primary reservoir target for the Bakken Formation is this clean interval the in upper middle member. That interval correlates across to a clean reservoir interval at Hardscrabble Peak.

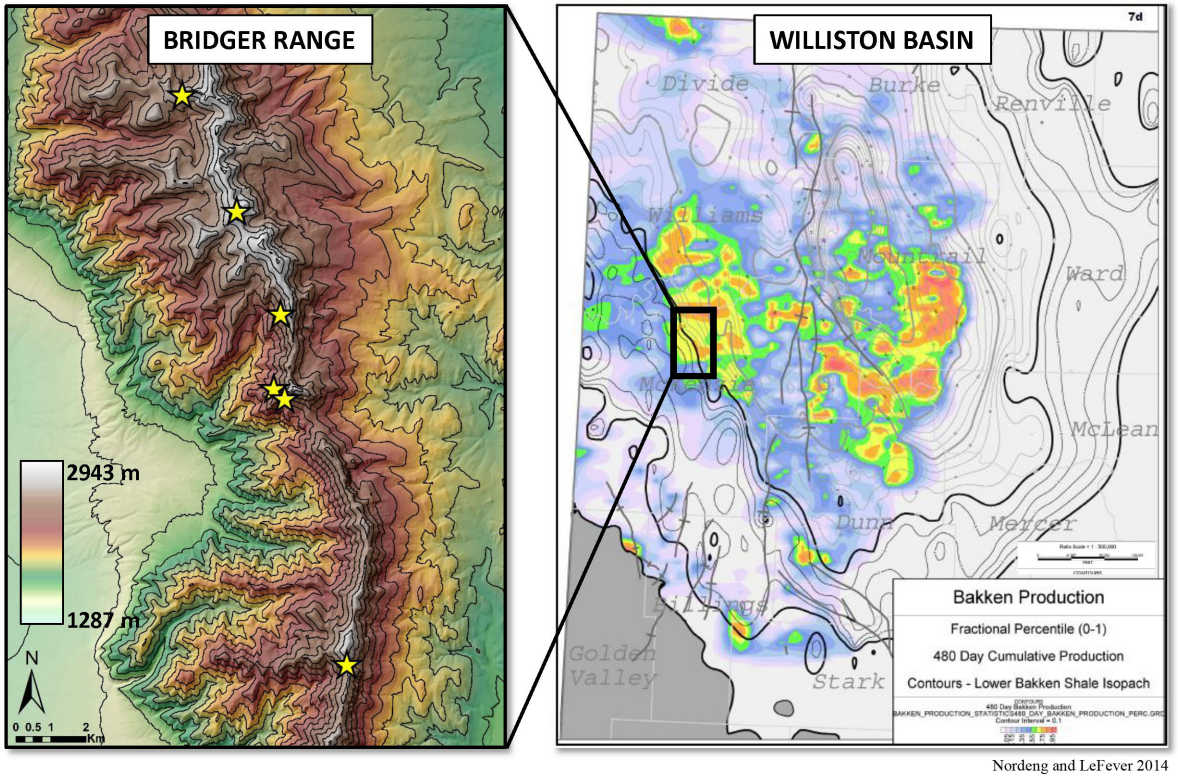
Bakken Production Heterogeneity



Nordeng and LeFever 2014

Presenter's notes: Hydrocarbon production rates of the Bakken Formation across the Williston Basin are highly variable and the geologic controls behind this heterogeneity are poorly understood. This is a 480 day cumulative production map from the Bakken in the Williston. The warm colors are high production rates, the cool colors are low and you can see significant production heterogeneity across the basin.

Bakken Production Heterogeneity



Presenter's notes: Even at a finer scale, production is highly variable. This outline is same aerial extent as our study area of the Sappington Formation in the Bridger Range, shown on the topographic map on the left. The box is placed in the Williston Basin in its most correlative position via the basin margin. It's about 17 km long. Even on this scale, there is significant heterogeneity, you can see lower production in the south, higher production in the north, and variable production in the middle.
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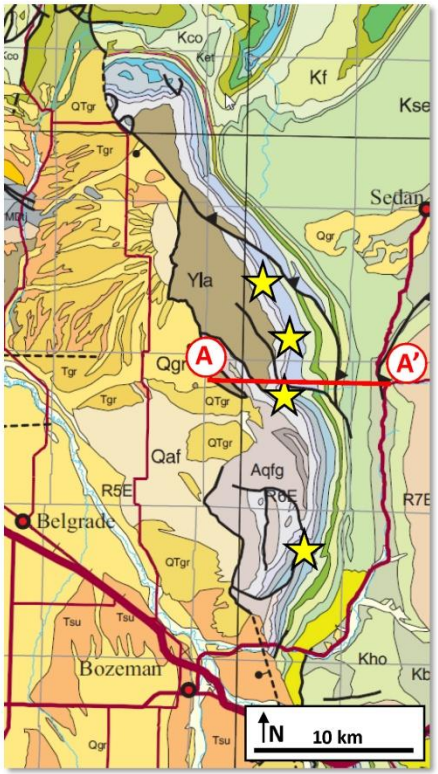
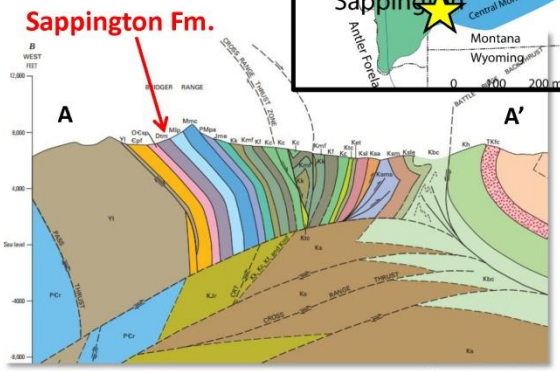
So the goal of my project is to better understand the lithologic heterogeneity of the Sappington Formation – the depositional, architectural and stratigraphic controls on heterogeneity – to better understand production heterogeneity of the Bakken Formation to improve exploration and exploitation of the Bakken Formation in the Williston Basin.

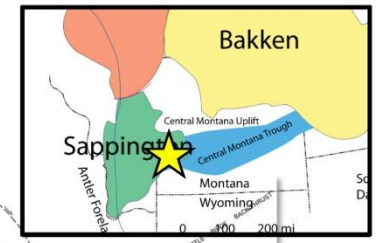
Study Area: Bridger Range



MT Bureau of Mines & Geology, 2007



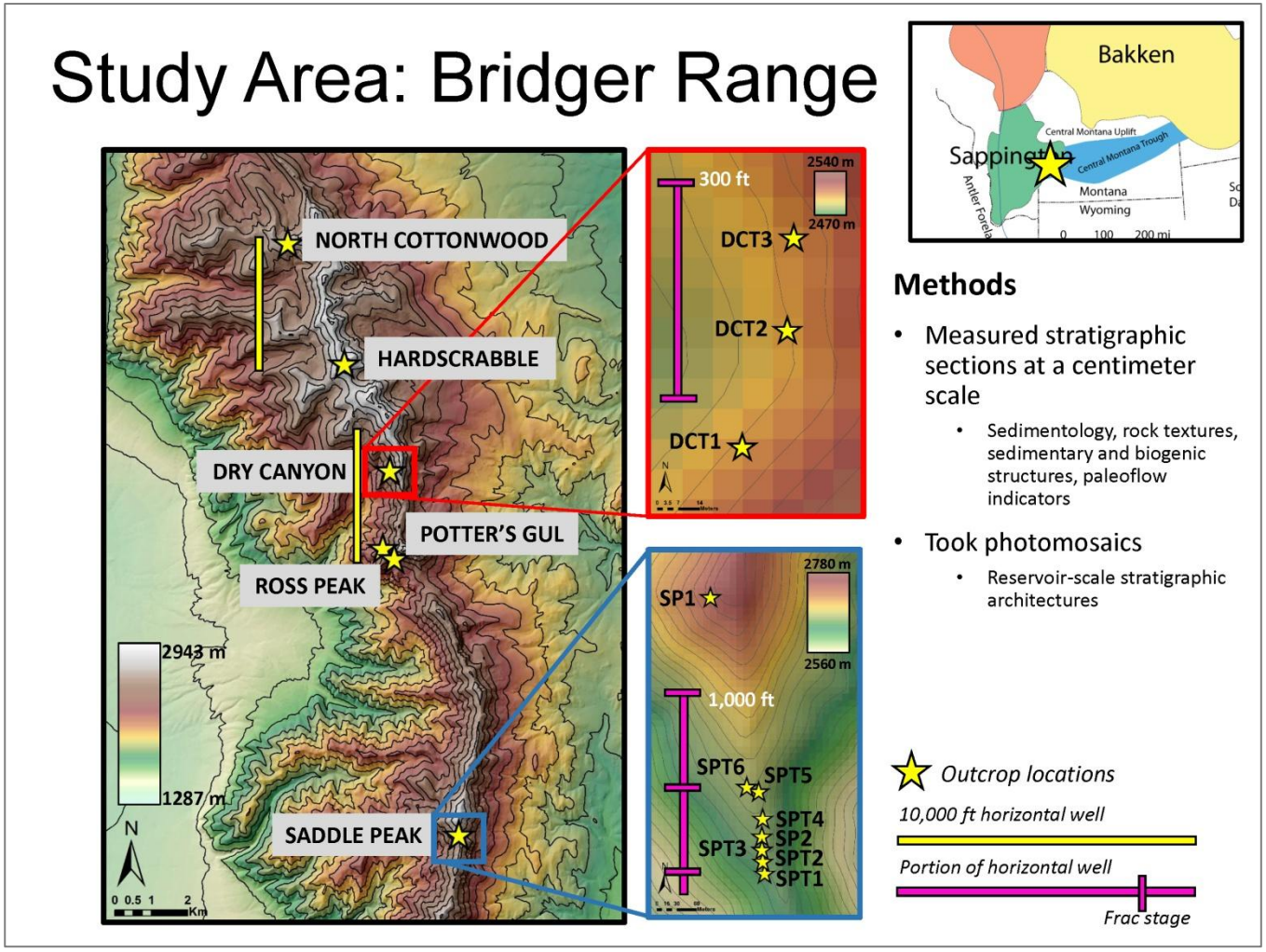
Skip et al., 1999



- Steeply-dipping Precambrian to Cretaceous age strata
- Most laterally-continuous, high-quality surface exposure of the Sappington Formation
- Sappington Formation relatively undeformed

★ *Main outcrops*

Presenter's notes: So let's go to the Bridger Range in Montana. The Bridger Range is located in southwestern Montana shown as this yellow star on this paleogeographic map. On the far left is a geologic map of the area, the Bridger Range is these blue and purple units striking north/south just north of Bozeman Montana. If we look at a cross section across the range from west to east, you can see the Bridger Range consists of steeply-dipping, Precambrian through Cretaceous strata. The highest quality, most laterally continuous outcrops of the Sappington Formation are along the ridgeline in the Bridgers.



Presenter's notes: I spent last summer in the Bridger Range, measuring outcrops across the range. On the left is a topographic map of the range, with outcrop locations designated by a yellow star. I measured multiple outcrops across the mountain range to determine the field-scale lateral lithologic heterogeneity, as well as three development scale outcrop transects at Dry Canyon and Saddle Peak. (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

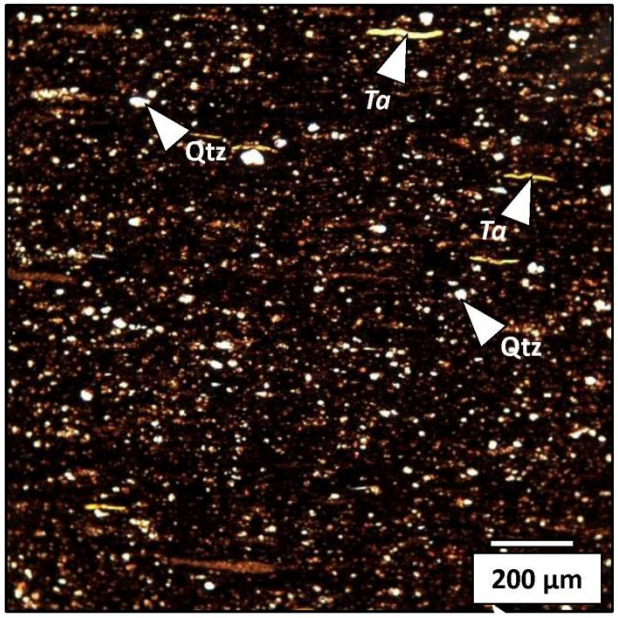
On the left map of the entire range, I've drawn 2-mile lateral wells, like are used in the Bakken, to show that my outcrops span the length of a lateral well. The smaller scale transects cover a couple hundred to 1,000 feet of a lateral well, so these outcrops are spaced on more of a frac-stage scale.

At every outcrop, I systematically measured stratigraphic sections at a centimeter scale and described sedimentology, rock textures, sedimentary and biogenic structures, and paleoflow indicators. I took photomosciacs to discern reservoir architectures and collected samples for thin section petrographic analysis, total organic carbon analysis and bulk mineral x-ray diffraction.

We identified 14 facies and 6 facies associations. In the following slides I'm going to show you some representative Sappington facies we identified alongside their correlative Bakken facies.

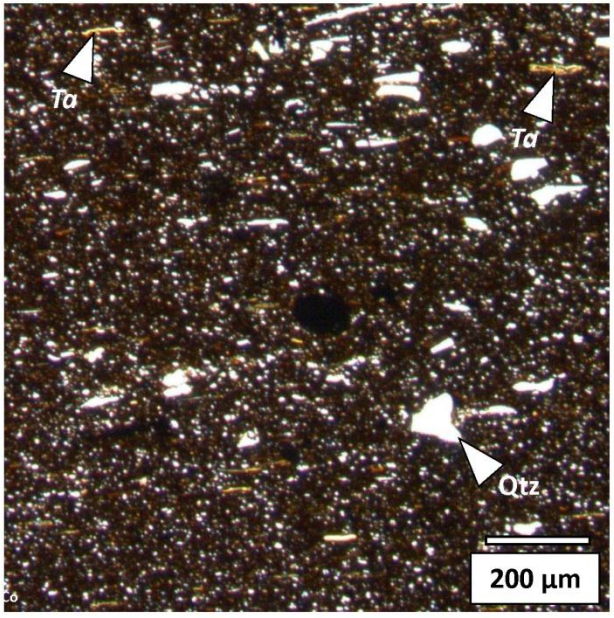
Source Lithofacies: Organic-rich mudstone

SAPPINGTON



Hardscrabble Peak, Bridger Range, TOC 15.3%, PPL

BAKKEN

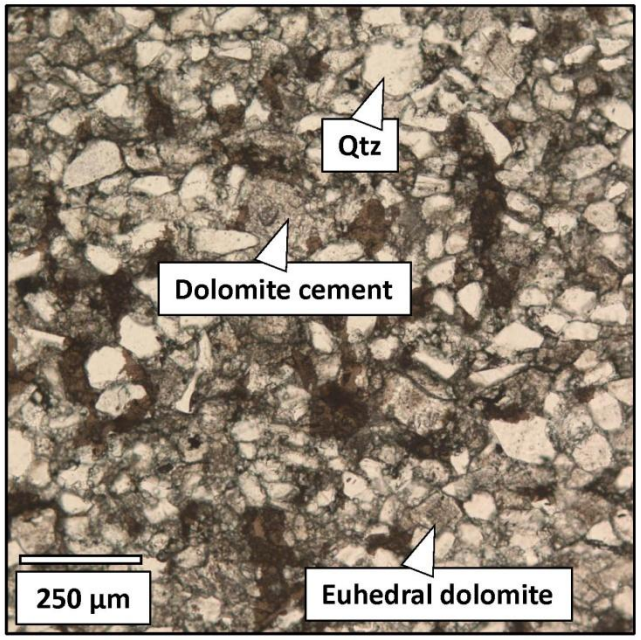


Williston Basin, TOC 14.3%, PPL

Presenter's notes: The main source facies is organic-rich mudstone. These are two photomicrographs of that facies from the Bridger Range on the left, and a Bakken core from the Williston basin on the right. Both samples have high TOC - At Hardscrabble Peak, in the Bridgers, the TOC for this sample is 15.3%. The TOC for the sample on the right is 14.3%. Both samples have algal cysts. These samples also contain some detrital quartz.

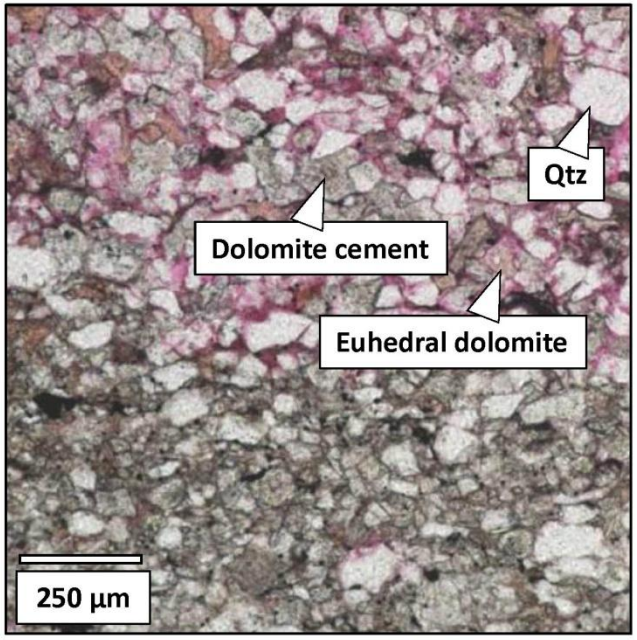
Reservoir Lithofacies: Ripple-laminated siltstone

SAPPINGTON



Hardscrabble Peak, Bridger Range, PPL

BAKKEN



Williston Basin, pink stain, PPL

Presenter's notes: One of the main reservoir lithofacies is ripple-laminated siltstone. Here are two photomicrographs from the Bridgers and the Williston Basin. The framework grains are mainly coarse silt-sized quartz with dolomite and calcite cement and digenetic dolomites rhombs (point out). Notice that the detrital quartz grains are a similar size and have similar rounding in the two samples. This similarity of textural and compositional maturity indicates a similar hydrologic depositional regime.

Reservoir Lithofacies: Low-angle- to planar-stratified siltstone

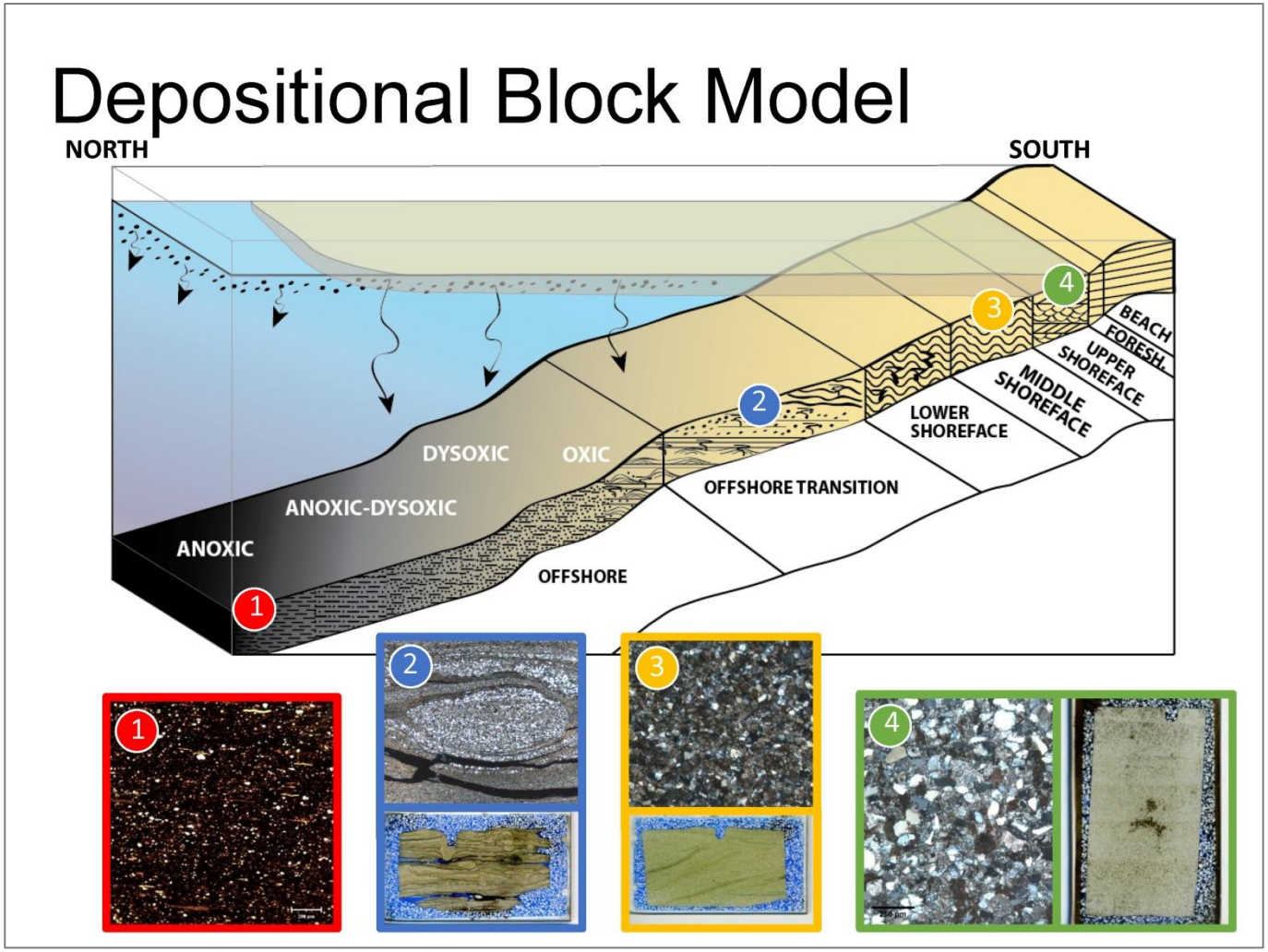
SAPPINGTON

Saddle Peak, Bridger Range

BAKKEN

Williston Basin

Presenter's notes: Another primary reservoir facies is low-angle to planar-stratified siltstone. This are thin section scans from Saddle Peak in the Bridgers and a Bakken core in the Williston Basin. Can see faint planar lamination and normal grading. The pink on this slide is porosity. This facies is also predominantly coarse silt to low very fine-grained quartz with dolomite and calcite cement as well as authentic zoned dolomite.



Presenter's notes: Now we'll zoom into just the Sappington Formation. This photomicrograph is of the primary source facies, organic-rich mudstone that I showed earlier. This represents suspension settle-out of pelagic sediment from surface waters in an anoxic offshore environment. Another fine-grainer facies, but a little coarser is this thinly bedded mudstone and siltstone. The yellow

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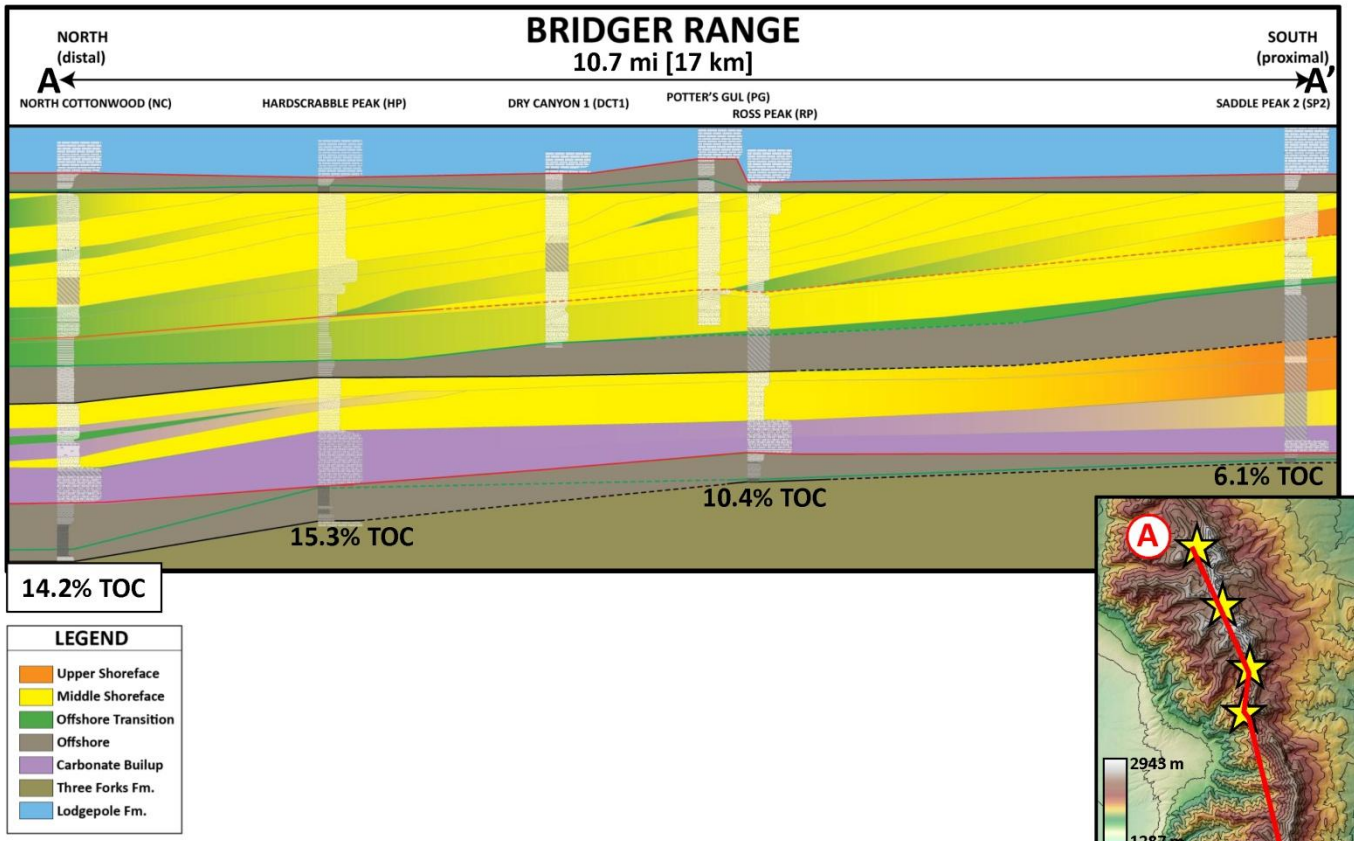
is the siltstone, the darker colors are the mudstone. We observe some bioturbation in this facies, shown as this burrow and interpret it to be deposited in the offshore transition. Moving up the profile, is ripple-laminated siltstone and plannar-stratified siltstone, both shown previously. These facies were deposited in a more proximal position on the profile under high rates of sedimentation and wave reworking. We interpret these facies to generally be deposited along a shoreface profile, as shown in the schematic block diagram.

Field Architecture



Presenter's notes: Architectures observed in the Sappington Formation are further evidence of deposition along a shoreface.
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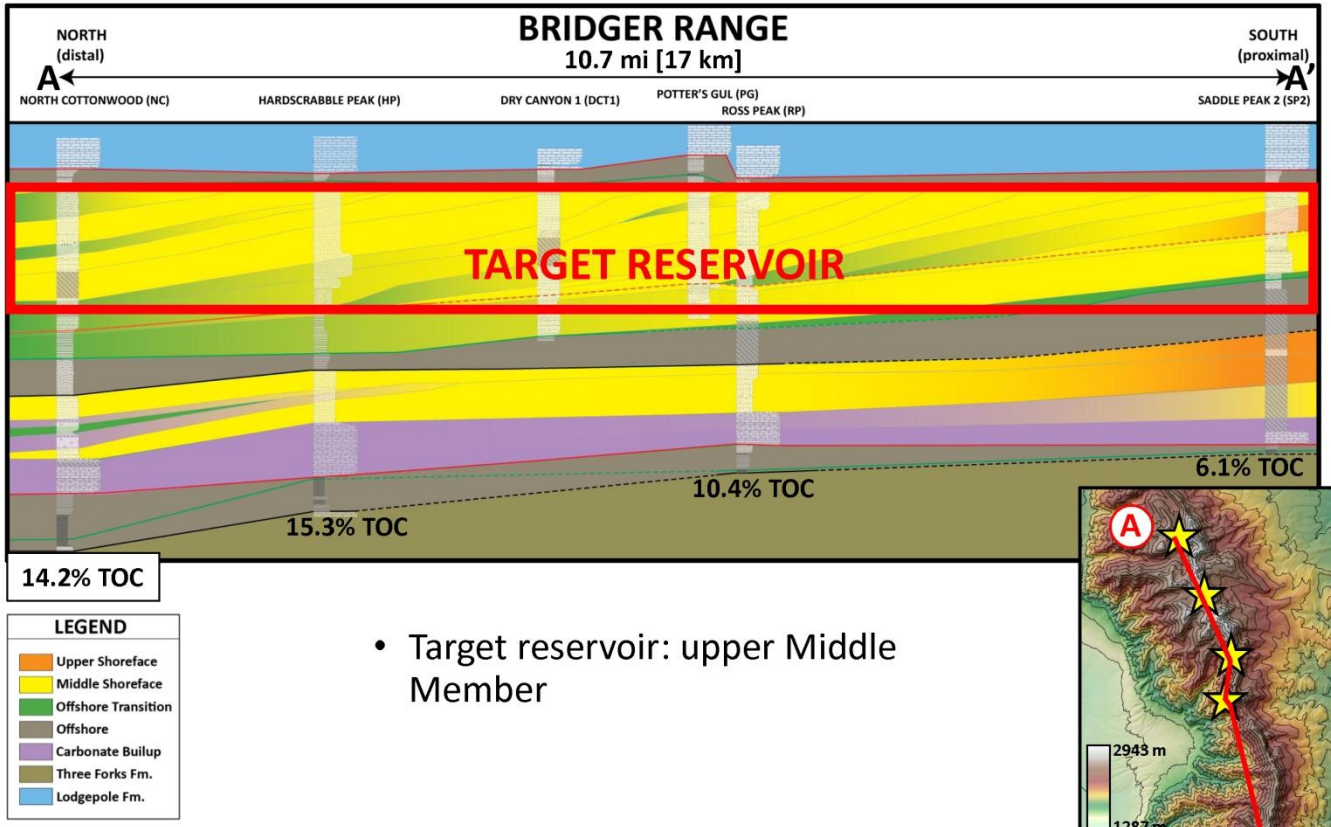
This is a stratigraphic cross section across the Bridger Range. These are the measured sections from outcrop. The green unit is the Three Forks Formation, overlying is the lower member, middle member and the upper member. The blue unit is the overlying Lodgepole Formation. The cross section is hung on the base of the upper shale member. The cross section goes from north on the left to south on the right. Remember the primary sediment source is from the south. The colors represent the different facies associations. The outline of the cross section is shown on the map in the bottom right.

We recognize proximal to distal relationships from south to north across the range including a decrease in grain size, increase in bioturbation, and increase in TOC in the lower shale. In the upper middle member, We have interpreted basinward-dipping clinoforms prograding from south to north based on facies relationships and stacking, paleoflow indicators, clinoformal bedding interpreted from the Hardscrabble photomosaic (which you will see in subsequent slides), and an event bed at the Dry Canyon transect (also in subsequent slides). The gradient for these clinformal beds is calculated based on field observations, the depositional dip of correlative event beds, corroborated by analogous modern prograding shorefaces.

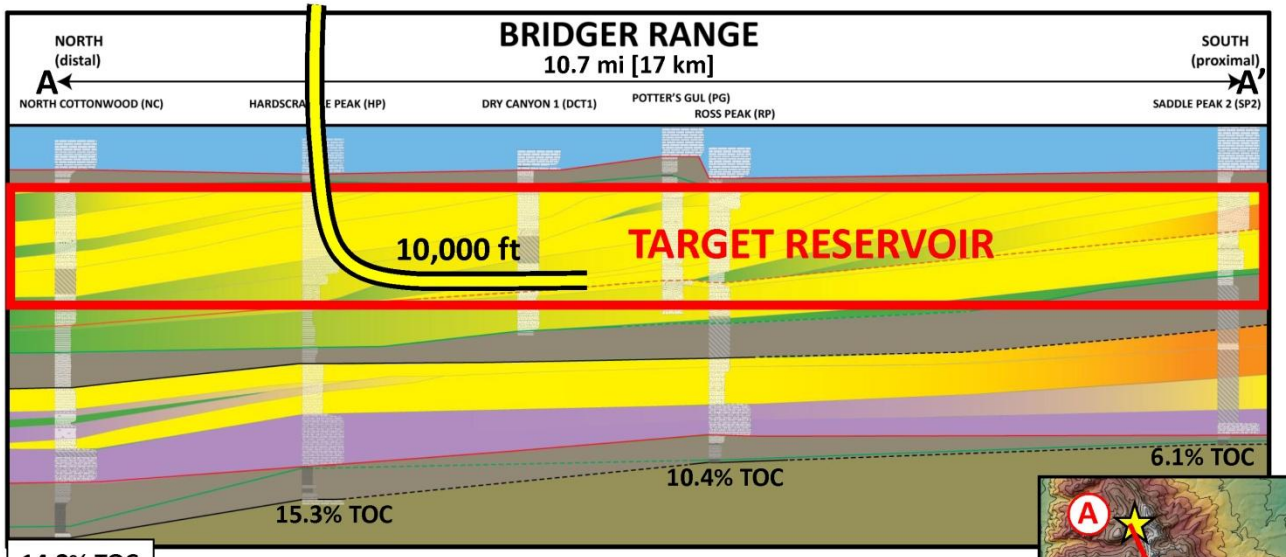
Field Architecture



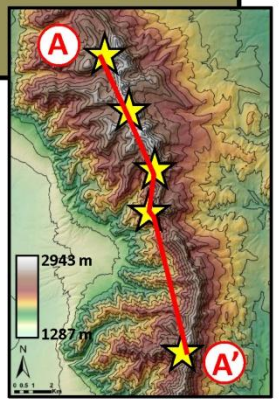
- Target reservoir: upper Middle Member

Presenter's notes: The main target interval for the Bakken Formation is in the upper middle member, which is where we see the best reservoir facies in the Sappington Formation. This is correlative to the lower GR interval shown previously. If we put in to scale 10,000 ft lateral well across the Bridger Range cross section….

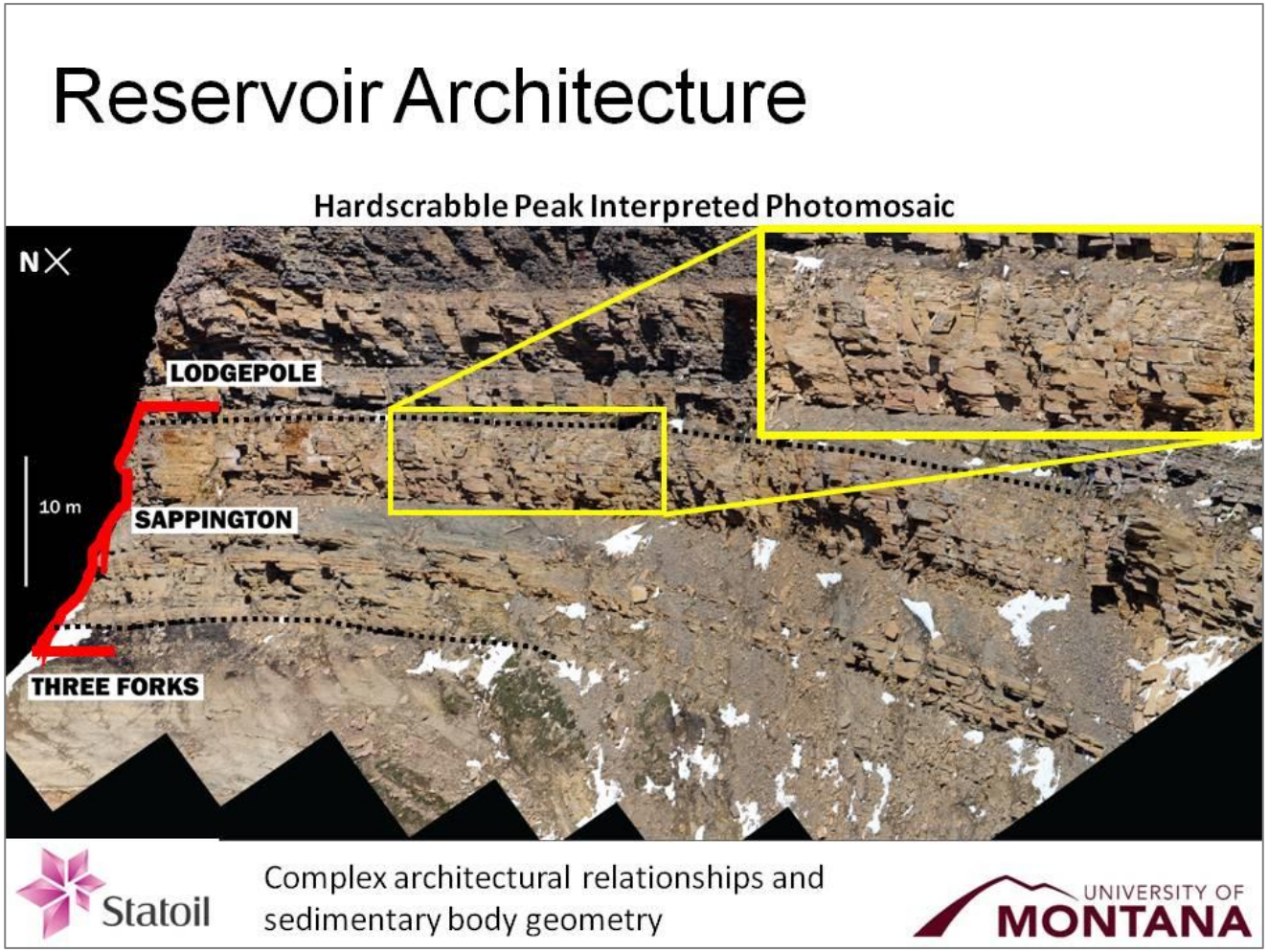
Field Architecture



- Target reservoir: upper Middle Member
- Significant heterogeneity on the field scale



Presenter's notes: …that well crosscuts prograding shoreface architectures and multiple lithofacies with variable reservoir quality. And, the reservoir quality decreases significantly to the north, paleo-basinward, within the length of one lateral well, represented by the darker colors. So there is significant lithologic heterogeneity on the field scale that has implications for reservoir connectivity and fluid flow.



Presenter's notes: Now we'll move from the field scale into the reservoir scale to look at the reservoir architecture of the Sappington Formation. This is an interpreted photomosaic from Hardscrabble Peak looking north into the slide. The Sappington Formation is outlined in red on the left with the major stratigraphic contacts with the underlying Three Forks Formation and the

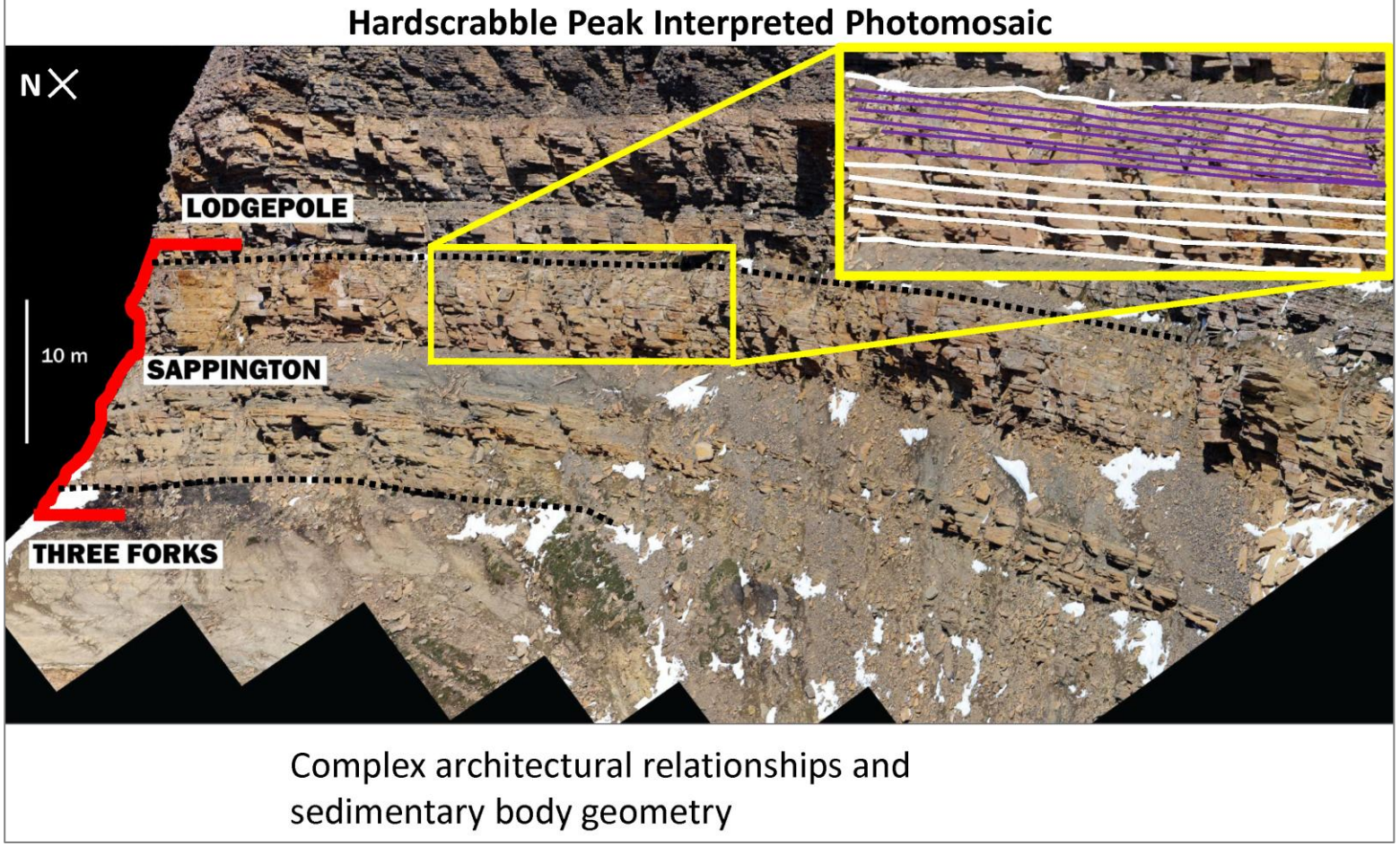
(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

overlying Lodgepole. Within the Sappington Formation, the dotted black lines separate the three members –the lower mudstone member, the middle siltstone and the upper mudstone member. The entire image is a couple hundred meters wide. The anticlinal form is structural, not primary.

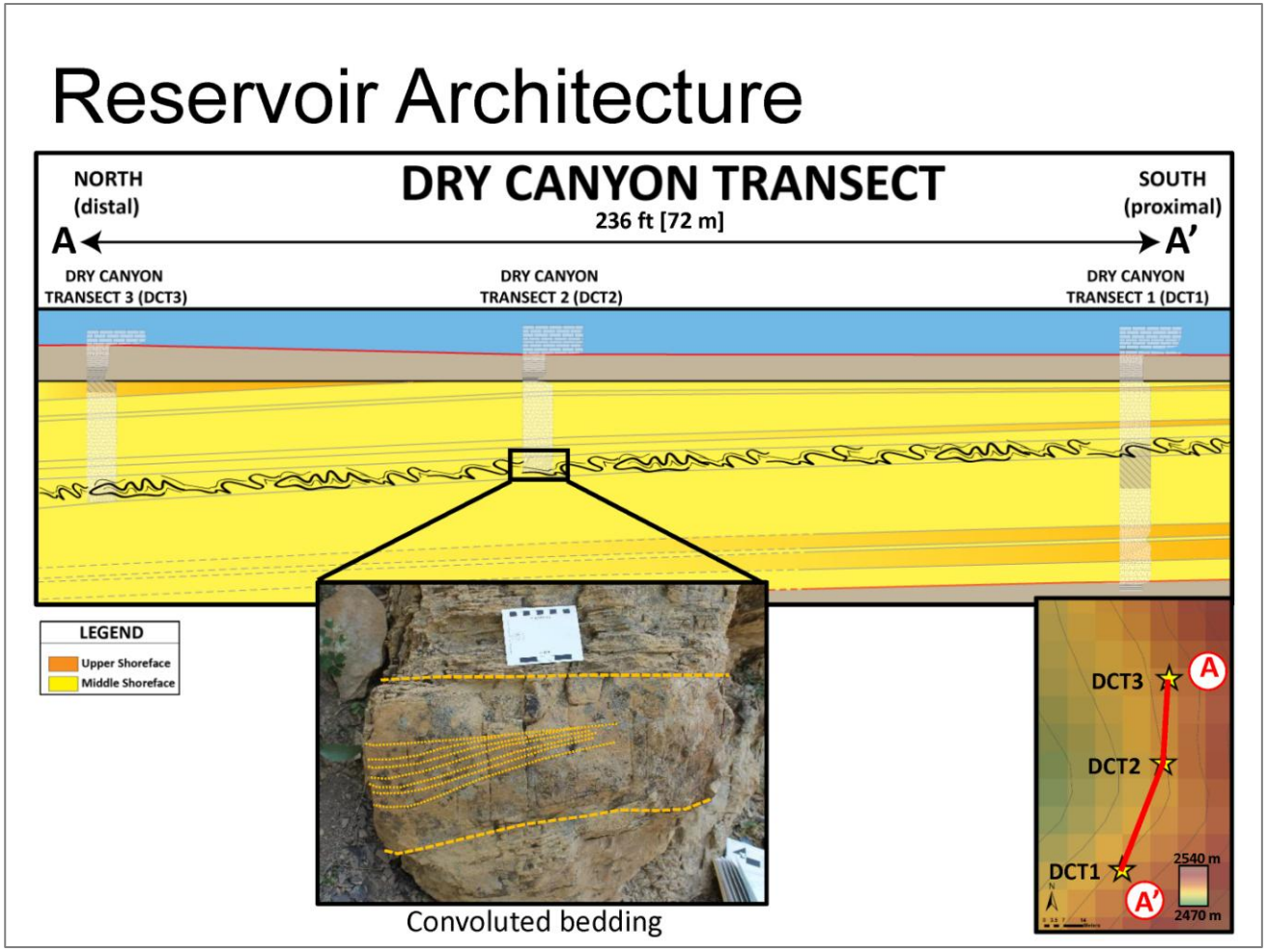
On the inset is a blow up of a section that appears to have clinoformal bedding. I am going to flip back and forth between the interpreted and uninterpreted section to show the character of the dipping beds.

Reservoir Architecture



Complex architectural relationships and sedimentary body geometry

Presenter's notes: and you can start to get a sense of the complex architectural relationships and sedimentary body geometry.



Presenter's notes: That lateral heterogeneity is also apparent at the other reservoir-scale transects. This is a stratigraphic cross-section also hung on the base of the upper member across three outcrops at Dry Canyon. Again, north is on the left, south on the right and the cross section is 236 ft across. The colors are representative of facies associations. This interval has convoluted bedding that is traceable across the transect. We think it is a correlative event bed and used it for correlations and to determine depositional gradient.
(Presenter's notes continued on next slide)

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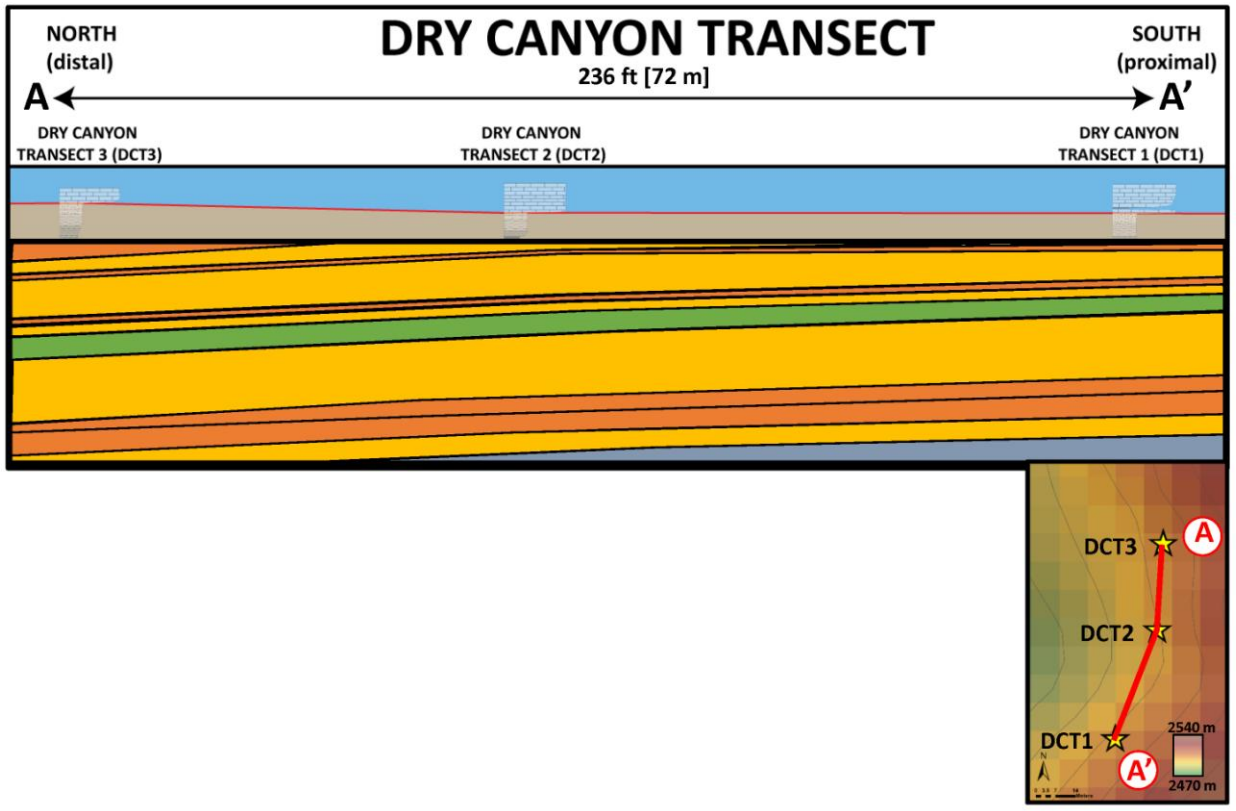
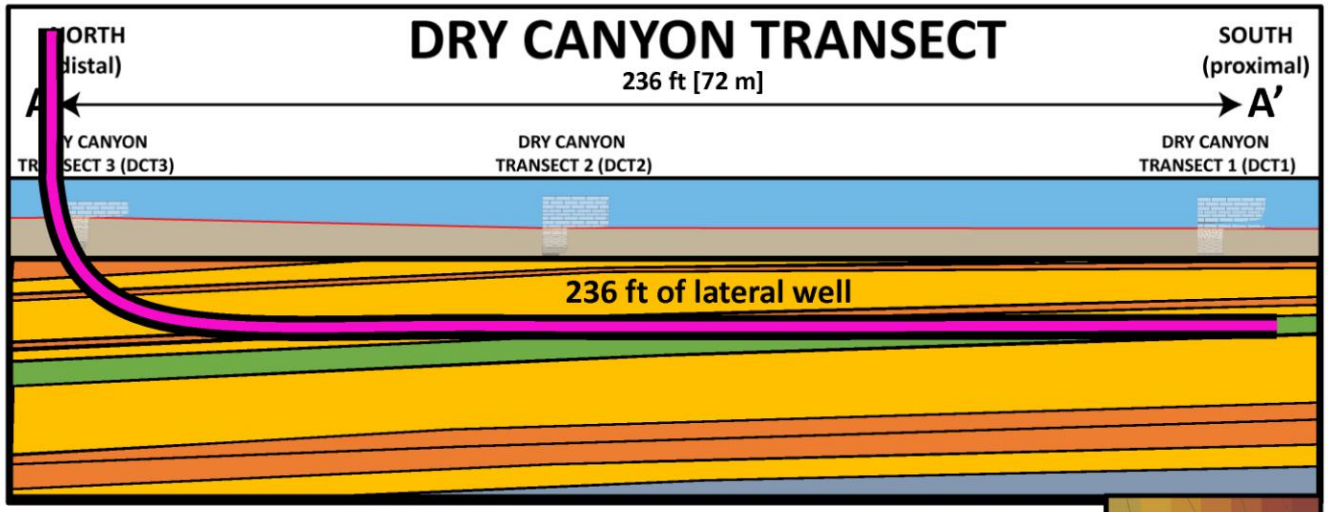
We can divide these strata up into flow units. We define a flow unit as internally homogenous reservoir unit and these ones are based on facies associations, surfaces and architectures. These units assume differing porosity and permeability from each other based on field observations. In this figure there are multiple stacked flow units that each have differing reservoir quality and connectivity. If we were to drill a lateral well through this depositional dip section, in a standard Bakken operator’s distance from the upper shale….

Reservoir Architecture

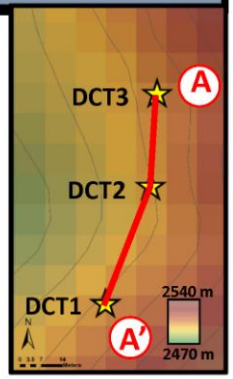


Presenter's notes: We can divide these strata up into flow units. We define a flow unit as internally homogenous reservoir unit and these ones are based on facies associations, surfaces and architectures. These units assume differing porosity and permeability from eachother based on field observations. In this figure there are multiple stacked flow units that each have differing reservoir quality and connectivity. If we were to drill a lateral well through this depositional dip section, in a standard Bakken operator's distance from the upper shale….

Reservoir Architecture

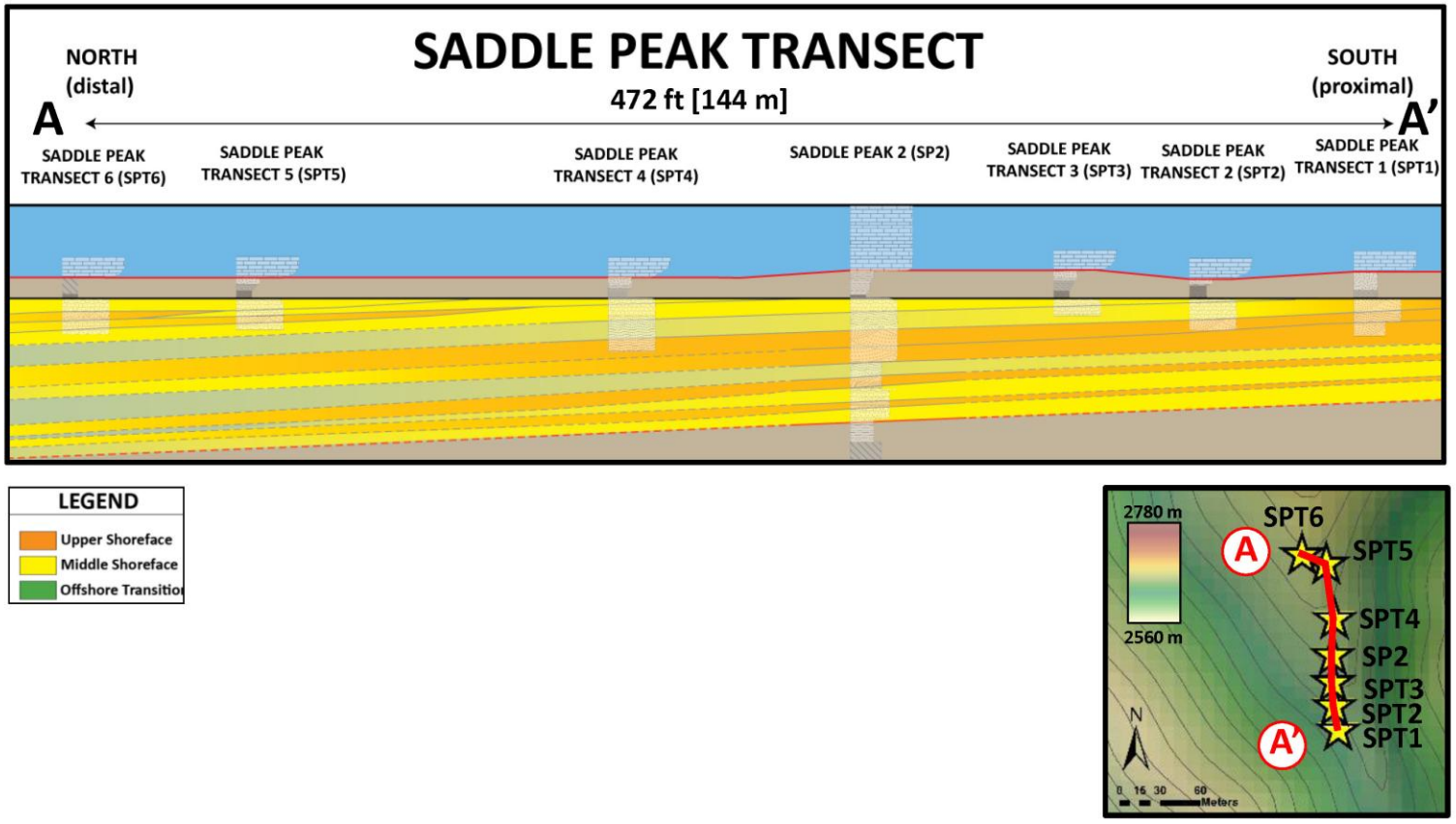


- Lateral well drills through 3 flow units in 236 ft
  - In 10,000 ft, 127 flow units
  - Assumes flow units are homogenous and have uniform properties
- Significant heterogeneity on the reservoir scale



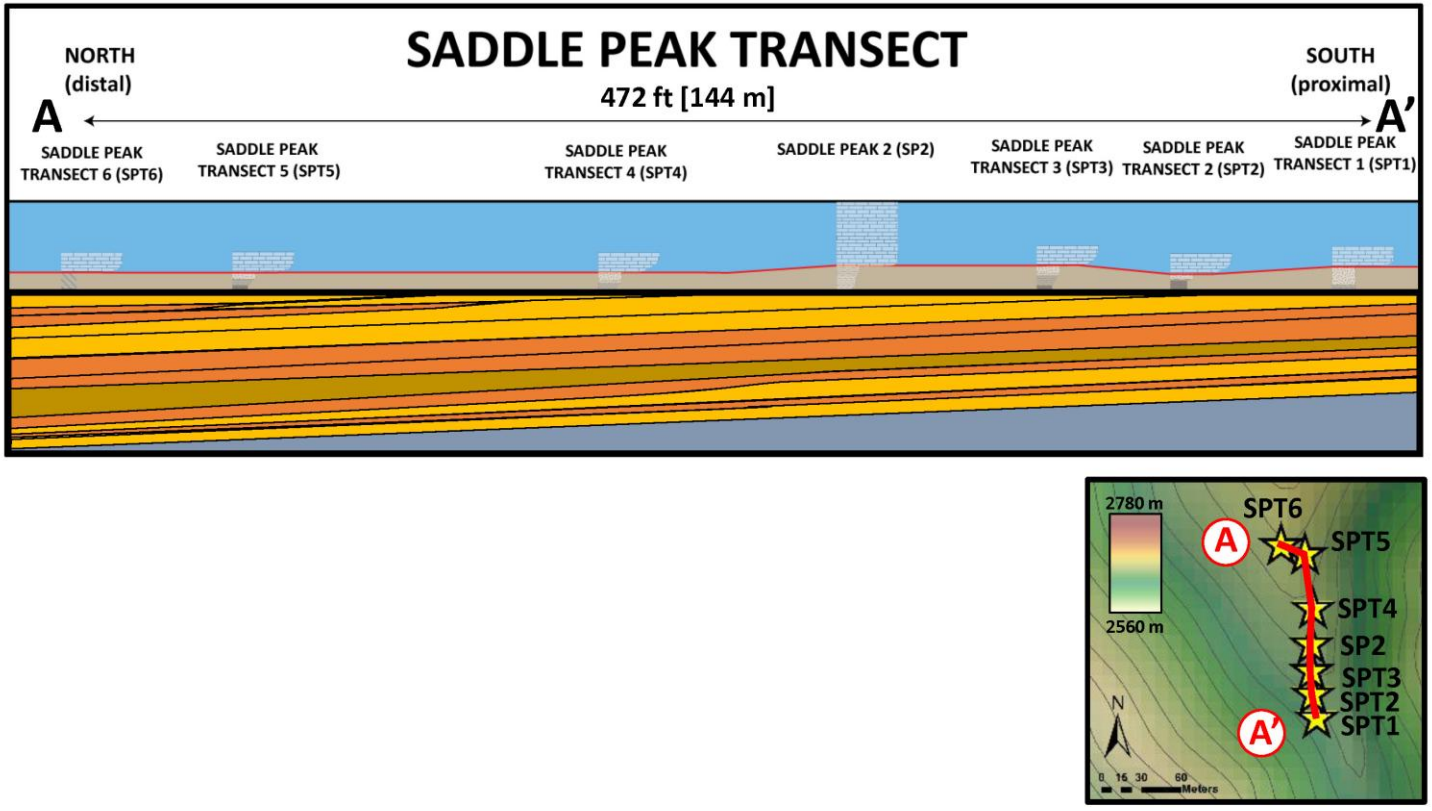
Presenter's notes: …..It would drill through 3 flow units in just 236 feet. At this dip, the well would go through 127 flow units in a 10,000 ft lateral! And that's with the assumption each flow unit is homogenous and has uniform properties, when in fact these units have differeing geologic and petrphysical properties which could decrease reservoir connectivity.

Reservoir Architecture



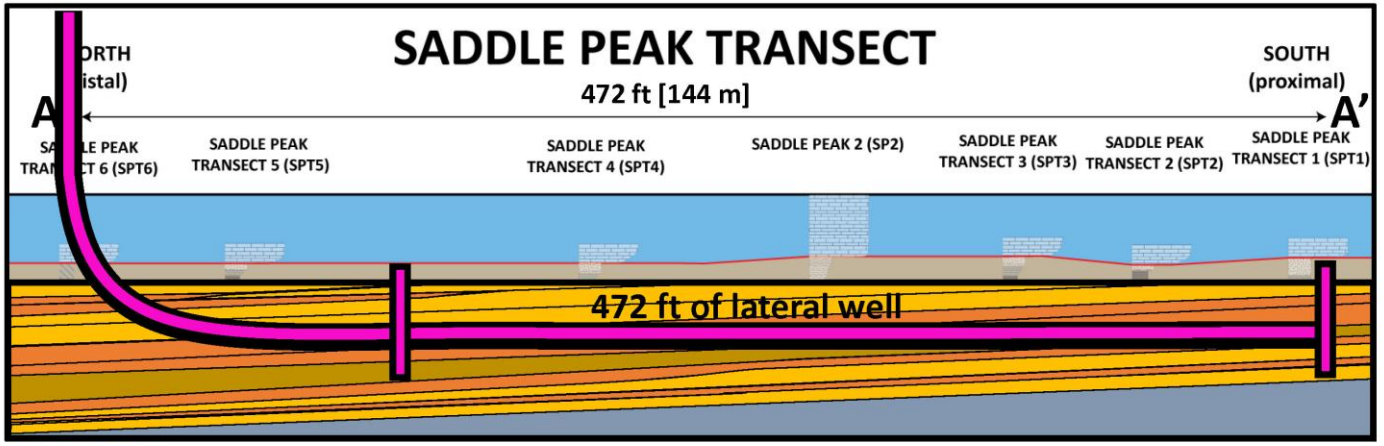
Presenter's notes: There is similar lateral lithologic heterogeneity at the Saddle peak transect. This is a stratigraphic cross-section also hung on the base of the upper member across seven outcrops at Saddle Peak. Again, north is on the left, south on the right and the cross section is 472 ft across. The colors are representative of facies association.

Reservoir Architecture

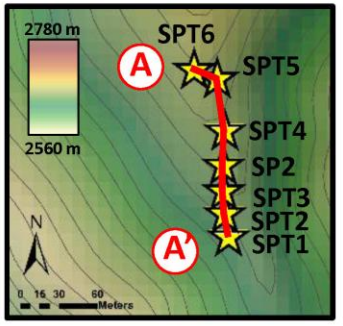


Presenter's notes: If we divide this cross section up into flow units, there are again multiple stacked flow units that each have differing reservoir quality and connectivity. If we were to drill a lateral through this depositional dip section, in a standard Bakken operator's distance from the upper shale….

Reservoir Architecture



- Lateral well drills through 7 flow units in 472 ft
  - In 10,000 ft, 148 flow units
  - Assumes flow units are homogenous and have uniform properties
- Significant heterogeneity on the reservoir scale



Presenter's notes: …..It would drill through 7 flow units in just 472 feet. At this dip, the well would go through 148 flow units in a 10,000 ft lateral! And again, that's with the assumption each flow unit is homogenous and has uniform geologic and petrophyscial properties. This is further evidence for significant heterogeneity on the reservoir scale which have implications for reservoir connectivity and fluid flow.

Implications

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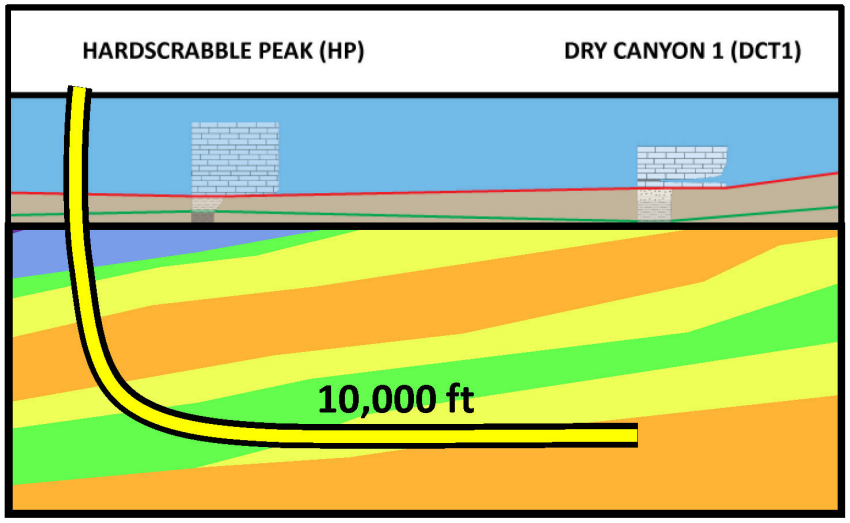
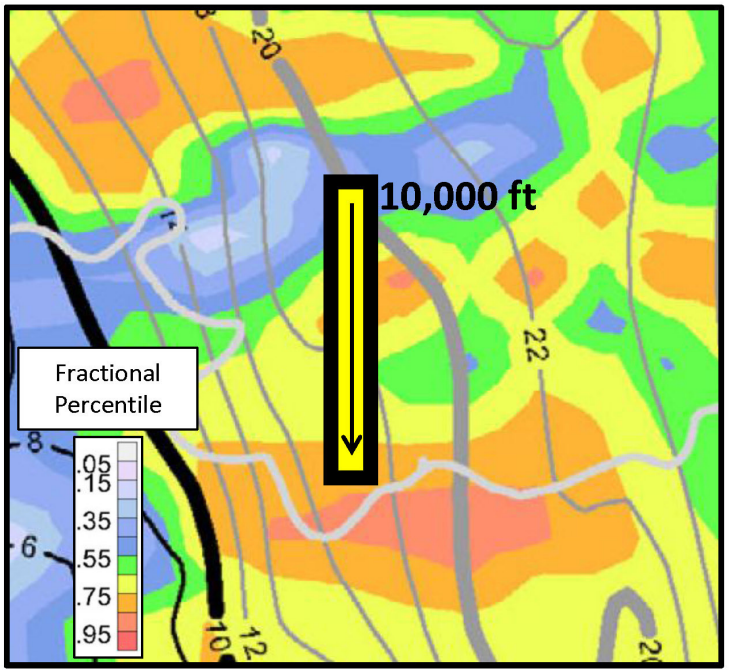


Bridger Range cross section, southwestern Montana

BAKKEN



Bakken production, Williston Basin

Nordeng and LeFever 2014

Presenter's notes: We infer that these observed architectures of the Sappington Formation may help explain production heterogeneity of the Bakken Formation. The cross section on the left from the Bridger Range shows dips and packages representative of outcrop observations. We've adjusted the colors of the stratigraphic packages to represent similar colors from the Bakken

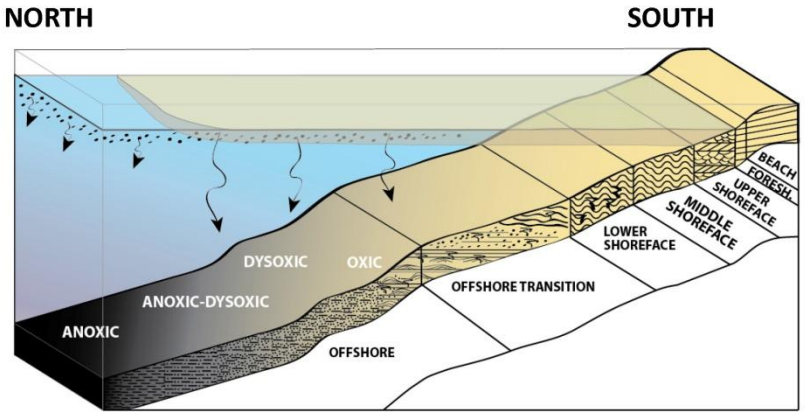
(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

production map on the right. The cool colors represent low production seen here, and the warm colors represent high production. Although we recognize that other geologic factors might be in play, the production heterogeneity observed along a 10,000 ft lateral well in the Bakken Formation as shown on the map to the right coincides with the facies heterogeneity observed along an idealized 10000 ft lateral in the Sappington Formation. For example, at the toe of this idealized lateral well in the cross section, we see coarse grained facies associations that could coincide with higher production observed in the Bakken Formation while near the heel of the well, we intersect a facies association with lower porosity and permeability that can coincide with these low production values observed on the Bakken Formation production map. This shows that the stratigraphic architectures might have strong implications on new development and secondary recovery for the Bakken Formation in the Williston Basin.

Conclusions

- 6 facies associations
  - 14 lithofacies
- Wave-storm-dominated shoreface system
- Observed complex clinoformal geometries in the Sappington Formation
- Stratigraphic architectures may help explain production heterogeneity of the Bakken Formation



Presenter's notes: In conclusion, we have identified 6 facies associations and 14 lithofacies for the Sappington Formation and interpret deposition to be along a wave-storm-dominated shoreface system. We observed complex clinoformal geometries in the Sappington Formation that are also indicative of a prograding shoreface environment. And these stratigraphic architectures and facies associations observed in the Sappington Formation analog may help explain production heterogeneity of the Bakken Formation in the Williston Basin.

Acknowledgments

Questions

Statoil

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