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ePS Stratigraphy, Diagenesis and Fracture Distribution of the Three Forks Formation, Williston Basin*

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Search and Discovery Article #50462 (2011)
Posted August 31, 2011

*Adapted from ePoster presentation at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 10-13, 2011

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Abstract

The Three Forks Formation could yield as much as 2 billion barrels of petroleum (NDGS, 2010). Previous outcrop studies date from the 1960s leave this formation almost uninvestigated in modern sedimentologic and stratigraphic terms.

The aim of the current work is to provide regional correlation of lithofacies and to document fracture distribution and trends in the formation based on nine outcrops in Wyoming, Montana and South Dakota, and cores from 21 wells in the Williston basin and a core from the Big Horn basin. The proposed stratigraphic correlation of the Three Forks Formation shows lateral and vertical facies changes based on both outcrops and cores.

Key stratigraphic surfaces recognized from the core data are traceable throughout the study area in well and outcrops. These major stratigraphic surfaces are a sequence boundary at the base of the Three Forks, a transgressive surface in the middle part of the Three Forks, and a sequence boundary at the top of the formation. Five interpreted facies associations are from the shallowest to the deepest:

(1) Upper supratidal sabkha;
(2) Llower supratidal sabkha
(3) Upper intertidal mud flat
(4) Lower intertidal mud flat
(5) Open marine.

Upper supratidal sabkha facies has shallowing upward stacking pattern. Mosaic, nodular and bedded anhydrite together with reddish and greenish silty claystone are dominant. Lower supratidal sabkha facies is greenish and reddish, silty, dolomitic claystones.
Upper intertidal mud-flat facies is composed of pinkish-grey siltsone with shrinkage cracks. Lower intertidal mud-flat to shallow subtidal facies is composed of gray, well cemented bioturbated sandy siltstone. Open marine facies consists of brown to gray, bioturbated, silty very fine-grained sandstone.

The lower and the middle parts of the Three Forks are dominated by supratidal sabkha deposits, whereas, the upper part is dominated by the intertidal and occasional open marine deposits. Diagenetic features include dolomitization, anhydrite precipitation and cementation, compaction, clay cementation, dissolution and pyritization.

Fracture patterns were described and compared with fracture distribution in overlying Bakken Formation. In most of the outcrop locations there is a systematic fracture distribution associated with major faults. Fractures have predominant strikes of 50, 120, 250, and 320 degrees. General spacing between major fractures of similar direction is 1m and less. Laminated layers tend to show more fractures than more massive beds.

Selected References

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Stratigraphy, diagenesis and fracture characterization of the Three Forks Formation, MT, WY and SD

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Department of Geology and Geological Engineering

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Dr. J. Frederick (Rick) Sarg

April the 11th, 2011
AAPG 2011 Annual Convention & Exhibition

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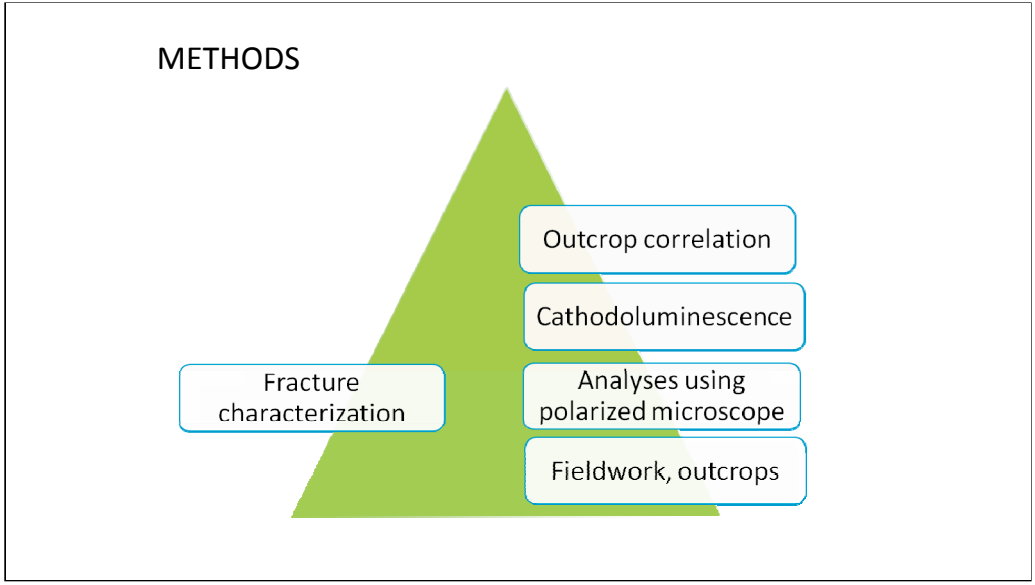

Presenter's Notes: The basis of this study is field work with outcrop description and fracture measurements. It was followed by laboratory analyses, such as thin-section description using polarized microscope, catholodoluminescence, and outcrop correlation incorporating all previous results.

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OBJECTIVES

- ✓ Construct outcrop correlation of the Three Forks Fm. in the sequence stratigraphic framework
- ✓ Interpret the environments of deposition
- ✓ Describe diagenetic changes within different facies.
- ✓ Propose fracture distribution model for the Three Forks Formation

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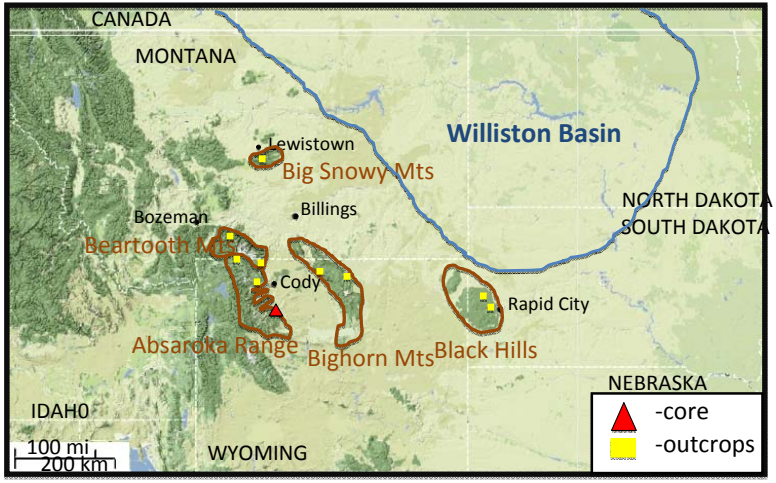
STUDY AREA, 9 OUTCROPS + 1 WELL



Presenter's Notes: Nine outcrops and a core from the Absaroka range were described: 2 outcrops are in SD, in the nothern and southern parts of the Black Hills uplift; 5 outcrops are in WY (2 in the Big Horn Mtns and 3 in the Absaroka Range); 2 outcrops are in MT(in the Beartooth and Big Snowy Mtns).

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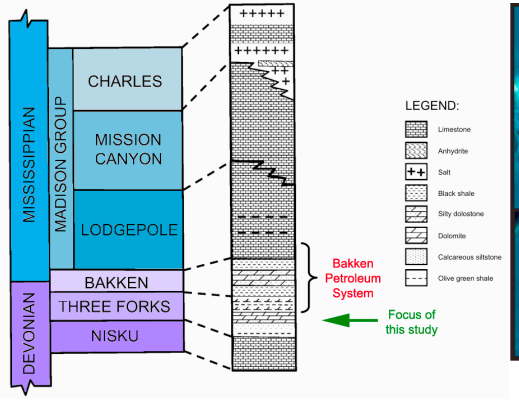
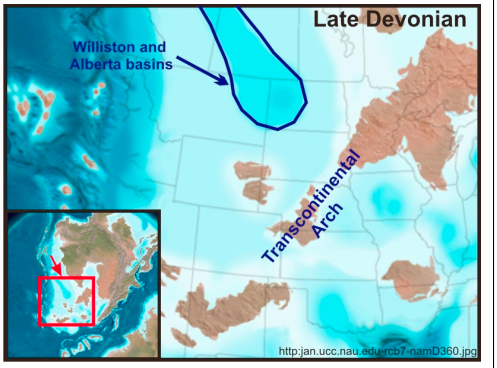
STRATIGRAPHY



after Sonnenfeld, 1996

PALEOGEOGRAPHY OF THE LATE DEVONIAN



Presenter's Notes: The Three Forks Fm is of Late Devonian age with the Bakken formation above and Birdbear or Nisku below. It is mostly dolomitic mudstones and siltstones. During Late Devonian time in MT, WY and SD the Three Forks Fm was deposited in the shallow, tidal-influenced epeiric sea. In ND, in the Williston and Alberta basin areas; in the central Mt trough and in western MT thicker sedimentary packages were deposited due to deeper water depth. From the east the Transcontinental Arch was rising providing sedimentary source for the area.

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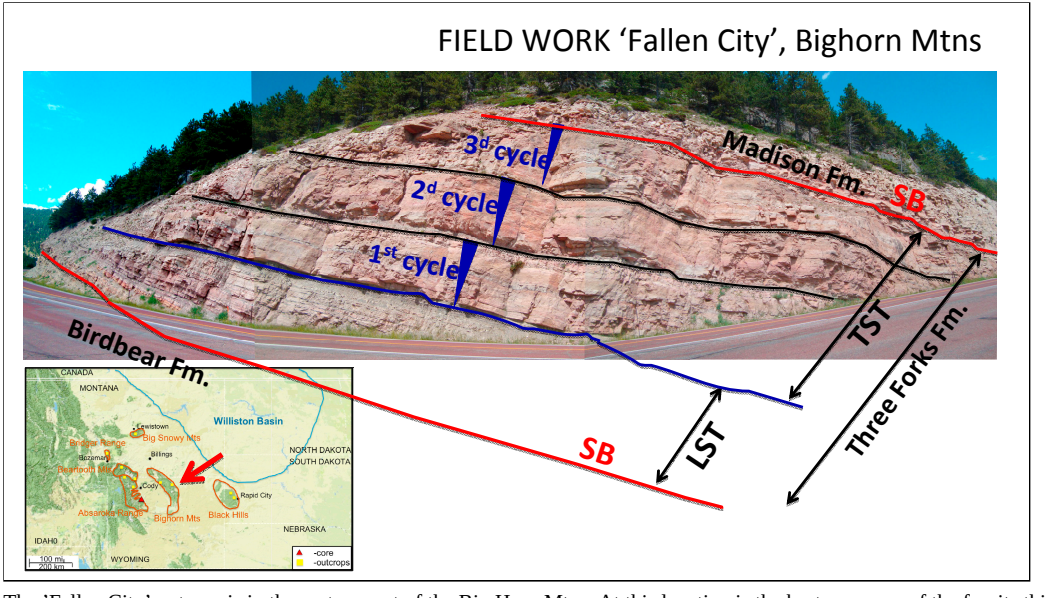

Presenter's Notes: The 'Fallen City' outcrop is in the eastern part of the Big Horn Mtns. At this location is the best exposure of the fm; its thickness is 20 m. The formation is bounded by SB at the top and bottom. These are conformable lower contact with the Birdbear Fm and low-angle upper unconformity with the Madison Fm. Two systems tracts were observed: LST and TST, with a very sharp regionally transgressive boundary between them. Within the TST three thickening upward cycles were identified.

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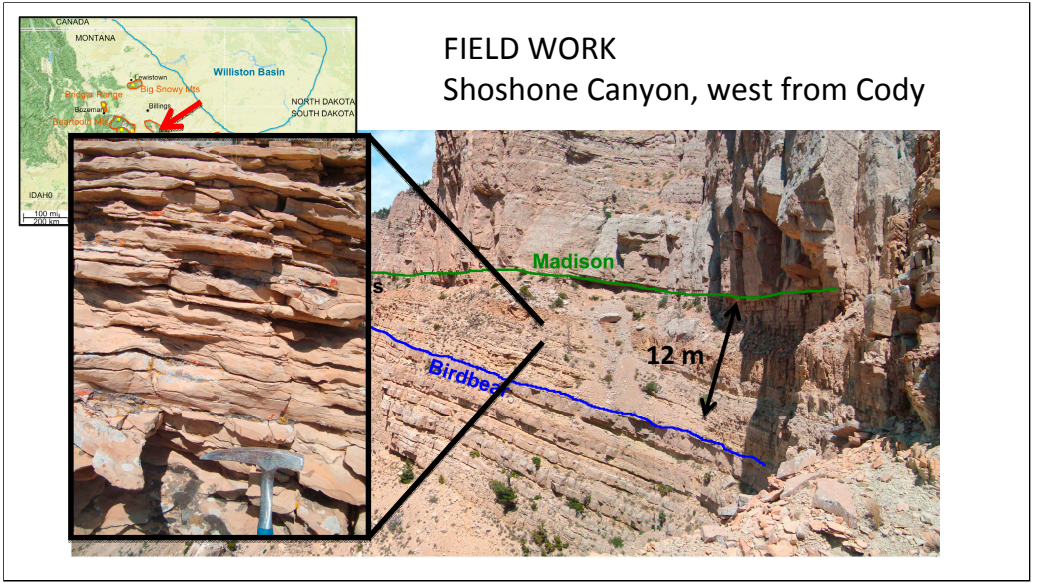

Presenter's Notes: The Shoshone Canyon outcrop is located in the western part of the Big Horn Mtns. There we can see how laterally continuous the formation is. Its thickness is 12 m. It is composed of bedded dolomitic siltstones.

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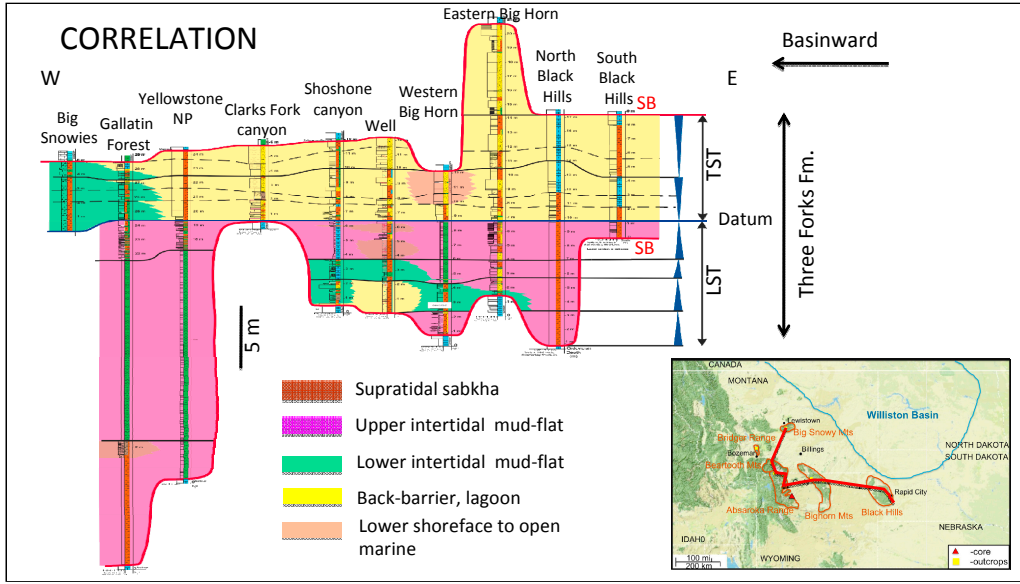

Presenter's Notes: This correlation of the Three Forks Fm incorporates nine outcrops from west to east and a core. Transgressive surface is a datum and is the best datum available with this dataset. Base of the Three forks Fm is irregular due to paleo-uplifts in the Black Hills and Big Horn areas. In the Absaroka Range no paleostructures were described in the literature, but because of a very thin section, we suspect a paleo-uplift there. The upper boundary of the formation is erosional, with approximately 15 m of absent strata.

The formation is bounded by SB above and below, with LST and TST with transgressive surface in between.The formation was deposited on the very shallow epeiric platform; that explains flat parasequence boundaries (in black); 5 facies are recognized. They are from shallowest to deepest: suptatidal sabkha, upper and lower intertidal mudflats, back-barrier/lagoon and open marine facies. The lower and middle parts are dominated by the upper intertidal facies, whereas the upper part by lagoon units.

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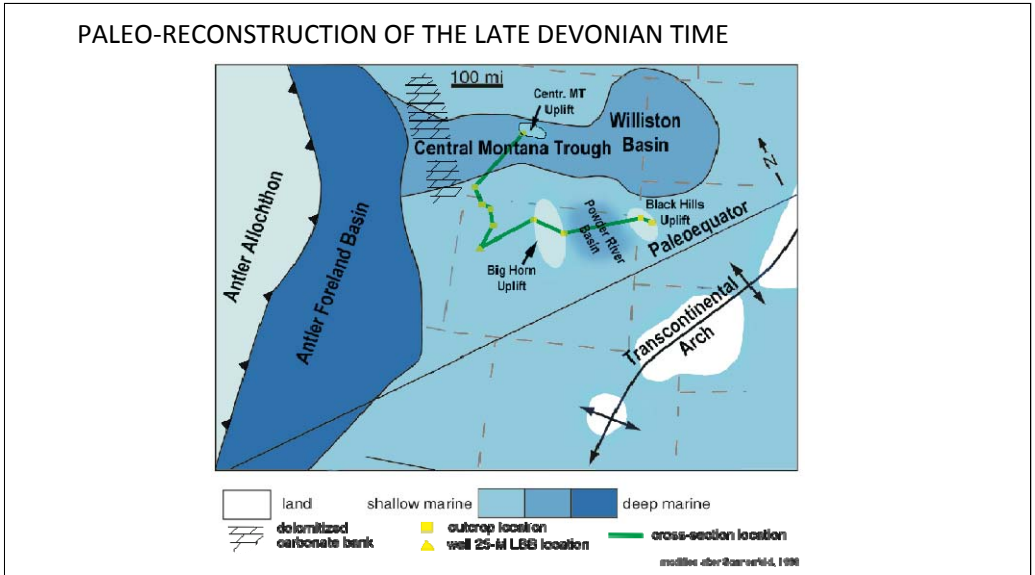

Presenter's Notes: During Late Devonian, Antler orogeny took place, resulting in easyward thrusting of the Antler Allochton, formation of the Antlerforeland basin, shallow bulg,e and back-bulge basins. MT, WY and SD were covered with shallow epeiric sea; the Williston basin, Central Montana Trough and Antler foreland basin had significantly deeper water depths. Big Horn and Black Hills areas were uplifted. In the western part of MT, in front of the Antler Foreland basin there was a bulge with carbonate bank growing on it. Our cross-section is in areas with varying relief and water depth, resulting in different stratal thicknesses.

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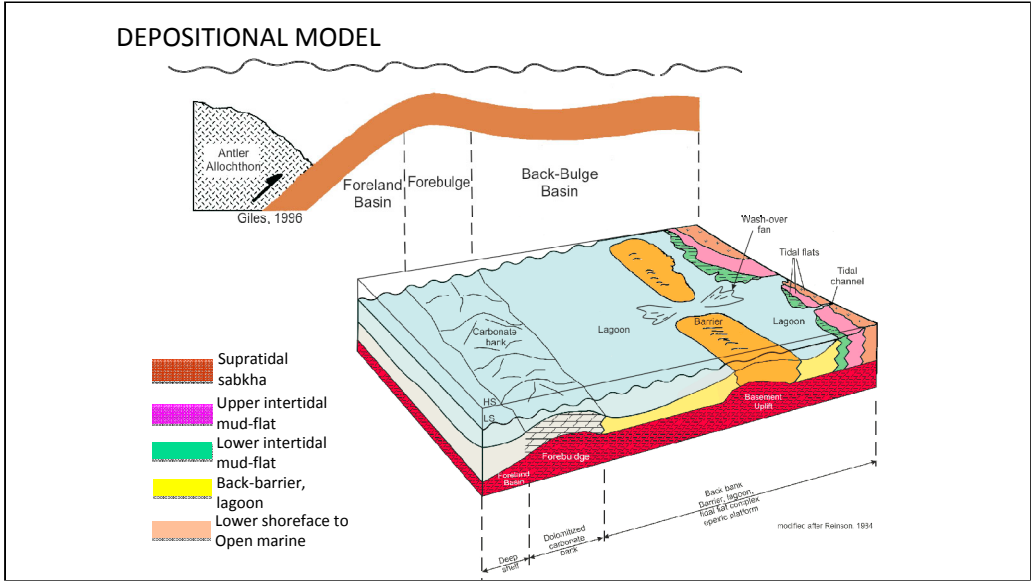

Presenter's Notes: In the Late Devonian during the lowstand, the area was a restricted tidal flat with sabkha and rare lagoons. During the highstand, lagoons were separated by uplifts, and sedimentary barriers were widespread. These barriers are interpreted as Sanish facies. Also carbonate bank growing on the bulge in the western part of present-day MT created additional restriction.

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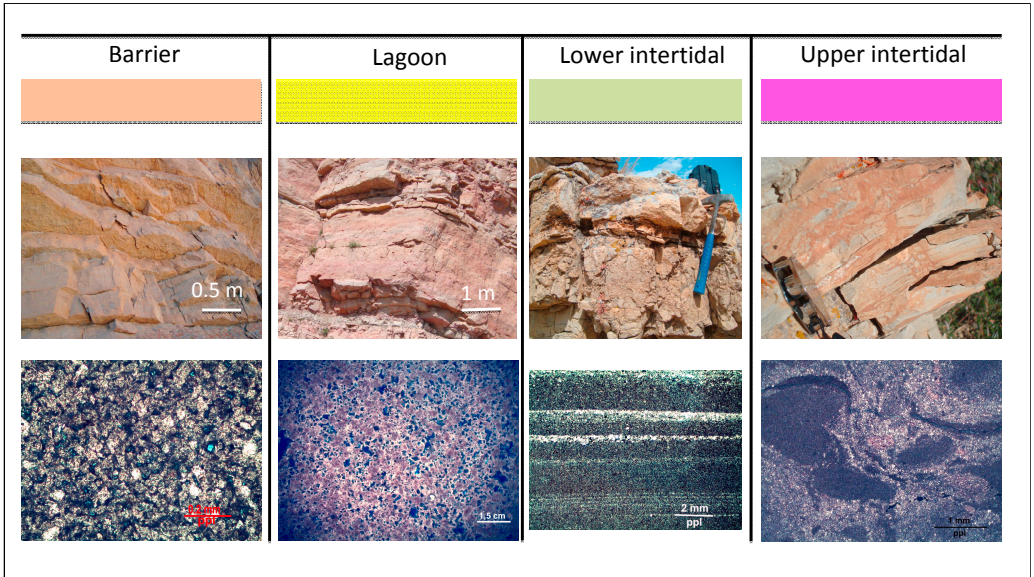

Presenter's Notes: Four of five facies are shown; supratidal sabkha is not shown on the slide. Barrier deposits or a Sanish member is a burrowed deeper water siliceous dolomite. Lagoon facies are massive mudstones with secondary calcite nodules after anhydrite. Lower intertidal facies are represented with yellow, rippled dolomitic siltstone. The Upper Intertidal facies are dolomitic mudstones with mudcracks, rip-up clasts and loading structures. The supratidal sabkha is characterized by scattered anhydrite nodules in dolomitic claystone, with rip-up clasts and loading structures.

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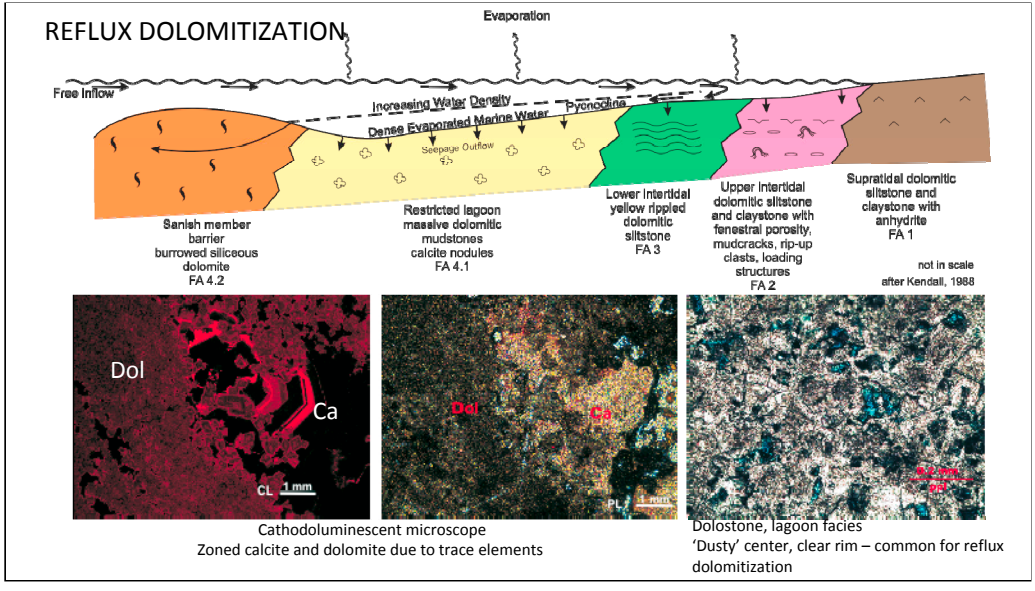

Cathodoluminescent microscope
Zoned calcite and dolomite due to trace elements

Dolostone, lagoon facies
'Dusty' center, clear rim – common for reflux dolomitization

Presenter's Notes: Dolomitization of the Three Forks Fm resulted from reflux processes. There was free inflow of marine waters to the back-barrier area. Less saline waters remained on the top of the water column while dense brines settled to create a pycnocline and dolomitize sediments below.
Dolomite rhombs have 'dusty' centers and clear rims, very typical of reflux dolomites. Under the cathodoluminescent microscope, clear zonation of dolomite crystals are seen, due to fast change in trace-element concentration in sea water.

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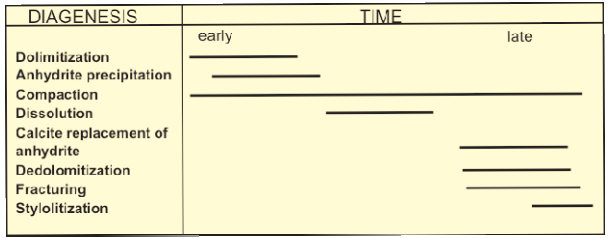
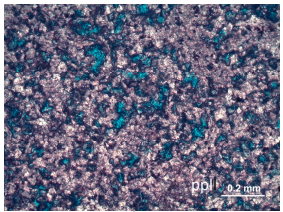
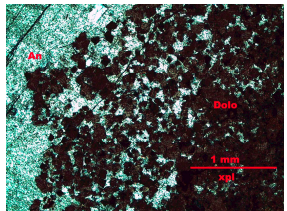
DIAGENESIS

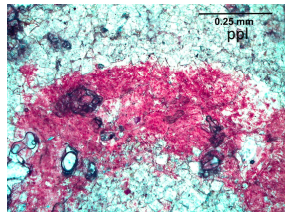




Dissolution



Anhydrite precipitation



Calcite replacement of anhydrite

Presenter's Notes: Diagenesis has a major control on rock properties of the Three Forks Fm. Among the main processes are dolomitization, anhydrite precipitation, compaction, dissolution, calcite replacement of anhydrite, dedolomitization.

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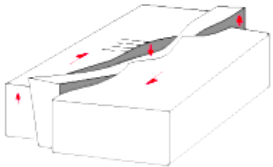
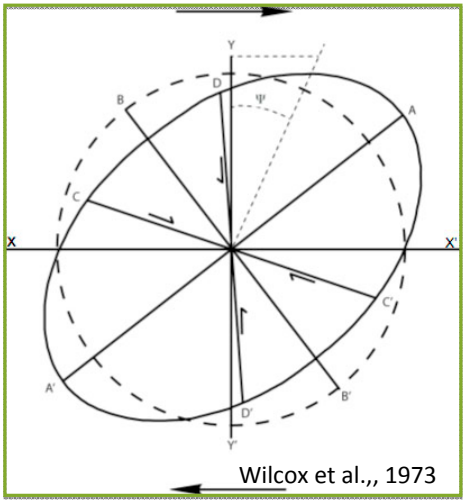
TECTONIC SETTINGS: WRENCH FAULTING



STRIKE	DESRIPTION
XX’	strike of primary wrench fault
CC’	low angle conjugate set
DD’	high angle conjugate set
BB’	bisecting conjugate set
AA’	long ellipse axis



Presenter’s Notes: Wrench faulting is a regional tectonic settings in MT, WY, SD and ND. Wilcox (1972) described fracture orientation for this setting, using strain ellipse. He predicted orientation of 3 fracture sets; low-, high-angle and bisecting conjugate sets depending on strike of primary wrench fault.

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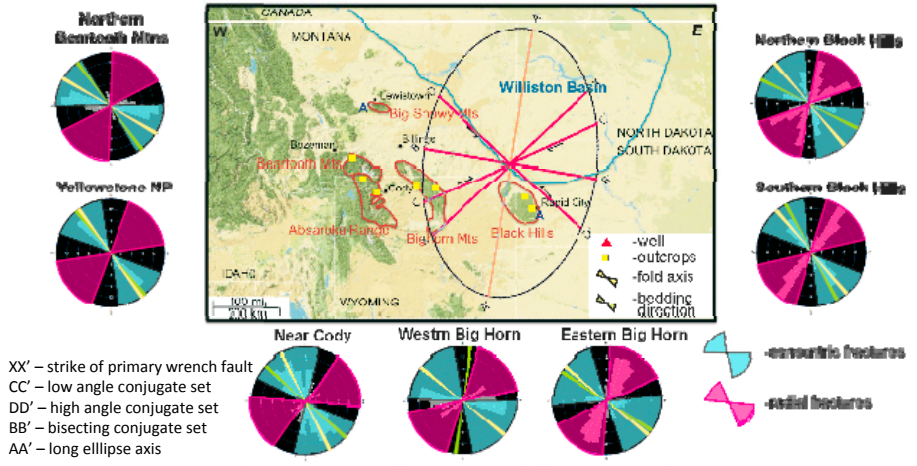
FRACTURES



XX' – strike of primary wrench fault
CC' – low angle conjugate set
DD' – high angle conjugate set
BB' – bisecting conjugate set
AA' – long elllipse axis

Presenter's Notes: Fracture trends in the Three Forks outcrops are similar to the Bakken fracture trends in the Williston basin. In the Three Forks Fm there are also conjugate sets due to tension stresses that are absent in the Williston basin. Back-barrier facies (laminated siltstones and massive mudstones) are fractured the most. There are many unconfined fractures extending into the Madison Fm because of similar mechanical rock properties .

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CONCLUSIONS

- ✓ The Three Forks Fm. has a sequence boundary at the bottom, the LST and TST with regionally mappable transgressive surface, erosional sequence boundary on the top with truncation below and downlap above it.

- ✓ In the lower and middle parts of the formation there are mostly upper intertidal facies; in the upper part - back-barrier, lagoon deposits.

- ✓ Diagenetic changes include dolomitization, anhydrite precipitation, compaction, dissolution, calcite replacement of anhydrite, dedolomitization, stylolitization.

- ✓ Lagoon facies showed the best continuity and reservoir quality due to dolomitization, dissolution and fracturing.

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CONCLUSIONS

- ✓ Fracture trends in the Three Forks Fm. are similar to the Bakken Fm. in the Williston basin. In the Three Forks Fm. there are also bisection conjugate sets due to tension stresses.

- ✓ Back-barrier facies (laminated siltstone and massive mudstone) are fractured the most. There are many unconfined fractures extending into the Madison Fm. because of the similar mechanical rock properties .

- ✓ The Three Forks Fm. is thickening to the west as we go seaward.

- ✓ The Three Forks play could be extended into MT and WY.

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ACKNOWLEDGMENTS

- ✓ **Dr. J Frederick (Rick) Sarg - advisor**
- ✓ **Dr. Stephen Sonnenberg**
- ✓ **Dr. John D. Humphrey**
- ✓ **Field assistants: Alain Gantyno, Jade Everett and Steve Angster**
- ✓ **Bakken consortium fellows**

Field assistants