Diagenesis of the Bakken Formation, Elm Coulee Field, Richland County, Montana*

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Search and Discovery Article #20160 (2012)**
Posted July 30, 2012

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Long Beach, California, USA, April 22-25, 2012

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Abstract

Elm Coulee Field, discovered in 2000 in Richland County, Montana, is the largest oil field in the Williston Basin. This field produces from the middle member of the Devonian-Mississippian Bakken Formation and has an estimated ultimate recovery of 200-250 MMBO. The Bakken's diagenetic history, in combination with horizontal drilling and hydrofracturing practices, makes it possible to get large recoveries from this low-permeability and low-porosity field.

The Bakken Formation at Elm Coulee Field is composed of three main members that average 40 feet in thickness. The lower and upper Bakken members consist of dark, organic-rich marine shales with silty laminations. The middle Bakken member is predominantly a silty dolostone. It contains six shallow-marine facies that include laminations, abundant burrows, and brachiopod and crinoid fragments.

Production at Elm Coulee would not be possible if the Bakken Formation had not undergone a variety of diagenetic stages that have resulted in a dolomite-rich reservoir rock with enhanced secondary porosity. The diagenetic sequence of the Bakken begins with mechanical compaction, early dolomitization of the original silty lime mud in a shelfal seepage-reflux setting, and pyrite formation. Next came a period of dedolomitization, deeper burial-related dolomitization, and formation of secondary mineral cements of anhydrite, sphalerite, and quartz. There are also two stages of fracturing at Elm Coulee. The first, mineralized vertical to subvertical fractures, is likely related to either underlying salt dissolution, the reactivation of basement faults, or pressure release from sediment dewatering, and the second stage, open horizontal fractures, is related to pressure release from the hydrocarbon expulsion process. The beginnings of hydrocarbon generation in the shales also expelled acids into the middle Bakken, dissolving parts of the dolomite rhombs, thereby forming narrow slot pores and larger dissolution pores which further enhanced the storage space for the subsequently expelled oil.

The results of this study indicate that the Bakken petroleum system within the Williston Basin is a complex system that has huge potential for future discoveries. Understanding the distribution of the facies and the diagenetic stages that have occurred within the middle Bakken

reservoir member is the key to determining new drilling targets within Elm Coulee and to the search for similar fields in this basin that may also be good production targets.

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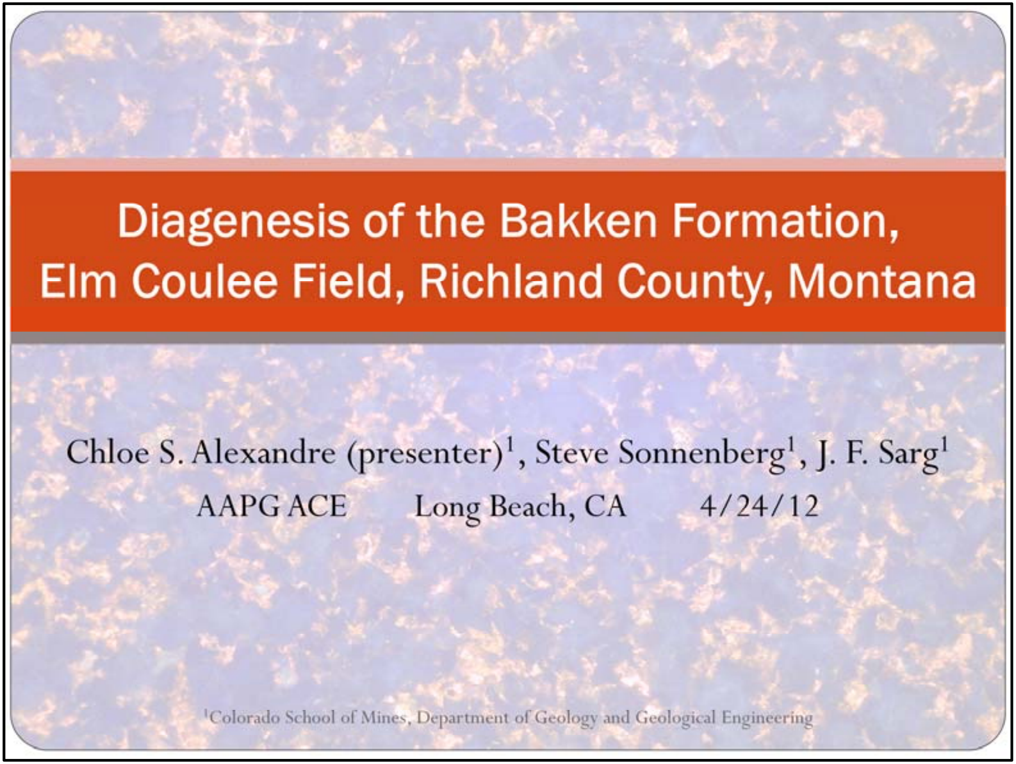


Presenter's notes: This article presents material from the first author's thesis (Alexandre, 2011).

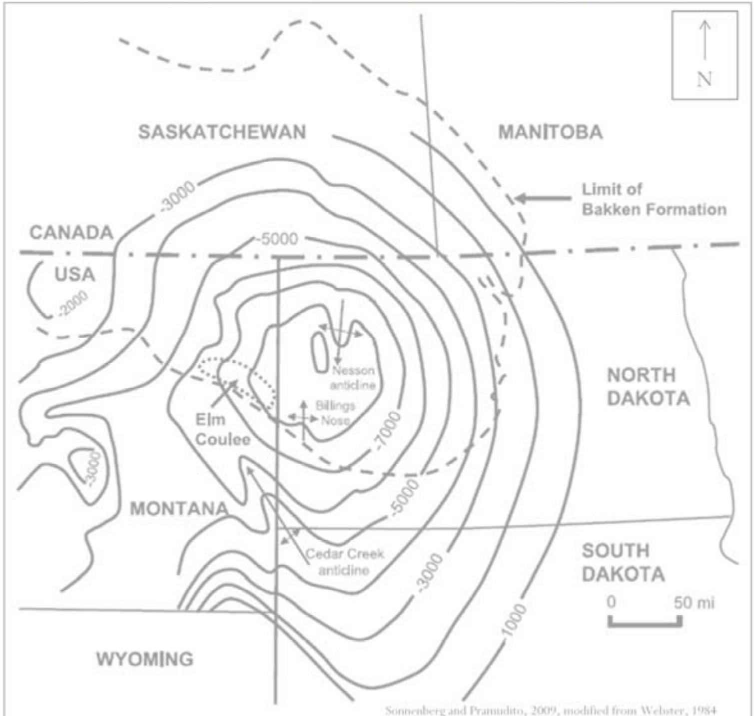
Outline

- The Bakken Formation at Elm Coulee Field
  - Background
  - Facies/reservoir description
  - Data set and methods used
- Diagenetic sequence
  - Mechanical and chemical compaction
  - Pyrite
  - Dolomitization
  - Fracturing
  - Sphalerite, anhydrite, and quartz cementation
  - Hydrocarbon generation
- Conclusions

Presenter’s notes:

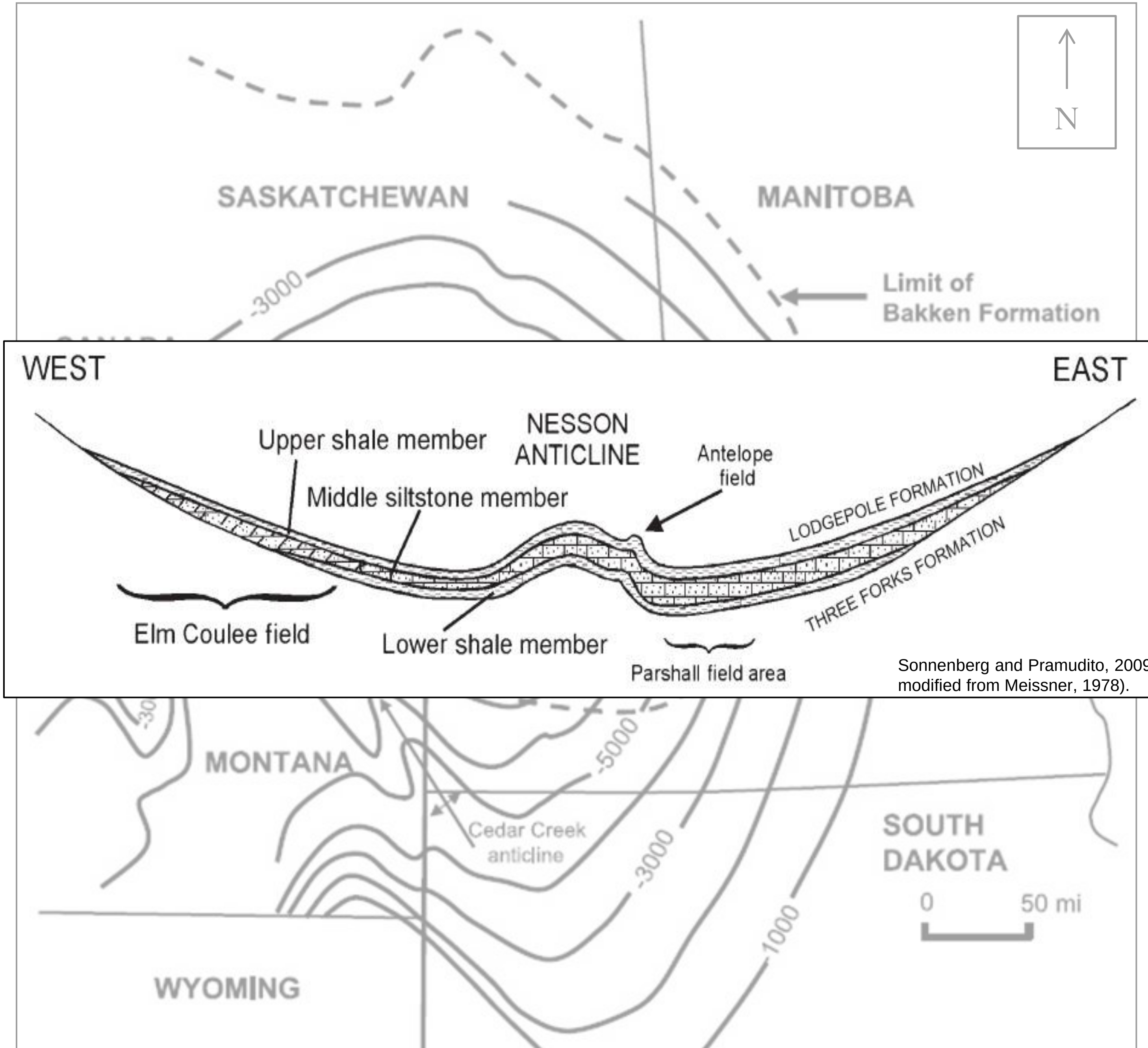
- This area in Richland County, MT, was mentioned in the literature as a potential target for production almost 60 years ago and later was referred to as a **“the sleeping giant.”**
- Elm Coulee was officially discovered by Dick Findley, and the **first well was drilled in 2000** by Lyco Energy Corporation.
- Thanks to technological advances in **horizontal drilling and hydrofracturing**, production is successful within the middle Bakken member at Elm Coulee.
- The field is expected to produce **200-250 million barrels of oil.**

The Williston Basin



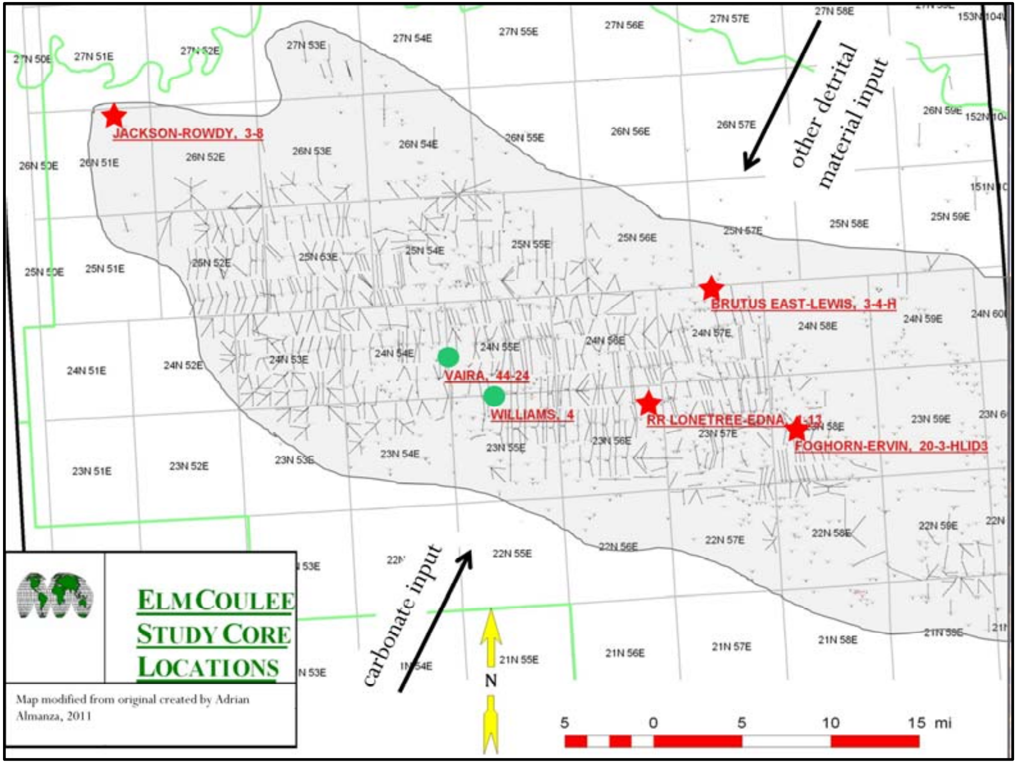
Presenter's notes: The Bakken Formation was deposited along the paleoequator, during Mississippian-Devonian.
The field is approximately **15 mile wide by 50 mile long.**

The Williston Basin



Sonnenberg and Pramudito, 2009, modified from Meissner, 1978).

Sonnenberg and Pramudito, 2009, modified from Webster, 1984

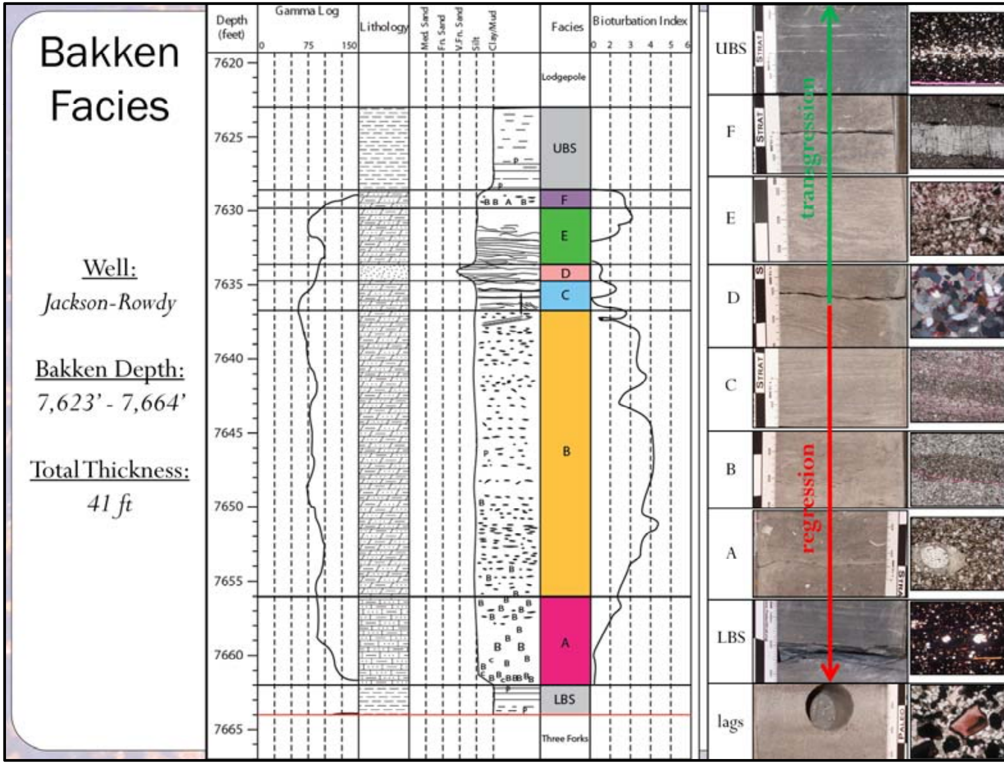


Presenter's notes: The Bakken in the field area was deposited along the edge of the basin, near the exposed Three Forks Formation; therefore, some allogenic dolomite could have also been brought into the basin by winds.

Large portion of silt from NE source settled to the bottom of the basin before reaching the western side where Elm Coulee is located, leading to clearer water more favorable to carbonate-forming organisms (more original lime mud). Shales were deposited in a stratified water column within an open-marine environment. Middle bakken is a dolomitized "longshore bar" OR "carbonate mud bank" OR carbonate shoal complex that was located just offshore.

Study included 123 thin-sections from red star wells, 12 from other wells.

Samples were stained for calcite/dolomite; some were stained with potassium ferrocyanide for ferroan content.



Presenter's notes: Middle Bakken: Shallow-Marine. Because dolomite is more brittle than calcite, it might fracture more readily. Other fields produce from facies C – E. Facies E contains both laminations and burrows (bioturbation index based on Reineck's 1963 classification). Well: Dry hole because of completion techniques? Lower Bakken Shale: 11.45% TOC; Upper Bakken Shale: 12.35% TOC.

The Diagenetic Sequence

Diagenesis is:

"all the chemical, physical, and biologic changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weather) and metamorphism"

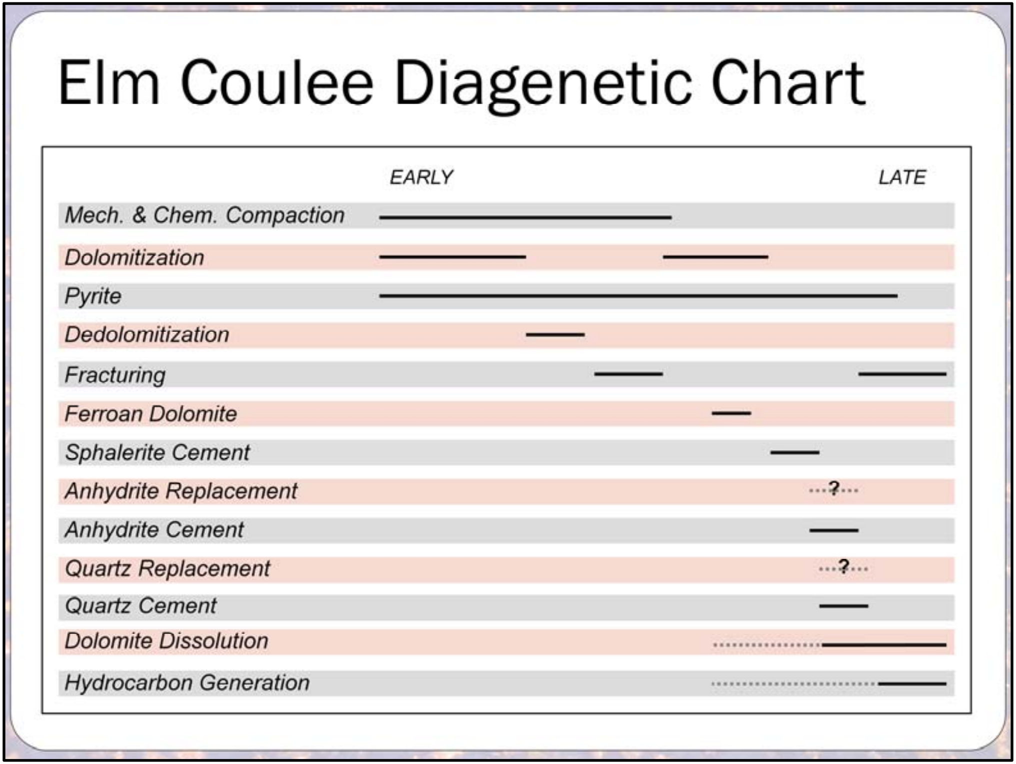
-Neuendorf et al., 2005

"a series of fluid-rock interactions in which material is either added or removed from the surfaces of detrital grains and/or previously formed authigenic crystals"

-Maliva and Siever, 1990

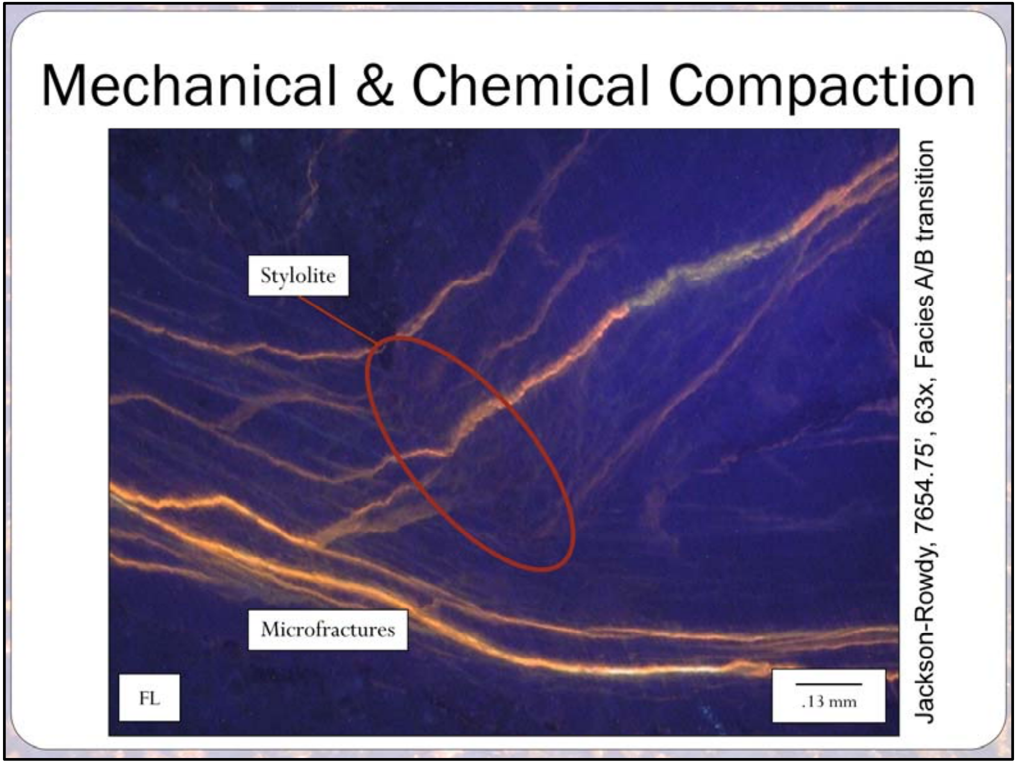
Presenter's notes: Diagenesis can both destroy (cementation, mechanical and chemical compaction) and enhance (dissolution, fracturing) reservoirs. Therefore, it is important to understand the diagenetic stages a reservoir has undergone in order to more accurately determine where the best targets are within a particular field.

As the information that follows indicates, at Elm Coulee diagenesis is responsible for creating a dolomite-rich rock, enhancing the rock with secondary porosity, and filling it with hydrocarbons.



Presenter's notes: For comparison, Pramudito (2008) did not evaluate dedolomitization, quartz cement/replacement, or hydrocabon generation; he shows anhydrite before dolomite and sphalerite cement/replacement, as well pyrite cementation at two different times.

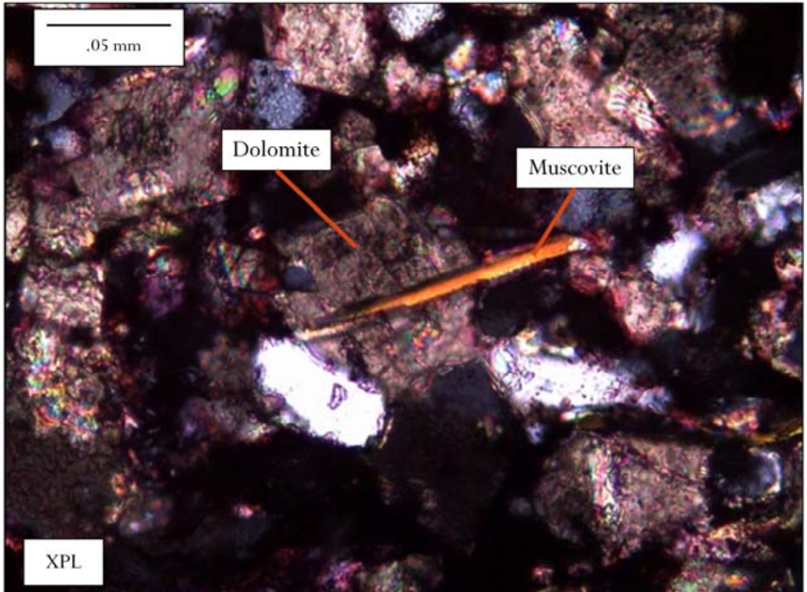
Pitman et al. (2001) record a very different diagenetic history. They show secondary quartz forming immediately after mechanical compaction. They note syntaxial calcite, illite and chlorite, ankerite and K-spar overgrowths. Similarities with the chart here include mechanical compaction, carbonate dissolution, fracturing, and hydrocarbon generation.



Presenter's notes: As soon as sediment is deposited, it begins to compact and dewater. Within the Bakken formation, compaction is evident in the flattening of mud-rich burrows, the distortion of dark organic material within the shales, and in this particular case, in the cracking of fossil fragments and the creation of stylolitic contacts between fossils.

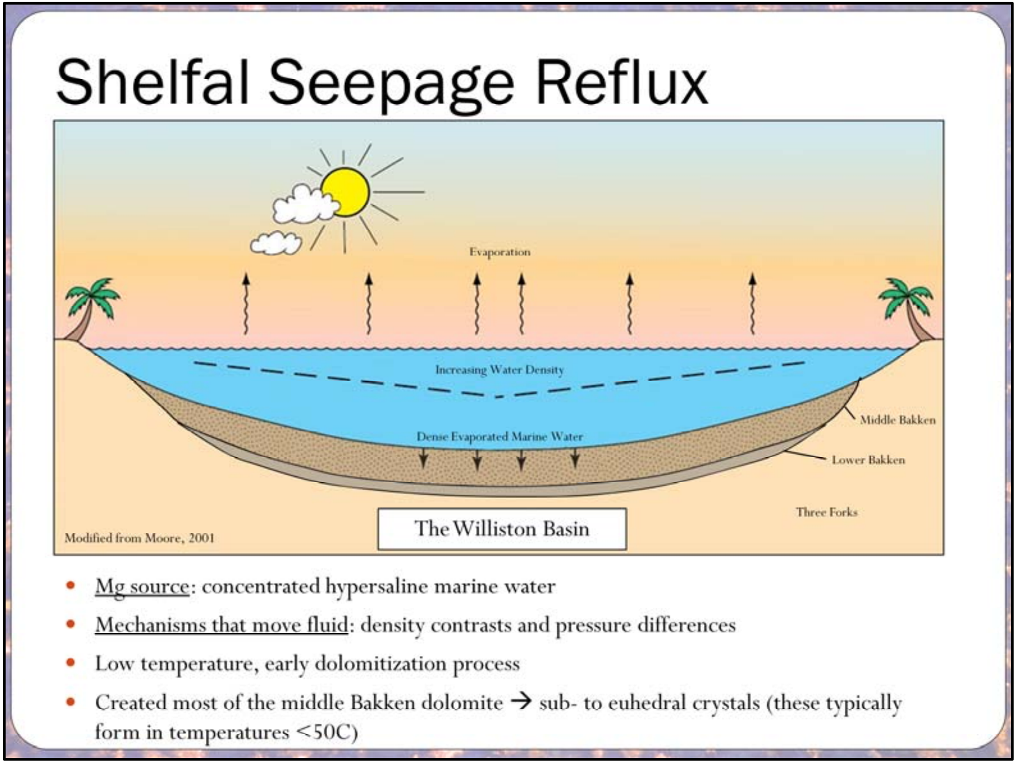
Evidence of burial-related mechanical and chemical compaction: Two large brachiopod fragments are intersecting and forming a stylolitic pressure-solution seam; the fossils also contain many fractures.

Early Dolomitization



Brutus East-Lewis, 10391.2', 200x, Facies C

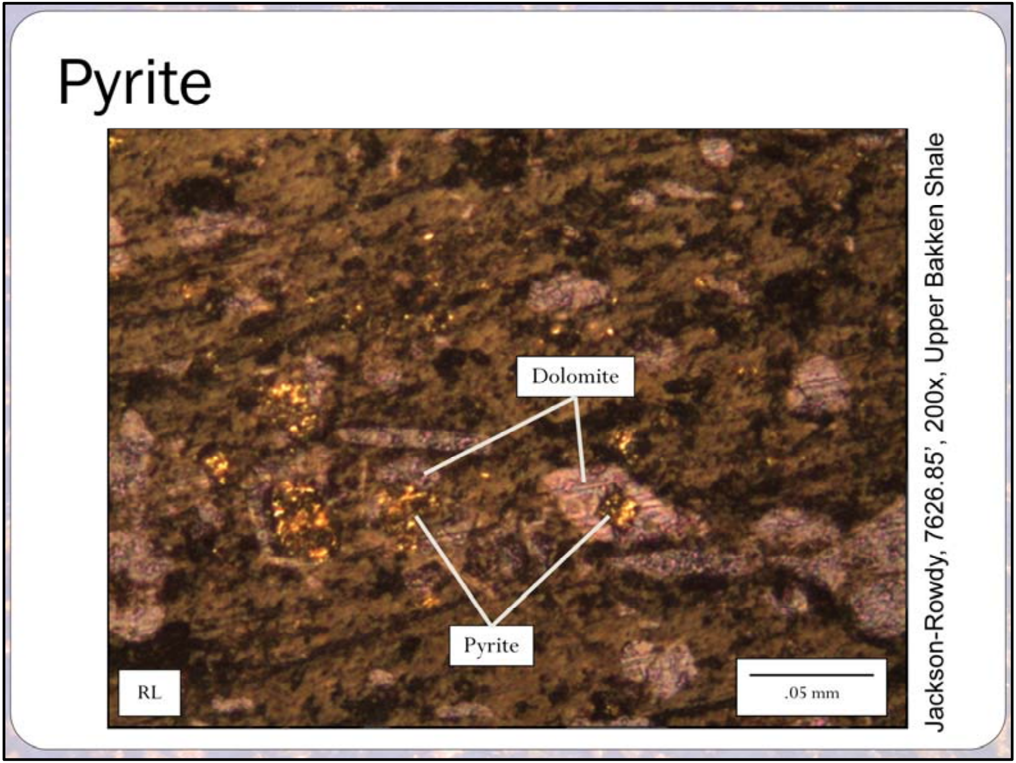
Presenter's notes: At Elm Coulee Field, dolomitization also began very soon after deposition, transforming the original silty lime mud into a silty dolostone. As shown in this image, some dolomite rhombs formed around detrital material, like the muscovite blade.



Presenter's notes: The Bakken formation, deposited along the paleoequator, hosted a limited suite of ichnofauna; a lack thereof in the Three Forks indicates that this area was a hot, stressed environment and likely evaporitic.

Most of the dolomite found in the middle Bakken is sub- to euhedral crystals, characteristic of lower-temperature dolomitization processes, and this kind of dolomite is found with varying amounts across the Williston Basin, not just at Elm Coulee. There must have been a process occurring that affected the whole area, rather than just a localized environment along one edge, like a mixing zone or sabkha.

With those pieces of evidence, our schematic diagram represents shelfal seepage-reflux dolomitization of the middle Bakken member. In this model, the upper waters within the Williston Basin would have been partially evaporated leading to a concentration of ions and increased density. This mineral-rich water then descended through the water column into the upper portions of the Bakken Formation, leading to the dolomitization of that limy sediment. This process substantially dolomitized the middle Bakken silty lime mud until the upper Bakken shale was deposited, essentially forming an aquitard above the middle Bakken sediments.

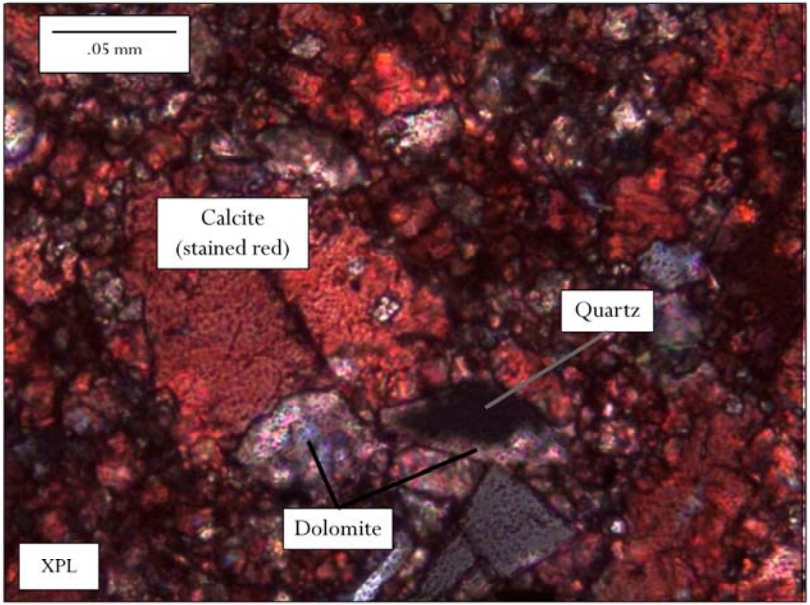


Presenter's notes: Pyrite also began to form very early in the diagenesis and continued to form until the hydrocarbon-generation process effectively stopped diagenesis in the field area. Pyrite is found in all three members of the Bakken Formation.

- Iron for these is Fe^{2+} in the pore waters, mostly liberated from iron oxides and hydroxides on clays and organic matter.
- Sulfide for the pyrite comes from bacterial reduction of dissolved sulfate in the pore waters (common in seawater→ creates H_2S).
- Fe^{2+} and H_2S react, especially in the anoxic sulfidic diagenetic environment.

In this image pyrite can be seen in the center of dolomite rhombs, indicating its formation shortly before the dolomite crystals.

Dedolomitization



Brutus East-Lewis, 10411.3', 100x, Facies B

Presenter's notes: At this point in the diagenetic sequence, dolomite continued to form for a while, but within some sections of the middle Bakken, the dolomite was replaced by calcite in the dedolomitization process. Some shift in fluid composition must have increased the Ca and decreased the Mg content causing the calcite to form at the expense of dolomite. Perhaps the Ca came from material released during the chemical compaction of some of the calcareous fossils.

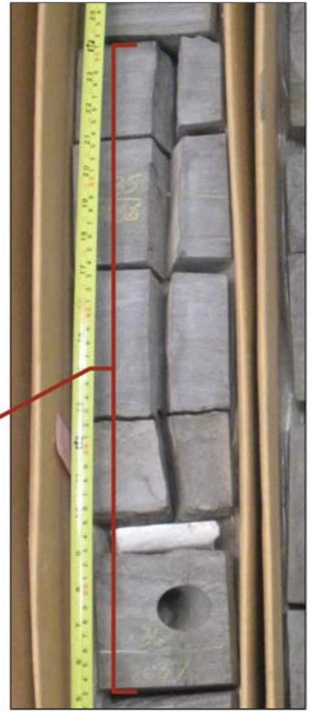
Ca could also have come from increase in Ca concentrations due to dolomitization changing the ratio, or from fractures connected to the Lodgepole Limestone.

Calcite (stained red) is pervasive in this sample. It forms around dolomite and detrital grains and contains floating bits of unreplaced dolomite within the crystals.

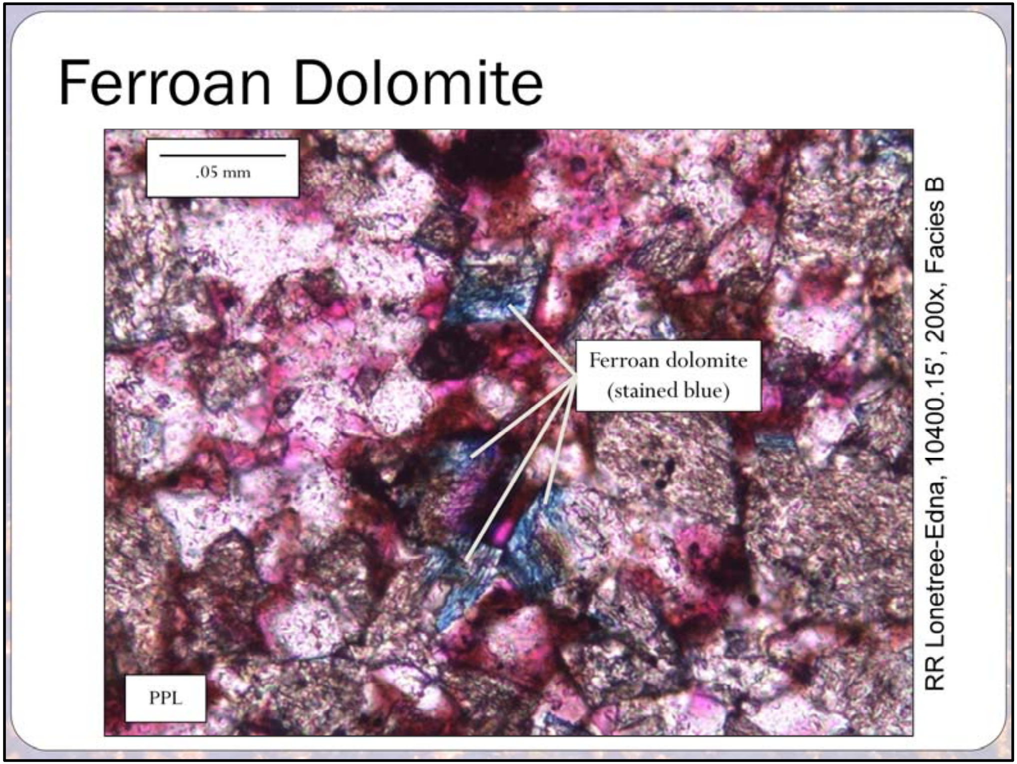
Fracturing (Stage 1)

Jackson-Rowdy, 7635.67' – 7637.1',
Facies B to Facies C transition zone

19-inch mineralized vertical fracture



Presenter's notes: The first stage of fracturing occurred next in the sequence. This stage of fracturing was likely due to the dissolution of underlying Prairie salt evaporites and the subsequent collapse of overlying sediment. Other possible causes suggested in literature are the Laramide orogeny, which began a few million years before the Bakken shales are thought to have generated their hydrocarbons, the reactivation of basement faults, or pressure release from dewatering and lithification of the sediment. This stage of fracturing was later mineralized with pyrite, dolomite, sphalerite, and anhydrite.

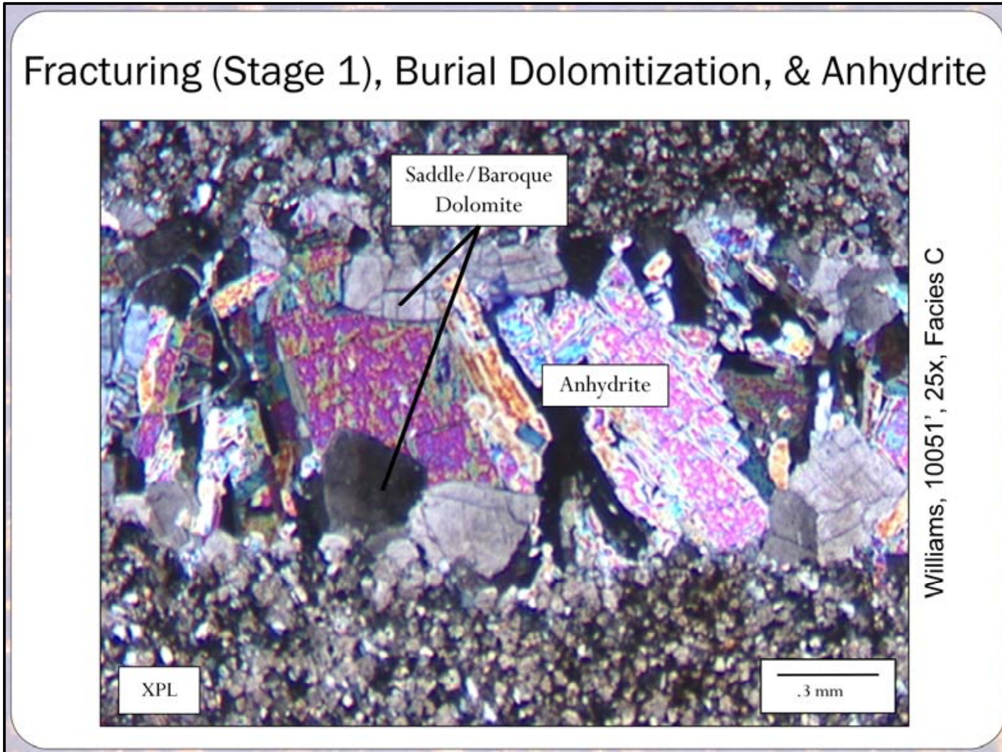


Presenter's notes: After the first stage of fracturing, dolomitization continued. Within this stage, some ferroan dolomite formed. This was first recognized after a brief cathodoluminescence study of one sample showed some variations within the dolomite composition. Further examination under the SEM revealed some dolomite rhombs had ferroan rims and nonferroan cores. Finally, staining the RR Lonetree-Edna and Foghorn Ervin thin-sections with potassium ferrocyanide shows that, although most of the ferroan dolomite appears as thin rims on the rhombs, occasionally the ferroan dolomite will make up the central portion of a rhomb or a middle portion that is then rimmed with more nonferroan dolomite.

Zonation could also be caused by dissolution and recrystallization of rhomb edges, multiple stages of dolomitization (drusy centers and clearer borders), or slightly different mineralogies.

Because Fe is more common in formation waters than seawater , it could also be a product of burial compaction dolomitization (Fe from sulfide minerals in the shales).

In this image are several dolomite rhombs that are partially made of ferroan dolomite (stained blue).



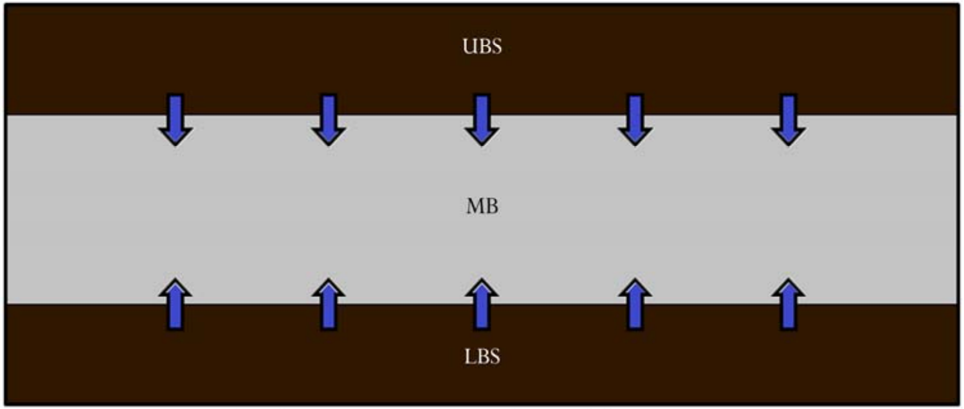
Presenter's notes: Finally at the end of dolomite formation, some saddle/baroque dolomite formed. This type of dolomite forms under high fluid temperatures.

Burial anhydrite: Anhydrite can be precipitated in the deep-burial environment as a cement and as replacement crystals and nodules in sandstones, limestones, and dolomites. In these cases, the anhydrite is not strictly an evaporite mineral, although the sulphate is usually derived from dissolution of evaporites within the basin.

Anhydrite may also be from fluids associated with fractures extending to the Three Forks, Nisku, or Prairie Evaporites.

Ca may have been derived from dolomitization process due to reaction with the sulphate-rich seawater (more likely for the less coarsely crystalline patchy cements).

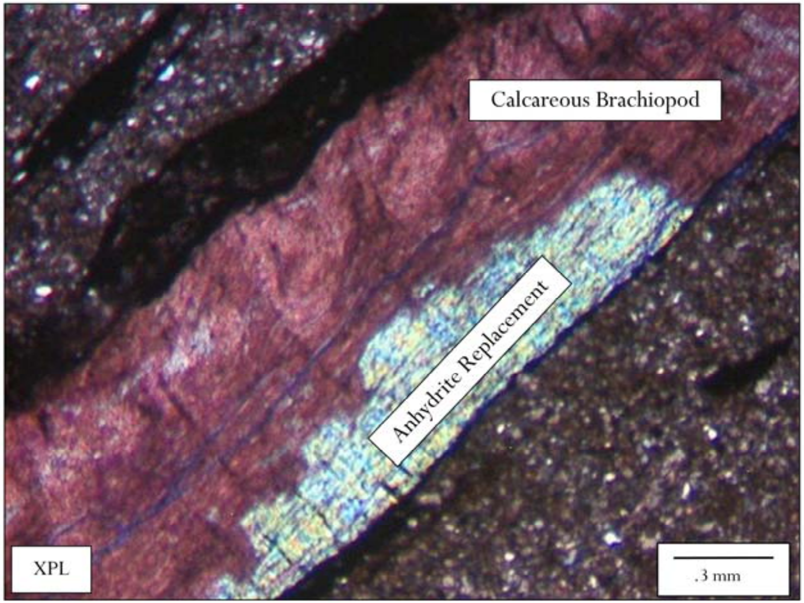
Burial Compaction



- Mg source: mineral-rich waters expelled from adjacent shales
- Mechanisms that move fluid: compaction and dewatering of shales during burial
- Higher temperature, later-stage dolomitization process
- Created higher-temperature Bakken dolomite including the "saddle dolomite" (these form in temperatures between 60 and 150C)

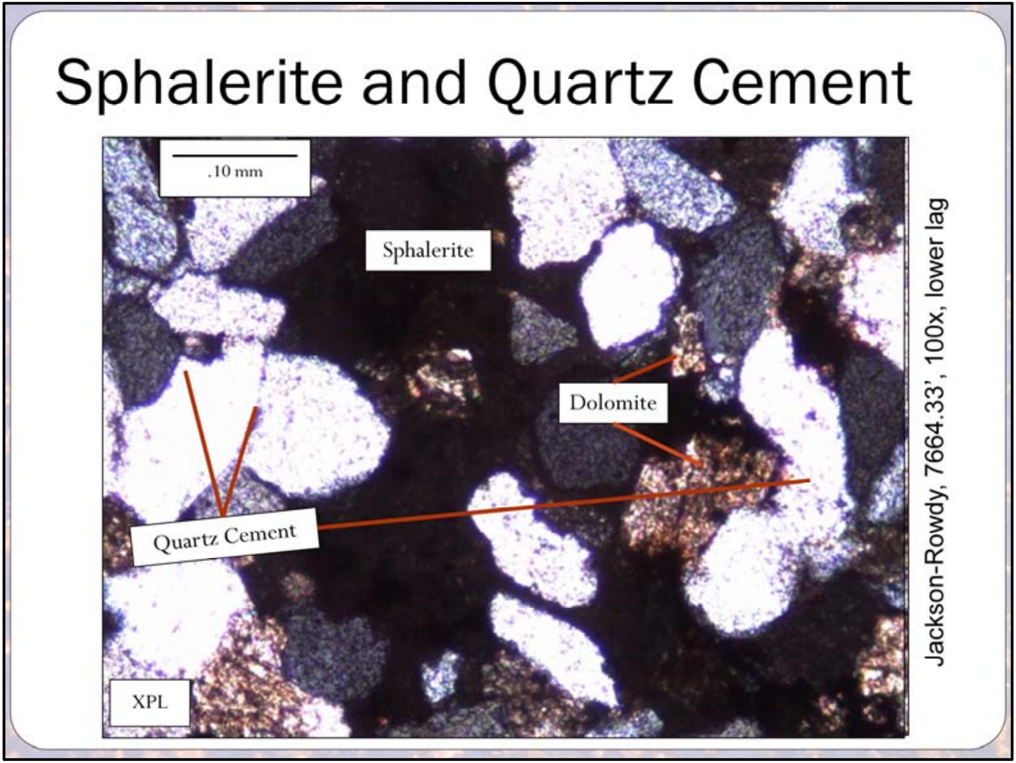
Presenter's notes: Because there are thick shales (now 20 feet for upper Bakken shale and 40 feet for lower Bakken shale) adjacent to the middle member, it seems likely that burial compaction led to the formation of the high-temperature dolomite. In fact, several of the later-formed diagenetic minerals in the middle Bakken, including sphalerite and bornite, may have formed as those organic-rich shales compacted during burial (50-70%) dewatering, with expulsion of warm, mineral-laden fluids into the adjacent rocks.
Conversion of smectite to illite at 2000m and 60C releases water and cations like Mg, which could have been used in dolomitization.

Anhydrite Replacement

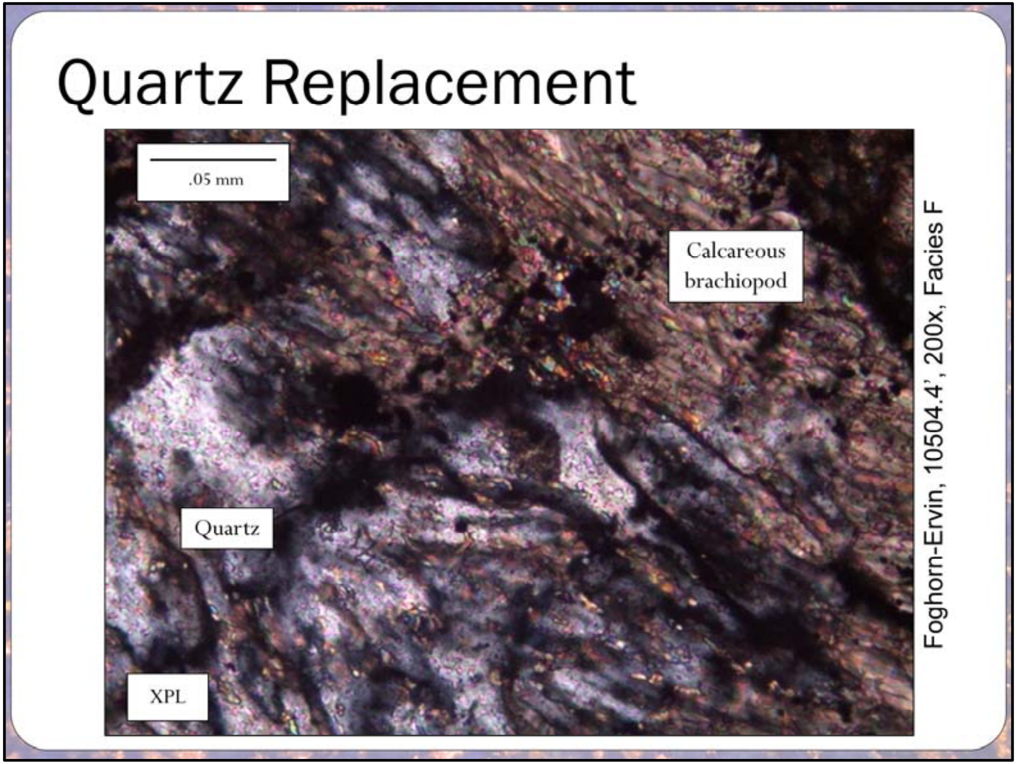


Williams, 10068', 25x, Facies A

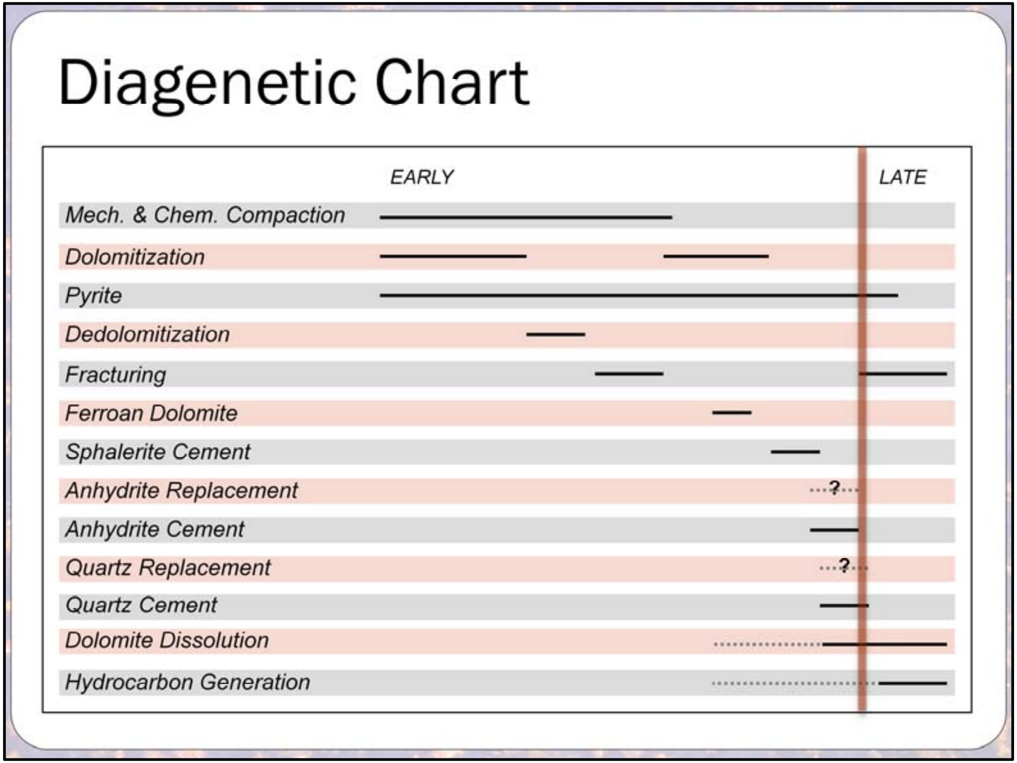
Presenter's notes: Anhydrite replacing calcite (stained red) in a brachiopod fragment. Because this type of replacement is rare, it is difficult to determine the timing of this process.



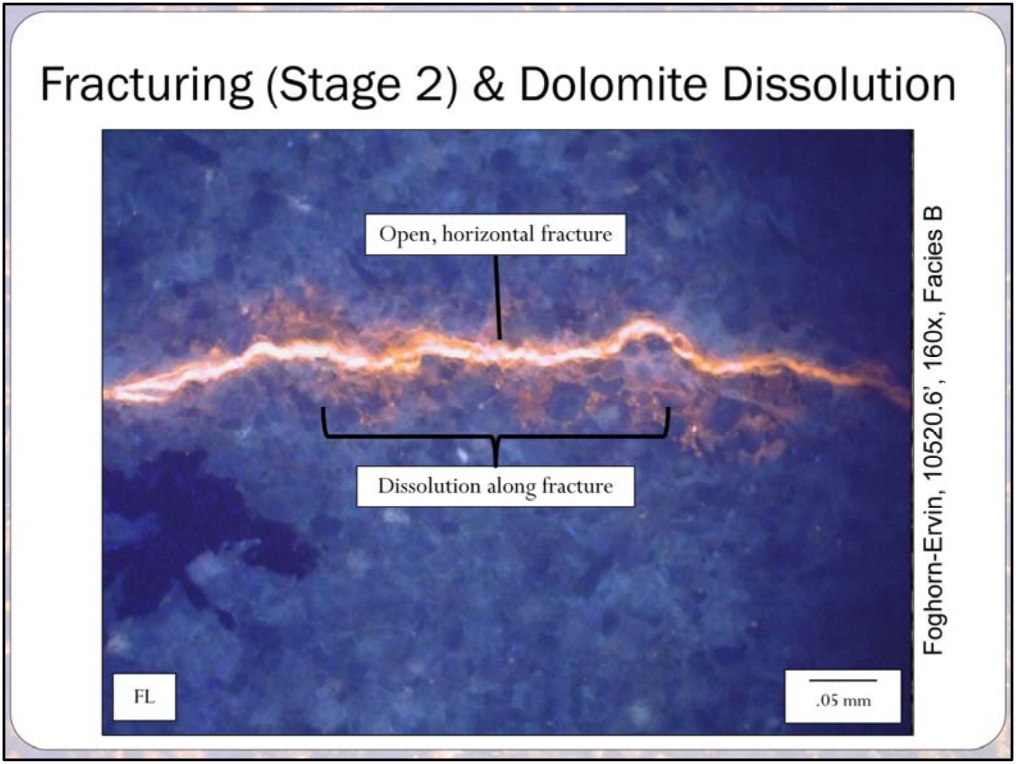
Presenter's notes: Sphalerite cement formed first, preventing later quartz cement from growing around those grains in the center of the image.



Presenter's notes: Partial silicification of a brachiopod. Some pyrite has also formed within the brachiopod. Like the previous example involving a fossil, this silica replacement is difficult to determine relative to timing of the process.



Presenter’s notes: The final three diagenetic processes are all related to one another. As organic matter began to transform into kerogen within the shales, organic acids were released. These acids migrated into the adjacent middle Bakken member and began to dissolve some parts of the dolomite rhombs leading to “slot” porosity and large rhombic dissolution porosity. The continuation of the hydrocarbon-formation process increased pressures within the shales, eventually leading to fracturing in the Bakken Formation and the expulsion of hydrocarbons into the middle Bakken. These processes were repeated until the conditions were no longer favorable for hydrocarbon formation.



Presenter's notes: HC emplacement and fractures occurred at 80 MA (Late Cretaceous), >100C, 2750 m depth (Pitman et al., 2001).
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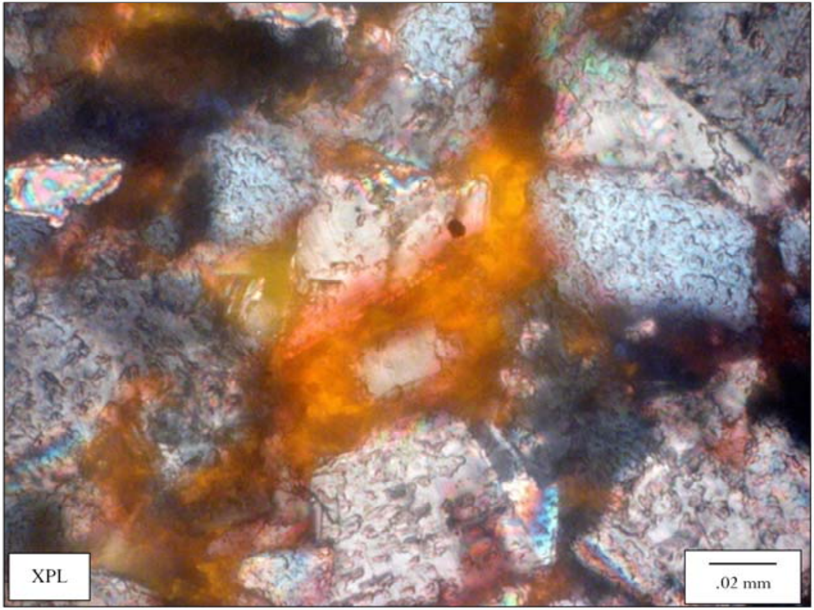
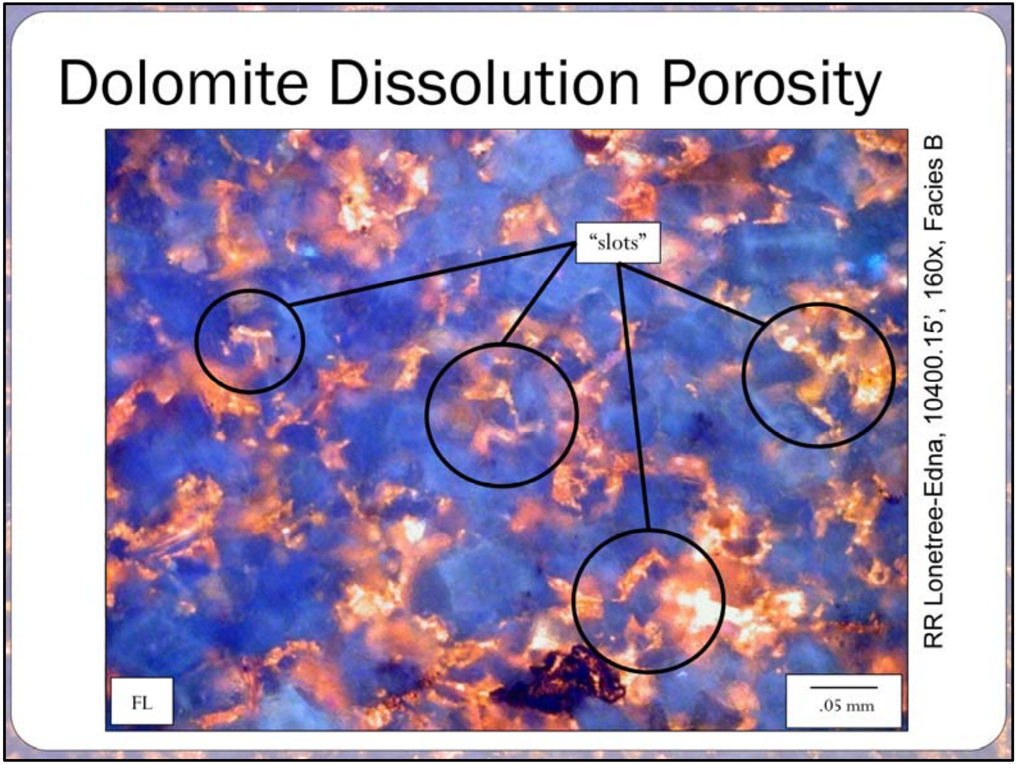
Enhanced porosity along an open horizontal fracture (from stage two of fracturing): The fracture likely occurred early in the hydrocarbon-generation/expulsion process; then organic acids released from that process passed through the fracture dissolving parts of the adjacent minerals and enhancing the porosity.
In the mesogenetic (burial) environment: greater burial, overburden pressure, temperature, and more saline pore waters. Smectites alter to illites. Quartz overgrowths, dolomite, ankerite, and chlorite can be precipitated, and plagioclase may be albitized. Also the generation of hydrocarbons may occur, leading to the formation of acidic pore waters, which in turn can leach grains and carbonate cements, producing secondary porosity (Pittman and Lewan, 1995).

Dolomite Dissolution Porosity



RR Lonetree-Edna, 10400.15', 400x, Facies B

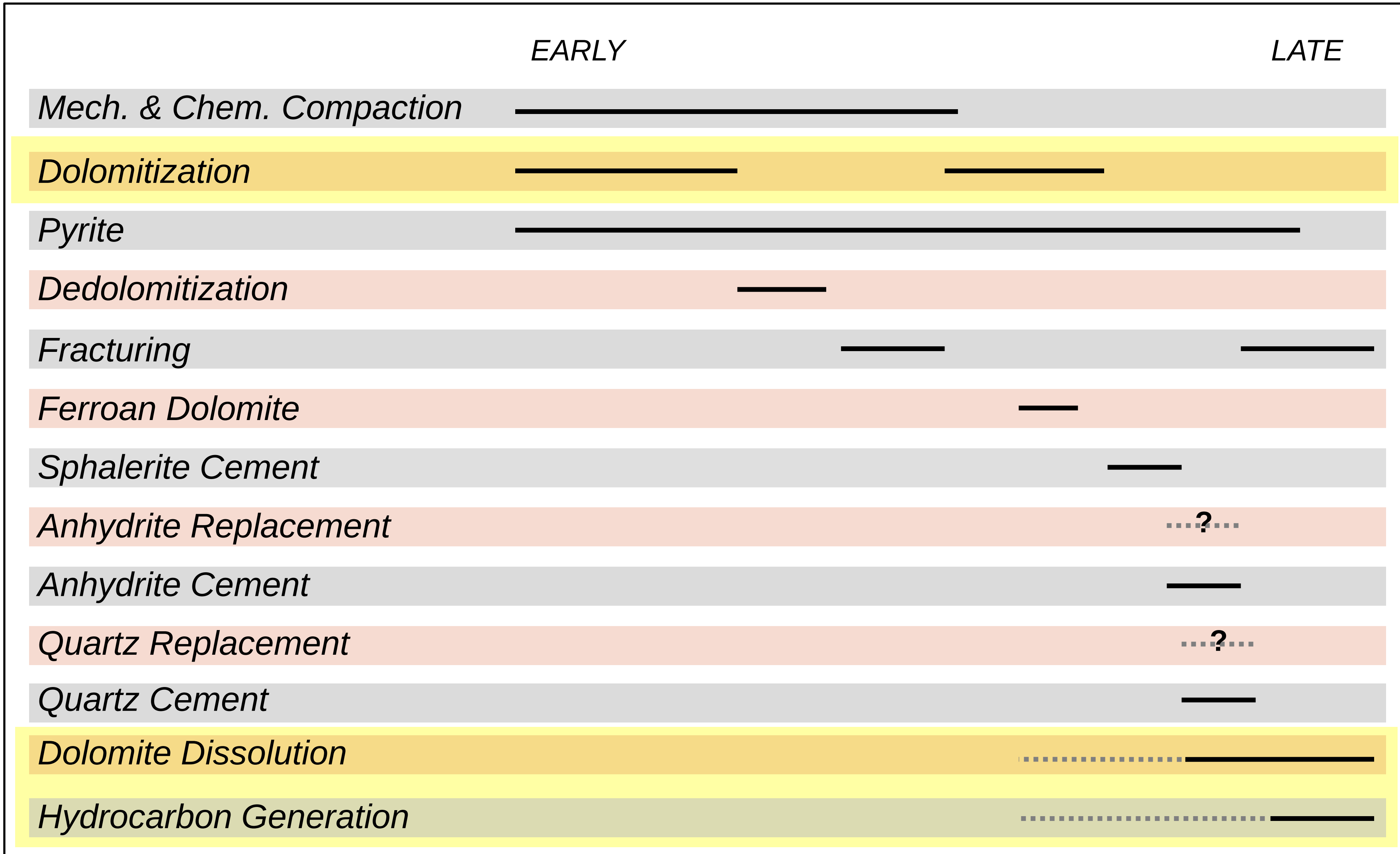
Presenter's notes: Great example of large dissolution pore; a large portion of this dolomite rhomb has been dissolved.



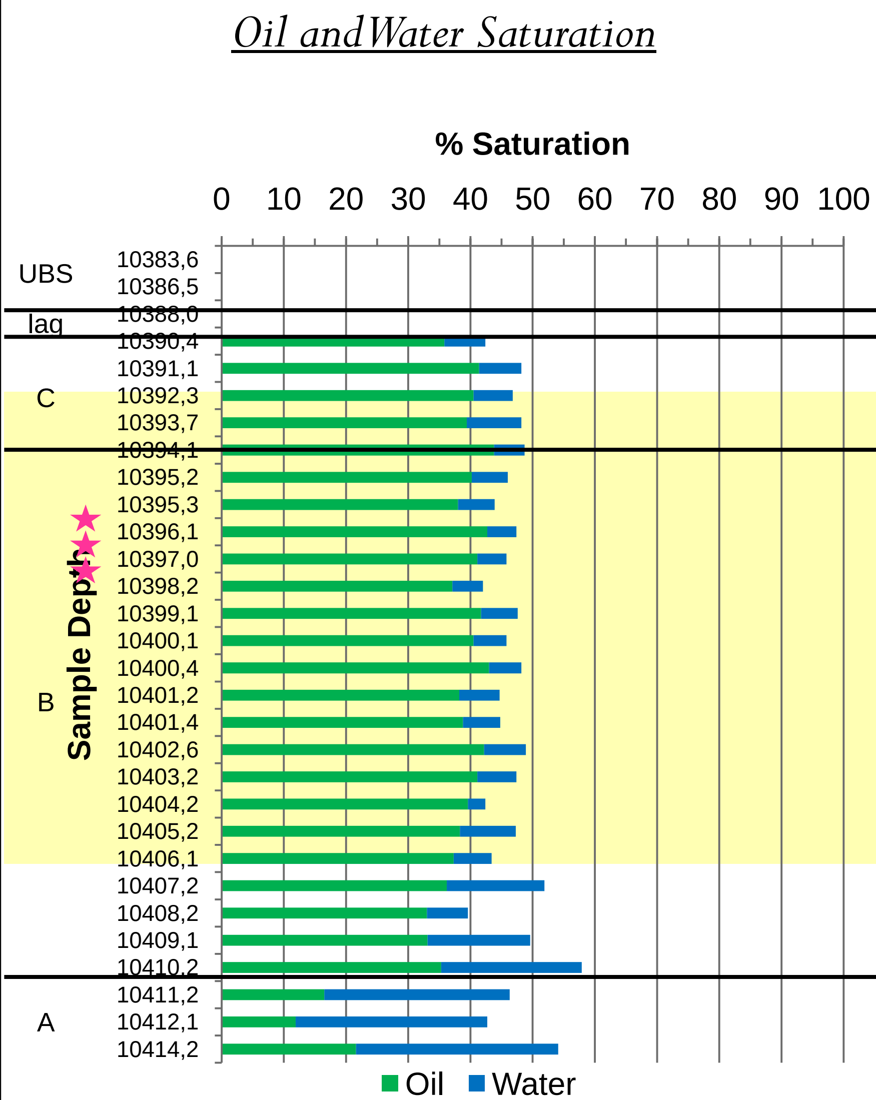
Presenter's notes: Another example of dissolution porosity. This type has been termed "slot" porosity. The slots simply refer to the roughly 6-micrometer-wide gaps located along the edge of the dolomite rhombs where material has been dissolved. With sufficient slots, they can link up, essentially acting like minifractures, increasing flow in the reservoir.

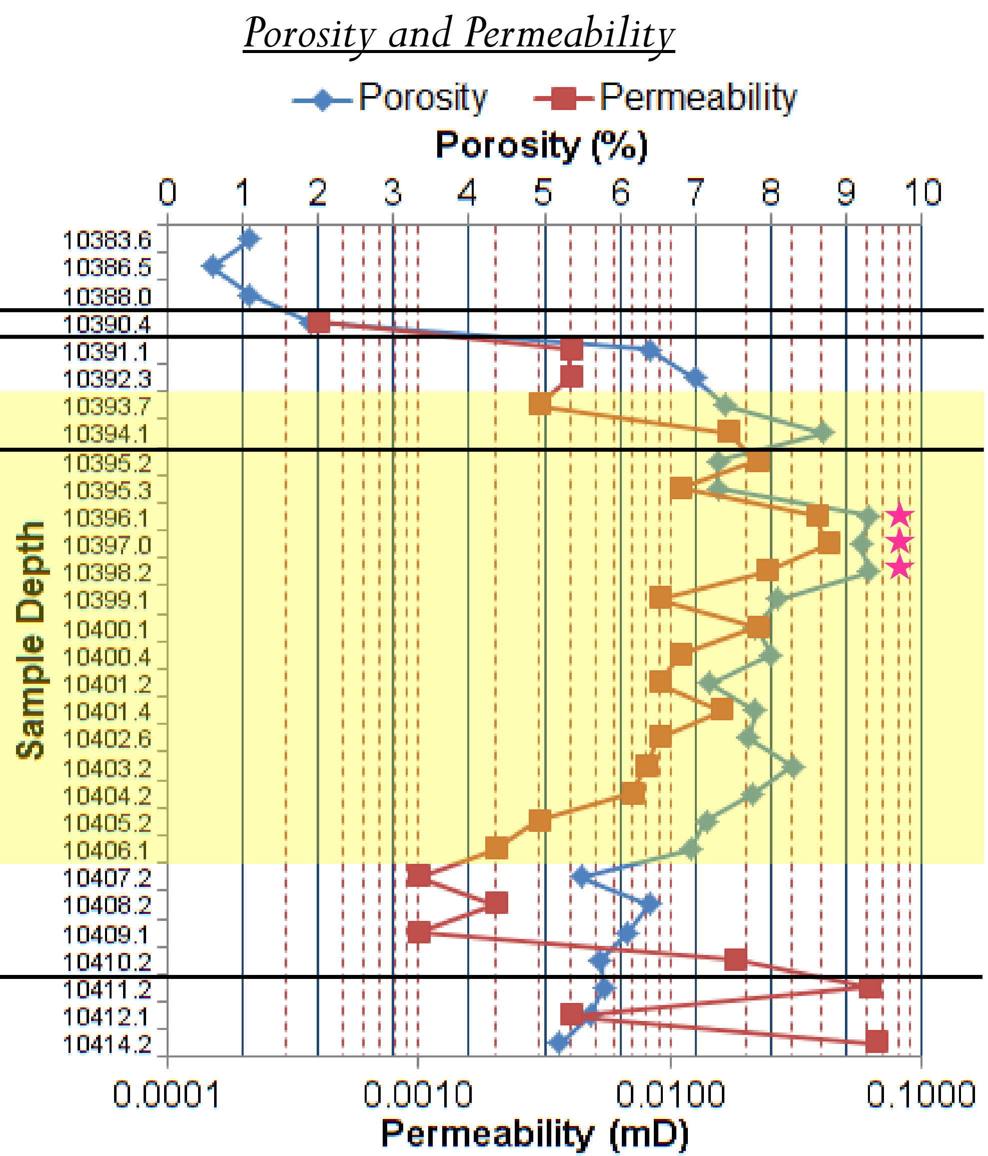
Conclusions

Diagenesis Created the Elm Coulee Field Bakken Reservoir



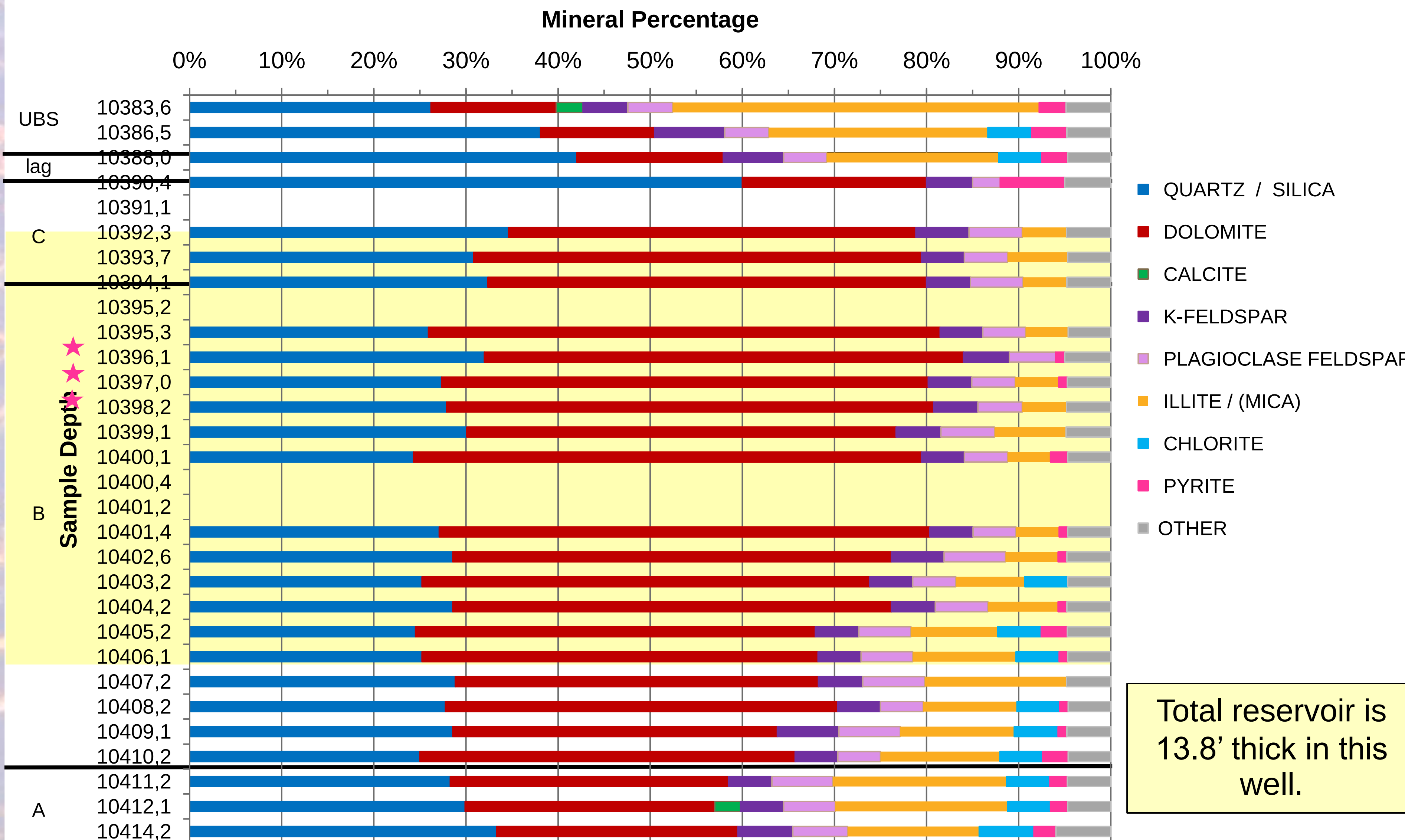
RR Lonetree-Edna





Total reservoir is 13.8’ thick in this well.

RR Lonetree-Edna



Total reservoir is 13.8' thick in this well.

Why is this study of diagenesis important?

- Other Bakken fields within the Williston Basin tend to produce from:
  - The laminated Facies C or E
  - The coarser grained, often oolitic Facies D
  - Reservoirs often rely on natural fractures

However…

- At Elm Coulee Field the best reservoir quality sections are found within:
  - The burrowed and bioturbated Facies B
  - ***The sections with the highest dolomite percentages***
  - ***And thus, the sections with the highest dolomite dissolution porosity***

Presenter's notes: We return to the fact of the importance of understanding the diagenetic stages the reservoir has undergone in order to more accurately determine where the best targets are within a particular field.

Presenter's notes: Special thanks to Steve Sonnenberg, Mike Hendricks, John Humphrey, Enerplus, and to all the Bakken Consortium Members for their support during my time working on this subject.