Sequence Stratigraphy of Lower Madison Strata in the Greater Williston Basin Area*

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Search and Discovery Article #51626 (2019)**
Posted December 11, 2019

*Adapted from oral presentation given at 2019 AAPG Rocky Mountain Section Meeting, Cheyenne, Wyoming, September 15-18, 2019
 DOI:10.1306/51626Petty2019

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Abstract

The Madison 2nd-order sequence is a late Devonian to early Carboniferous sequence that was originally defined in Wyoming outcrops, where it is bounded by major, regional, subaerial unconformities. The basal unconformity beveled the Williston basin area during Famennian exposure forming a low-relief surface. Following unconformity development, a slow transgression occurred, and this led to shallow-water deposition of Bakken and Bakken-equivalent sediments in partially connected basins. In the greater Williston basin area, a 2nd-order maximum flooding surface separates underlying Bakken and equivalent stratal units (Englewood, Cottonwood Canyon) that were deposited in separate basins, from overlying Lodgepole stratal units that represent sediments deposited after maximum flooding. The 2nd-order transgression corresponded with a rapid, 100-meter relative sea-level rise that inundated western North America with open-marine Lodgepole deposition.

Regionally, the maximum flooding surface may overlie: 1) a stylolitic contact, 2) a transgressive lag deposit, or 3) a heterogeneous, glauconitic, skeletal-intraclastic grainstone, packstone and wackestone unit. In western basin-flank outcrops (Little Rocky Mountains, Big Snowy Mountains, and Little Belt Mountains), the maximum flooding surface is overlain by dark, thinly bedded, argillaceous, deep-water mudstone and skeletal mudstone. Deep-water carbonate bioherms grew locally in the sediments overlying the maximum flooding surface. The dark mudstone transitions upward and landward (Bighorn Mountains, Black Hills) into skeletal wackestone. These deposits are overlain by five cycles that are defined in landward areas by vertical transitions from a skeletal-oolitic grainstone to a peloidal mudstone. The cycles parallel biozones, marker beds and sequence boundaries. Cycles are progradational into the Williston Basin and aggradational in central Montana. In the Williston Basin, the basal skeletal-oolitic unit (Scallion) transitions seaward to a crinoid-dominated packstone and wackestone facies that transitions further seaward to a clinoform-toe skeletal wackestone and mudstone-dominated facies that downlaps on the maximum flooding surface.

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By
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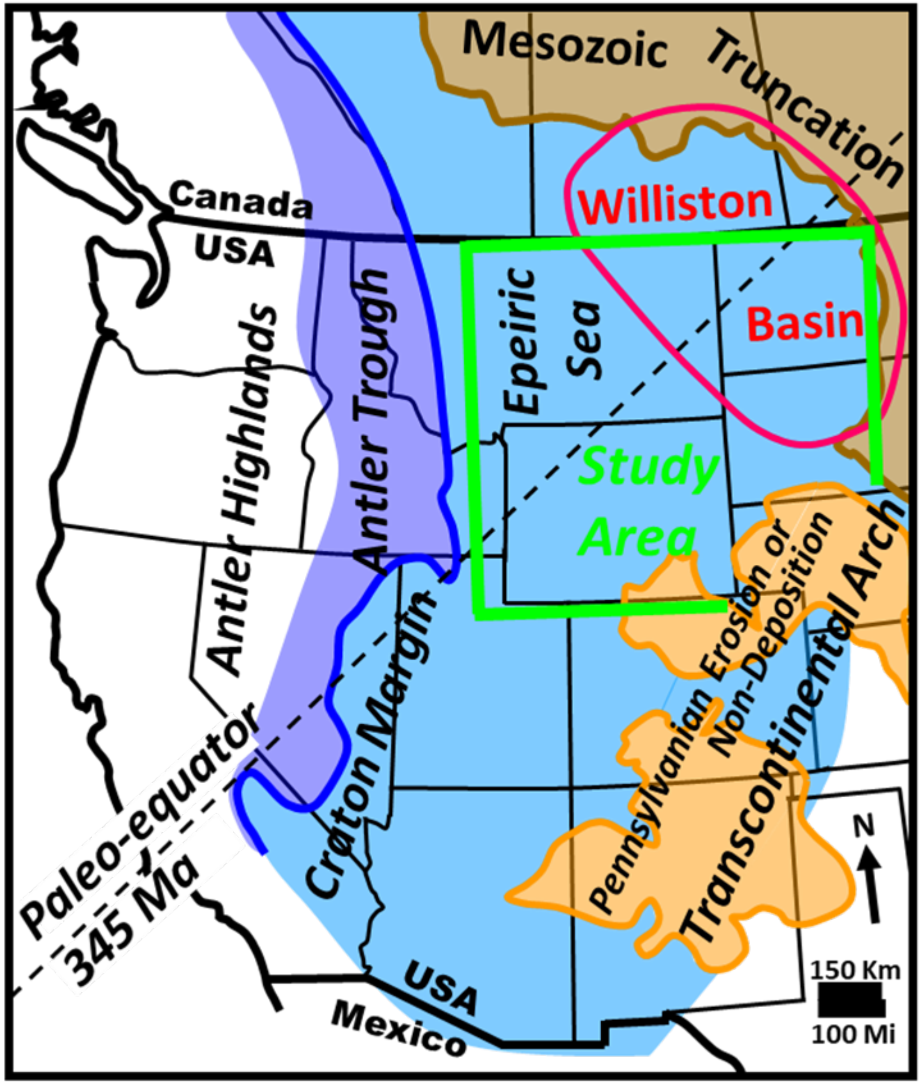
Rocky Mountain Section of AAPG Meeting
September, 2019

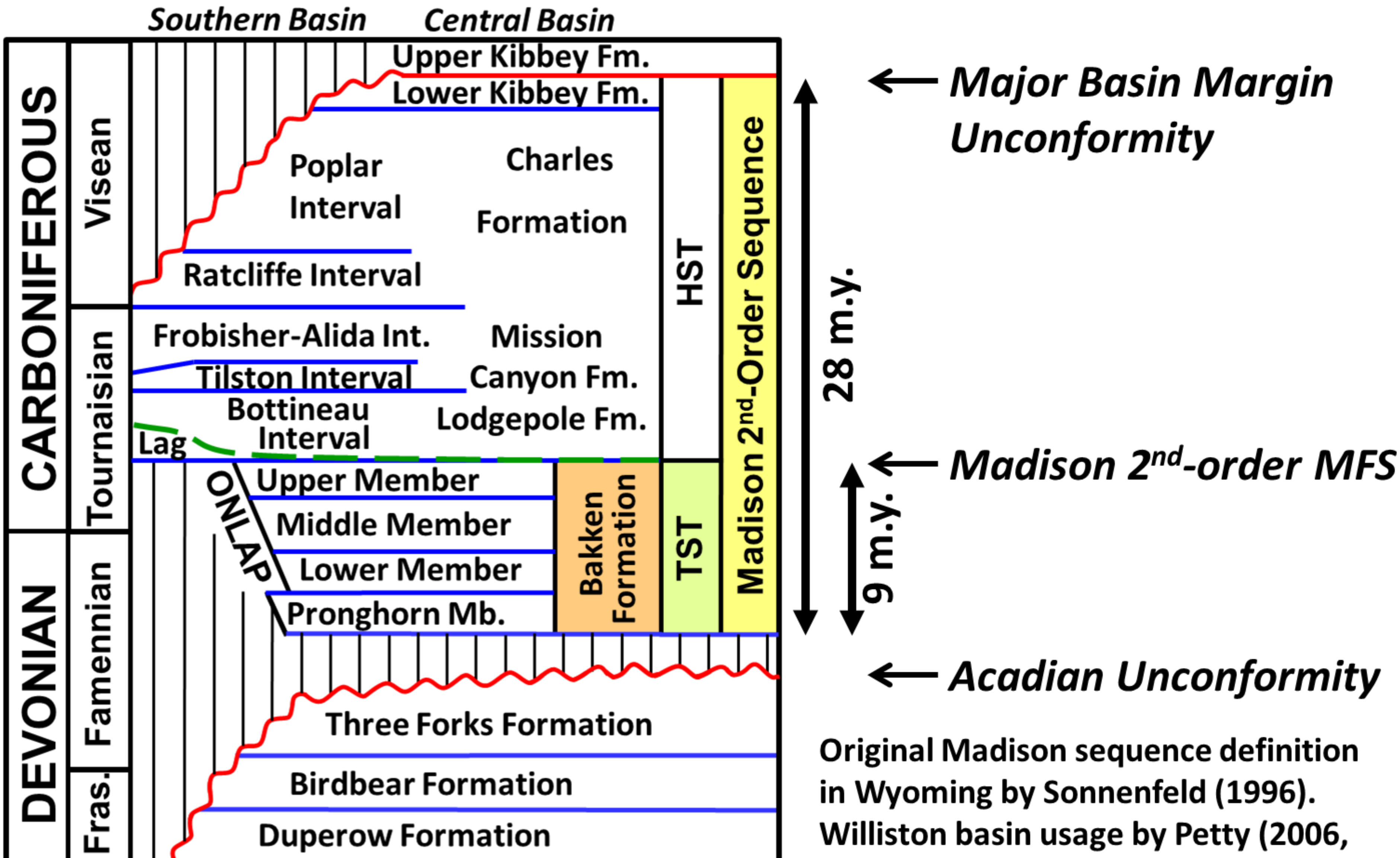


EARLY MISSISSIPPIAN PALEOGEOGRAPHY Lower Lodgepole Deposition

Constructed using maps in Procter and Macauley (1968), De Voto (1980), Gutschick and Sandberg (1983), Armstrong and Mamet (1988), Poole and Sandberg (1991), and Richards et al. (1993). Paleo-equator location from Blakey (2013).

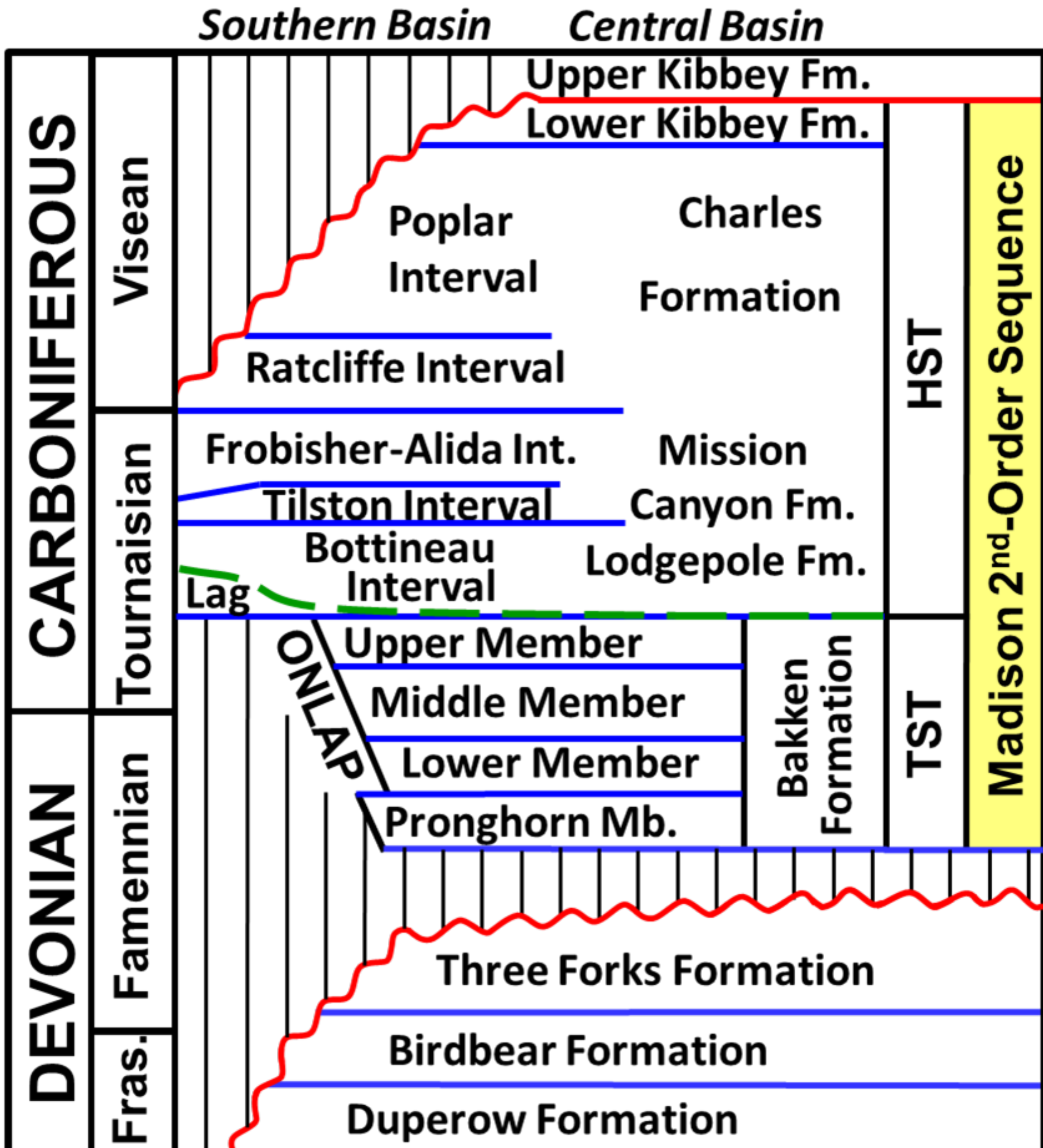
Note: 1) Study area location, 2) Epeiric sea (light blue), and 3) paleo-equator

Williston Basin Stratigraphic Column



Original Madison sequence definition in Wyoming by Sonnenfeld (1996). Williston basin usage by Petty (2006, 2010, 2017, 2019)

Williston Basin Stratigraphic Column

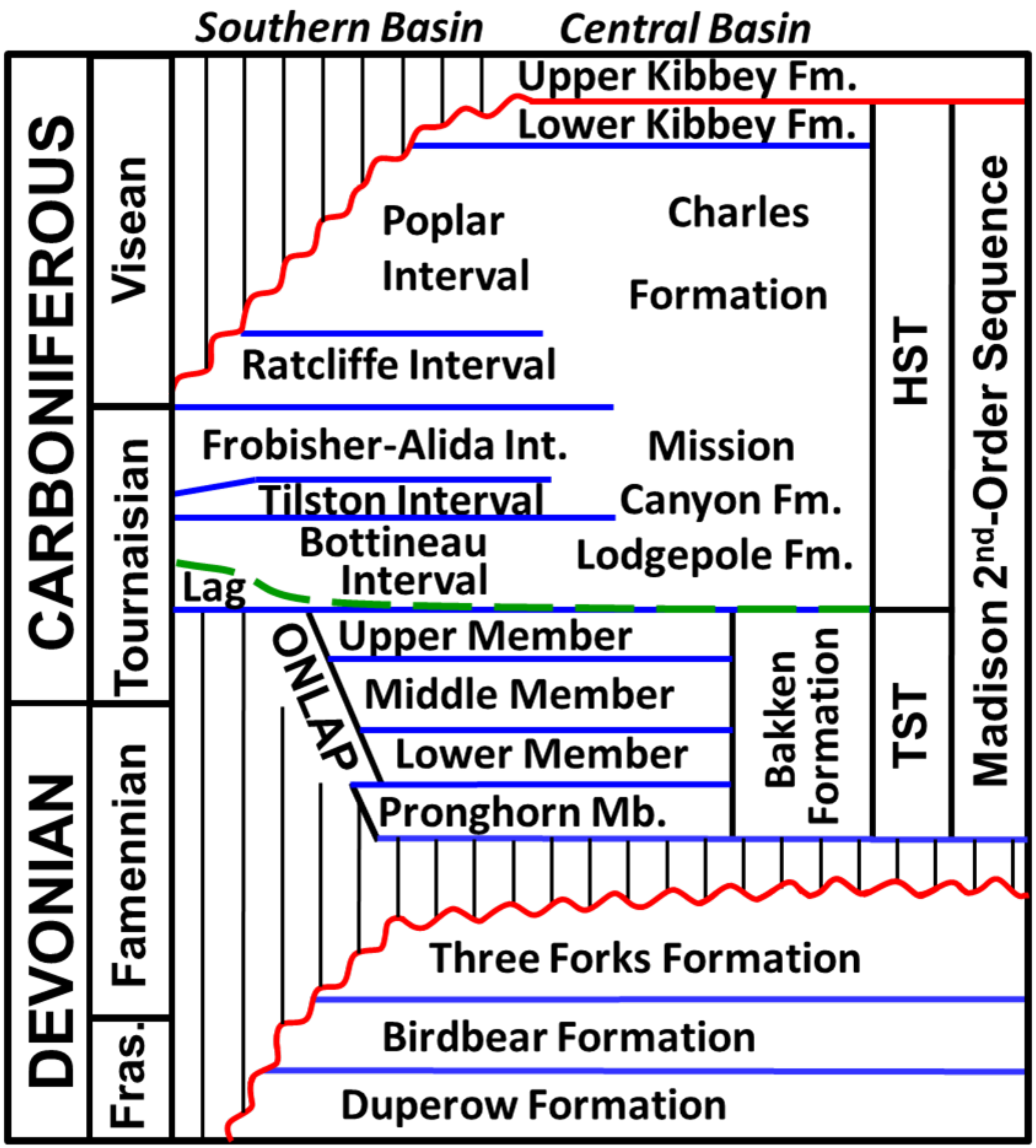


Subject of this presentation

Overview of Controversial Issues Related to Lower Madison Sequence Stratigraphy

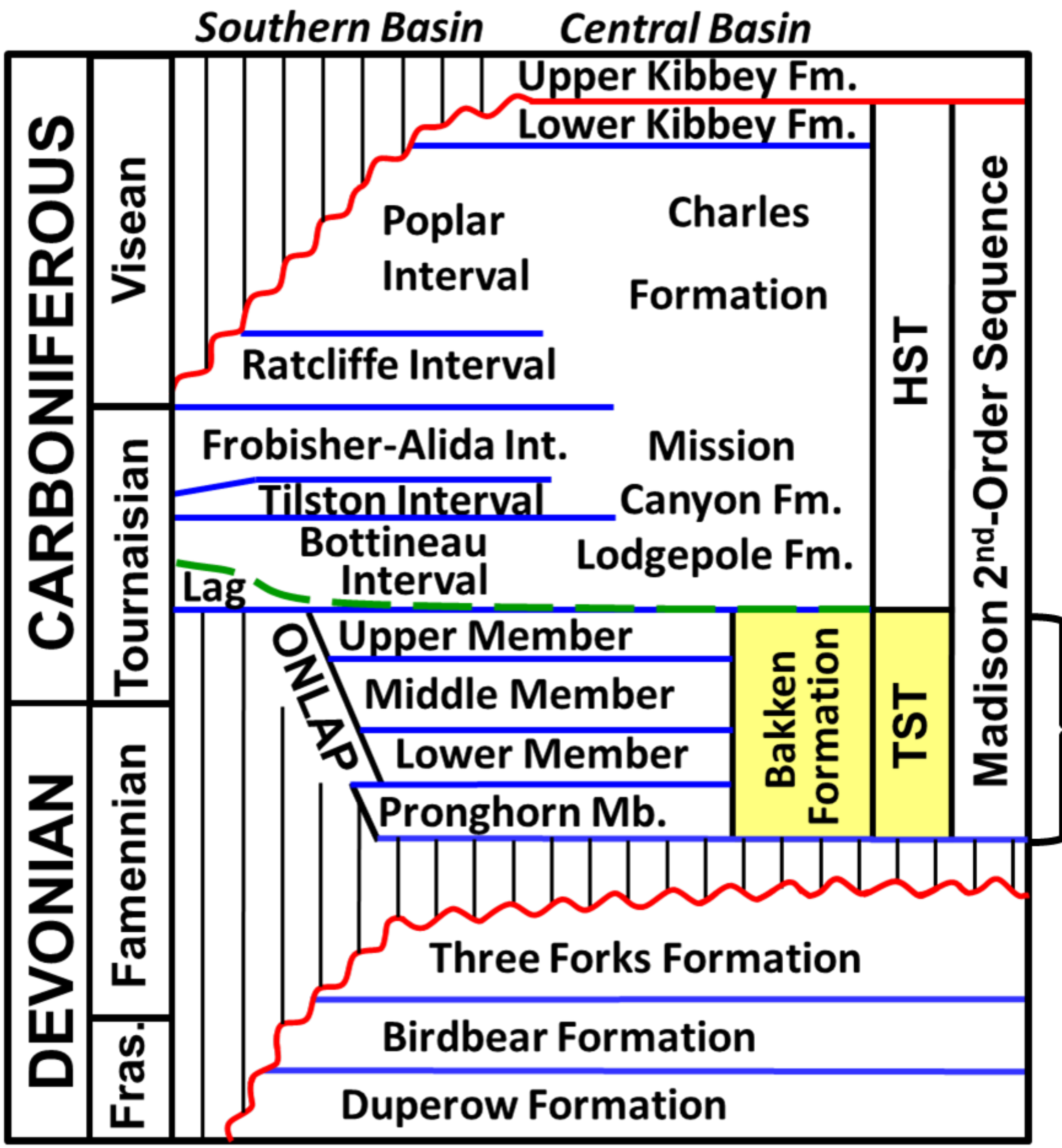
- Bakken sequence stratigraphy is controversial
- Origin of Bakken shale controversial
  - Deep-water vs. shallow-water origin
  - Depositional environment interpretation
- Bakken to Lodgepole transitional nature controversial
- Placement of Madison MFS debated
- Origin of Lodgepole cycles has been debated
- Exact number of Lodgepole cycles has been argued
- Chronostratigraphy of Lodgepole facies controversial

Williston Basin Stratigraphic Column



Basal Unconformity for Madison Sequence = Acadian Unconformity (Wheeler, 1963; Schleh, 1966; Boyd, 1997; Petty, 2017) = Peneplainal erosion (Clement, 1987)

Williston Basin Stratigraphic Column



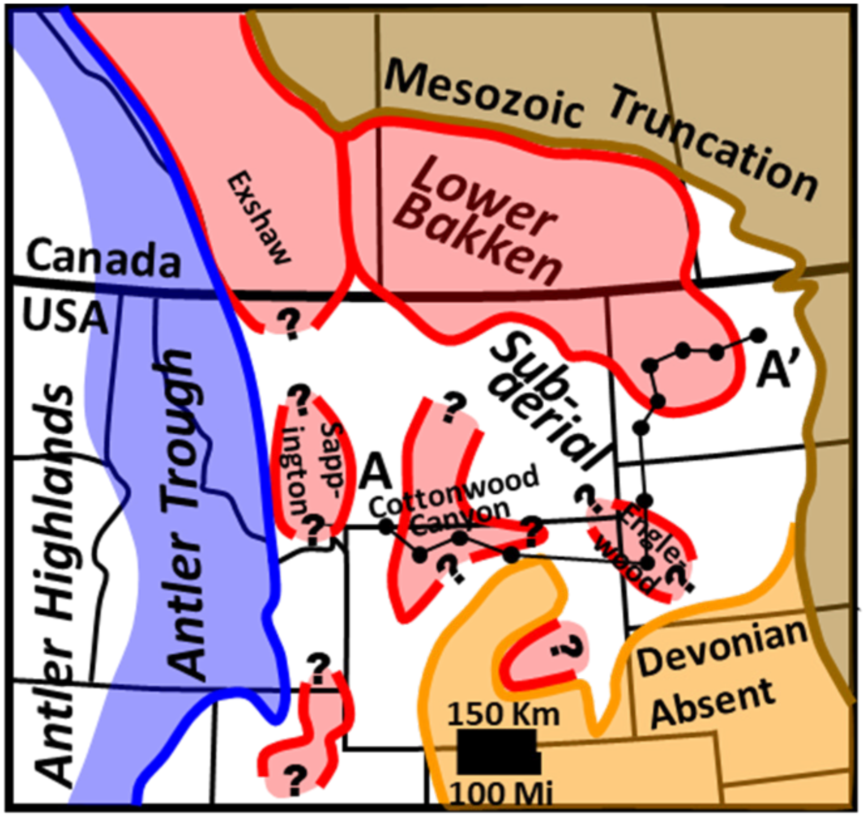
<u>TST</u> (Petty, 2006, 2010, 2019)

<u>LST/TST</u> = (Skinner et al., 2010, 2015)

- Pronghorn = LST
- Bakken Mbs. = TST

PALEOGEOGRAPHY

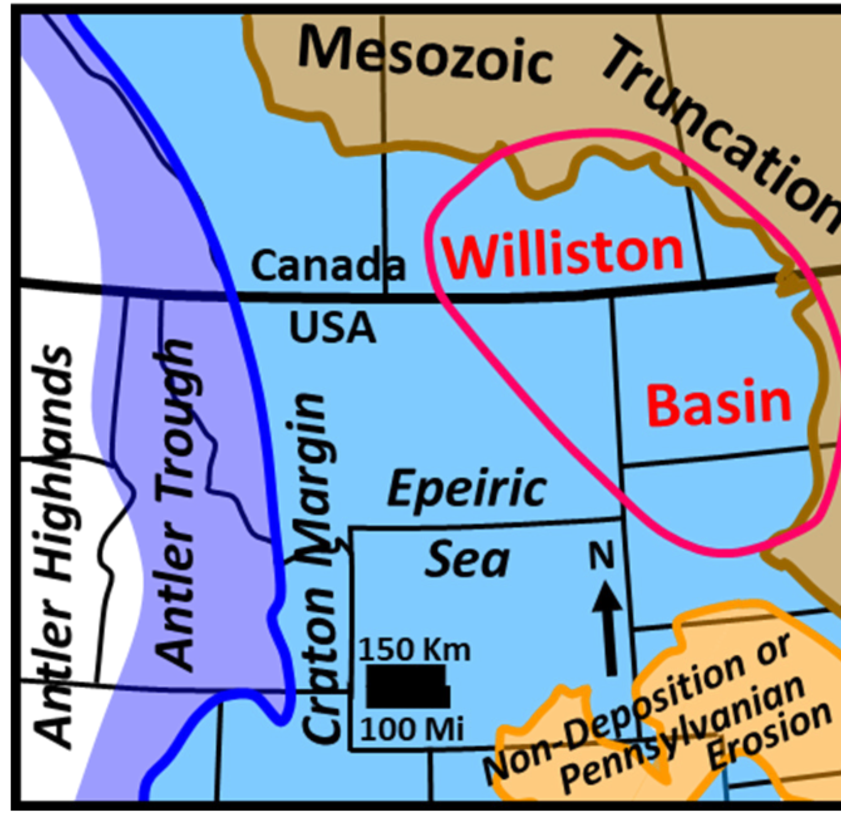
Lower Bakken and Equivalent



Constructed using maps in Sandberg and Klapper (1967), Baars (1972), Sandberg (1988), Richards et al. (1994), Smith and Bustin (2000), and Skinner et al. (2015)

Maximum Flooding Event

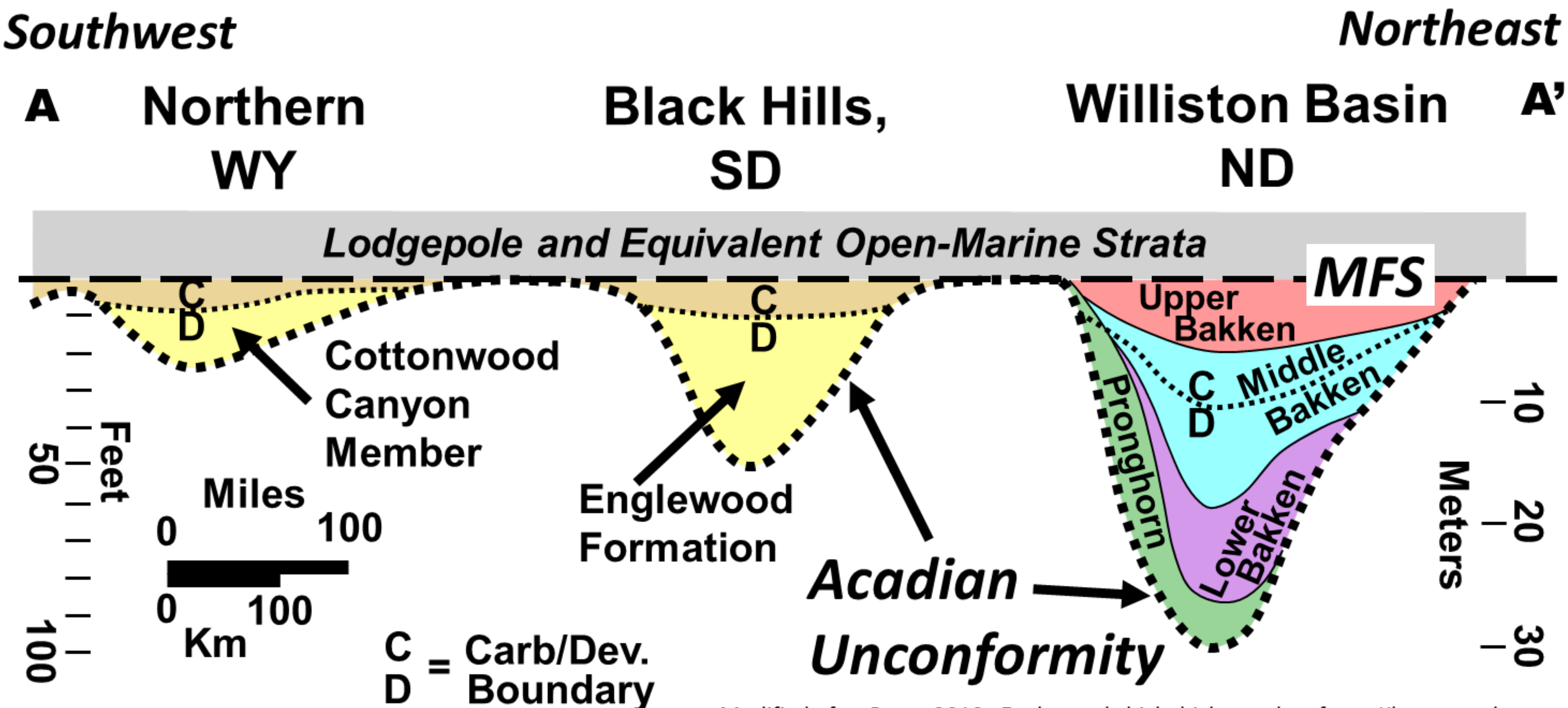
Lower Lodgepole



Constructed using maps in Procter and Macauley (1968), De Voto (1980), Gutschick and Sandberg (1983), Poole and Sandberg (1991), and Richards et al. (1993).

Lower Bakken deposition in low-accommodation, partially connected sub-basins

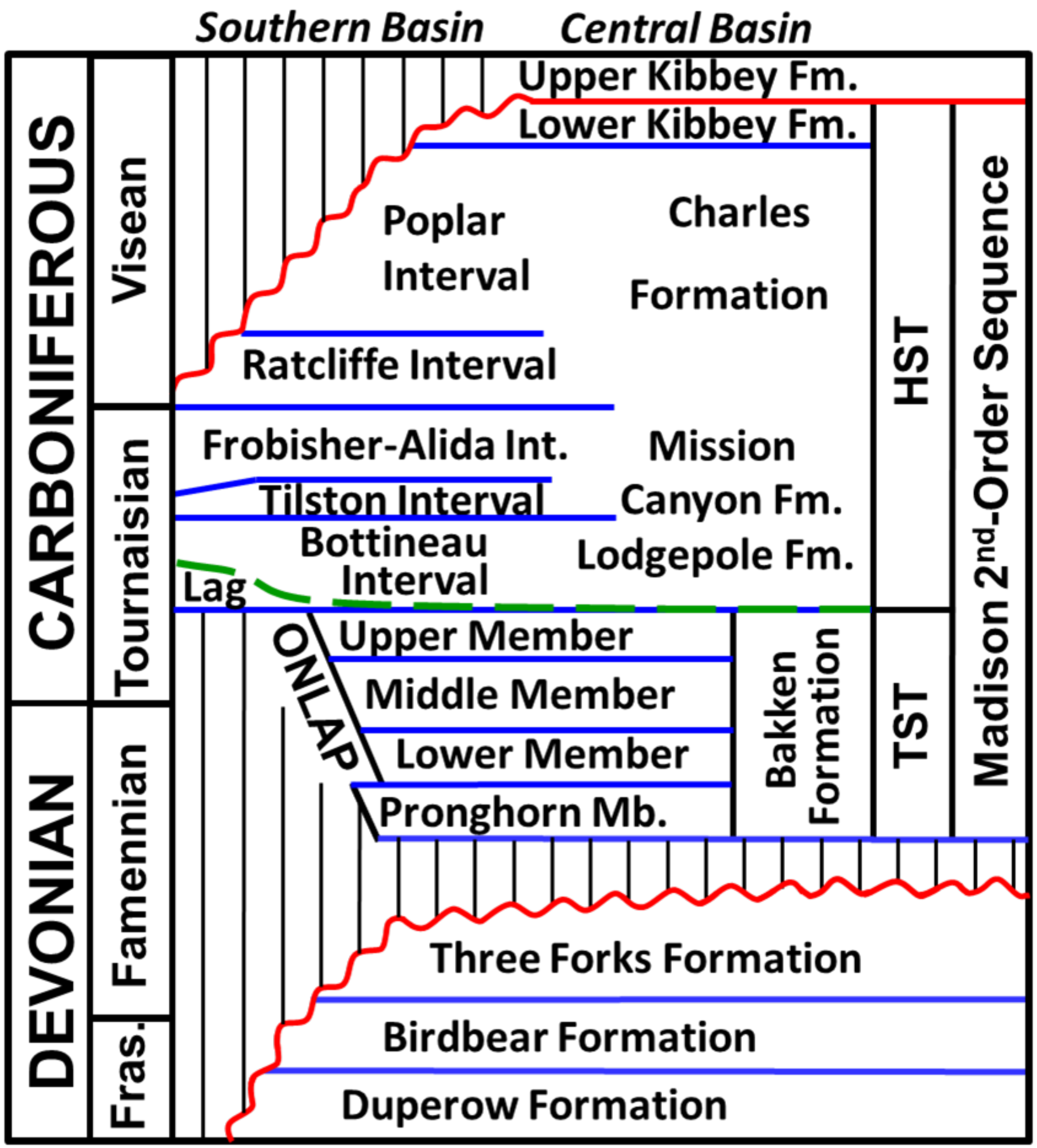
Basal Lodgepole deposition in an epeiric sea



Modified after Petty, 2019. Englewood thick thickness data from Klapper and Furnish, 1962. Cottonwood Canyon thickness data from Sandberg and Klapper, 1967.

- Stratigraphic characteristics indicate shallow-water deposition:
  - Bakken and equivalent units confined to basinal areas
  - No direct landward equivalent strata
  - Unequivocal shallow-water middle Bakken deposition
  - Shallow-water coastal onlap during Bakken deposition
- Interpretation: epeiric lagoonal environment with 0-30 m water depth

Williston Basin Stratigraphic Column



100 m sea-level rise
Smith (1977); Petty (2019)

2nd-Order Maximum Flooding Surface

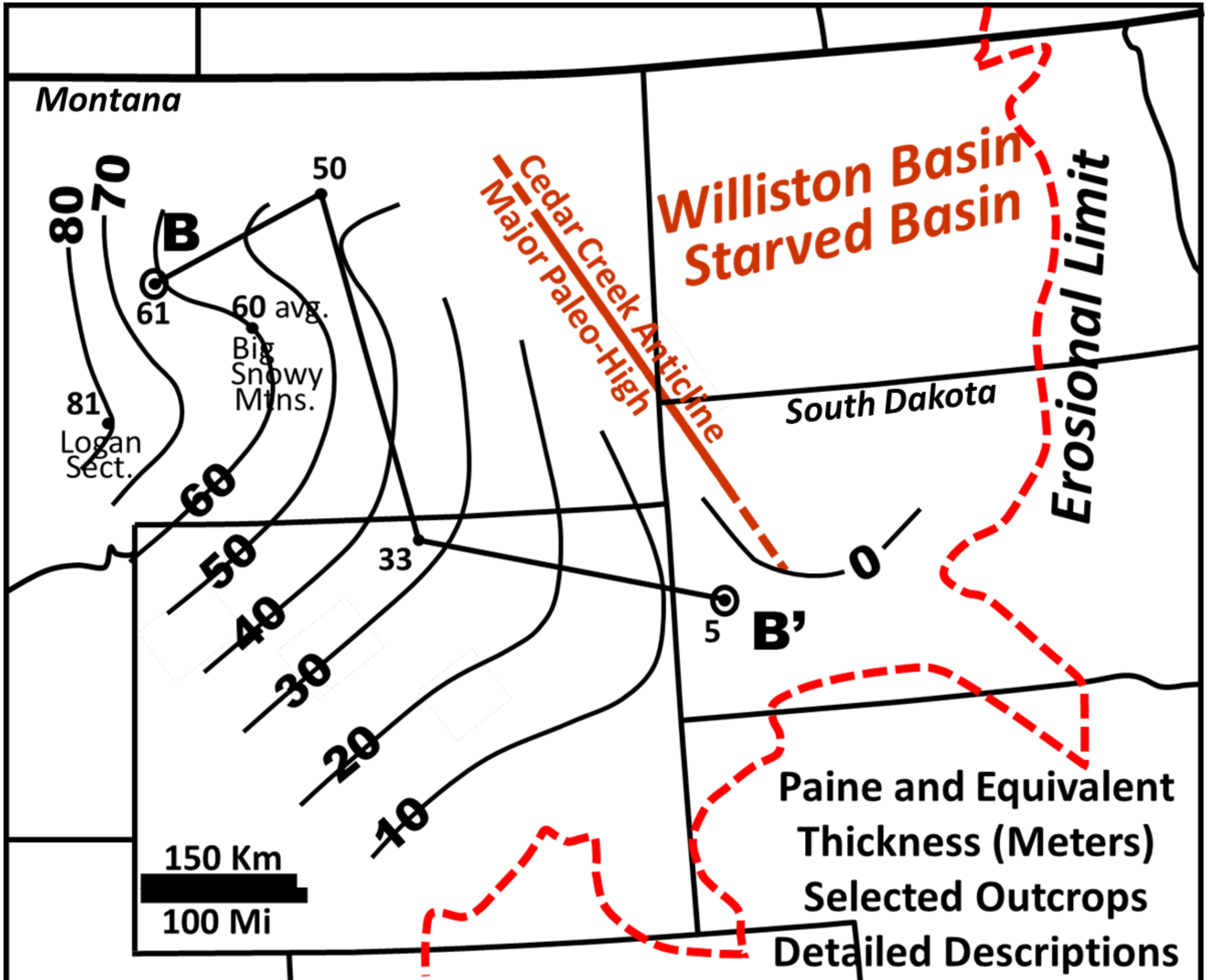
After Sonnenfeld (1996), Petty (2003, 2006, 2010) and Skinner et al. (2010)

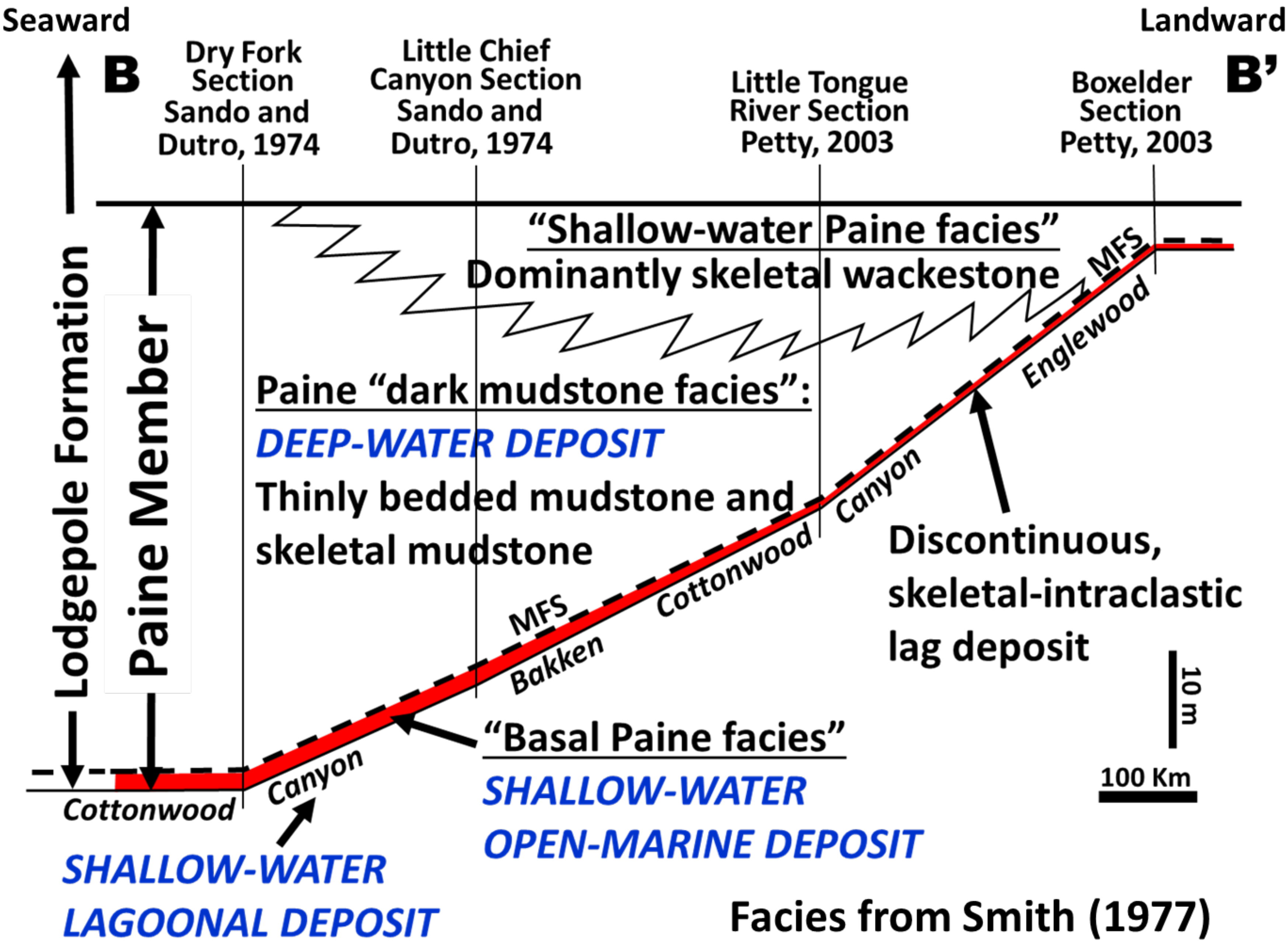
Note: Bakken shale deep-water advocates place a MFS within the Bakken shales

Maximum Flooding Surface

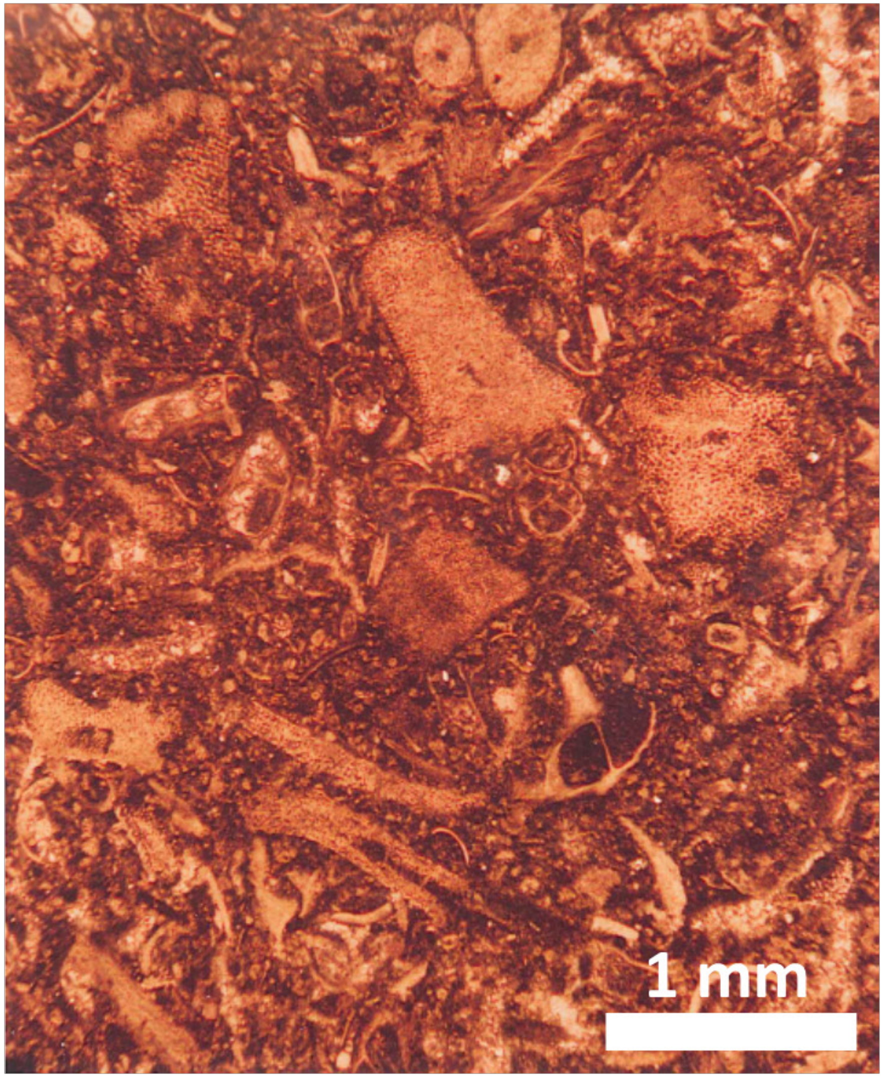
- To the extent that they define it, advocates for deep-water Bakken mud deposition commonly place a maximum flooding surface somewhere within the Bakken shales (e.g., Angulo and Buatois 2012; Egenhoff and Fishman 2013; Jin et al. 2015; Nandy et al. 2014, 2015; Borcovsky et al. 2017; Sonnenberg 2017), although it is usually not clear whether this refers to a 2^{nd}, 3^{rd} or 4^{th}-order flooding surface.
- Most Madison sequence stratigraphy researchers place the Madison 2^{nd}-order maximum flooding surface (or a major flooding event) above the Bakken, and at or near the base of the Lodgepole (e.g., Smith, 1977; Hendricks, 1995; Sonnenfeld, 1996; Petty, 2003, 2006, 2010, 2019; Skinner et al., 2010)

Paine Member of Lodgepole Formation





Facies from Smith (1977)



Unit 1c (6 ft thick) of Sando and Dutro (1974) in Dry Fork section, Little Belt Mountains, MT
Sample from trench 1.0 m above base of Paine

Basal Paine Facies

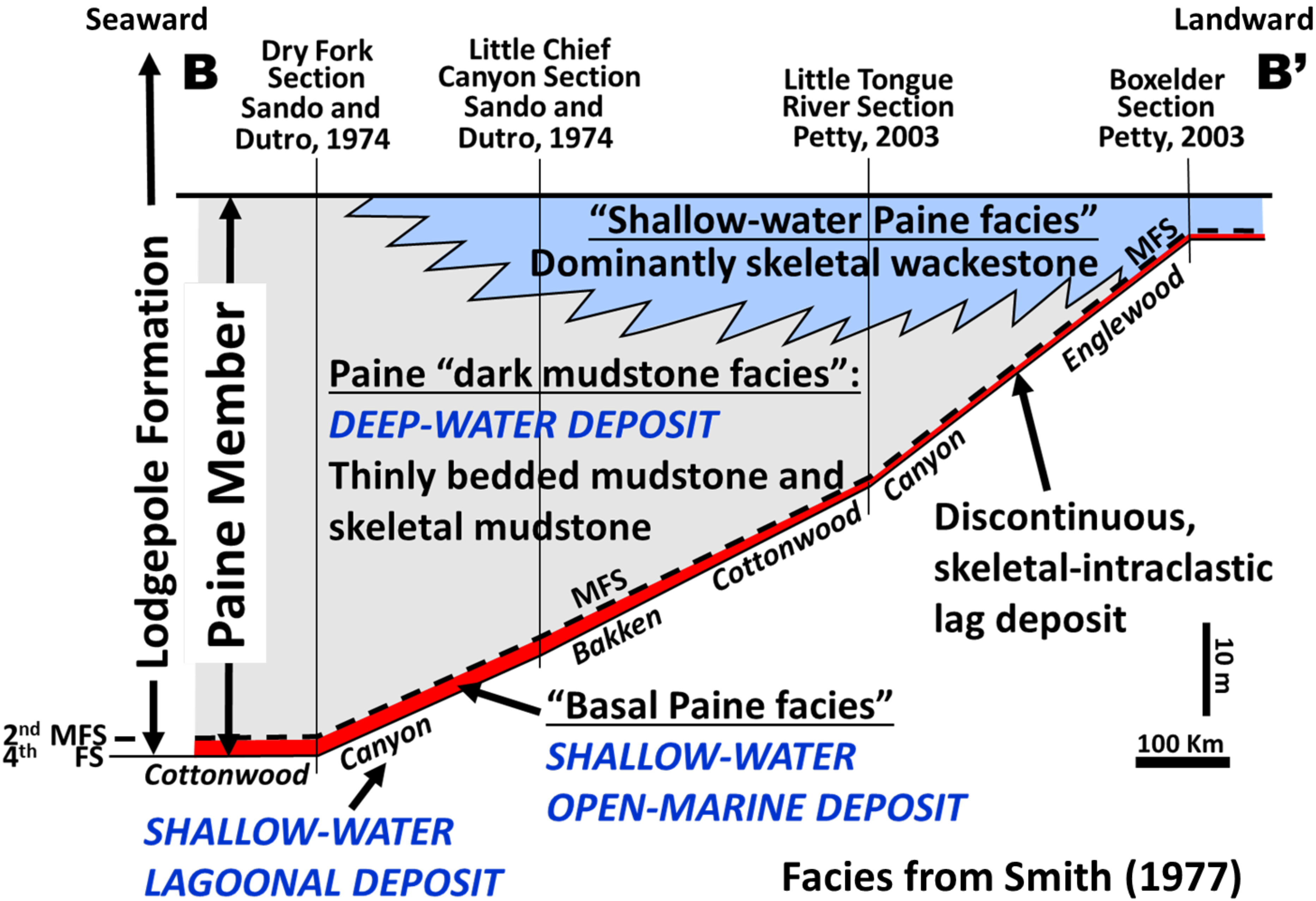
- Discontinuous, glauconitic, heterogeneous, skeletal wackestone and packstone, minor grainstone
- Smith (1977, p. 192) argued that the "basal Paine facies" represents a "relatively rapid transgression of the Madison sea."

Interpretation:

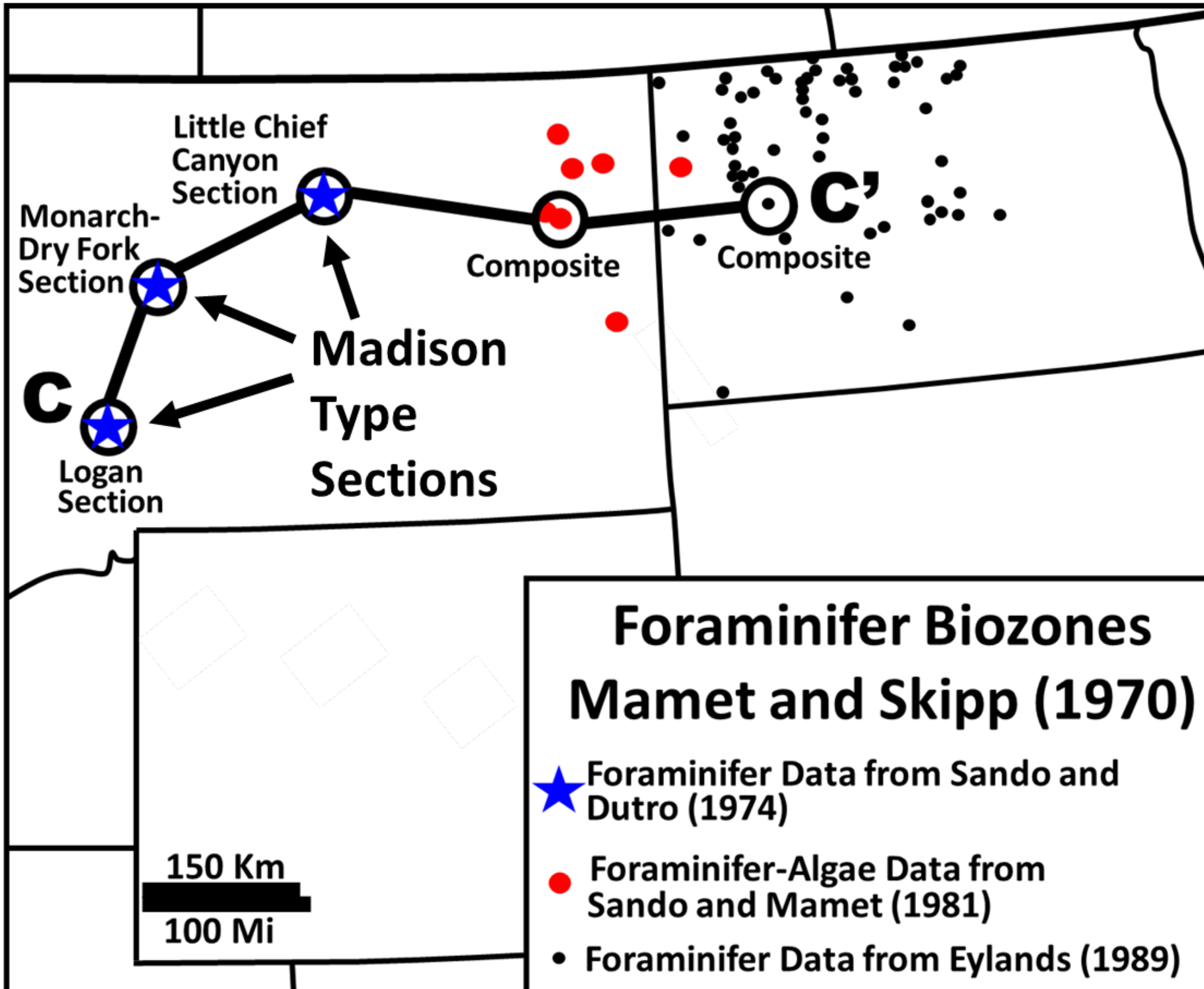
- *Transgressive deposit formed during maximum flooding*

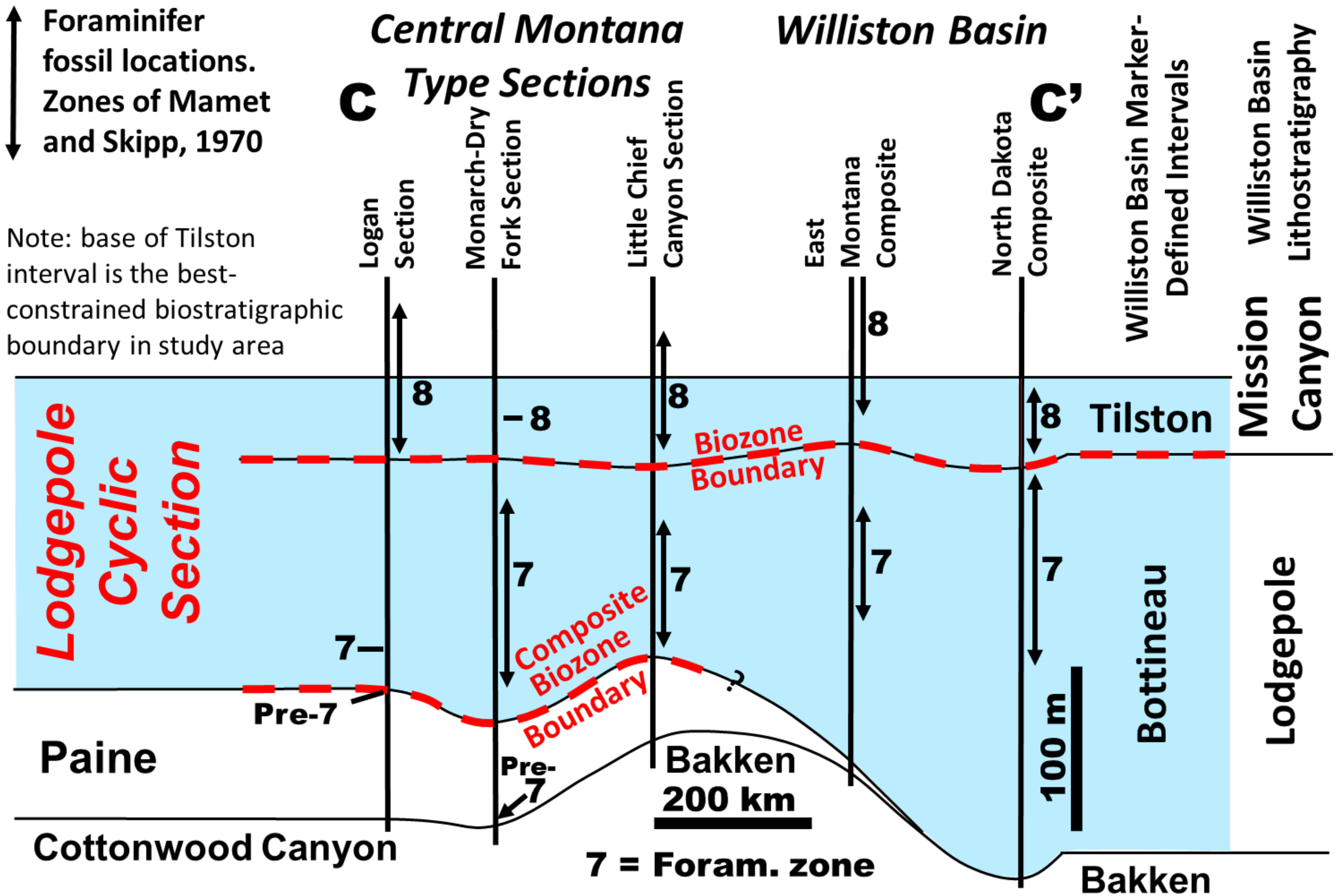
Note:

- *Not same unit as Scallion*


Seaward
Landward
B
B'
Dry Fork Section Sando and Dutro, 1974
Little Chief Canyon Section Sando and Dutro, 1974
Little Tongue River Section Petty, 2003
Boxelder Section Petty, 2003
"Shallow-water Paine facies"
Dominantly skeletal wackestone
MFS
Englewood
Lodgepole Formation
Paine Member
Paine "dark mudstone facies":
DEEP-WATER DEPOSIT
Thinly bedded mudstone and skeletal mudstone
Canyon
Cottonwood
Discontinuous, skeletal-intraclastic lag deposit
MFS
Bakken
10 m
"Basal Paine facies"
SHALLOW-WATER OPEN-MARINE DEPOSIT
2nd MFS
4th FS
Cottonwood
Canyon
100 Km
SHALLOW-WATER LAGOONAL DEPOSIT
Facies from Smith (1977)

Lower Madison
Foraminifer Sequence Biostratigraphy





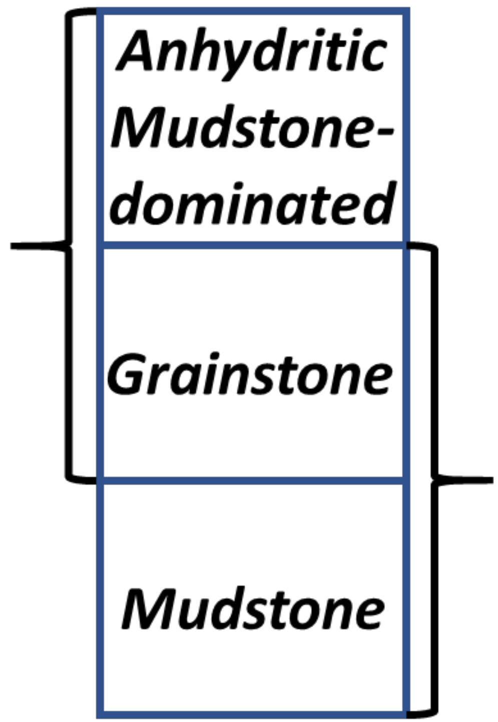
Correlations from Petty, 2005, Fig. 4. Foraminifera data from Sando and Dutro (1974), Sando and Mamet (1981), and Eylands (1989). Composite boundary includes data from Sando and Bamber (1984).

Lodgepole Cycles

- Exact number of cycles is controversial
- Five cycles widely recognized in Lodgepole and equivalent strata:
  - Smith (1972a, 1972b) in central Montana
  - Wilson (1975): "Oolite-grainstone cycles" of Smith (1972)
  - Haines (1999) in southern Alberta
  - Petty (2003) in northwest South Dakota
  - Petty (2005) in northern Wyoming
  - Petty (2019) in Williston basin
- Middle cycles are generally thinner, may be discontinuous and may not be recognized in some areas

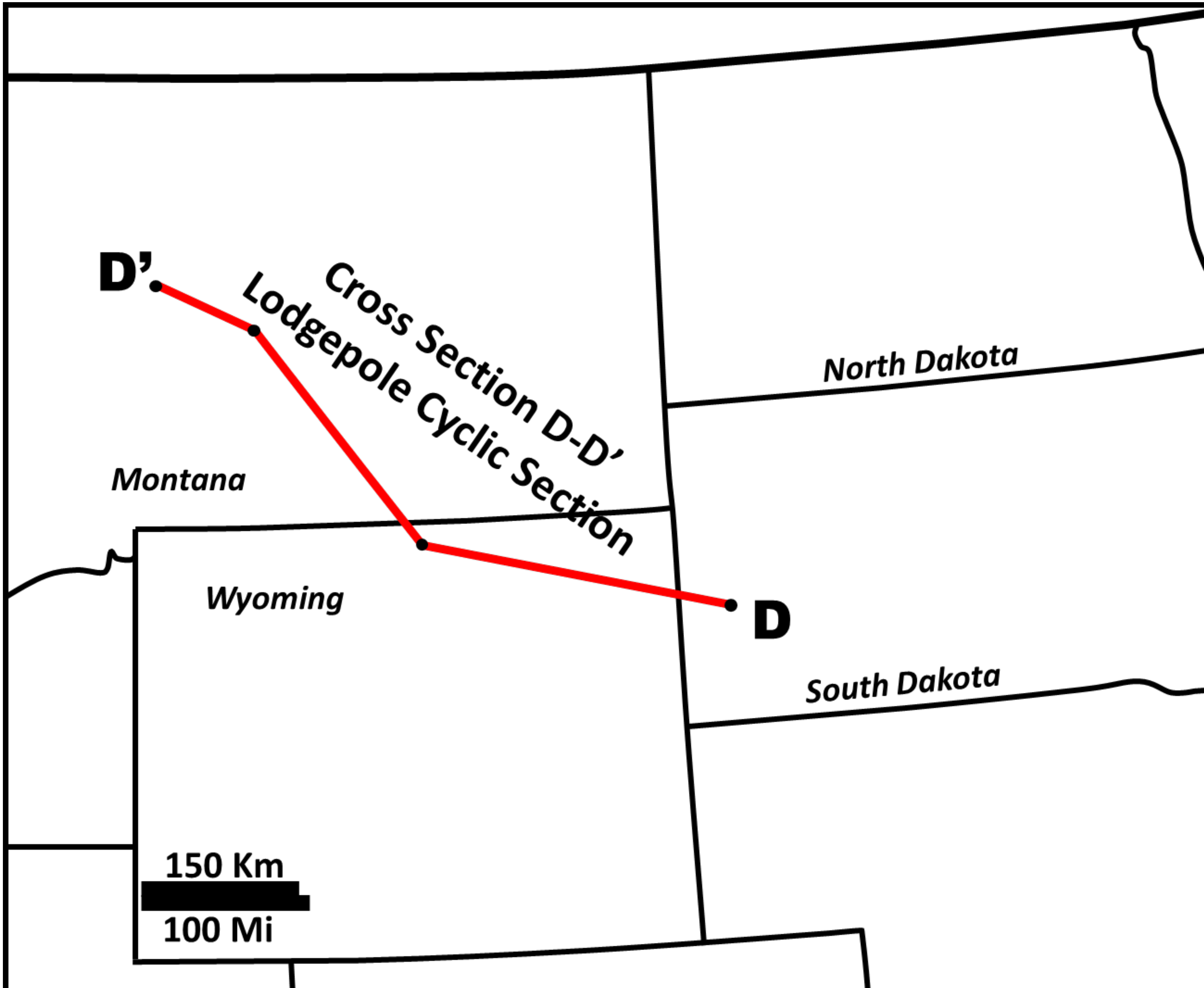
Cycle Definition Varies:

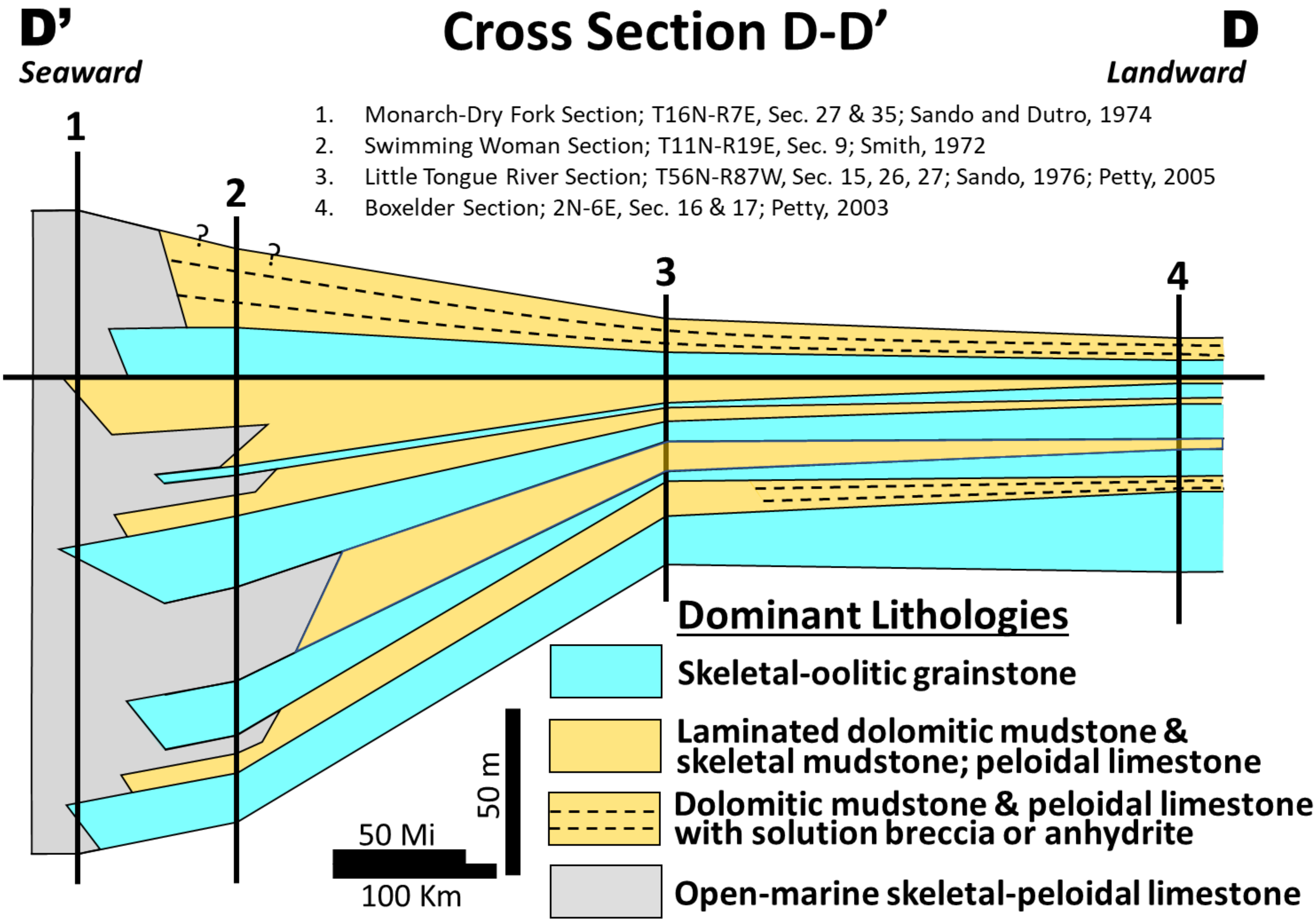
<u>Williston basin:</u>
Tilston interval
Petty, 2005



<u>Central Montana:</u>
Cycle 5 of Smith, 1972a, 1972b

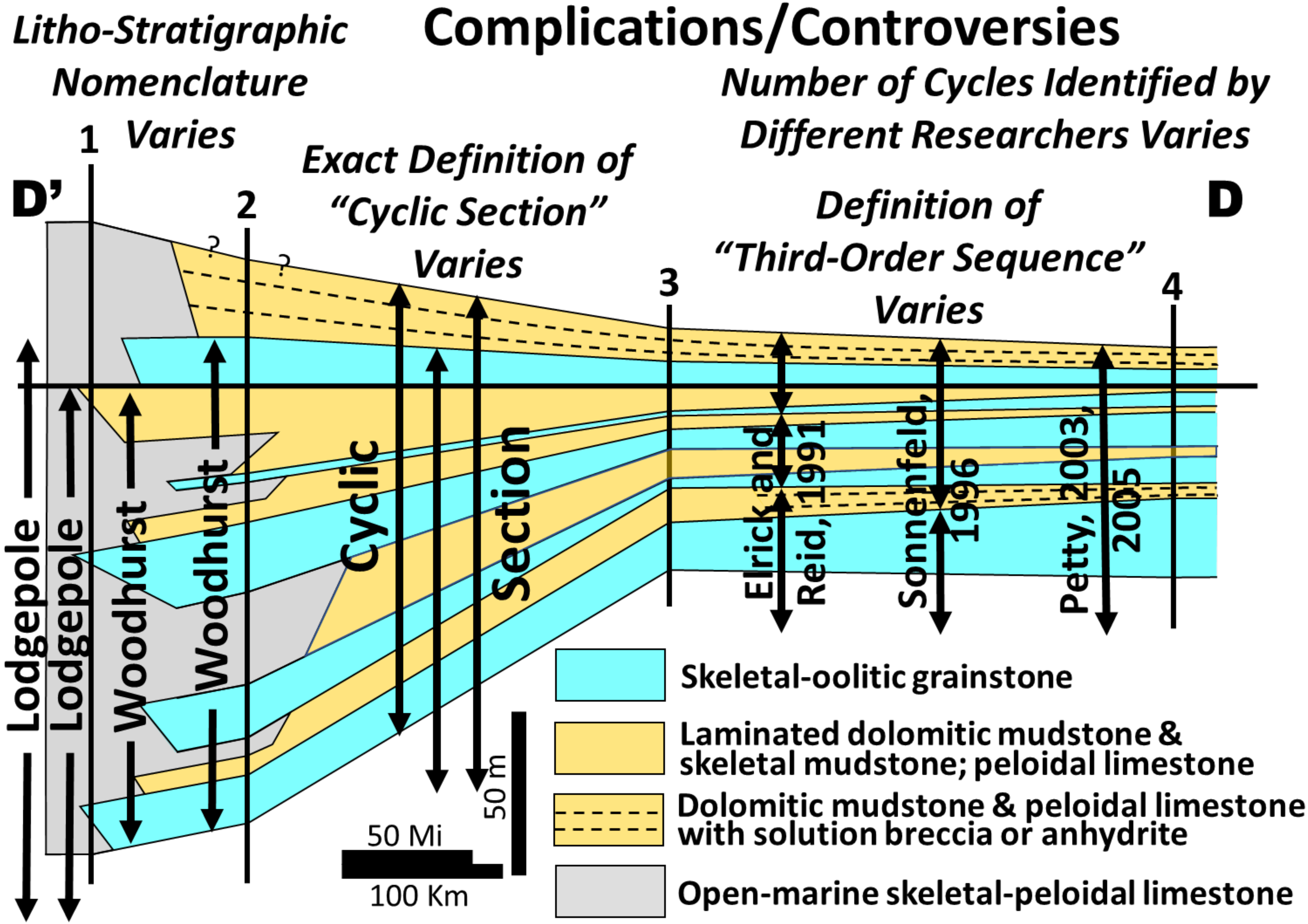
<u>Bottom line:</u> As used here, correlations start in Williston basin and extend to other areas


D'
Cross Section D-D'
Lodgepole Cyclic Section
North Dakota
Montana
Wyoming
D
South Dakota
150 Km
100 Mi

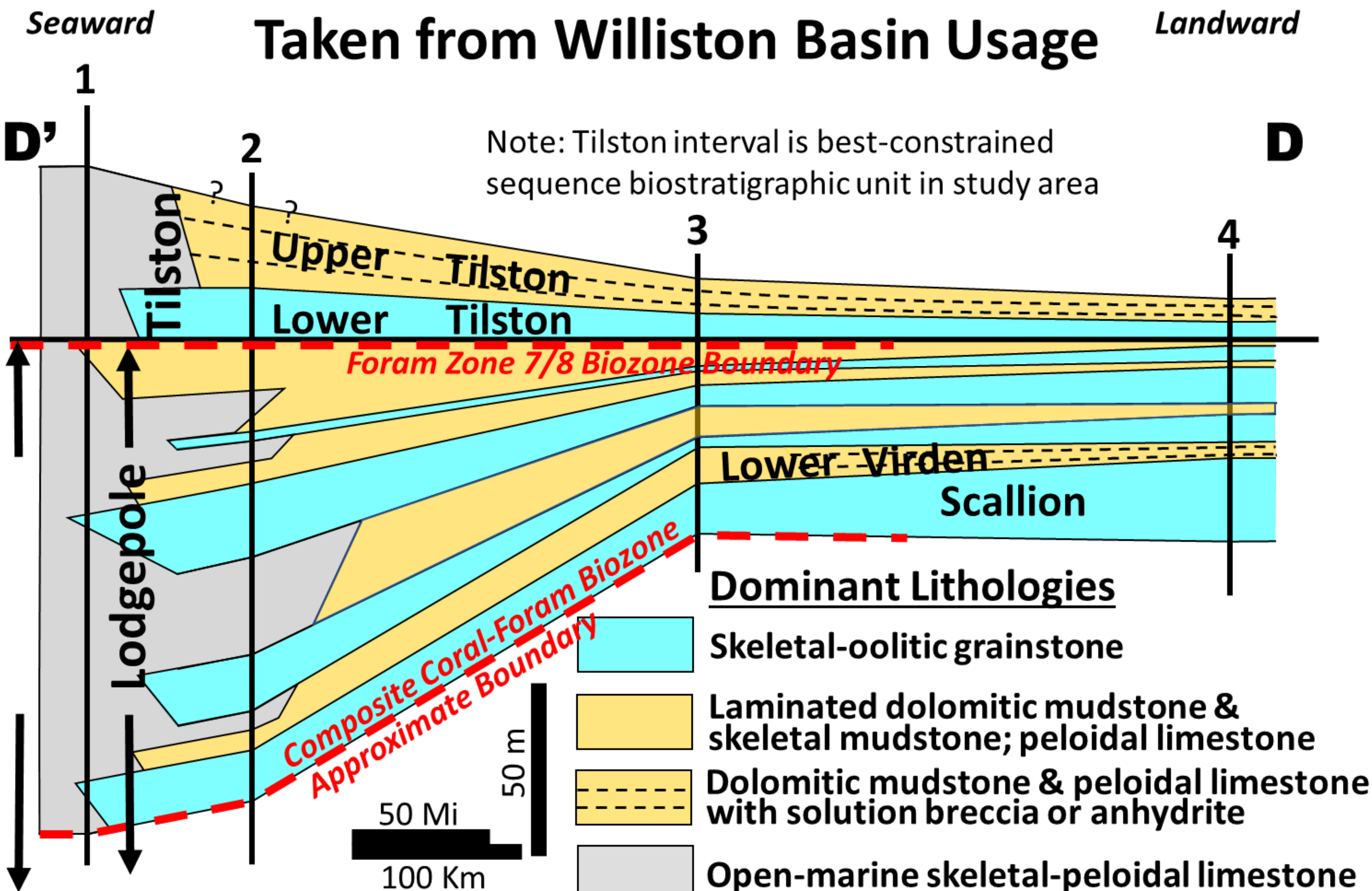


D'
Seaward
Cross Section D-D'
D
Landward
1. Monarch-Dry Fork Section; T16N-R7E, Sec. 27 & 35; Sando and Dutro, 1974
2. Swimming Woman Section; T11N-R19E, Sec. 9; Smith, 1972
3. Little Tongue River Section; T56N-R87W, Sec. 15, 26, 27; Sando, 1976; Petty, 2005
4. Boxelder Section; 2N-6E, Sec. 16 & 17; Petty, 2003
1
2
3
4
?
?
Dominant Lithologies
Skeletal-oolitic grainstone
Laminated dolomitic mudstone & skeletal mudstone; peloidal limestone
Dolomitic mudstone & peloidal limestone with solution breccia or anhydrite
Open-marine skeletal-peloidal limestone
50 m
50 Mi
100 Km

Complications/Controversies



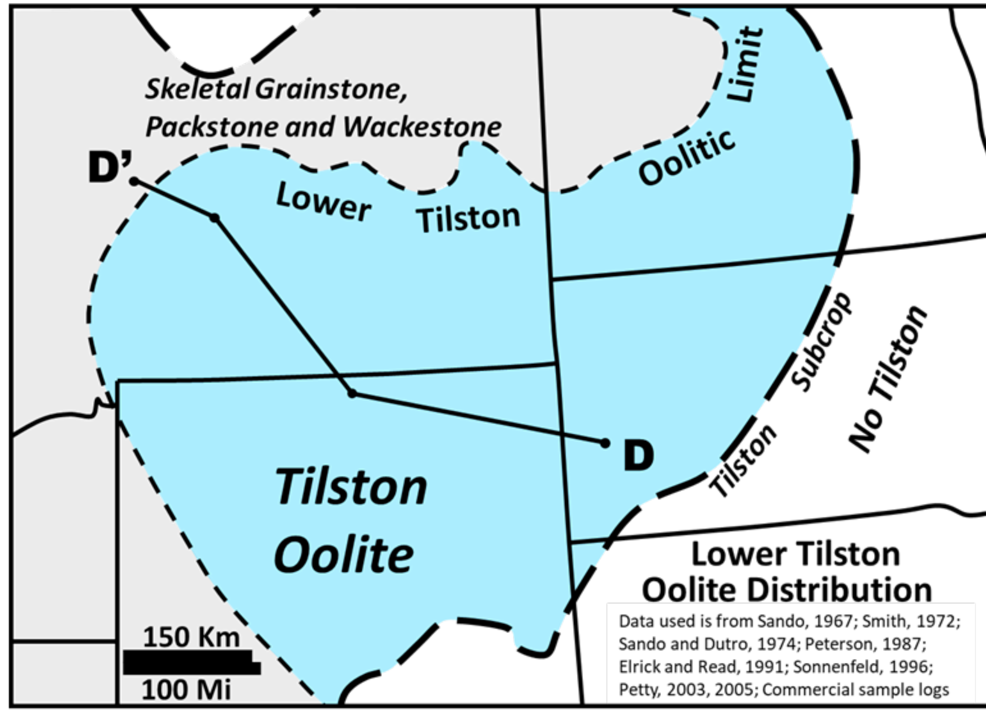
Nomenclature Terminology Used Here Taken from Williston Basin Usage

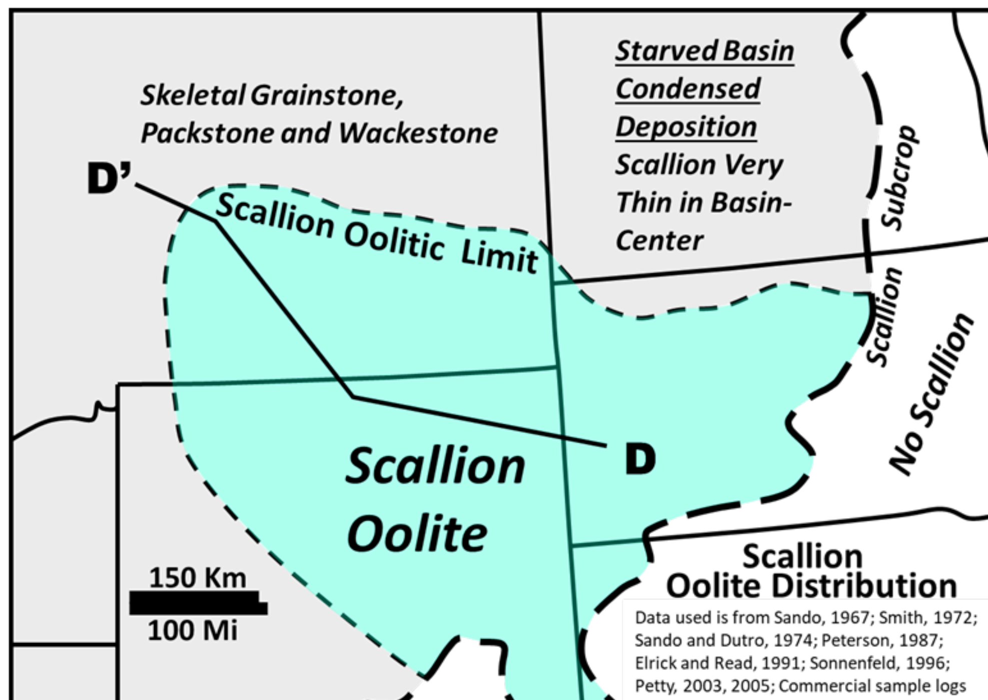


Lower Tilston Oolite

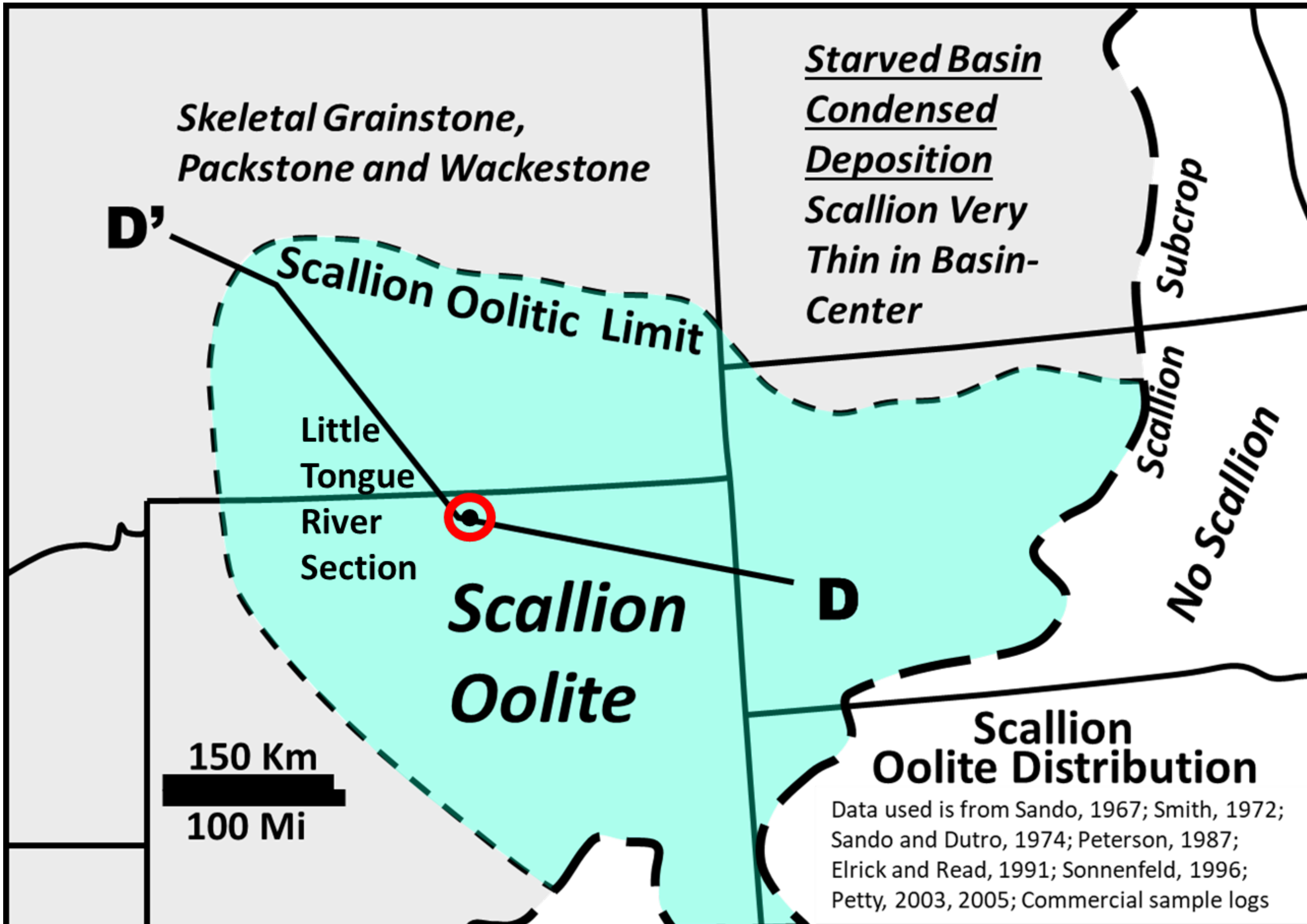
Note: massive, fabric-destructive dolomitization occurred in some landward areas

Scallion Oolite

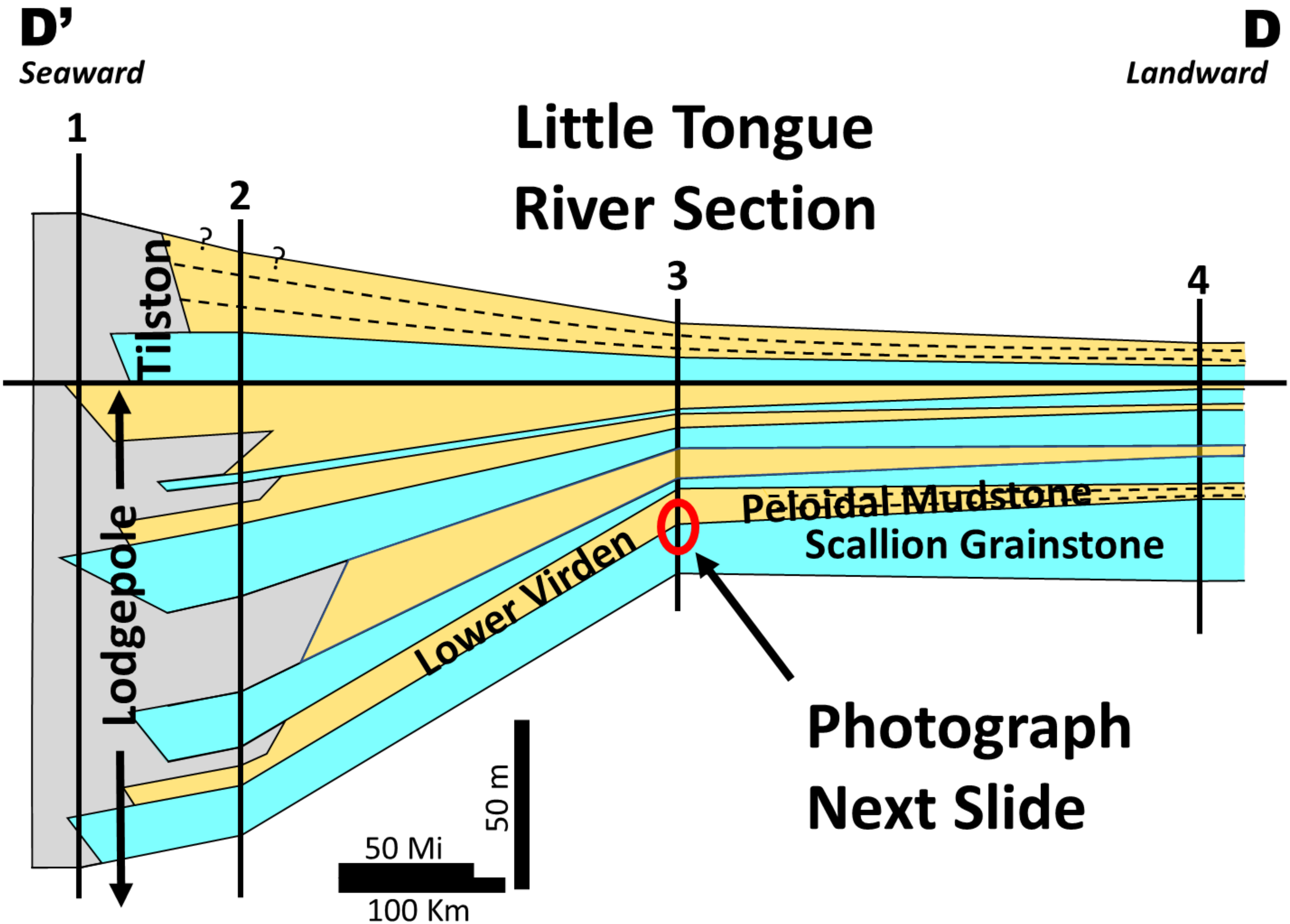




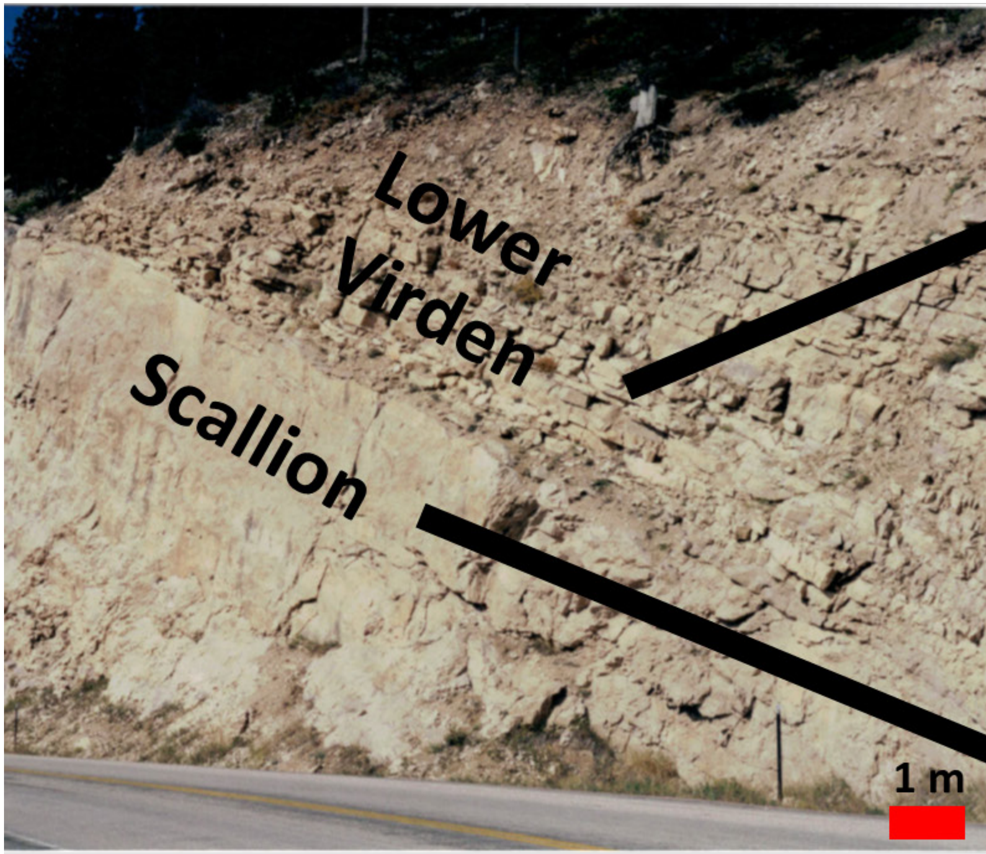
Top-Scallion Contact in Little Tongue River Section, Wyoming

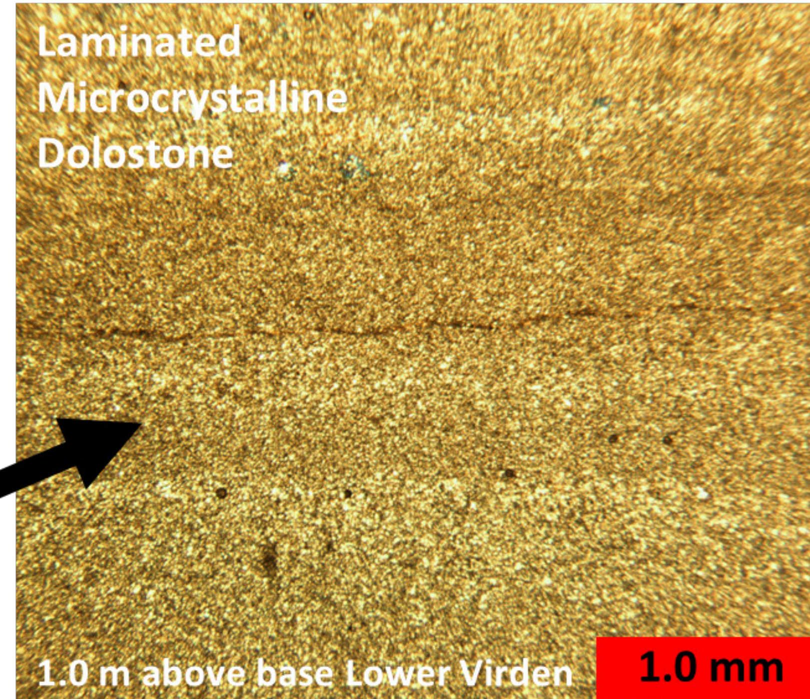


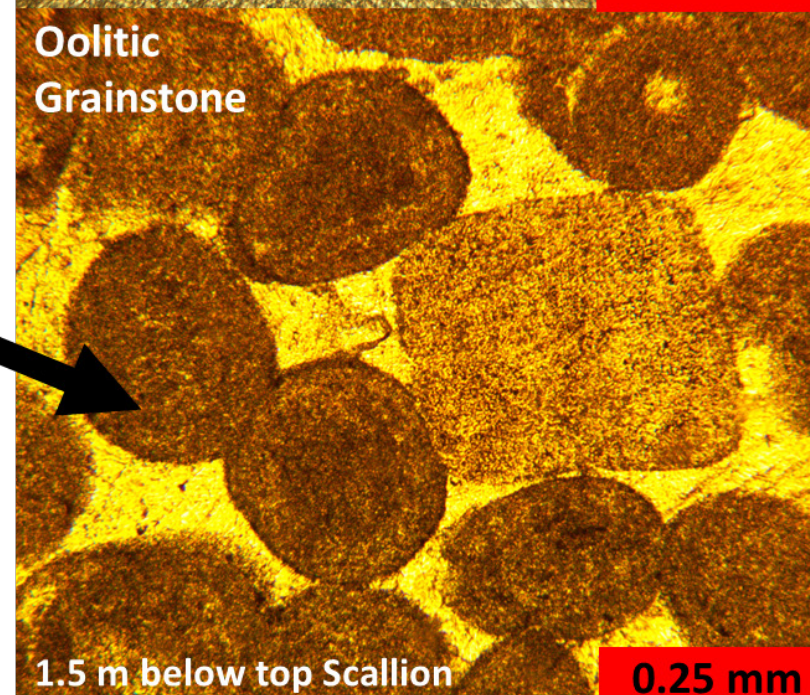
Little Tongue River Section



Little Tongue River Section
Section 27, T56N-R87W
Bighorn Mountains, WY

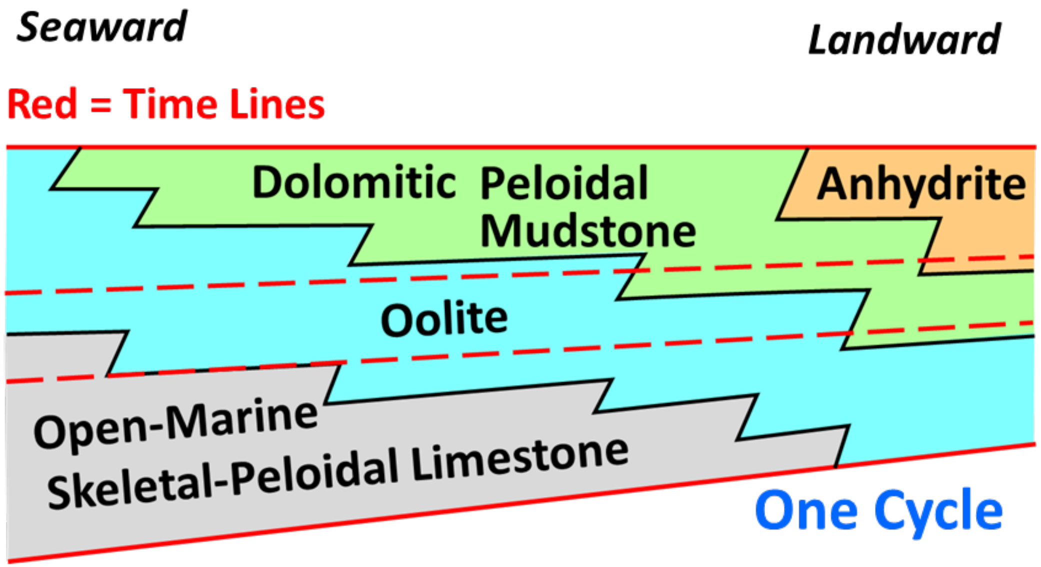


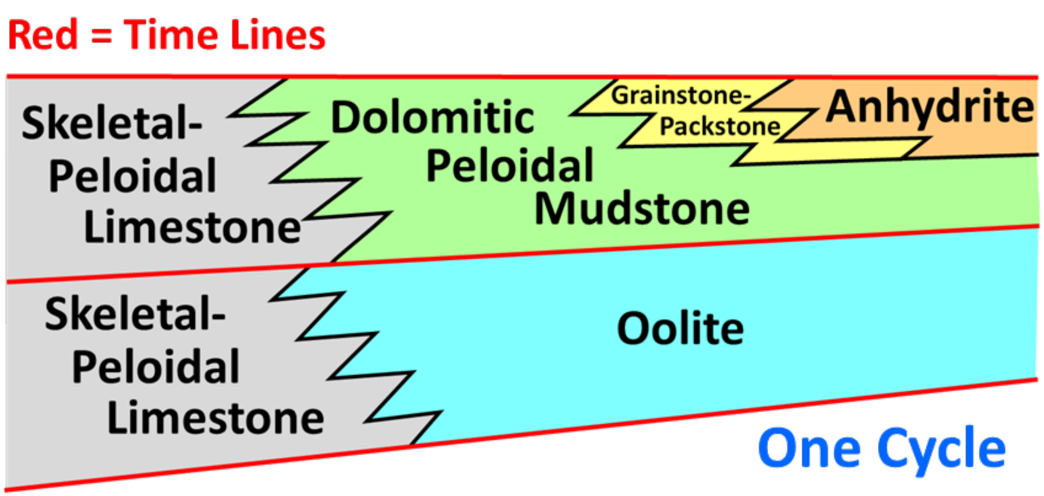




Thickly bedded, cross-stratified Scallion, overlain by thinly bedded Lower Virden

Discussion:
End-Member Mechanisms for Cycle Formation





<u>Mechanism 1.</u>

- Single facies association with diachronous facies; cyclicity caused by transgression induced by sea-level rise
- Most popular mechanism
- These facies relationships are not mappable in areas with dense control

<u>Mechanism 2.</u>

- Two facies associations; each is broadly synchronous; cyclicity caused by paleoclimate change: arid (mudstone) to humid (oolite)
- These lateral facies transitions can be mapped within an inferred chronostratigraphic interval in an area with dense control (Tilston in North Dakota; Petty, 2005)

Lower Madison Sequence Stratigraphy
Key Conclusions

- Bakken is Transgressive Systems Tract for Madison
    - Shallow-water Bakken and Bakken-equivalent units formed by coastal onlap in partially-connected basins
- Madison Maximum Flooding
    - Occurred after all Bakken deposition
    - Relatively rapid, regional sea-level rise (≈100 m)
- Basal Lodgepole (Paine equivalent)
    - Widespread open-marine, deep-water deposition
- Middle/Upper Lodgepole shallow-water cyclic deposition
    - Hemi-cycles represent synchronous facies associations linked to specific environmental conditions