

A Facies and Flow Unit Approach to Porosity Occurrence in the Madison Reservoirs (Frobisher-Alida and Tilston Intervals) of Western North Dakota

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Abstract

The Frobisher-Alida and Tilston intervals are log-marker defined stratigraphic units within the Mississippian Madison Group. The Frobisher-Alida interval is a third-order sequence, while the Tilston interval is the uppermost fourth-order cycle within the underlying third-order sequence. These intervals consist dominantly of carbonate and evaporite lithologies. Cores will illustrate porosity occurrence in the different types of flow units that characterize the Frobisher-Alida and Tilston intervals in western North Dakota. The Bluell-B1 dolostone flow unit in Elkhorn Ranch field represents a lagoonal facies. Porous stromatolitic dolostone occurs widely in this facies but the best reservoir quality is in a burrowed dolostone subfacies that formed near the center of the lagoon. Rival limestone reservoirs in Indian Hill and Glass Bluff fields represent a bar-island-shoal complex. Interparticle and fenestral porosity occurs in skeletal-oolitic-pisolitic packstone and grainstone. Sherwood-E dolostone in Davis Creek field and Sherwood-C dolostone in Big Stick field represent a restricted-marine facies. Intercrystal dolomite porosity occurs in burrowed, peloidal mudstone. The Glenburn-A calcareous dolostone flow unit in TR field represents a low-energy, open-marine facies. Intercrystal dolomite porosity occurs in the matrix of skeletal wackestone and packstone. A middle Frobisher-Alida limestone in northwest North represents a high-energy, open-marine facies. Skeletal grainstone is the dominant lithology. Effective porosity occurs in interparticle pores between crinoid and bryozoan fragments. A lower Tilston limestone flow unit in southwest North Dakota formed in a vast oolitic shoal that extended from North Dakota to Wyoming. Porosity occurs in interparticle pores between ooid grains.

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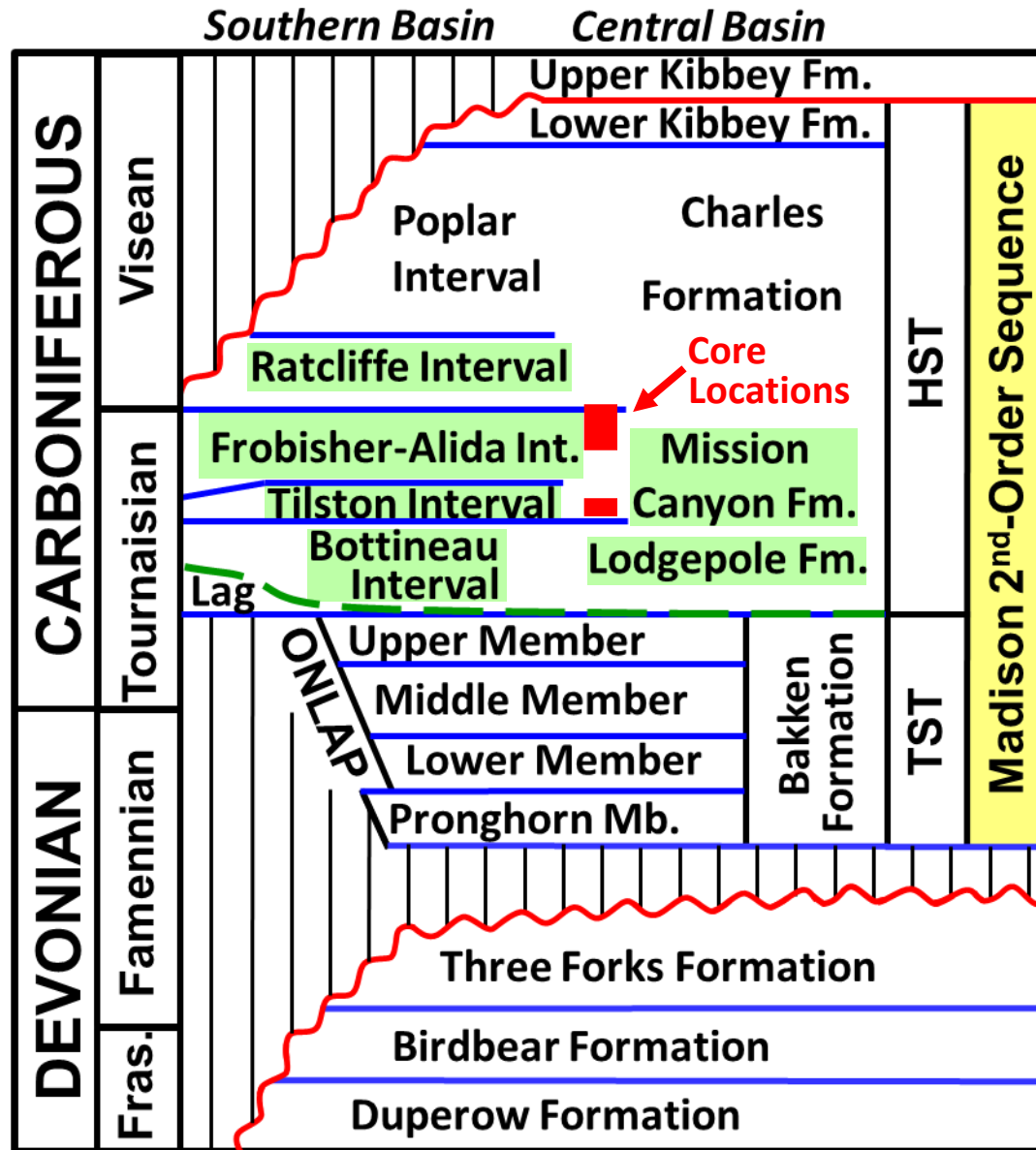
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Western North Dakota**

**Presented By David M. Petty
Pre-Meeting Core Conference
AAPG Rocky Mountain Section Meeting
June, 2023**

Williston Basin Stratigraphic Column



Major Basin Margin Unconformity

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

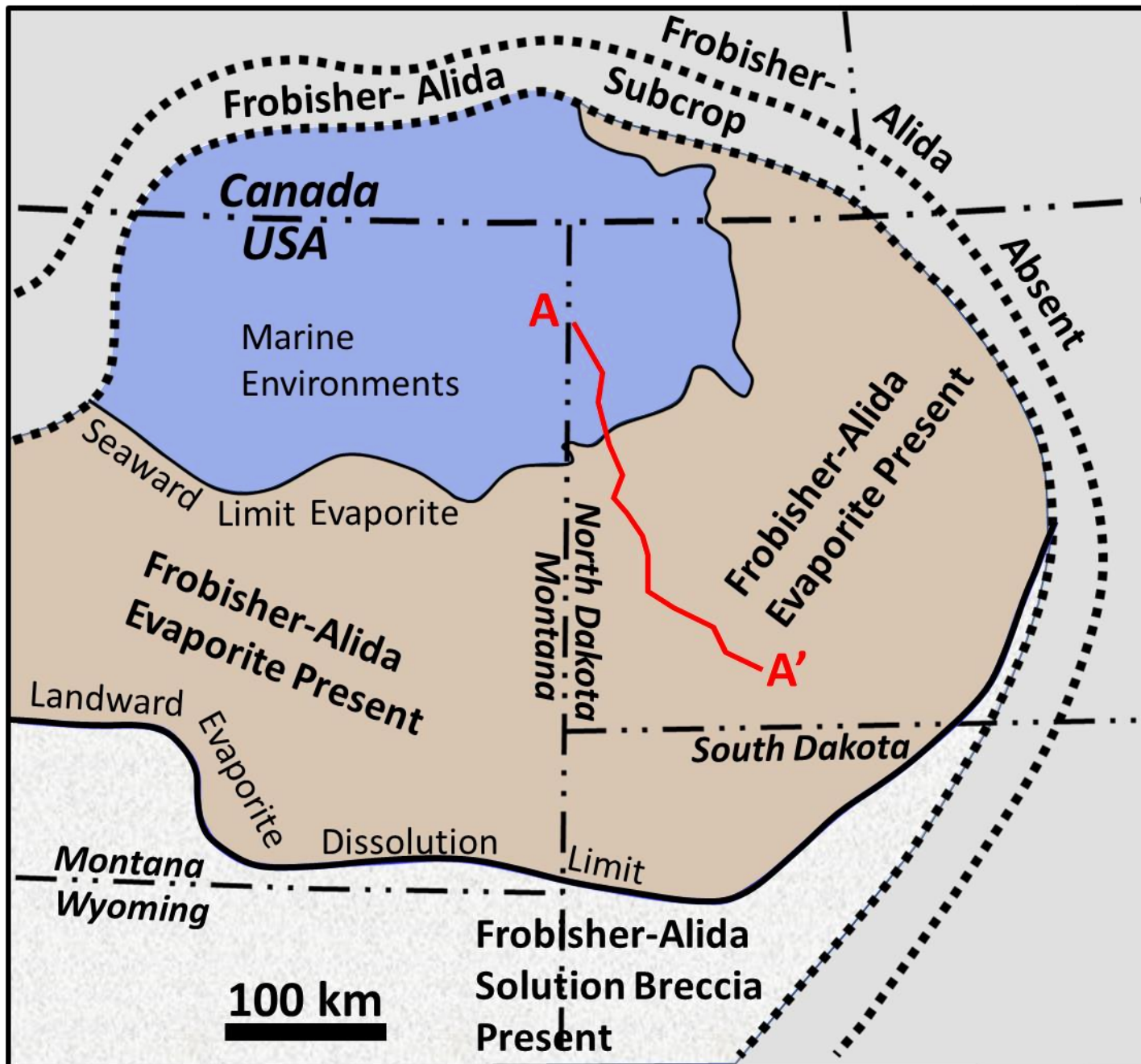
28 m.y.

Madison 2nd-order MFS

Acadian Unconformity

Intervals are log marker-defined units (Carlson and LeFever, 1987) that parallel biostratigraphic zones (Petty, 2005, 2010, 2019b). Formations are lithology-defined units that may be diachronous.

Frobisher-Alida Paleogeography

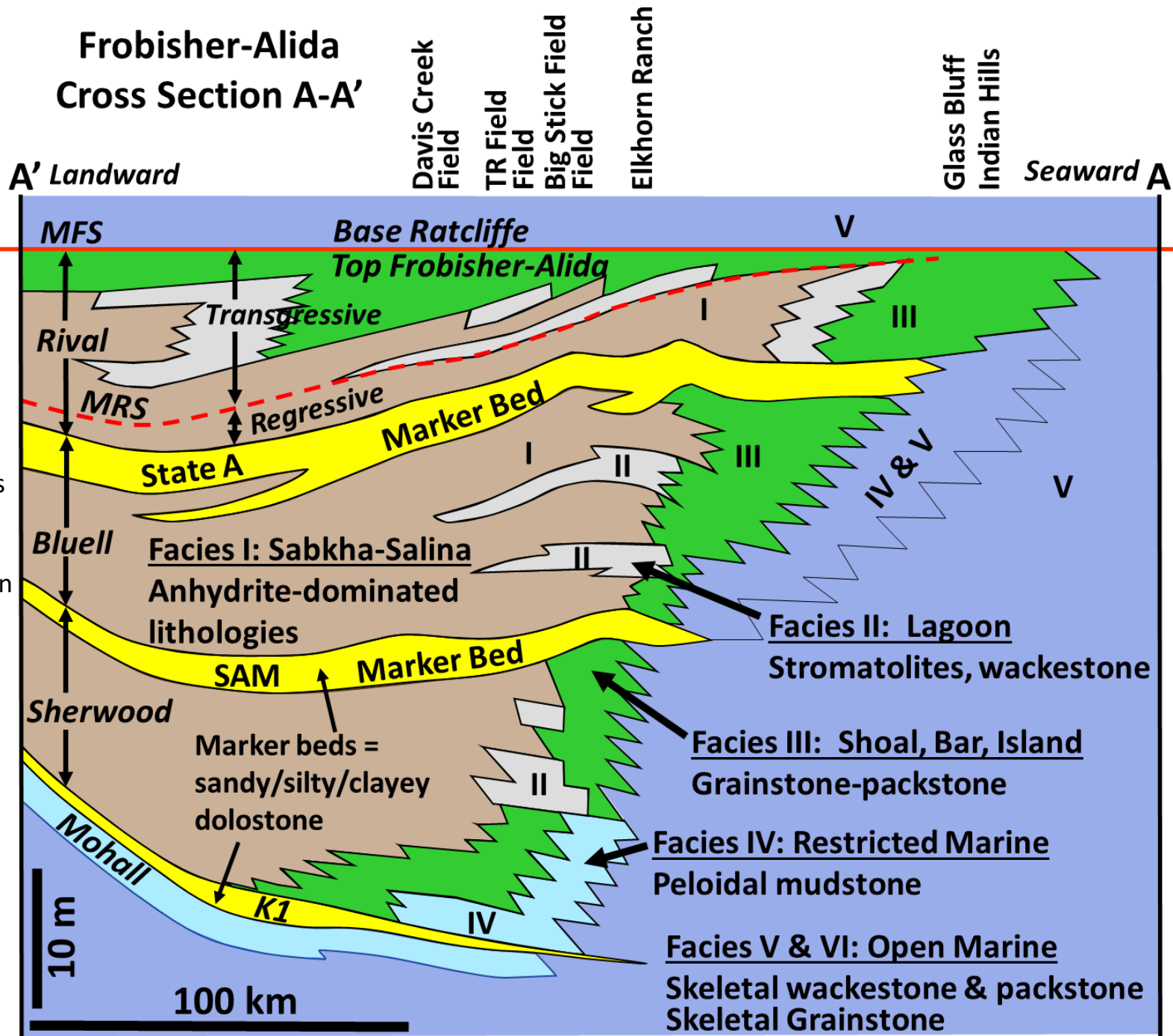


Modified
after Petty
(2010, Fig. 3)

Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)


Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

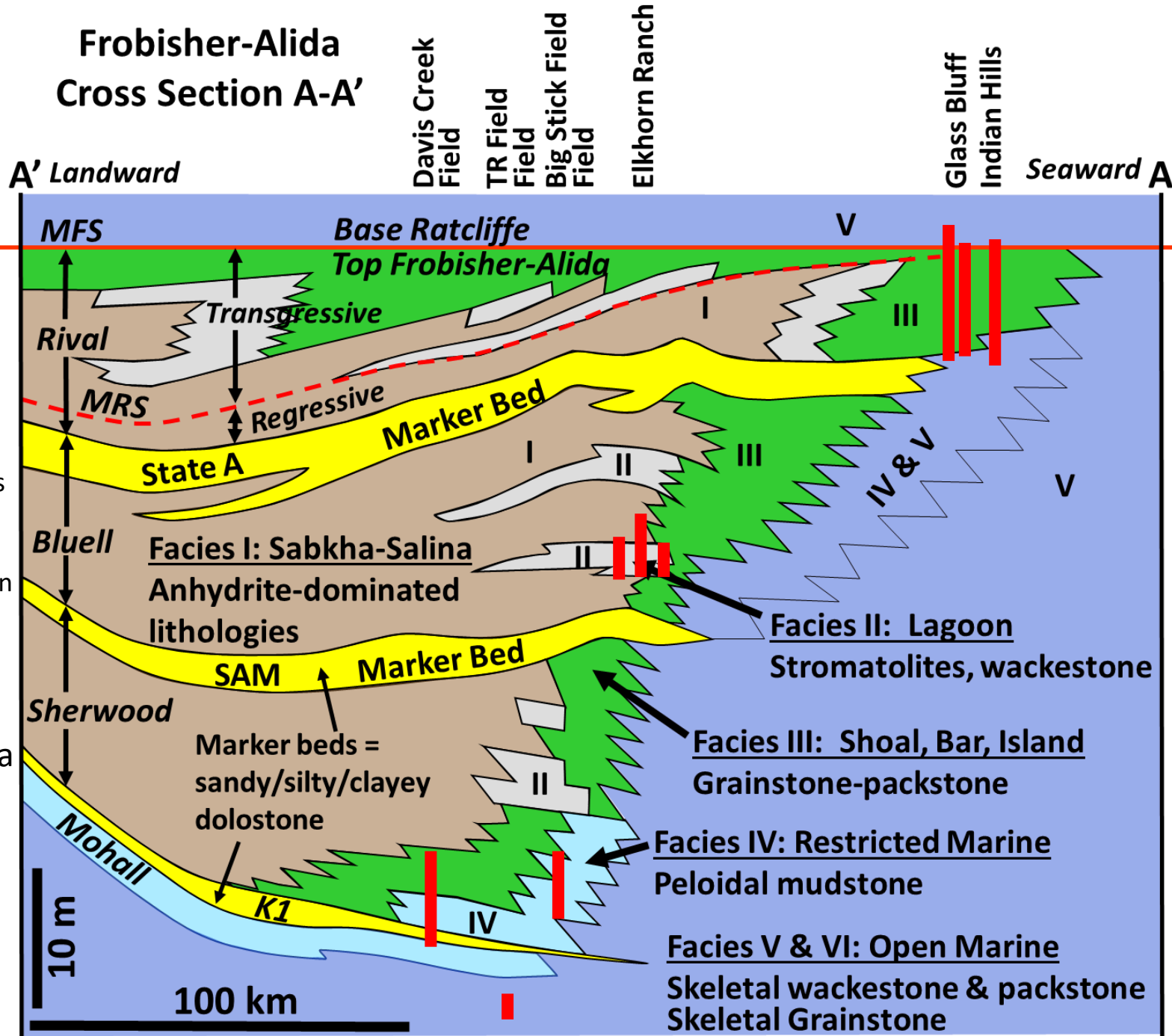


Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)

Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

 = Location of Frobisher-Alida cores except facies VI



MFS = Sequence Boundary after Galloway, 1989

Frobisher-Alida Cross Section A-A'

Davis Creek Field

TR Field

Big Stick Field

Elkhorn Ranch

Photo:
Top Frobisher-Alida 3rd-order sequence

Glass Bluff Indian Hills

Seaward A

A' Landward

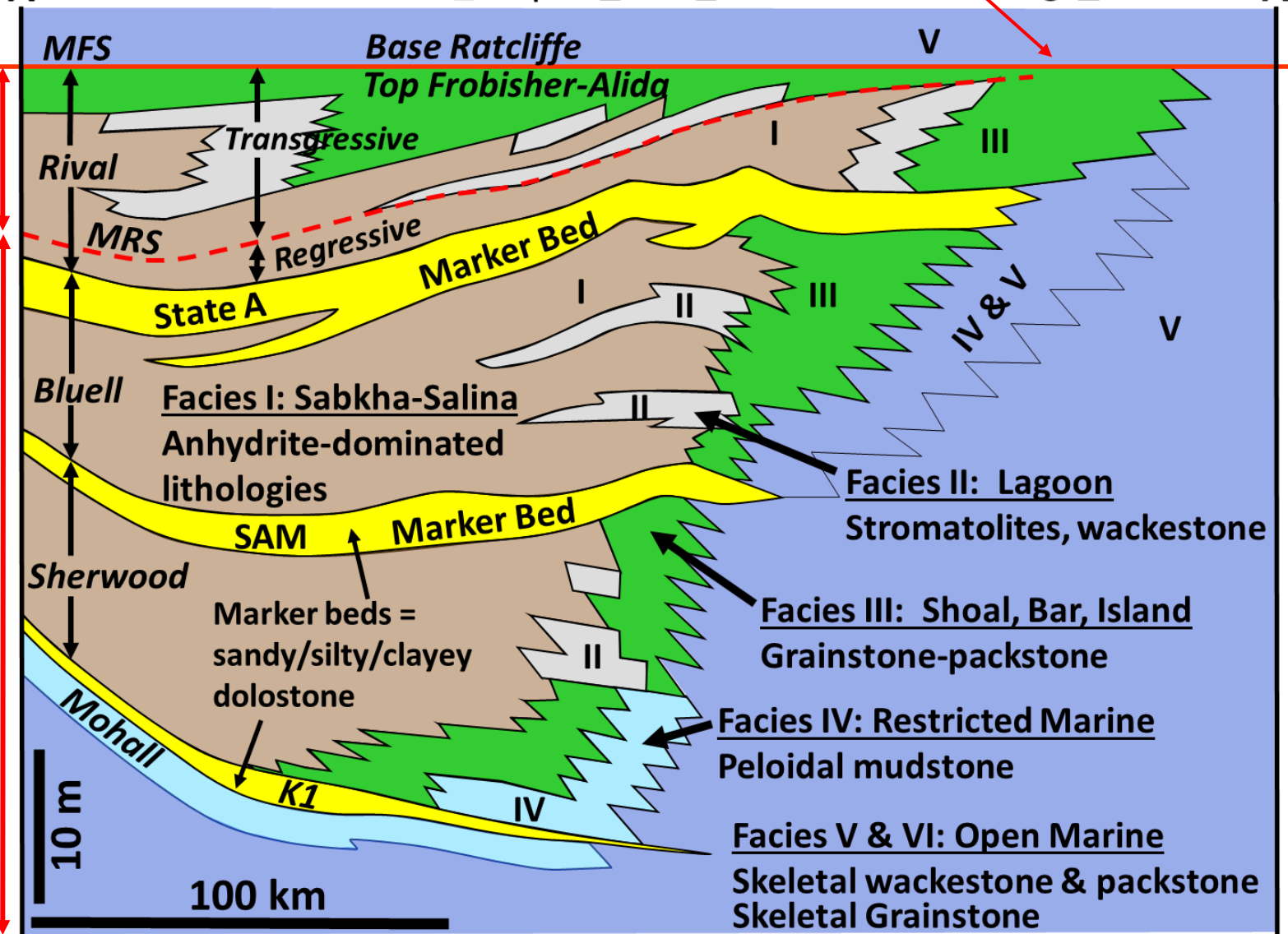
MFS
Transgressive Systems Tract

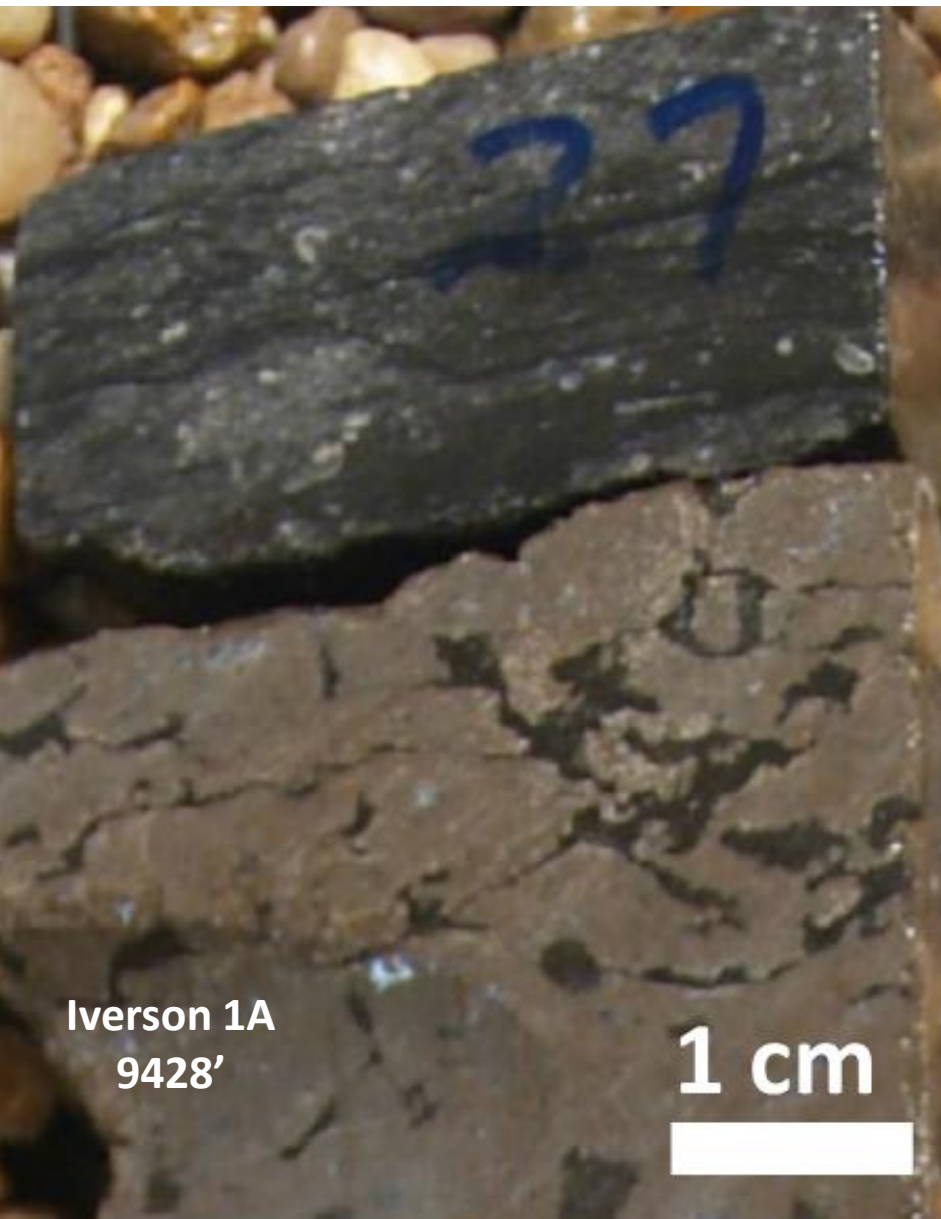
MRS

Regressive Systems Tract

Surfaces and systema tracts after Embry, 1993, 2002, 2009

Sequence stratigraphy after Petty, 2010





← Midale black skeletal wackestone;
estimated depth of deposition = 40-60 m

← Midale-Rival contact = MFS

← Rival facies III with black Midale
sediment fill in fenestral pores;
estimated depth of deposition = 0-5 m

**Midale-Rival (Facies III)
Contact in
Glass Bluff field**

Facies II

Lagoonal Environment

**Stromatolitic Boundstone, Intraclastic-Peloidal-
Calcimicrobial/Algal Wackestone & Packstone**

Dolostone Flow Units

Cores

State #1-16; 144-101-16 SESW (NDIC # 9578): 9460-9470'


USA # 3-29; 144-101-29 NWSE (NDIC # 9182): 9240-9250'

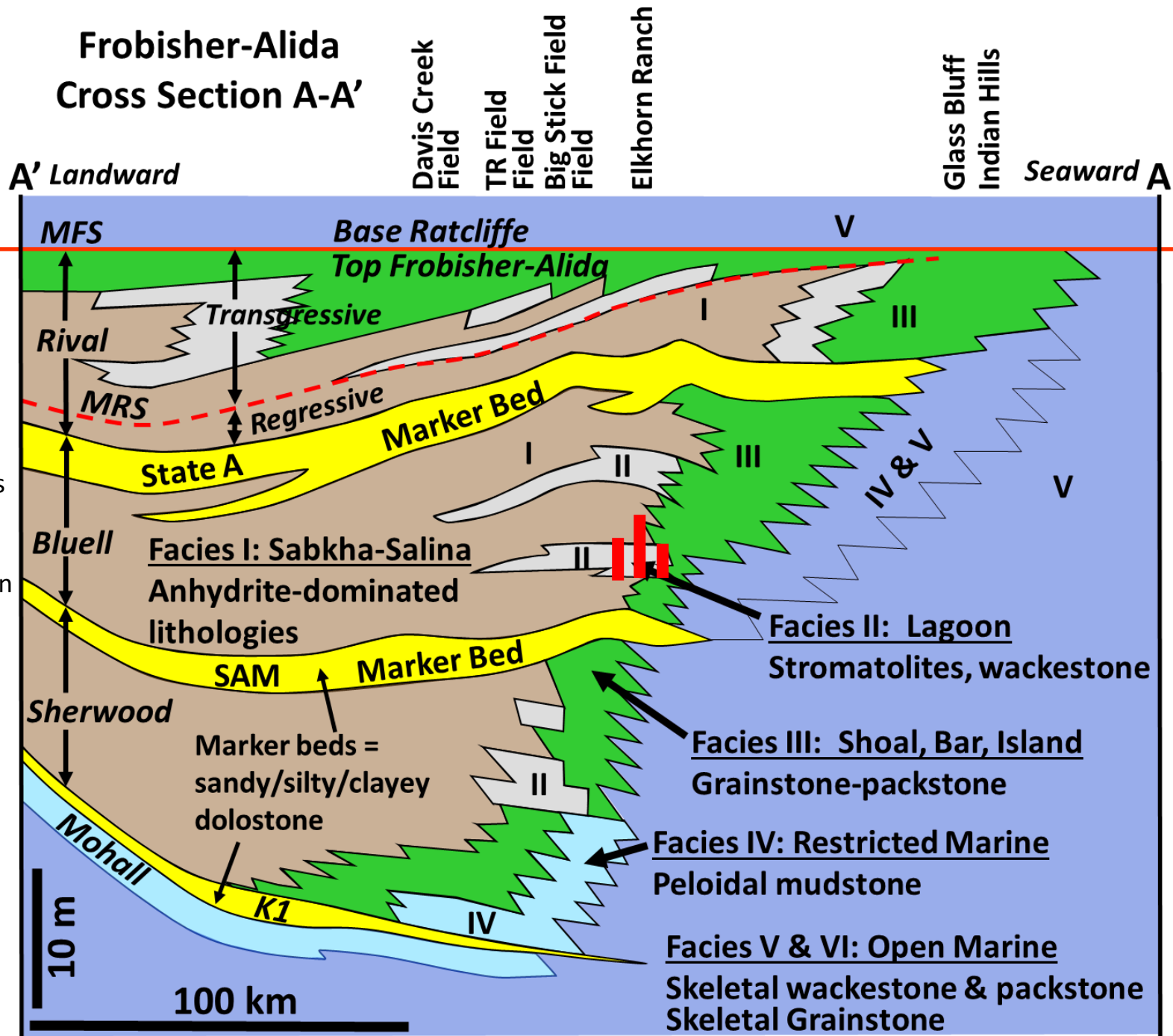
Fed. # 1-33; 144-101-33 SESW (NDIC # 10229): 9290-9302'

Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)

Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

 = Location of facies II cores



144-101-33

USA #1-33

NDIC # 10229

Photograph
from NDIC

9291.5

Blueell-B1 Flow Unit
Elkhorn Ranch Field

9291.5''

$\phi = 11.1\%$

$K_a = 0.26 \text{ md}$

This lithology (stromatolitic dolostone) commonly occurs at the top of the flow unit and in landward portions of the lagoon. This is a key characteristic lithology for facies II; however, while it may be porous, stromatolitic boundstone commonly has low permeability.

9297.8

9298



144-101-33

USA #1-33

NDIC # 10229

Blueell-B1 Flow Unit
Elkhorn Ranch Field

9297-99'

Routine and SCA Plug Analyses:

$\emptyset = 16.5\%$ $Ka = 10$ md

$\emptyset = 17.2\%$ $Ka = 12$ md

$\emptyset = 18.0\%$ $Ka = 14$ md

$\emptyset = 18.1\%$ $Ka = 13$ md

$\emptyset = 22.8\%$ $Ka = 27$ md

$\emptyset = 19.0\%$ $Ka = 24$ md

$\emptyset = 1.5\%$ $Ka = 0.1$ md

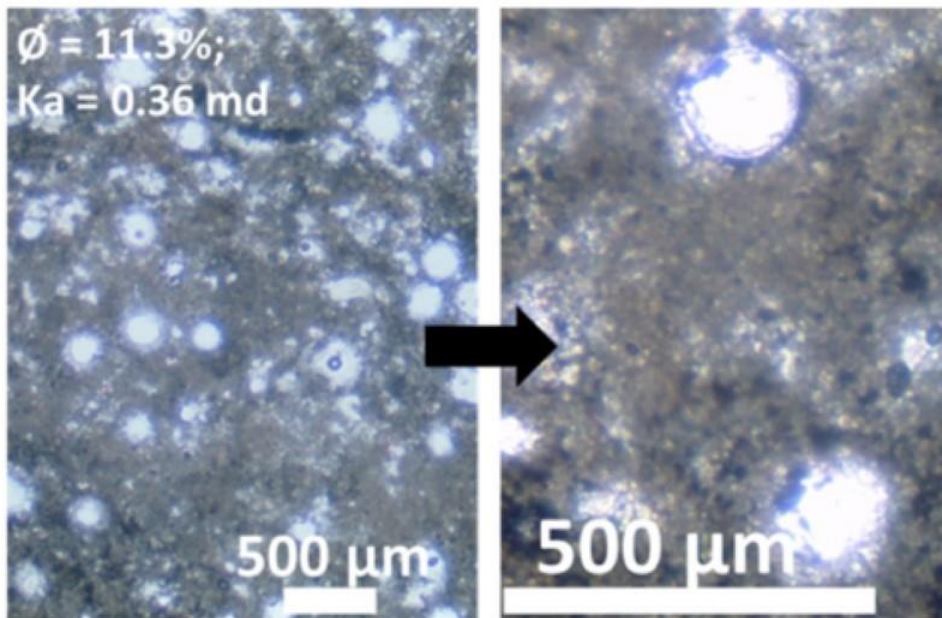
$\emptyset = 22.2\%$ $Ka = 28$ md

Photograph
from NDIC

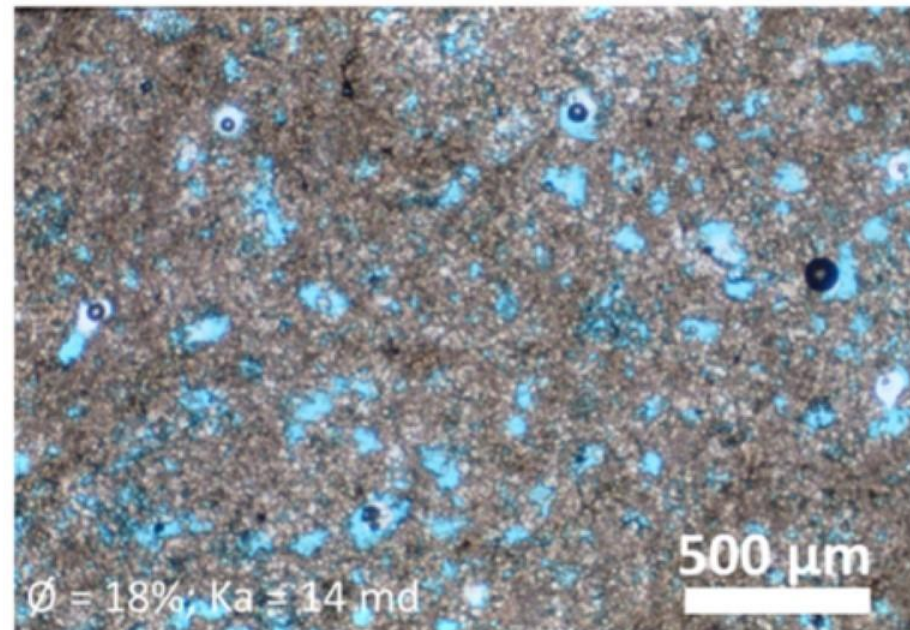
This lithology (bioturbated dolostone) commonly occurs near the middle of the flow unit and near middle of the lagoon, where the best reservoir rock occurs.

Calcispheres in Facies II

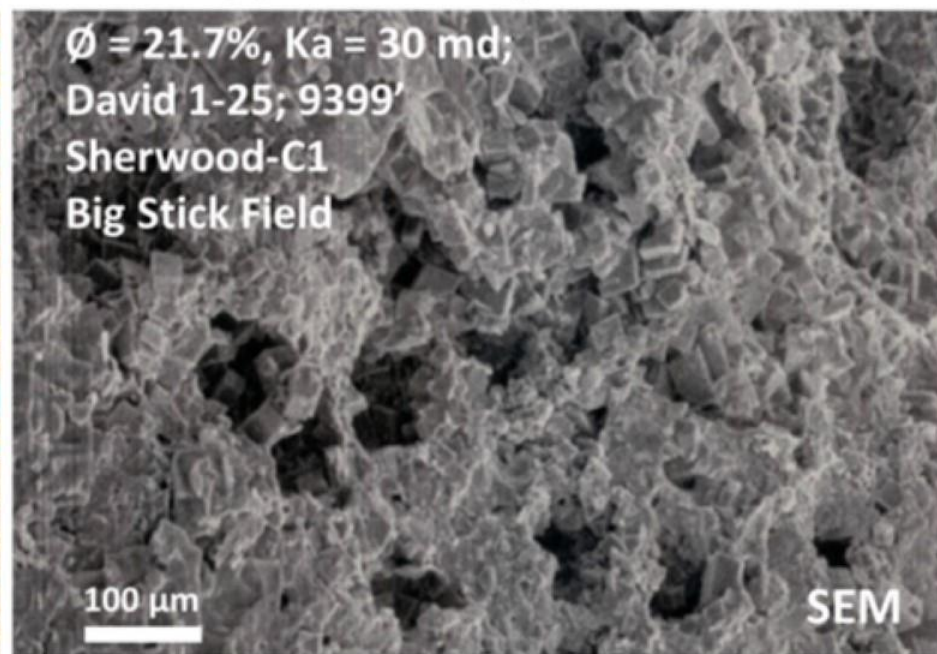
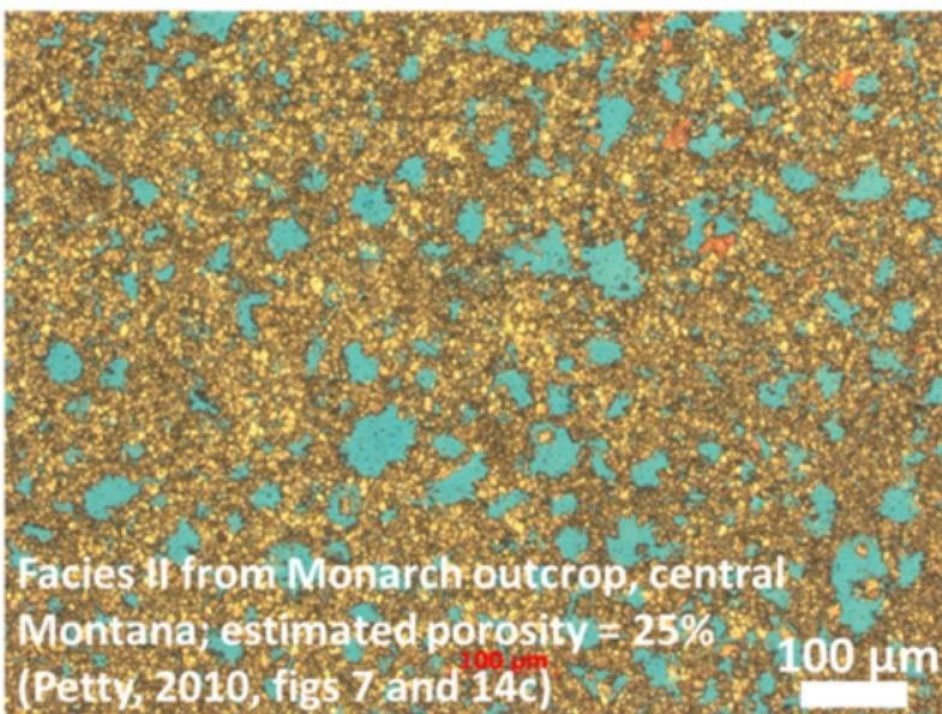
- Calcispheres are walled, spherical grains with a diameter of 60—250 μm (Scholle and Ulmer-Scholle, 2003)
- A range of origins have been assigned. Paleozoic calcispheres are most commonly referred to as algae or problematica.
- In the Mission Canyon, calcispheres are very common in facies II; they are characteristic of stressed environments
- Calcisphere-moldic porosity commonly occurs in the best facies II reservoir rock in the Bluell-B1 zone (next slide top photographs) and other facies II zones (next slide bottom photographs).



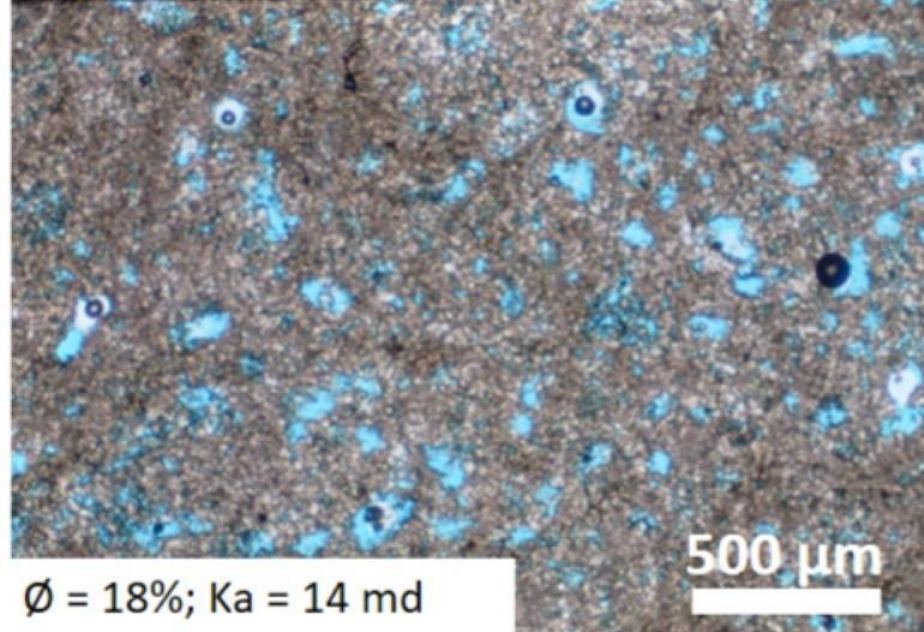
Amerada St. 1-16; (NDIC #9578); 9460-61'



UVI 1-33; (NDIC #10229); 9797.9'



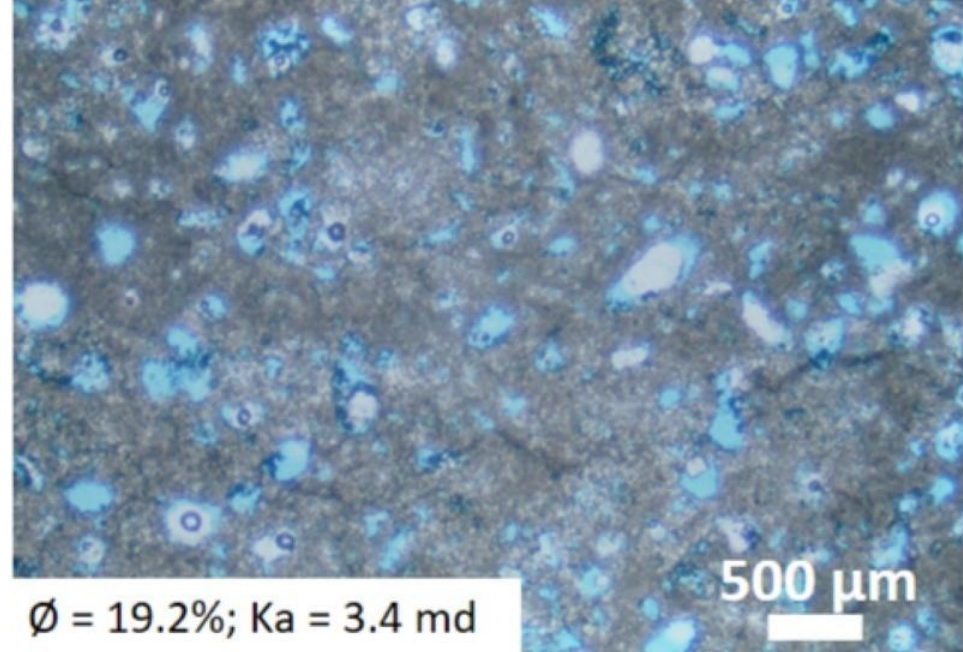
SEM close-up view of calcisphere-moldic pores



$\emptyset = 18\%$; $K_a = 14$ md

500 μm

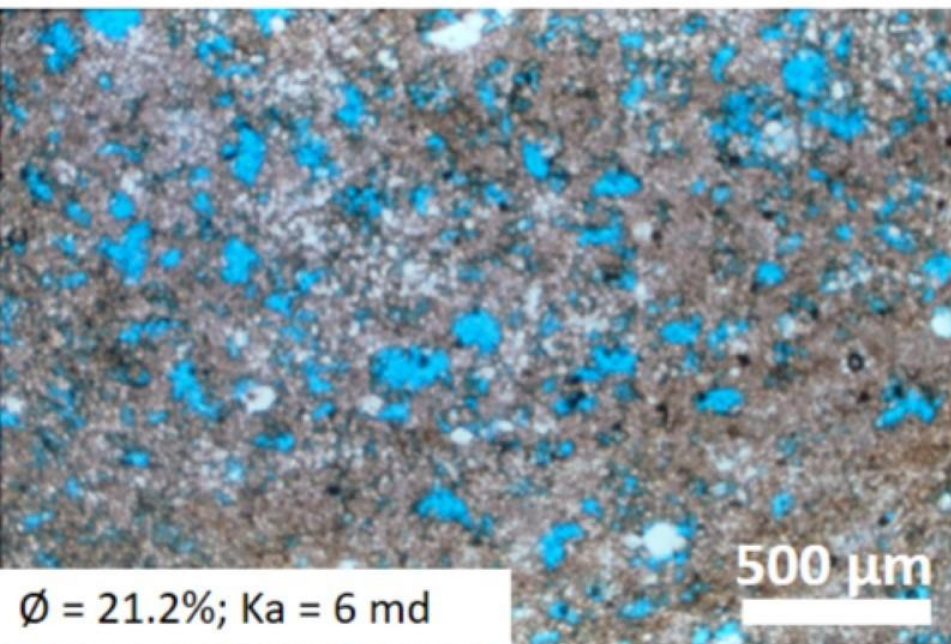
UVI 1-33; (NDIC #10229); 9797.9'



$\emptyset = 19.2\%$; $K_a = 3.4$ md

500 μm

Amerada St. 1-16; (NDIC #9578); 9465-66'

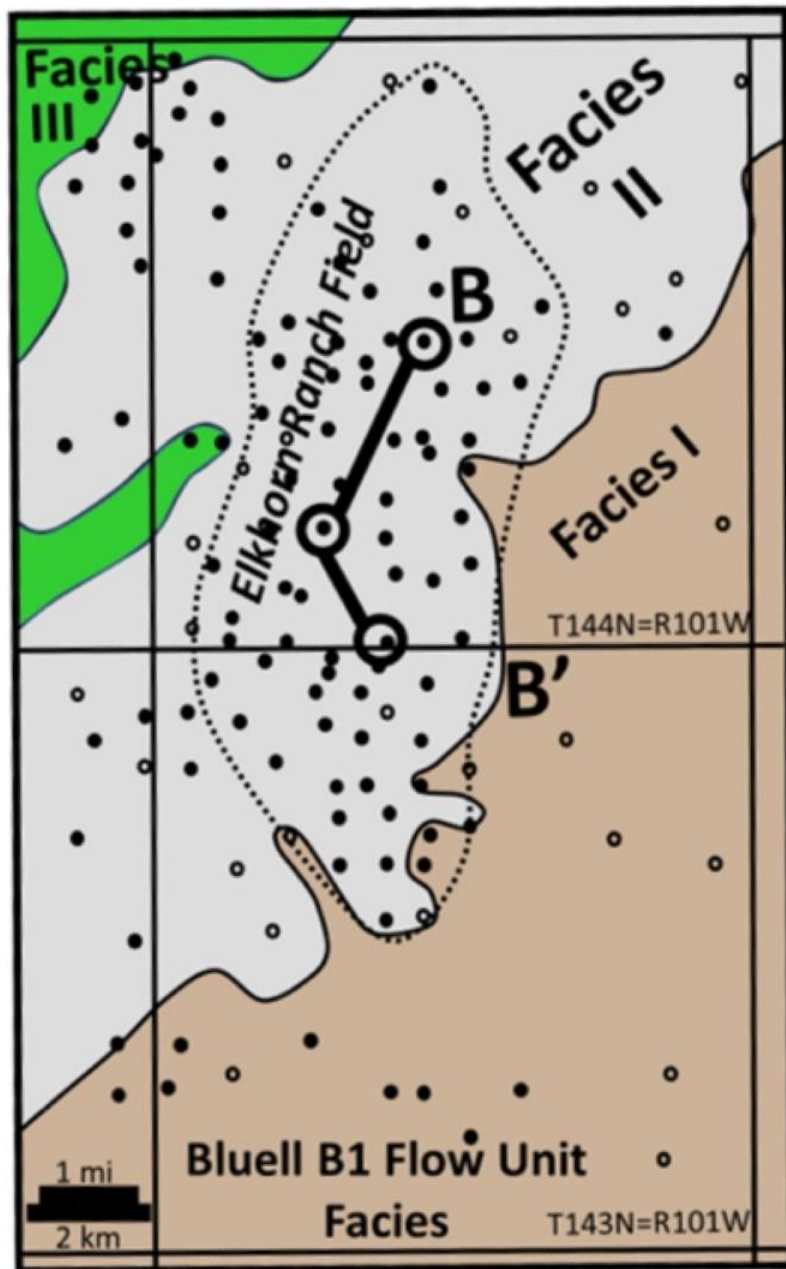


$\emptyset = 21.2\%$; $K_a = 6$ md

500 μm

Hamilton 3-29; (NDIC #9182); 9245'

Calcisphere-moldic and intercrystal porosity
in facies II in display cores



Blueell-B1 Flow Unit Facies

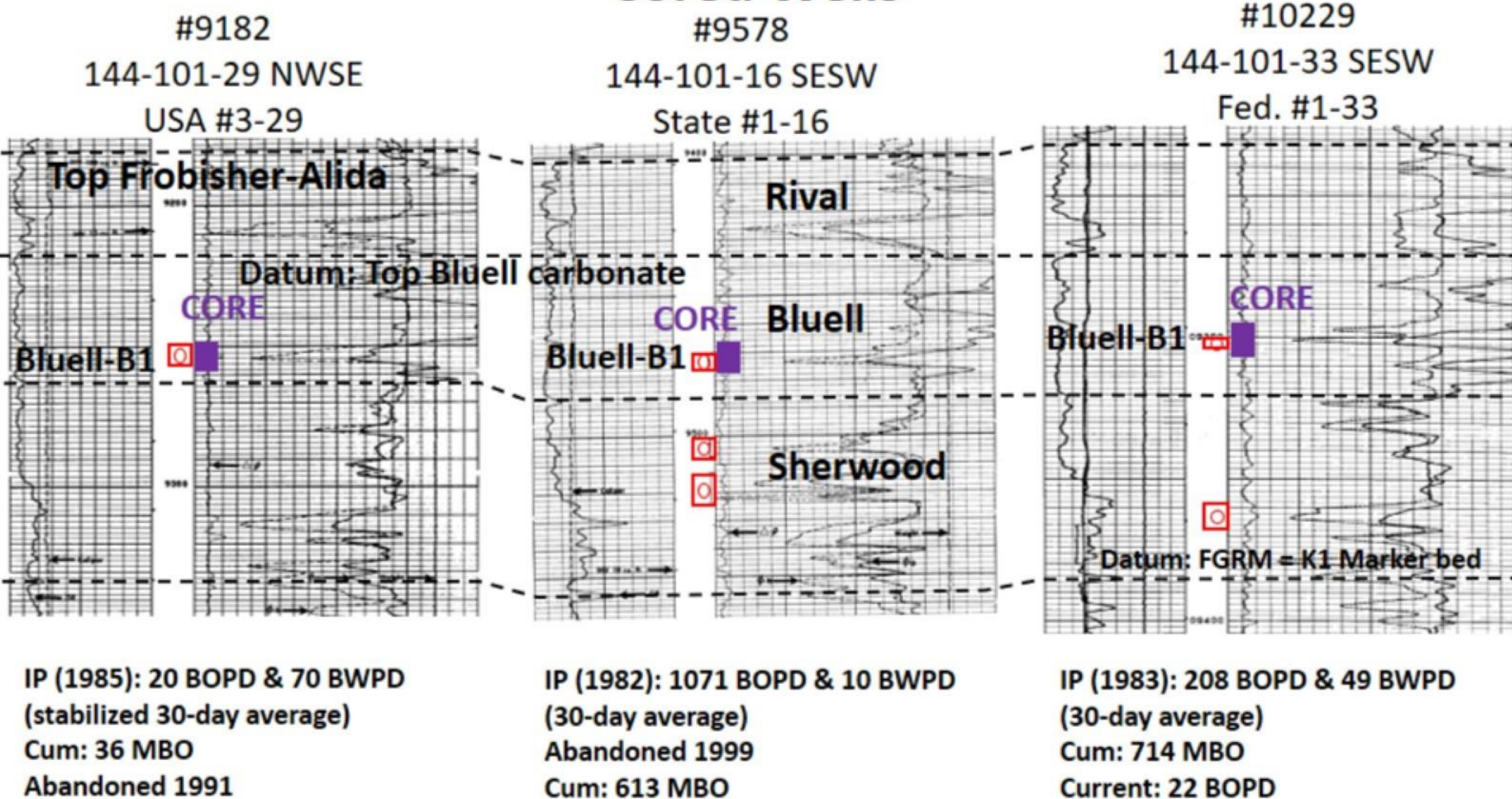
- = Vertical Penetration Producer
- = Vertical Penetration Dry Hole

∞ = Cross section B-B'

B

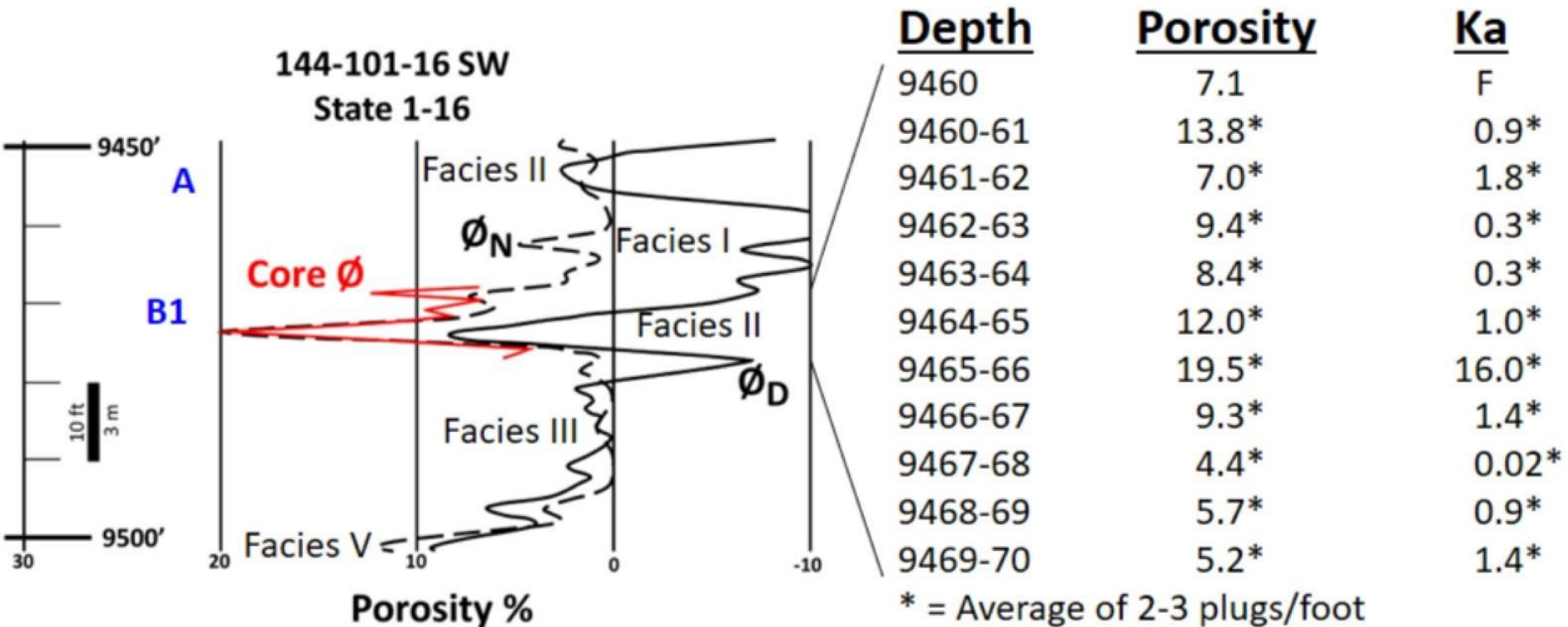
Blueell B1 Flow Unit Cored Wells

Landward
→

B'

Note: 1) in landward-seaward direction, there is some porosity “shingling” within B1 flow unit but porosity appears interconnected, and 2) purple represents core display

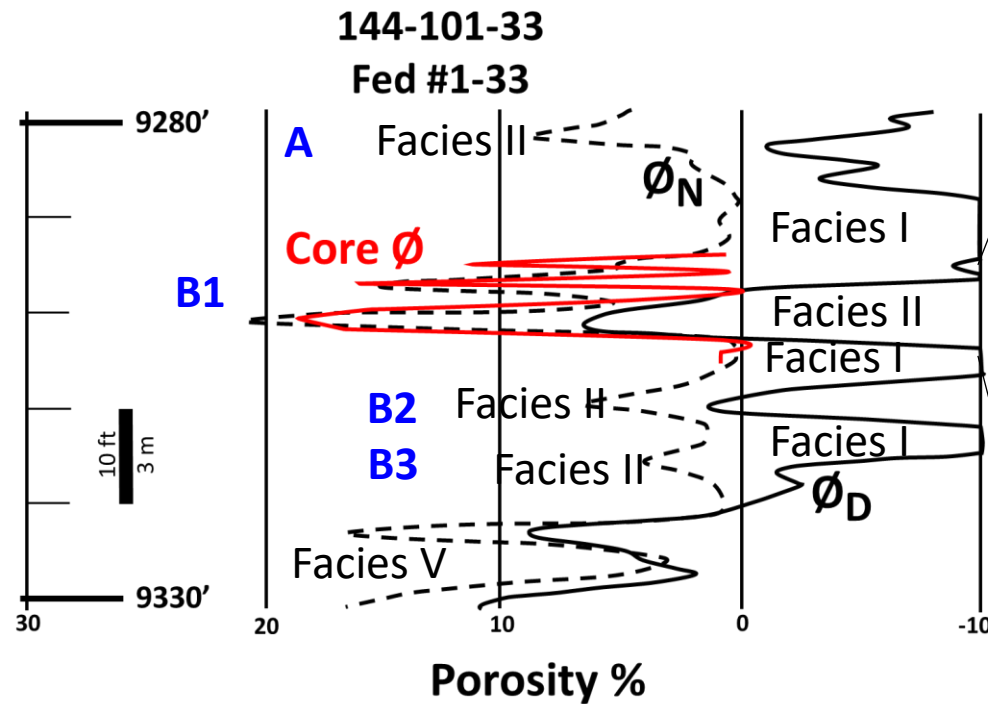
Facies II Data: 144-101-16 SW; Amerada St. #1-16 (NDIC #9578)



IP (1982):
 1071 BOPD & 10 BWPD
 Bluell-B1, Sherwood-A
 & Sherwood-B
 (30-day average)
 Abandoned 1999
 Cum: 613 MBO

Example of One-Foot Detail				
Depth	Porosity	Avg. Porosity	Ka	Avg. Ka
9465-66a	16.6		6.0	
9465-66b	19.2	19.5	3.4	16.0
9465-66c	22.8		38.4	

Facies II Data: 144-101-33 SESW; UVI #1-33 (NDIC #10229)

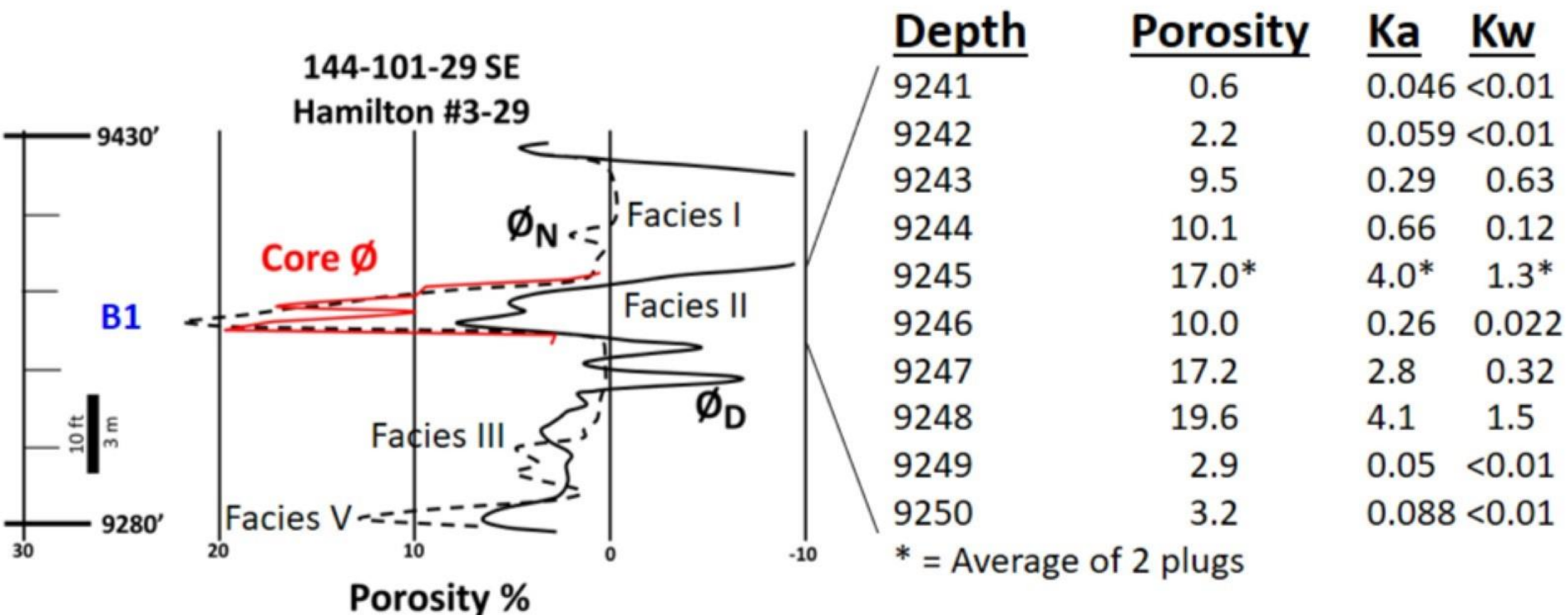


IP (1983): 208 BOPD & 49 BWPD (30-day average)
 Bluell-B1 (3') & Sherwood-C (8')
 Cum: 717 MBO
 Current: 30 BOPD

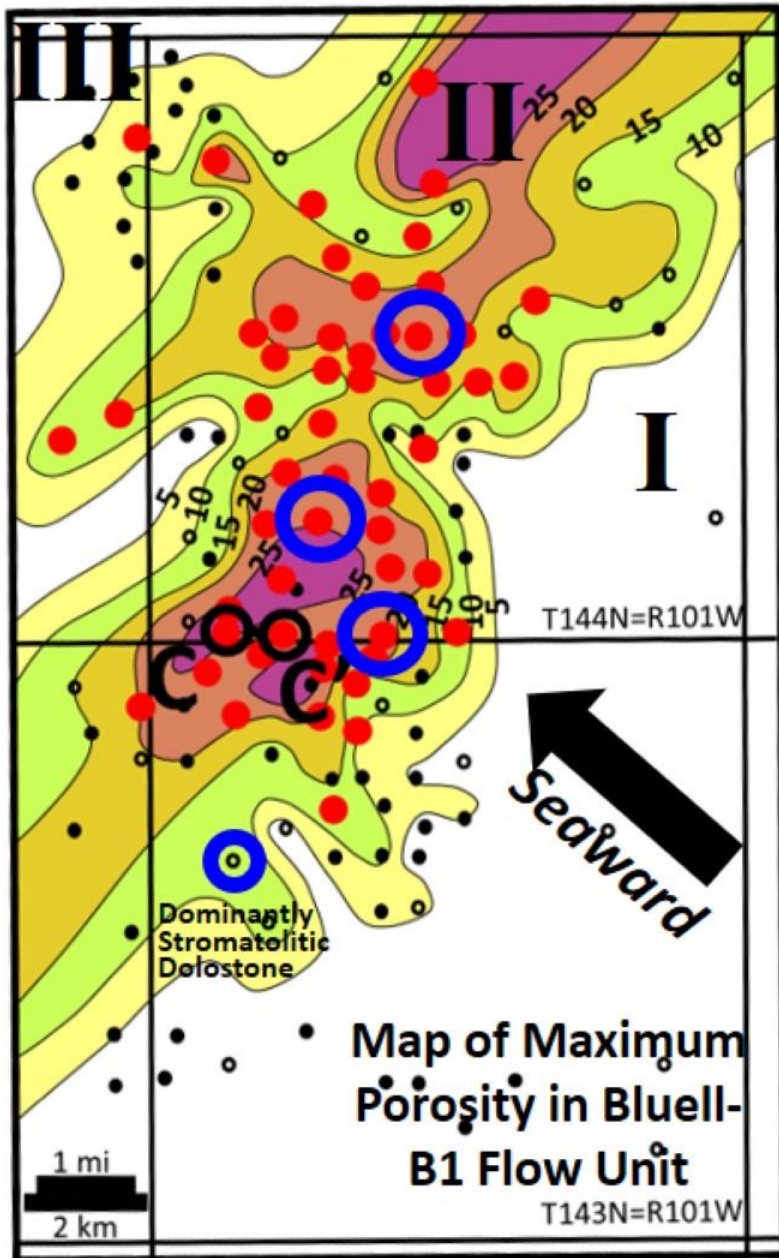
<u>Depth</u>	<u>Ka</u>	<u>Porosity</u>
9290-91	0.4	0.11
9291-92	11.1	0.26
9292-93	0.5	0.15
9293-94	15.6*	1.7*
9294-95	0.5	0.50
9295-96	4.4	0.17
9296-97	15.6*	3.5*
9297-98	18.0*	14.*
9298-99	16.4*	20.*
9299-00	0.4	0.06
9300-01	0.4	0.46
9301-02	0.5	0.08

* = Average of 3-5 plugs/foot (2" diameter)
 used for routine and special core analysis
 testing

Facies II Data: 144-101-29 SE; Hamilton #3-29 (NDIC #9182)



IP (1985): 20 BOPD & 70 BWPD
(stabilized 30-day average)
Cum: 36 MBO
Abandoned 1991



Bluell-B1 Flow Unit Maximum Porosity*

● = B1 Producer

○ = Core Displays

○ = Core; No Display

∞ = Cross section C-C'

* Maximum porosity = maximum CNL porosity (\emptyset_N); this is for facies II only and is caused by thin-bed effect and lithology characteristics in this facies

Blueell B1 Flow Unit

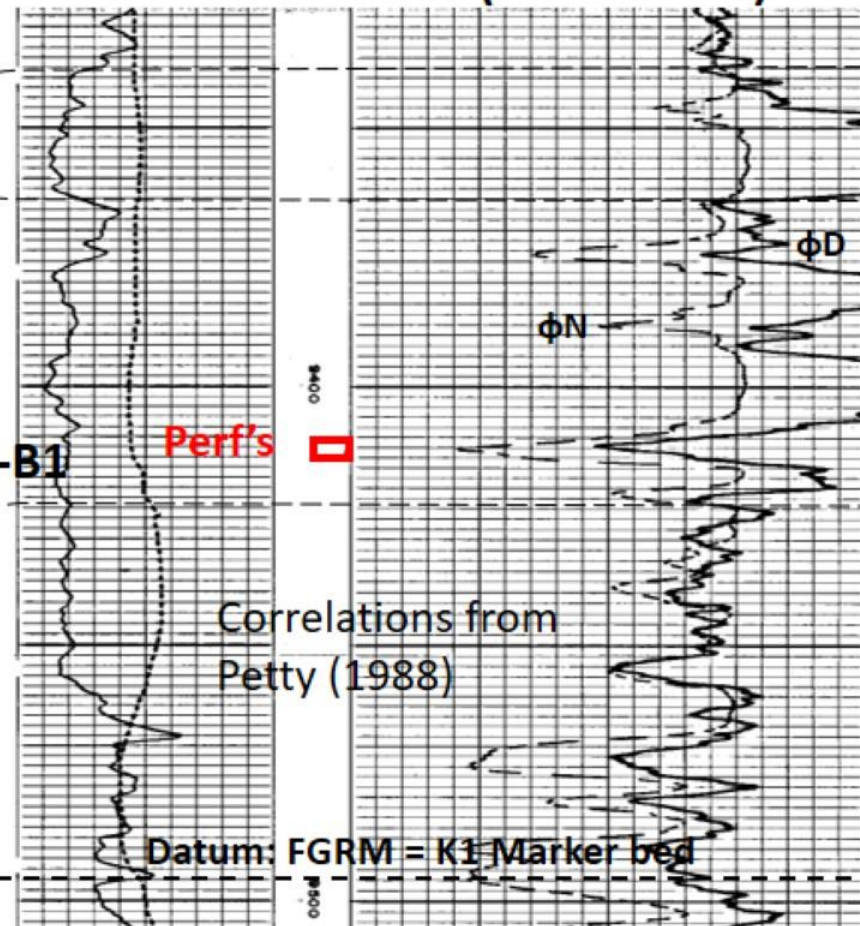
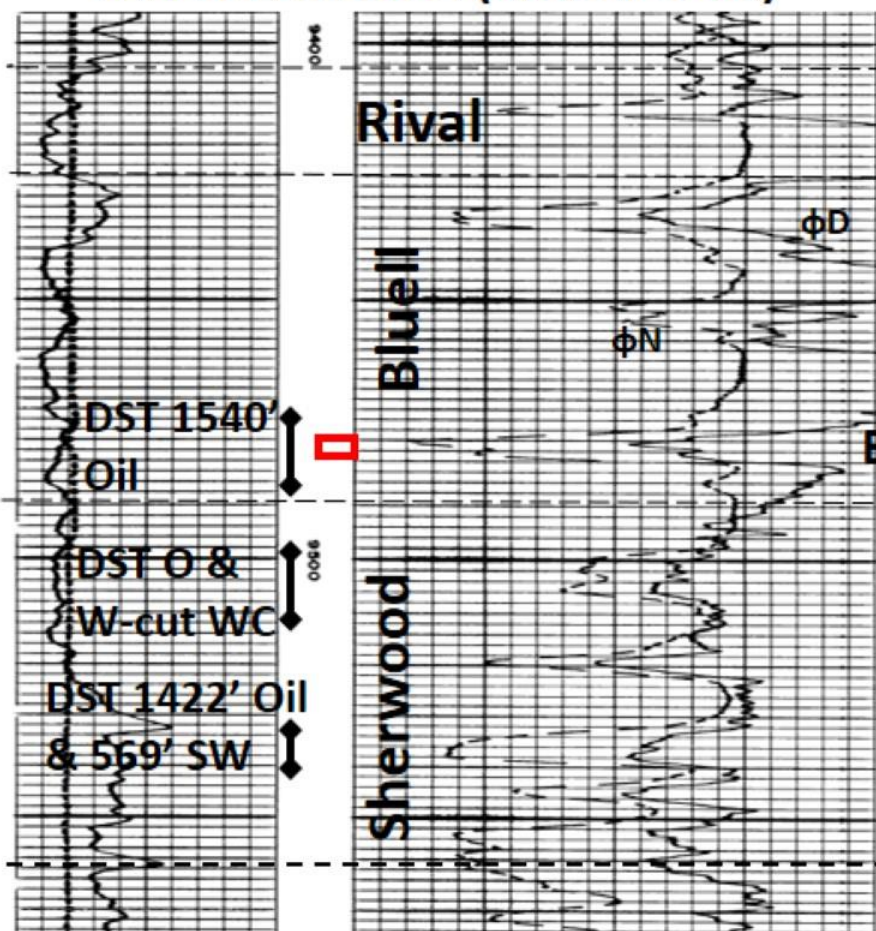
Selected B1-Only Completions

C

C'

144-101-31 SESE (NDIC # 5554)

144-101-32 SESW (NDIC #5423)



IP 1975: 346 BOPD & 26 BWPD (30-day)

IP 1974: 257 BOPD & 104 BWPD (30-day)

Cum 518 MBO & 166 MBW(1996)

Cum 518 MBO & 450 MBW (1998)

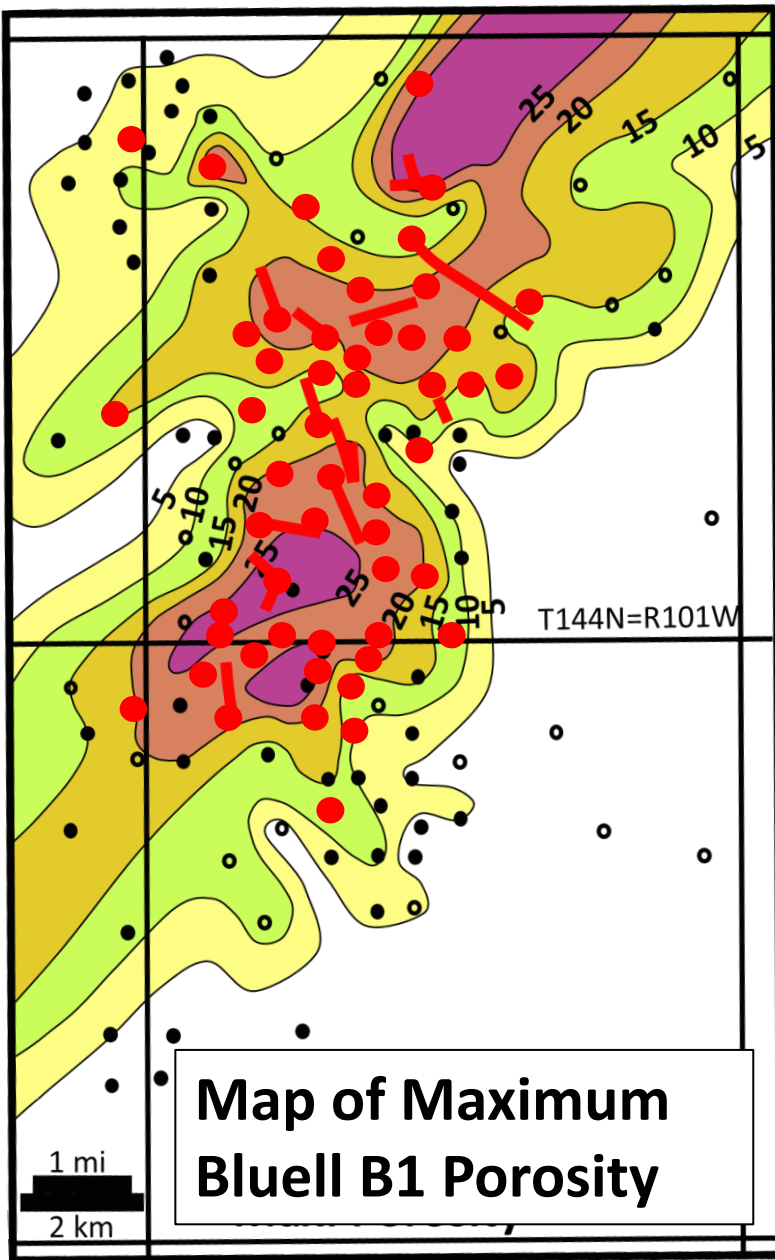
Correlations from
Petty (1988)

Datum: FGRM = K1 Marker bed

Elkhorn Ranch Field Blueell-B1 Flow Unit Development

- = Blueell-B1 Vertical Completion
- = Blueell-B1 Horizontal Completion

- Vertical development during 1970's-1980's; some individual B1 completions produced >500,000 BO
- 3 new-drill horizontal wells drilled 1997-2013 with average production of 397 MBO as of mid-2021
- 9 re-entry horizontal wells drilled 2006-2007 with average production of 198,000 as of mid-2021



Facies III

Barrier Bar-Island/Shoal Complex

**Skeletal*-Oolitic-Pisolitic-Intraclastic-Peloidal
Grainstone & Packstone**

Skeletal* =

**Calcareous Algae & Calcimicrobial Grains Landward
Open-Marine Grains Seaward**

Limestone Flow Units

Cores

Hicks #1, 151-102-6 N2SW (NDIC #10536): 9470-9502'


Iverson #1A, 151-103-1 NWNE (NDIC #10942): 9425-9450'

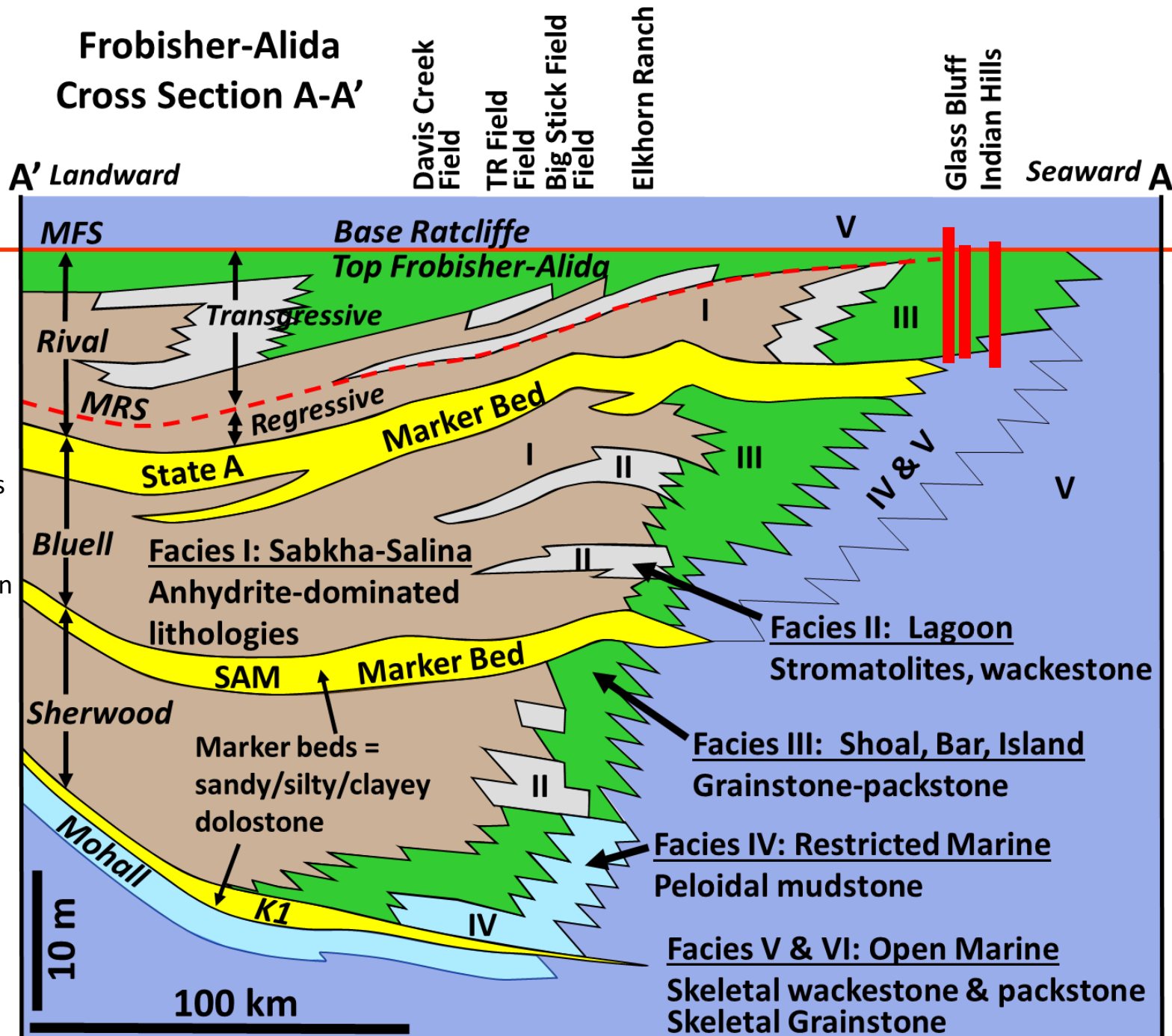
Deer Pass #20-1, 153-101-20 SESW (NDIC #10431): 9060-9090'

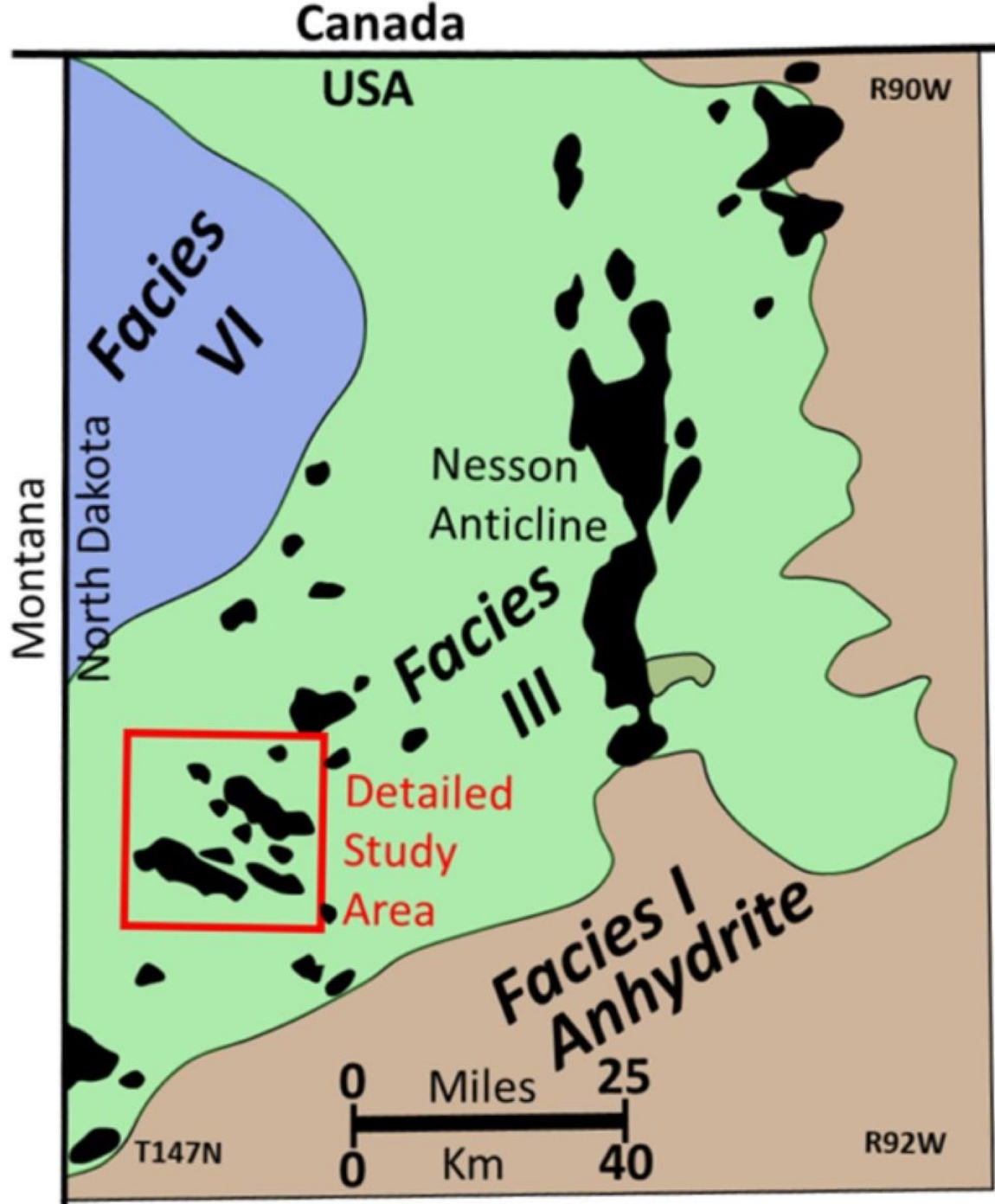
Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)

Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

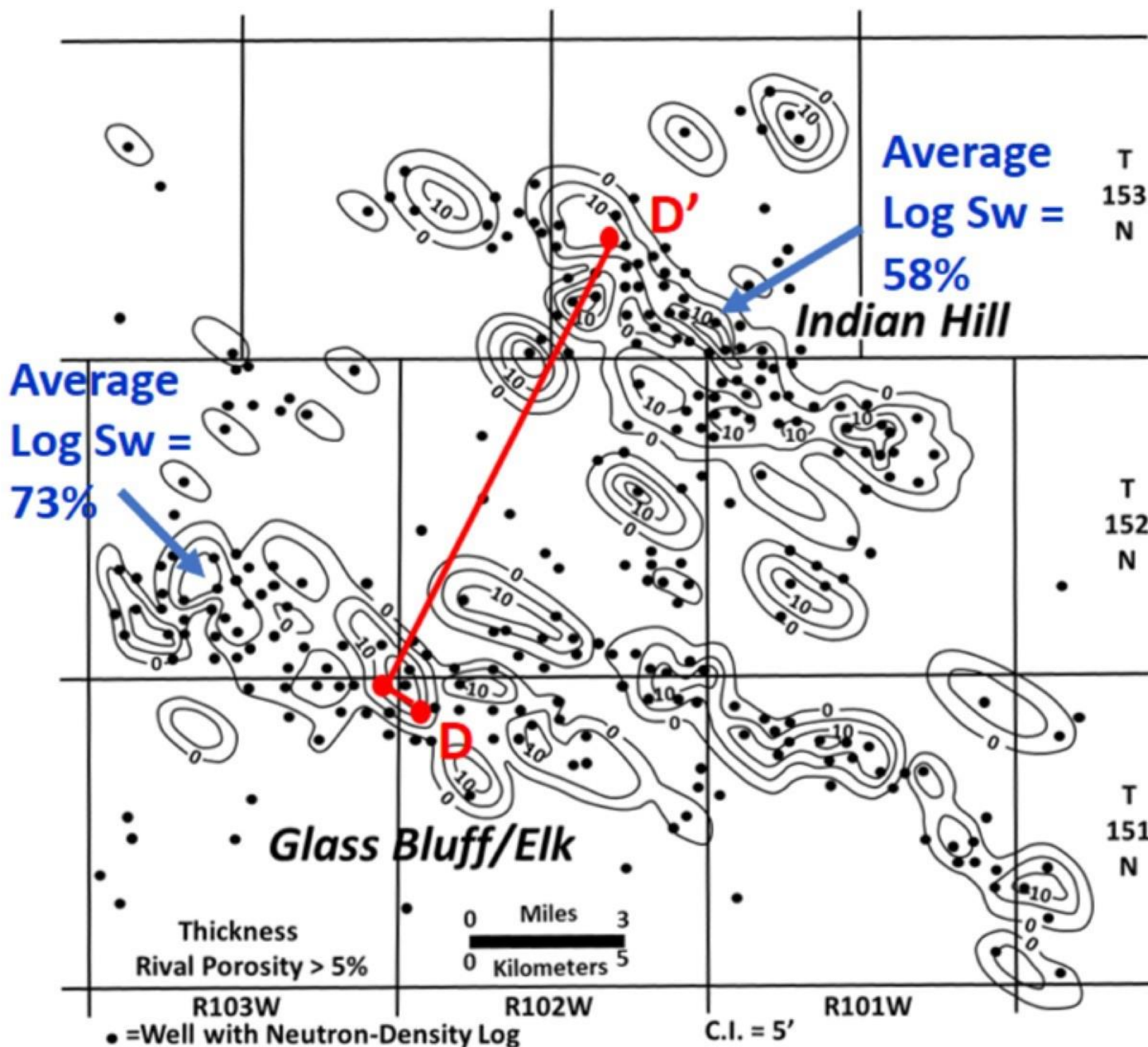
 = Location of facies III cores





Rival Subinterval Regressive Portion Paleogeography

 = Rival production



**Rival
Subinterval**

**Porosity
Thickness
>5%**

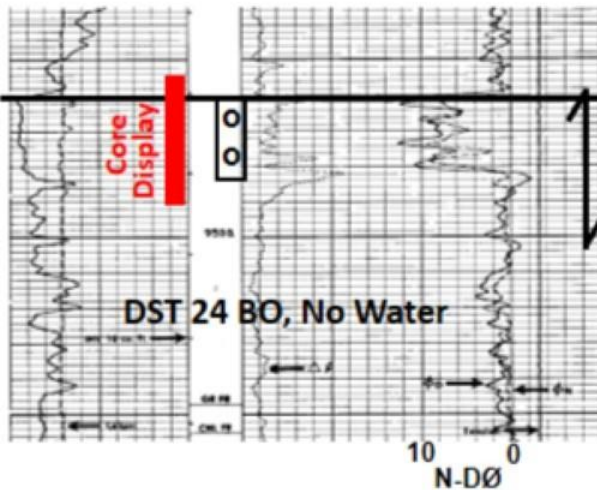
C.I. = 5'

*This map
constructed in
mid-1990's;
Not updated*

Cross Section C-C': Glass Bluff/Elk Field/Indian Hill

D

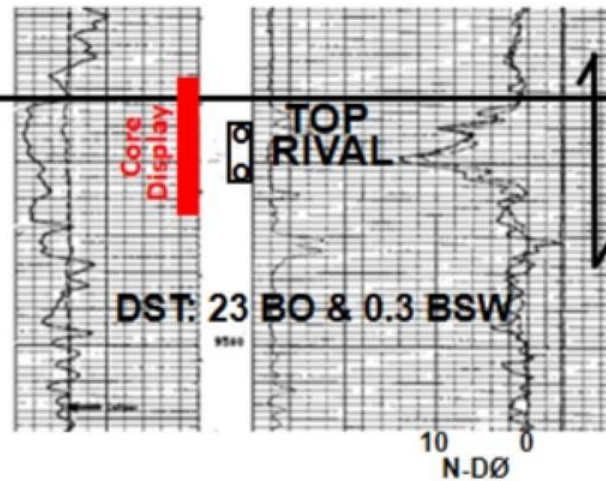
Hicks #1
SW Sec. 6, T151N-R102W
NDIC #10536



IP 112 BOPD, 0 BWPD
Cum 190 MBO & 245 MBW
commingled w/ Ratcliffe

Note: this well has average reservoir quality

Iverson #1A
NE Sec. 1, T151N-R103W
NDIC #10942

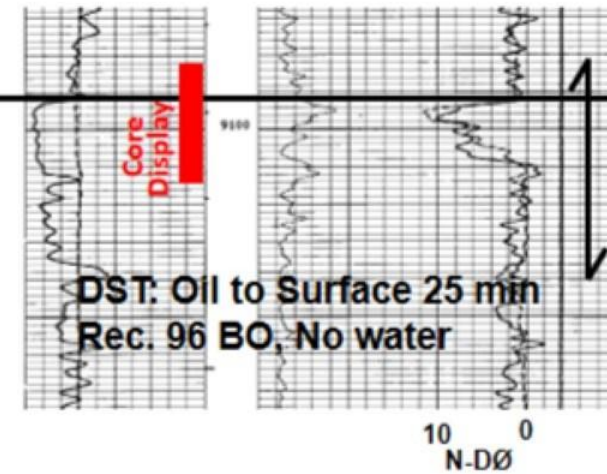


IP 200 BOPD, 3 BWPD
Cum 348 MBO & 144 MBW

Note: this well has best reservoir quality (core Ka & SW) in Glass Bluff-Elk fields

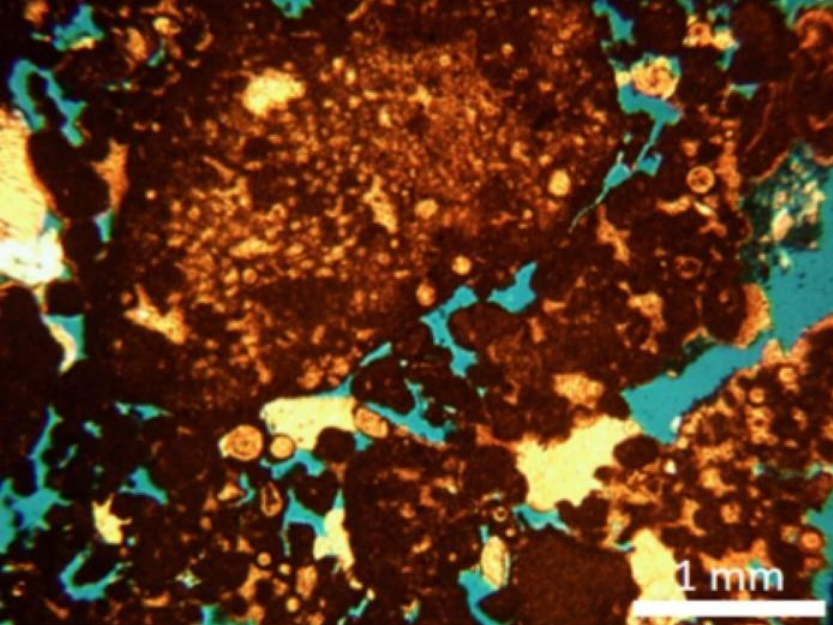
D'

Deer Pass 20-1
SESW Sec. 20, T153N-R101W
NDIC #10431

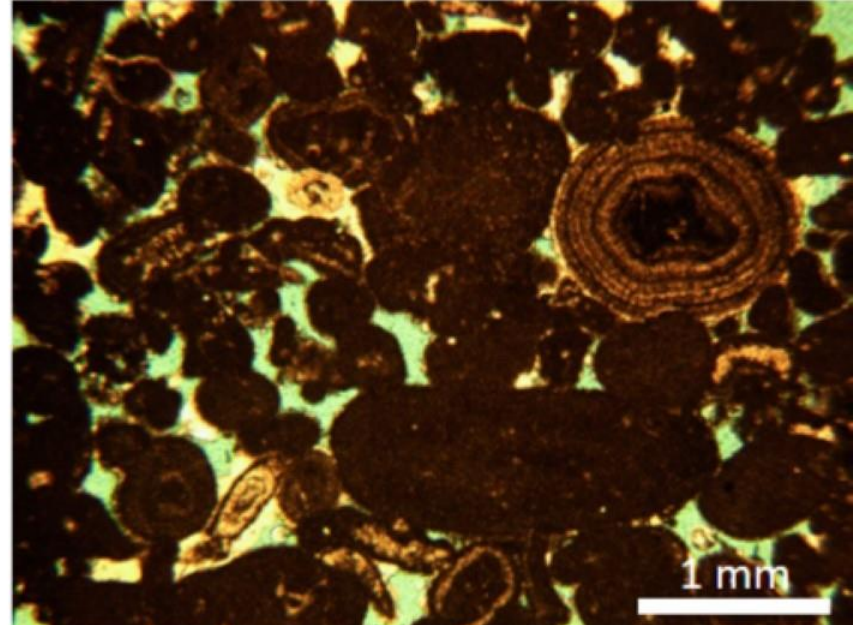


Competed in Red River
Twin Well Rival Completion:
30-day IP: 411 BOPD & 1 BWPD
Cum 784 MBO, 63 MBW

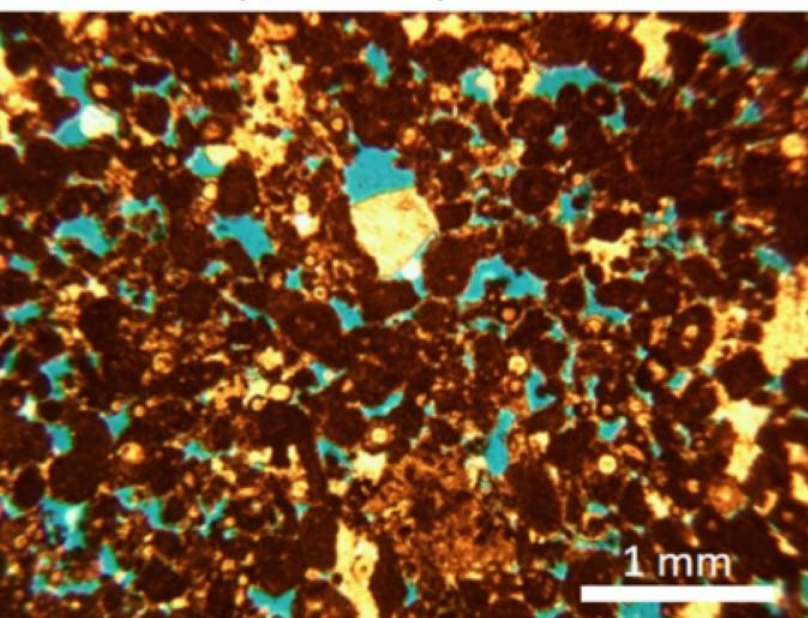
Note: this well has the best reservoir quality (core Ka and Sw) in Indian Hill Field



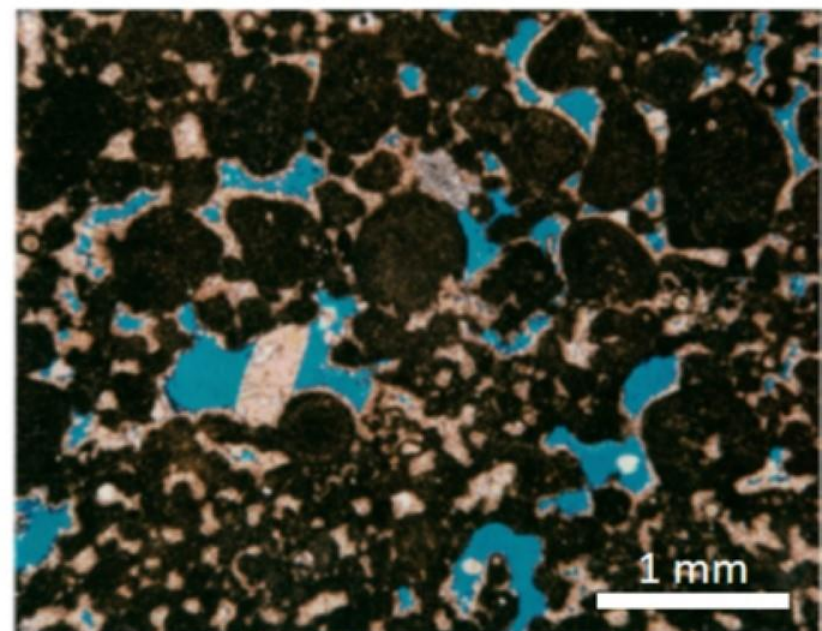
Deer Pass 20-1, 153-101-20 SESW
9071', $\phi = 10.3\%$, $K_a = 304$ md



Iverson #1A, 151-103-1 NWNE
9444', $\phi = 10.7$, $K_a = 104$ md



Deer Pass 20-1, 153-101-20 SESW
9072'; $\phi = 11.7\%$, $K_a = 62$ md



Deer Pass 20-1, 153-101-20 SESW
9076'; $\phi = 7.9\%$, $K_a = 8.6$ md

**Hicks #1,
151-102-6 NESW**

**Poorly connected
Fenestral porosity;
Micritized matrix**

**$\emptyset = 10.4\%$,
 $K_a = 0.2$ md**

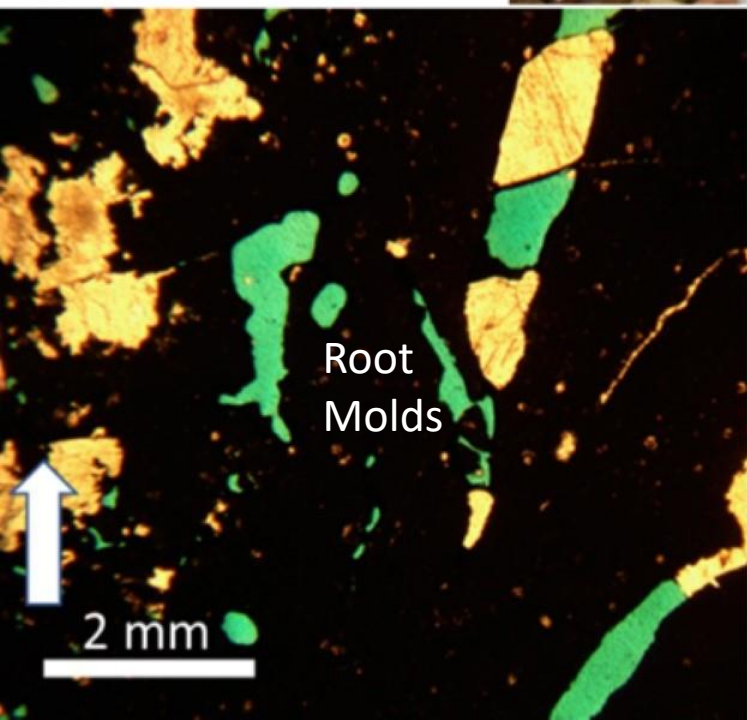


Root
Molds



Root
Mold

9477



Root
Molds

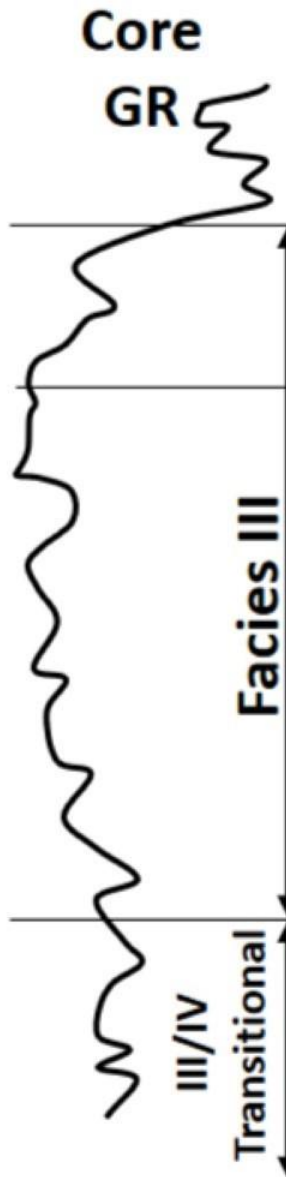
2 mm

Photograph
from NDIC

Iverson 1A

151-103-1 NWNE

NDIC #10942

Core GR	Depth	Porosity	Ka	
	9425-26	0.7	0.7	<u>9420-27.5</u> : basal Ratcliffe: black, argillaceous, open-marine skeletal wackestone; base is maximum flooding surface
	9426-27	0.6	0.01	
	9427-28	0.5	0.05	
	9428-29	1.7	0.02	<u>9427.5-32</u> : top Rival: peloidal-intraclastic packstone/grainstone; abundant cemented and sediment-filled fenestral pores; low porosity due to equant calcite cementation
	9429-30	4.0	0.02	
	9430-31	4.2	0.02	
	9431-32	3.4	0.02	
	9432-33	5.8	28.	<u>9432-45</u> : Rival reservoir; peloidal-intraclastic-microbial grainstone and packstone; locally oolitic; abundant <i>Ortonella</i> packstone (Locklin and Damp, 1995); early bladed and equant cement prevented compaction and preserved primary interparticle pores in samples with good permeability; early equant cement completely occluded porosity locally
	9433-34	8.9	1.5	
	9434-35	11.1	0.01	
	9435-36	5.8	0.01	
	9436-37	8.2	0.01	
	9437-38	8.2	0.01	
	9438-39	10.8	5.70	
	9439-40	11.0	3.00	
	9440-41	10.3	6.30	
	9441-42	13.2	10.	
	9442-43	8.5	0.18	
	9443-44	10.7	104.	
	9444-45	8.1	18.	<u>9445-50</u> : skeletal-peloidal grainstone/packstone/wackestone; no visible porosity in thin section; lack of early cement allowed compaction to destroy interparticle porosity
	9445-46	5.7	0.01	
	9446-47	7.9	0.01	
	9447-48	6.2	0.01	
	9448-49	4.7	0.01	
	9449-50	2.5	0.01	

Hicks #1

151-102-6 N2SW

NDIC #10536

Facies III

Transitional

Depth	Porosity	Ka
9470-71	1.2	0.03
9471-72	1.5	0.01
9472-73	1.6	fr
9473-74	1.5	0.01
9474-75	1.1	0.01
9475-76	9.1	1.5
9476-77	10.4	0.2
9477-78	6.6	0.01
9478-79	4.6	0.01
9479-80	7.2	0.31
9480-81	10.2	7.0
9481-82	10.3	2.4
9482-83	9.1	1.8
9483-84	8.4	0.45
9484-85	7.3	0.30
9485-86	8.0	0.14
9486-87	9.0	0.23
9487-88	11.0	0.47
9488-89	9.7	0.98
9489-90	6.1	0.01
9490-91	7.8	0.01
9491-92	7.8	10.0 ??
9492-93	4.6	0.09
9493-94	2.0	0.01
9494-95	1.3	0.01
9495-96	1.0	0.01
9496-97	0.7	0.01
9497-98	2.1	0.07
9498-99	0.9	0.01
9499-00	0.9	0.01
9500-01	0.9	0.01
9501-02	0.9	0.01

9455-74: basal Ratcliffe: black, argillaceous, open-marine skeletal wackestone; base is maximum flooding surface

9474-75: top Rival: calcite-cemented peloidal packstone

9475-76: skeletal-oolitic-peloidal grainstone; interparticle porosity

9476-94: microbial-intraclastic-peloidal grainstone and packstone with fenestral and interparticle porosity; best permeability occurs in calcite cement-reduced interparticle porosity

9494-9502: skeletal-peloidal grainstone/packstone/wackestone; compaction has destroyed interparticle porosity

Deer Pass 20-1

153-101-20 SESW

NDIC #10431

Core
GR

Facies III

III/IV
Transitional

Depth	Porosity	Ka
9060-61	1.1	-
9061-62	1.1	0.01
9062-63	1.7	0.01
9063-64	1.0	0.24
9064-65	0.7	0.01
9065-66	1.1	0.01
9066-67	1.3	0.01
9067-68	3.0	0.01
9068-69	6.6	49.
9069-70	9.3	18.
9070-71	10.3	304.
9071-72	11.7	62.
9072-73	9.0	6.60
9073-74	7.4	0.01
9074-75	8.1	0.17
9075-76	8.2	5.30
9076-77	7.9	8.60
9077-78	5.6	0.01
9078-79	3.7	0.03
9079-80	7.5	20. ??
9080-81	4.7	0.01
9081-82	2.4	0.01
9082-83	3.0	0.65
9083-84	2.2	0.01
9084-85	1.4	0.01
9085-86	0.3	0.01
9086-87	0.3	0.01
9087-88	0.4	0.01
9088-89	0.3	0.01
9089-90	0.4	0.01

9060-68: basal Ratcliffe: black, argillaceous, open-marine skeletal wackestone; base is maximum flooding surface

9068-77: microbial-intraclastic-oolitic-peloidal grainstone with fenestral and interparticle porosity; best permeability occurs in calcite cement-reduced interparticle porosity

9077-81: microbial-intraclastic-oolitic-peloidal grainstone with fenestral and interparticle porosity occluded with coarse, late calcite and saddle dolomite

9080-90: skeletal-peloidal grainstone/packstone/wackestone; compaction has destroyed interparticle porosity

Facies IV

Restricted-Marine Facies

**Burrowed, Sparsely Fossiliferous, Peloidal
Mudstone-Wackestone**

Dolostone Flow Units

Cores


State #32-33, 139-100-32NWSE (NDIC #12430): 9276-9302'

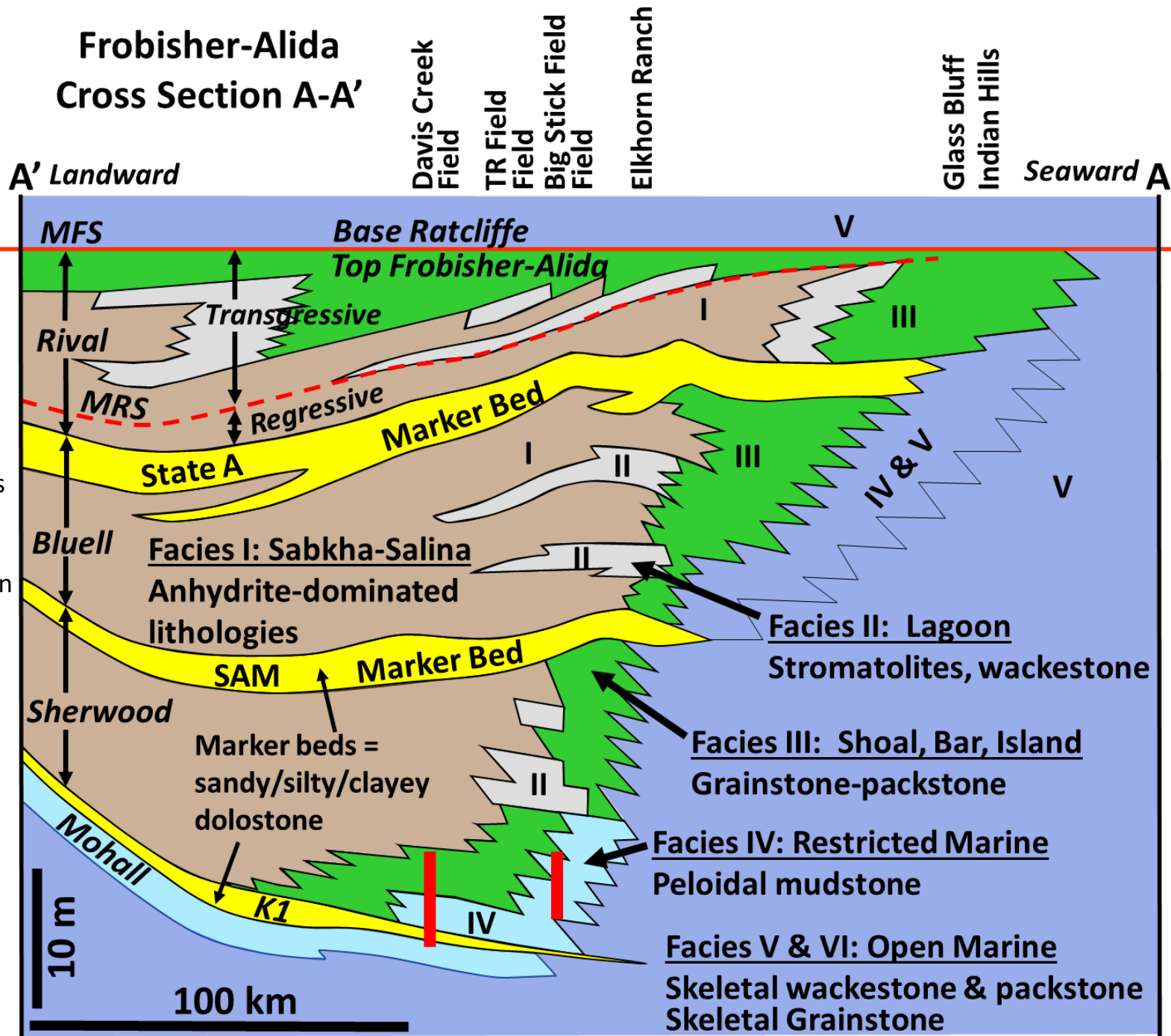
David 1-25, 142-101-25 SWNE (NDIC #7273): 9410-9430'

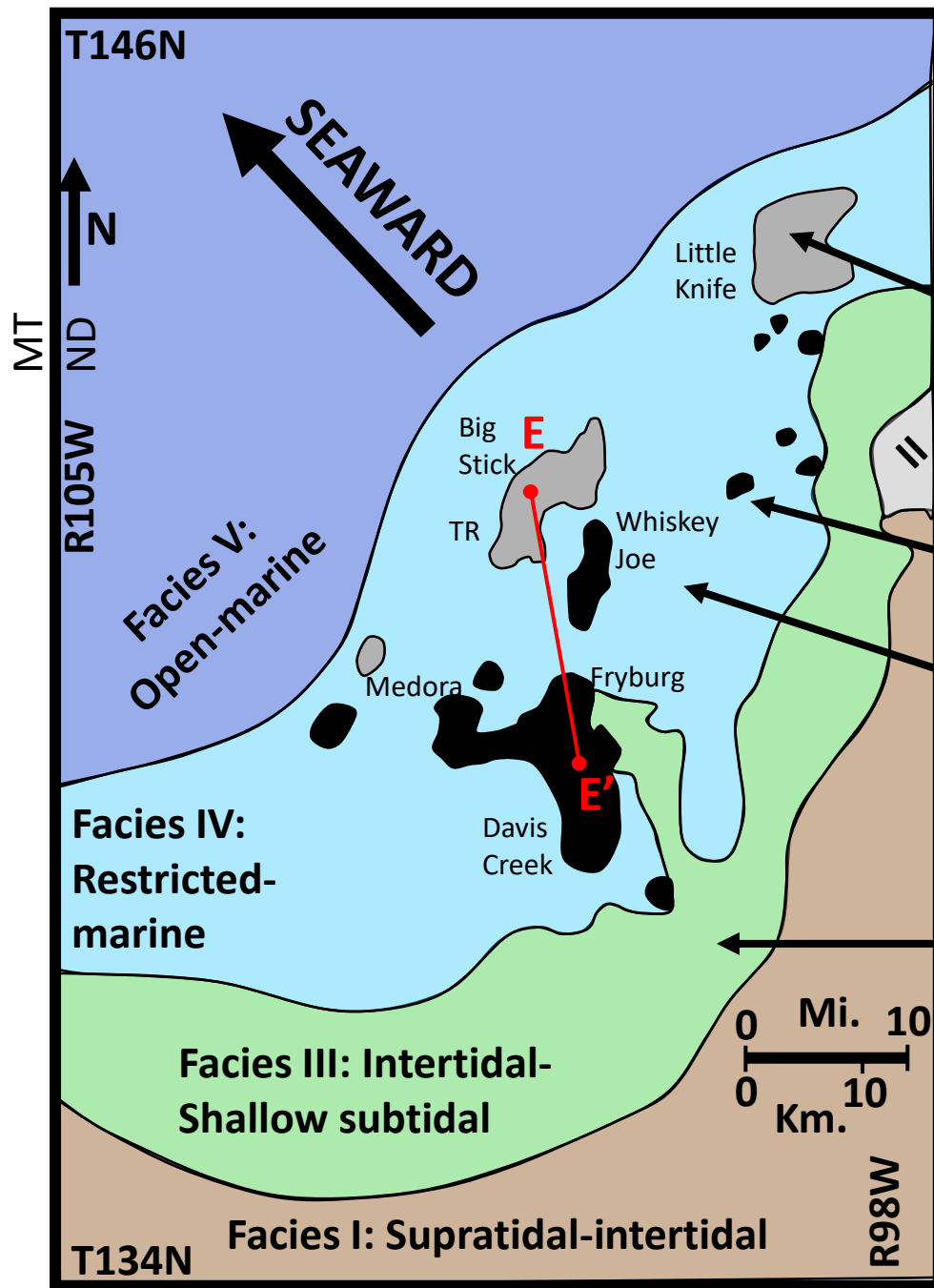
Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)

Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

 = Location of facies IV cores





Sherwood-E Facies Southwest North Dakota

Modified from Petty (1996, fig. 17)

Grey = Oil fields with secondary or minor production from Sherwood-E

Black = oil fields with Sherwood-E as main flow unit

Restricted-marine conditions induced by saline waters that stressed environment

Low-relief, intertidal to shallow subtidal shoal-barriers allowed high-saline waters formed in sabkha-salina to flow seaward (suggested by Fischer et al., 1987)

E

Stratigraphic Cross Section E-E'

E'

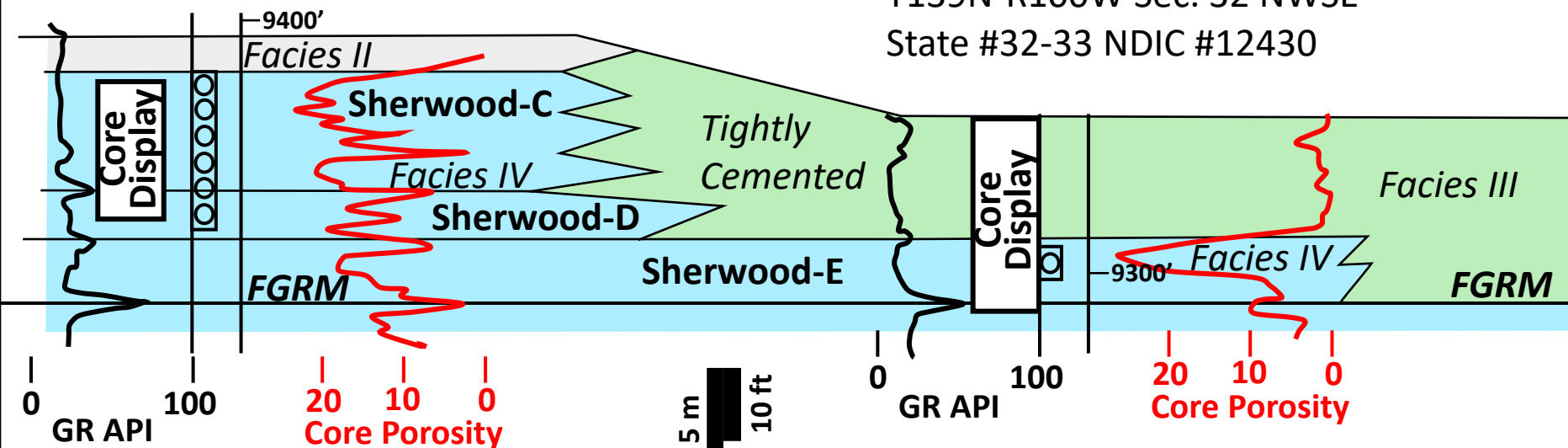
T142N-R101W Sec. 25 SWNE

David #1-25 NDIC #7273

Landward (Updip) →

T139N-R100W Sec. 32 NWSE

State #32-33 NDIC #12430



30-day IP: 1,732 BOPD & 0 BWPD

Cum: 1,062,790 BO & 413,983 BW

30-day IP: 58 BOPD & 23 BWPD

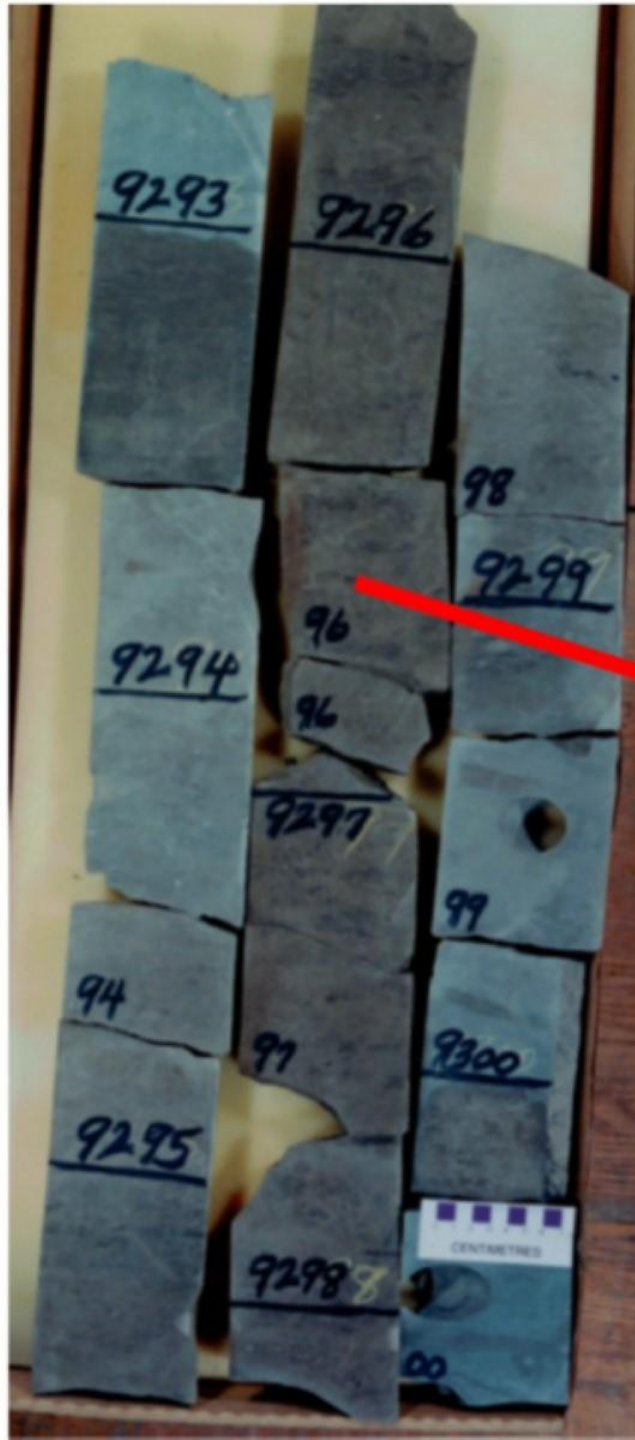
Cum: 203,467 BO & 371,702 BW

FGRM = Fryburg gamma-ray marker bed = K1 marker bed = base Sherwood

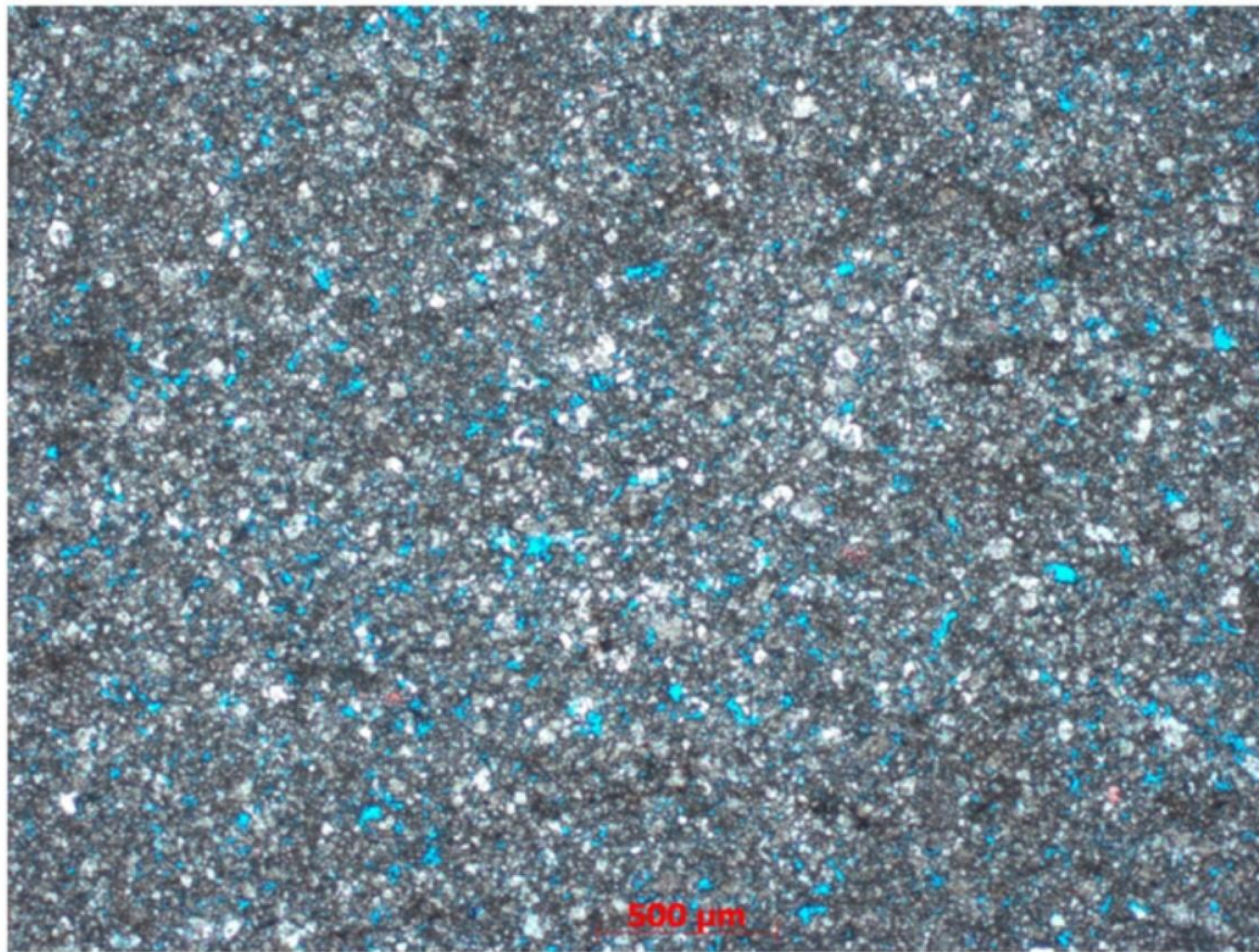
139-100-32; State #32-33

Sherwood-E Flow Unit: 9294-9299'

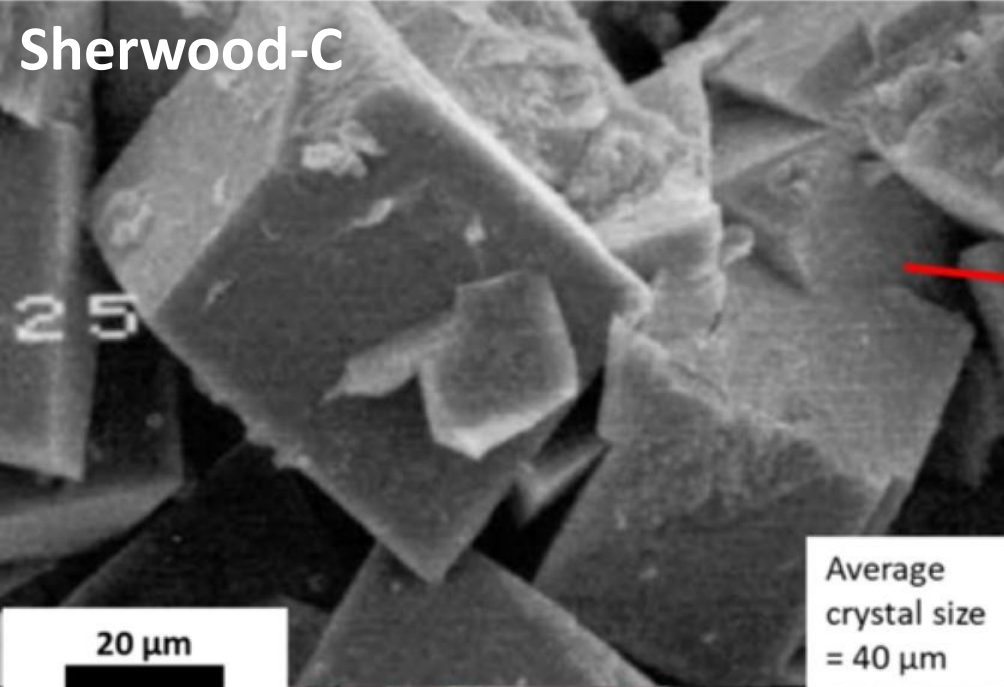
9296' ϕ = 26%; Ka = 21 md



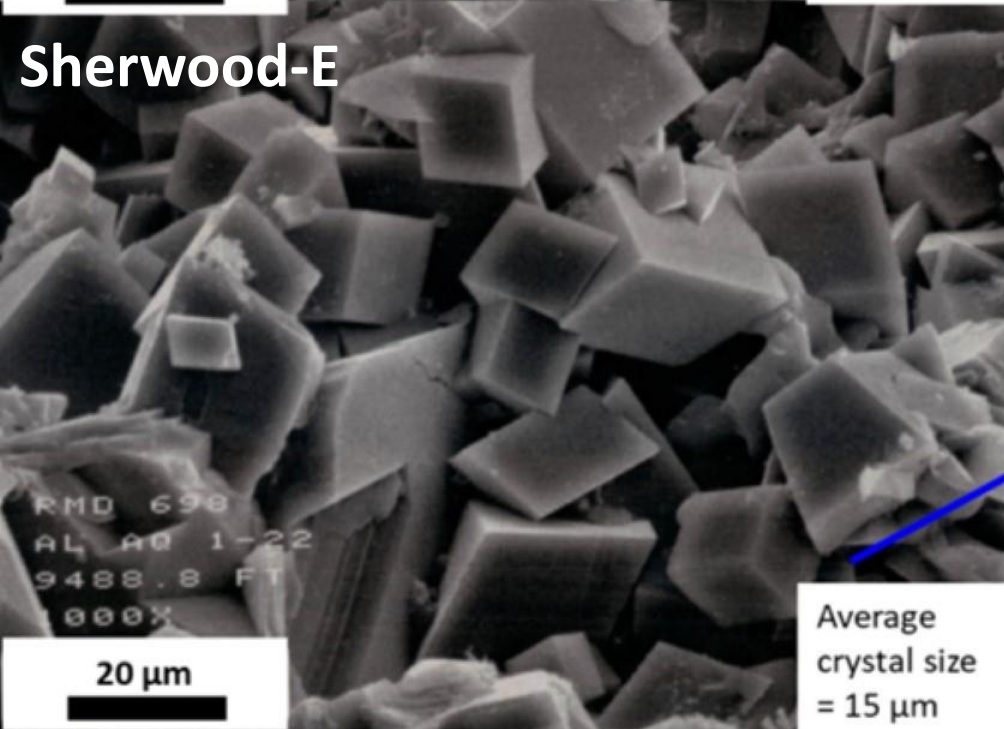
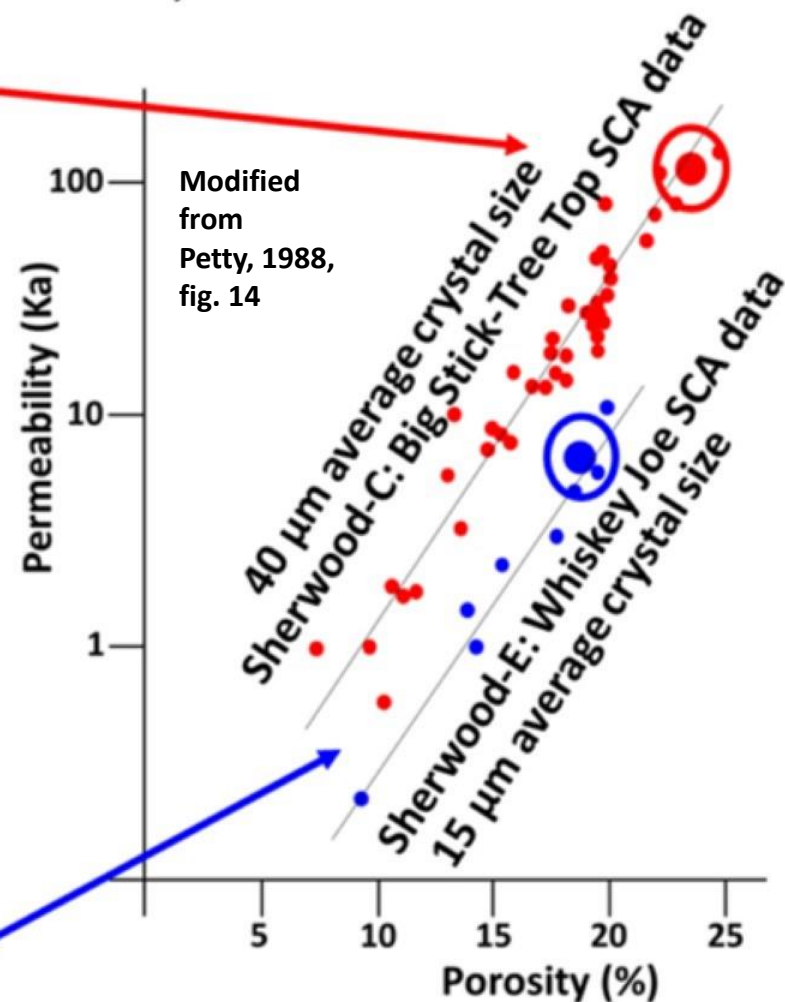
139-100-32; State #32-33
Sherwood-E Flow Unit: 9296'
9296' \varnothing = 26%; Ka = 21 md
Average crystal size \approx 15 μ m



500 μ m



David #1-25, 142-101-25 SWNE
 Sherwood-D; 9422'
 $\emptyset = 23.4\%$, $K_a = 113$ md



USA #1-22, 141-100-22 NENE
 Sherwood-E; 9488'
 $\emptyset = 18.8\%$, $K_a = 6.3$ md

David #1-25; 142N-101W, Sec. 25 SWNE; NDIC #7273

		Routine Core Analysis					Special Core Analysis					
		Permeability to air (md)				Type	Plug Data					
		<u>Depth</u>	<u>Max.</u>	<u>90 degree</u>	<u>Vertical</u>	<u>Porosity</u>	<u>Analysis</u>	<u>Depth</u>	<u>Porosity</u>	<u>Perm. (Ka md)</u>		
Sherwood-C Facies IV		9410-11	46		58	20.0	Plug		9410-11	19.5	30.0	
		9411-12	88		73	22.0	Plug					
		9412-13	48		41	18.3	Plug		9412.5	20.7	42.1	
		9413-14	122		169	23.1	Plug		9413.0	22.3	44.3	
		9414-15	220		195	235	17.8	W.C.		9413.5	21.0	17.6
		9415-16	327		325	386	19.5	W.C.		9415.0	22.9	73.9
		9416-17	36		27	15	10.8	W.C.				
		9417-18	69		64	67	17.2	W.C.		9417-18	24.7	129.0
		9418-19	80		73	26	18.0	W.C. VF		9418-19	19.2	22.0
		9419-20	1935		1.8	1094	2.6	W.C. VF				
		9420-21	254		126	64	19.0	W.C.				
		9421-22	514		503	436	20.1	W.C.		9421-22	24.4	109.6
		9422-23	697		503	630	21.6	W.C.		9422.0	23.4	113.0
		9423-24	752		641	547	19.9	W.C.		9422-23	21.0	80.5
Sherwood-D Facies IV		9424-25	0.29		2.8	13	17.9	W.C.				
		9425-26	287		260	132	16.6	W.C.				
		9426-27	0.16			36	6.7	Plug				
		9427-28	194		193	13	17.2	W.C.				
		9428-29	3.8			2.3	12.1	Plug				
		9429-30	17		17	11	10.3	W.C.				

Note: whole-core routine-core analysis permeability data is not valid

State #32-33; 139N-100W, Sec. 32 NWSE; NDIC #12430

<u>Depth</u>	<u>Ka</u>	<u>Ø%</u>		
9276.0- 77.0	<.01	0.6		
9277.0- 78.0	0.01	0.9		
9278.0- 79.0	<.01	0.7		
9279.0- 80.0	<.01	3.4		
9280.0- 81.0	0.12	4.9		Facies III
9281.0- 82.0	0.01	1.9		Limestone: medium-grained microbial-
9282.0- 83.0	<.01	1.9		intraclastic grainstone at top, transitional to
9283.0- 84.0	<.01	1.7		very fine grained, intraclastic-skeletal
9284.0- 85.0	0.42	0.8		grainstone at base
9285.0- 86.0	<.01	0.8		Low porosity; calcite-cemented
9286.0- 87.0	0.08	2.1		
9287.0- 88.0	<.01	0.8		
9288.0- 89.0	1.83	0.6		
9289.0- 90.0	1.55	0.7		
9290.0- 91.0	<.01	1.5		
9291.0- 92.0	<.01	1.7		
9292.0- 93.0	<.01	1.7		
9293.0- 94.0	0.72	9.6	Sherwood-E Flow Unit	Facies IV
9294.0- 95.0	1.78	17.7		Dolostone: sparsely fossiliferous, peloidal
9295.0- 96.0	6.29	21.9		mudstone-wackestone
9296.0- 97.0	20.5	26.1		Intercrystal porosity
9297.0- 98.0	10.4	21.8		
9298.0- 99.0	3.03	20.4		
9299.0- 00.0	0.12	8.9		
9300.0- 01.0	0.01	8.9	Top K-1	
9301.0- 02.0	0.01	7.4	Top Mohall	
9302.0- 03.0	<.01	6.0		

Facies V
Open-Marine (Low-Energy)
Skeletal Wackestone & Packstone


**Dolomitic Limestone and
Calcareous Dolostone Flow Units**

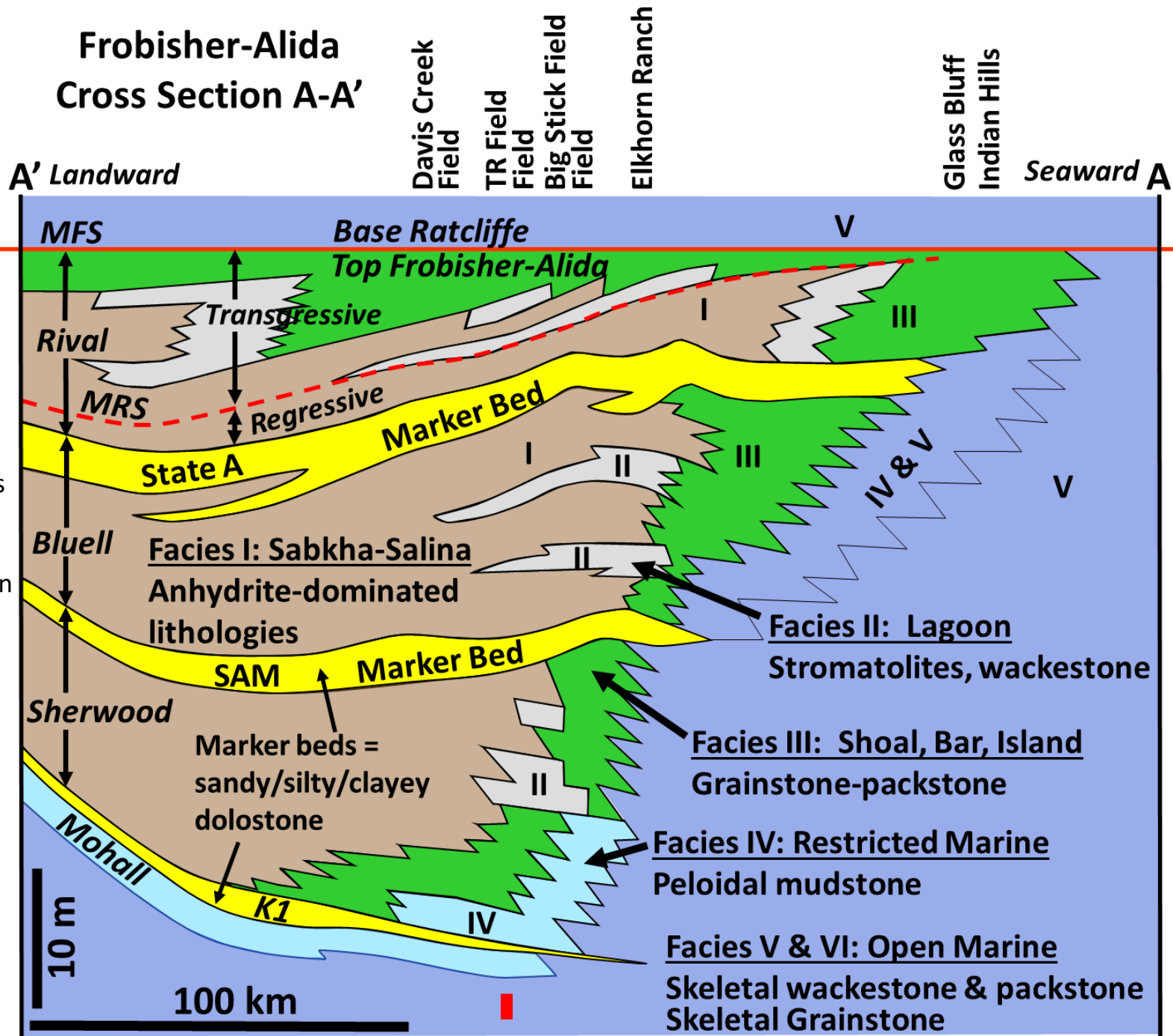
Core
State #4-23; 141-101-23 SESW (NDIC # 6701): 9173-9191'

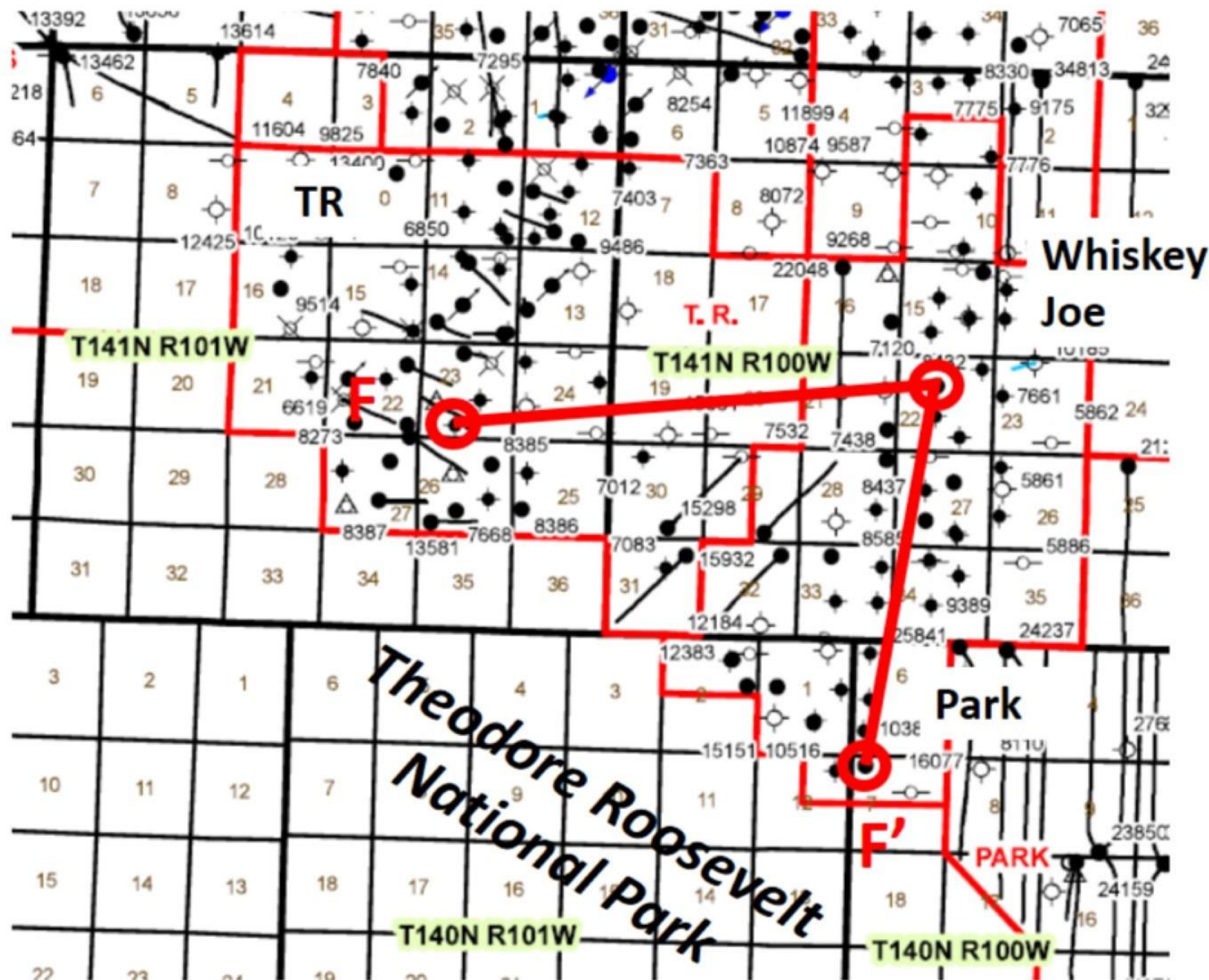
Frobisher-Alida Facies Model

Modified from cross sections in Petty (2010)

Rival, Bluell, Sherwood and Mohall correlations between north-central ND and southwest ND taken from LeFever and Anderson, 1989

 = Location of facies V core





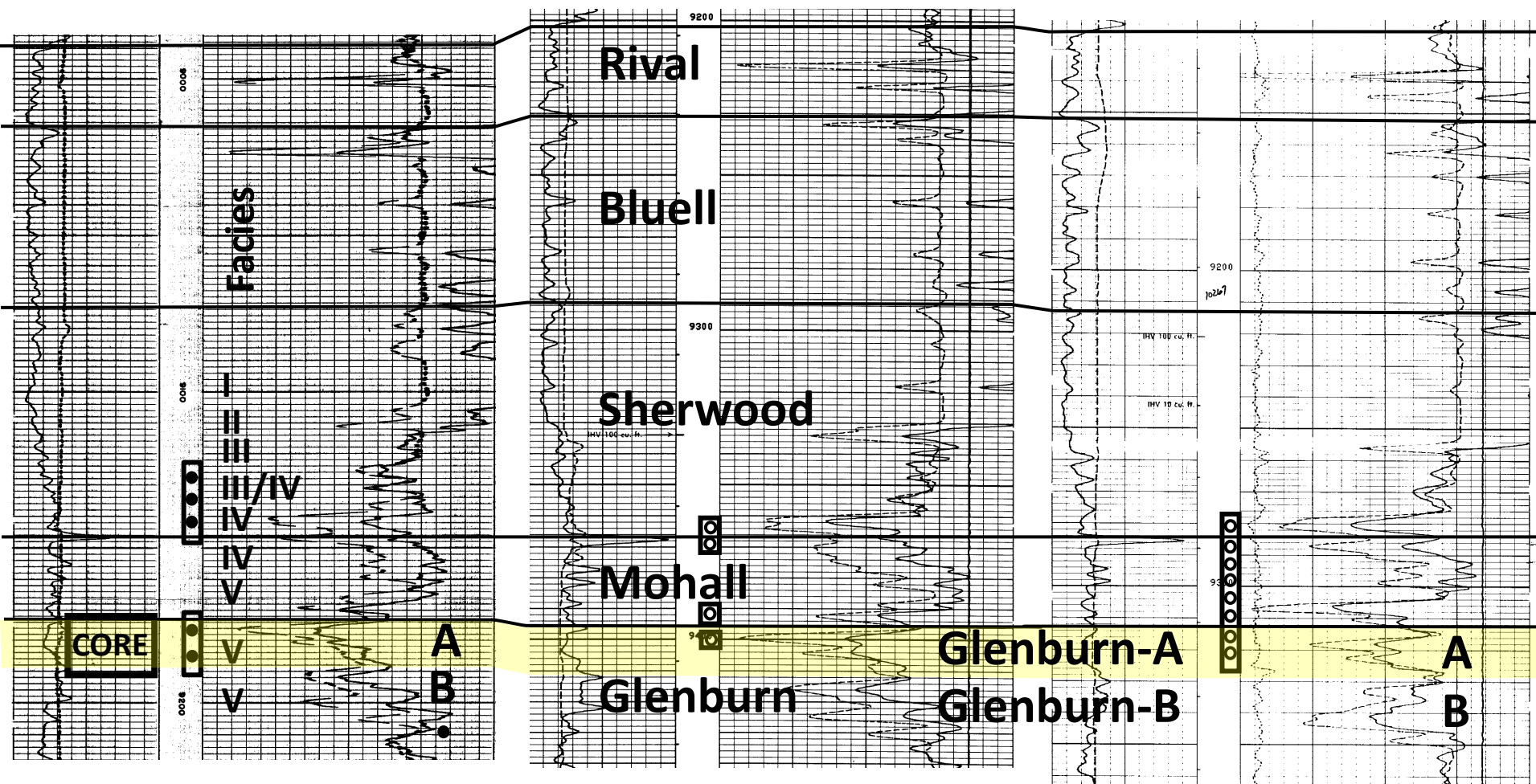
F

F'

State #4-23 NDIC #6701
141-101-23 SESW

141-100-22 SENW

140-100-7 NWNW



Cum 232 MBO &
1,185 MBW

Cum 337 MBO &
2,122 MBW

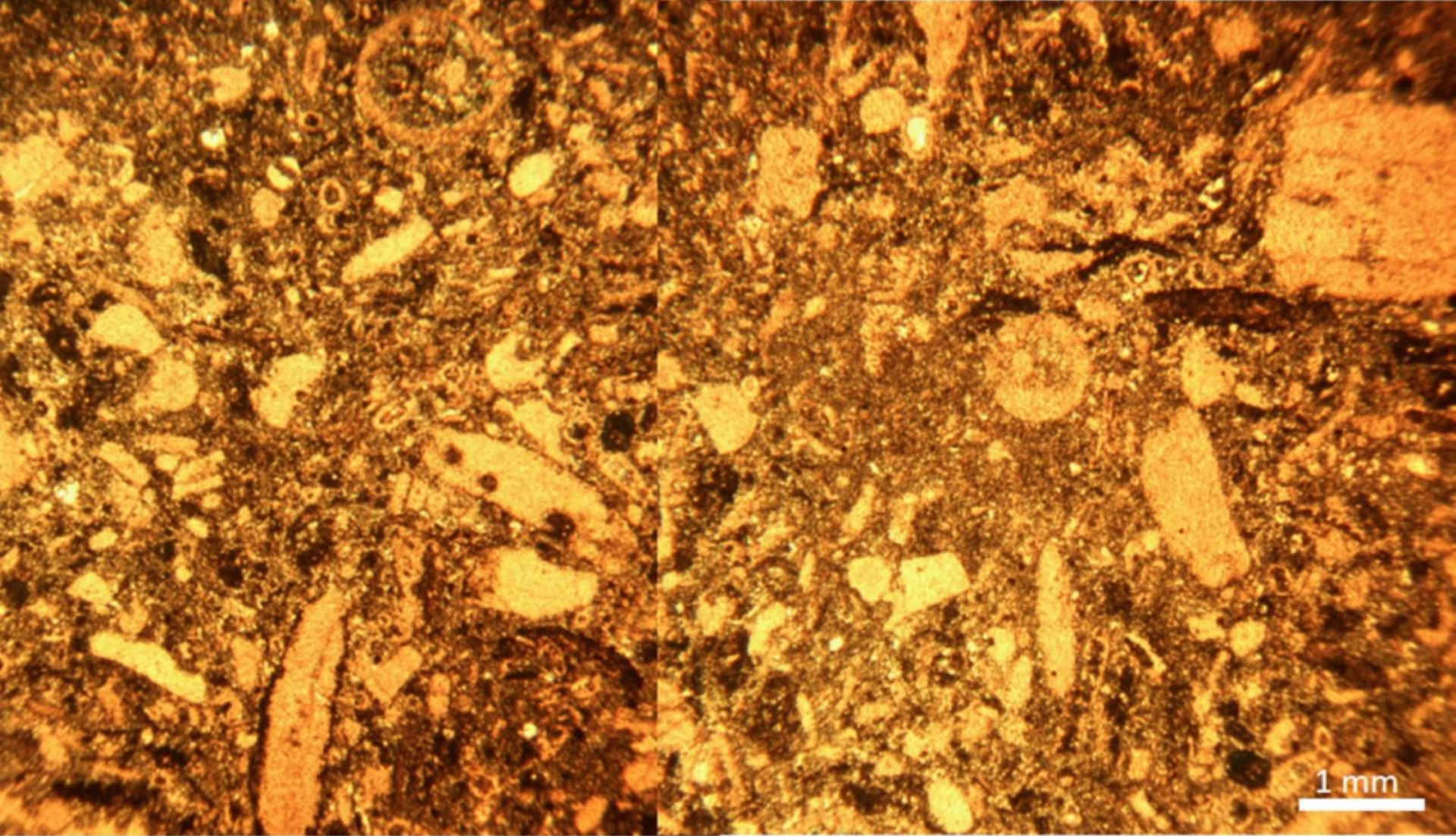
Cum 689 MBO &
936 MBW

Chambers #4-23 NDIC #6701
141-101-23 SESW

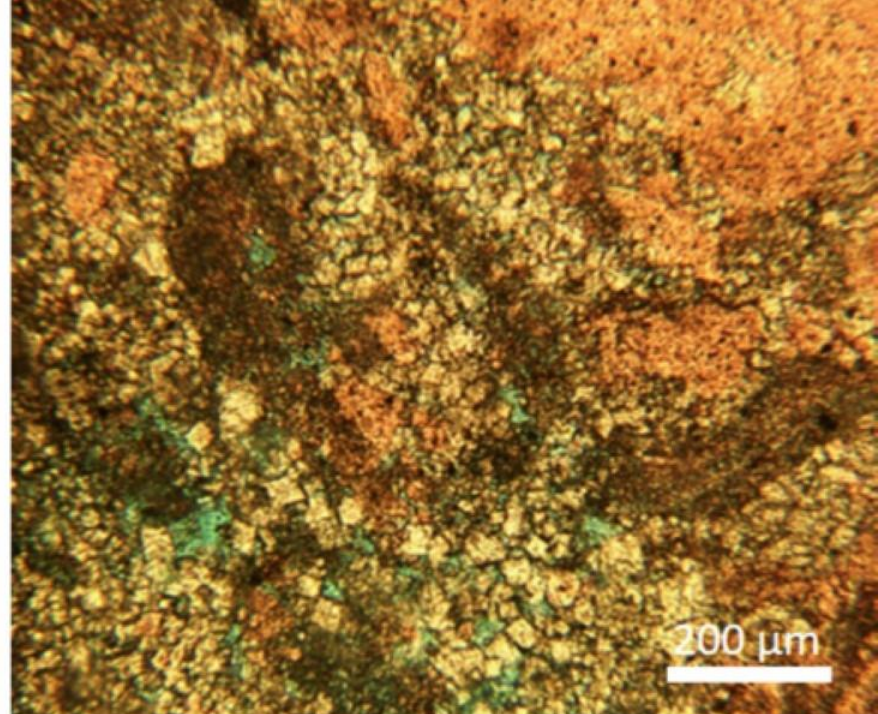
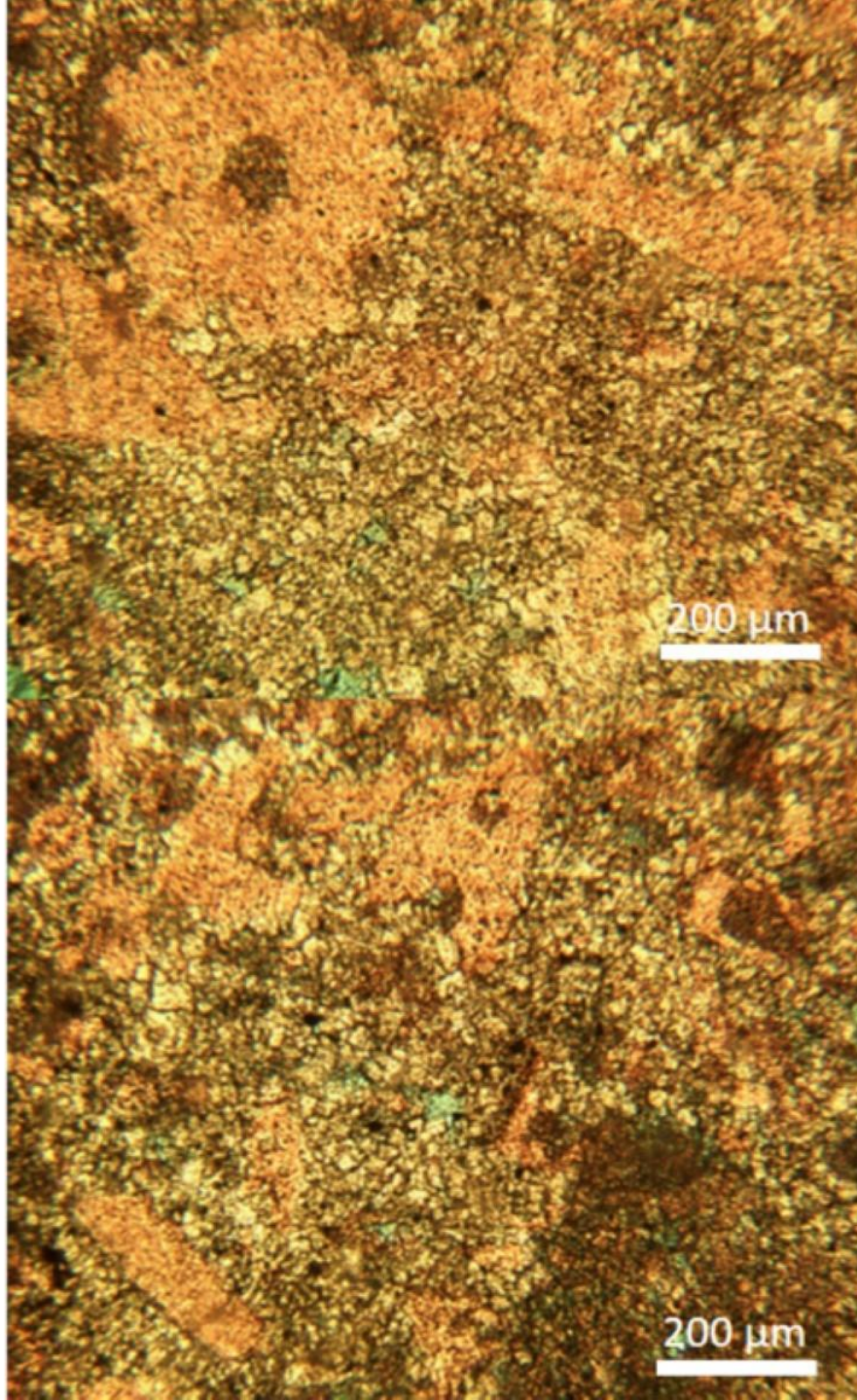
DEPTH	PERM. TO AIR (MD) MAX. 90 DEG. VERTICAL	FOR. FLD.
9174-75	0.05	6.6
9175-76	6.6	11.5
9176-77	10	10.5
9177-78	8.2	12.1
9178-79	9.1	17.0
9179-80	3.0	12.3
9180-81	5.5	14.9
9181-82	7.9	15.8
9182-83	1.7	10.9
9183-84	1.1	11.6
9184-85	0.91	10.0
9185-86	1.6	10.6
9186-87	0.60	10.2
9187-88	0.38	9.2
9188-89	0.51	9.0
9189-90	0.96	8.2

Sample with thin
section

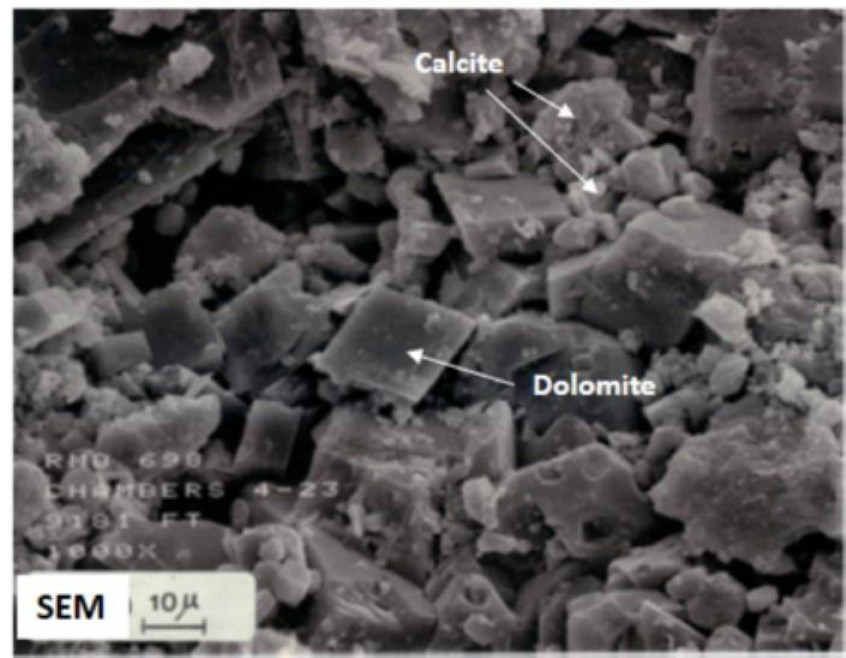
Glenburn-A



**Chambers #4-23 NDIC #6701
141-101-23 SESW
9181' Glenburn-A
 $\emptyset = 15.6\%$, $K_a = 3.3$ md (from SCA)**



141-101-23 SESW 9181'



Facies VI

Open-Marine (High-Energy)

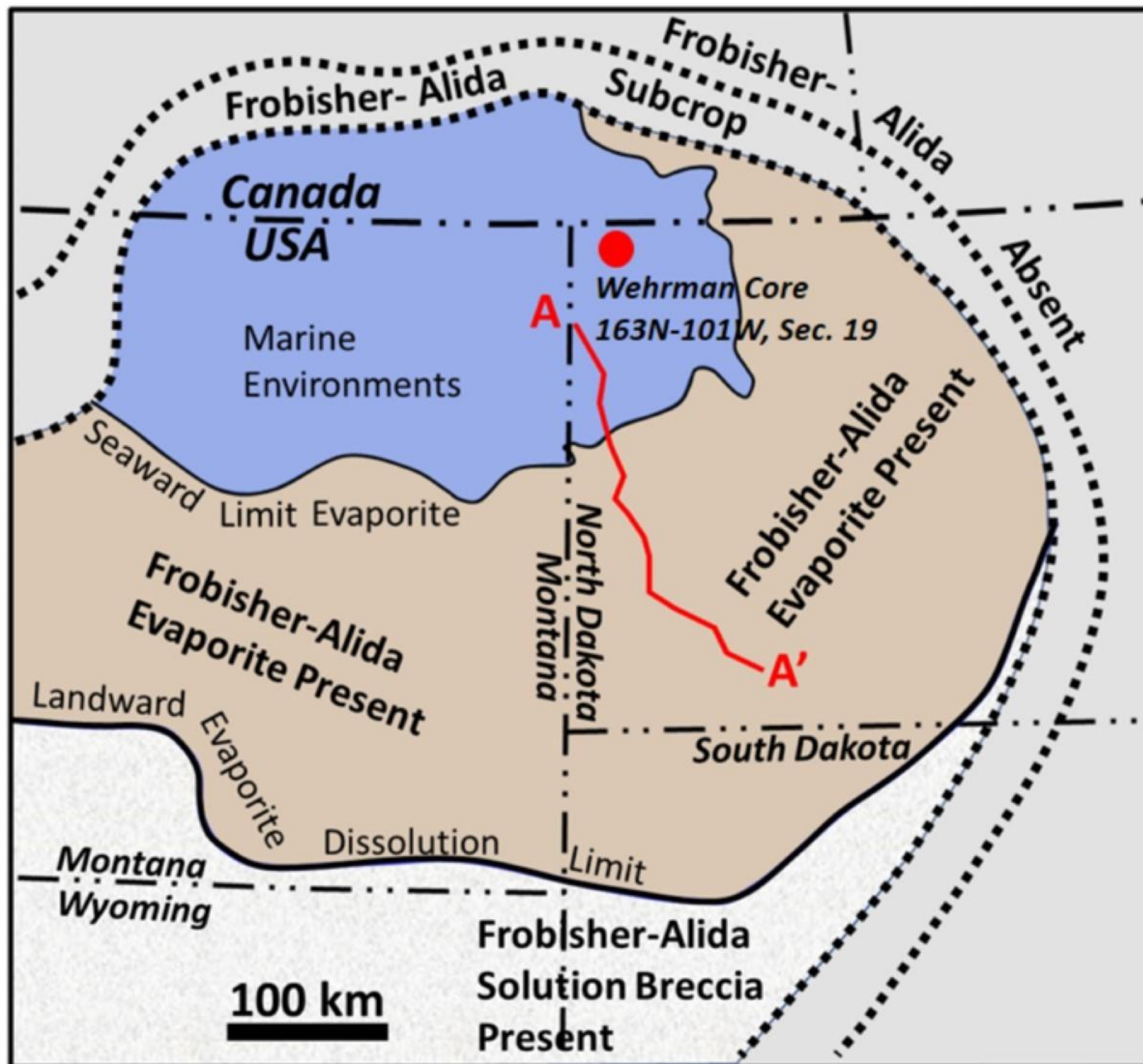
**Crinoid-Bryozoan Skeletal Grainstone:
Mounds or Mechanical Accumulations**

Limestone Flow Units

Core

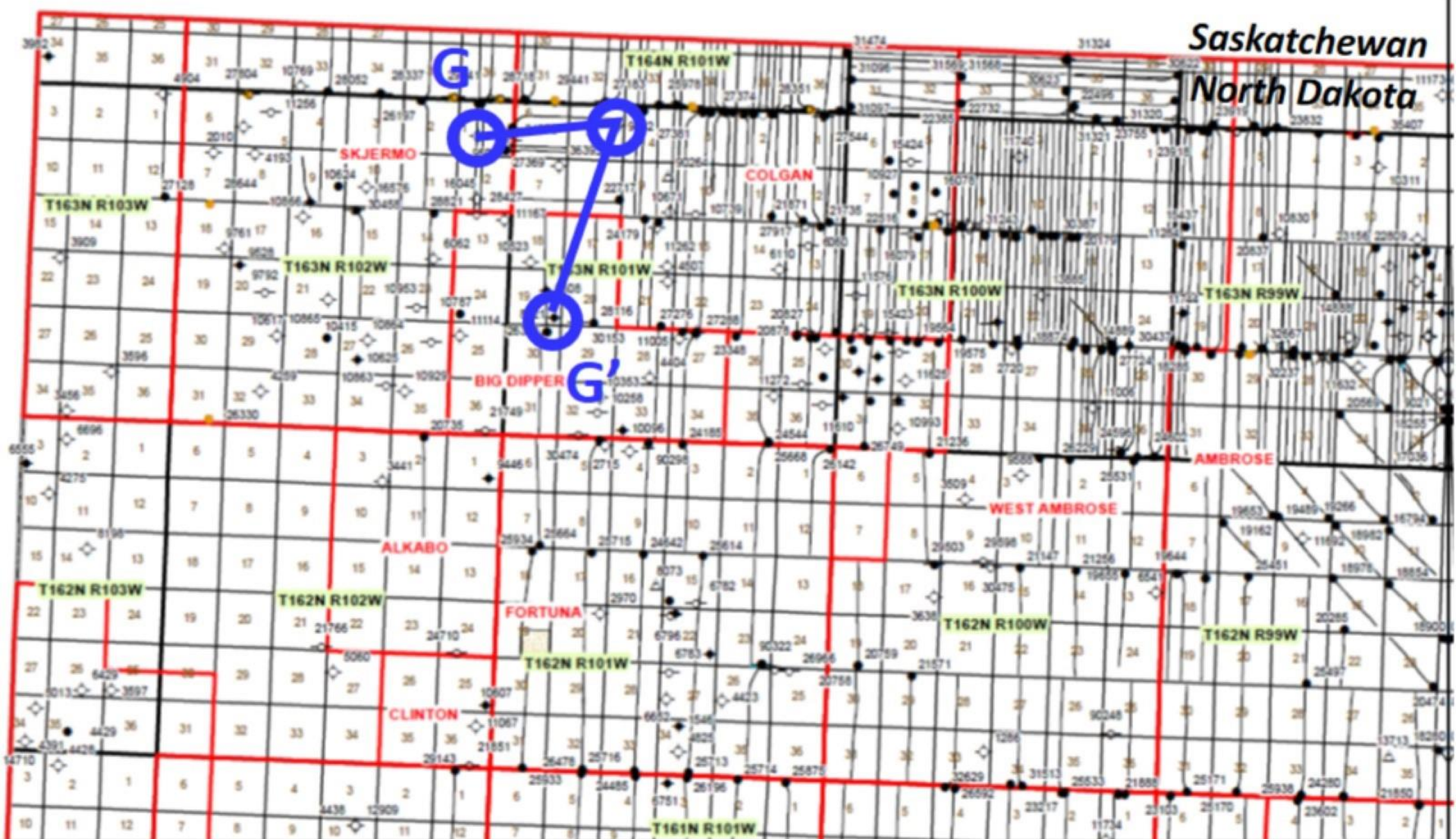
Wehrman #1-19, 163-101, Sec. 19 (NDIC #8721): 7216-7246'

Frobisher-Alida Paleogeography



Modified
after Petty
(2010, Fig. 3)

Saskatchewan North Dakota



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0 2 4 8 Miles

Prepared by N.D.I.C.
Oil and Gas Division

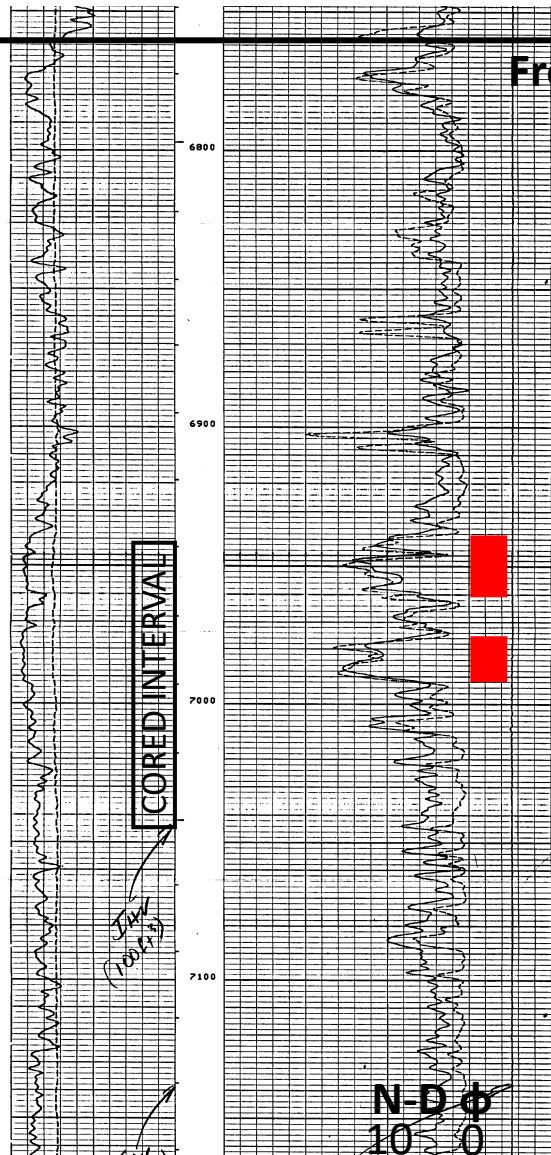
12/6/2019
10:09:49 AM



G

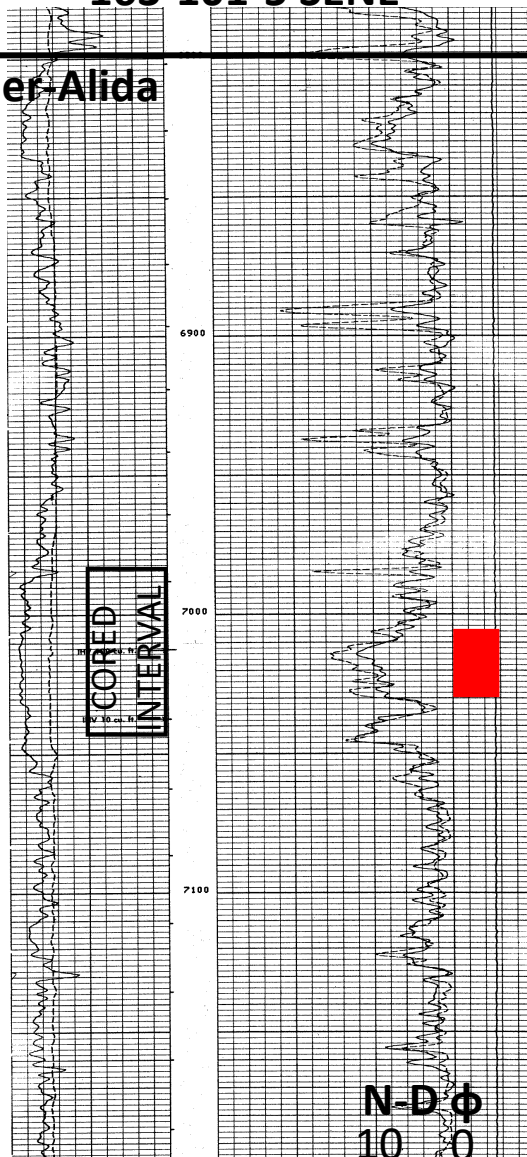
#9503 Tangedal 1-1

163-102-1 NESW

**Frobisher-Alida**

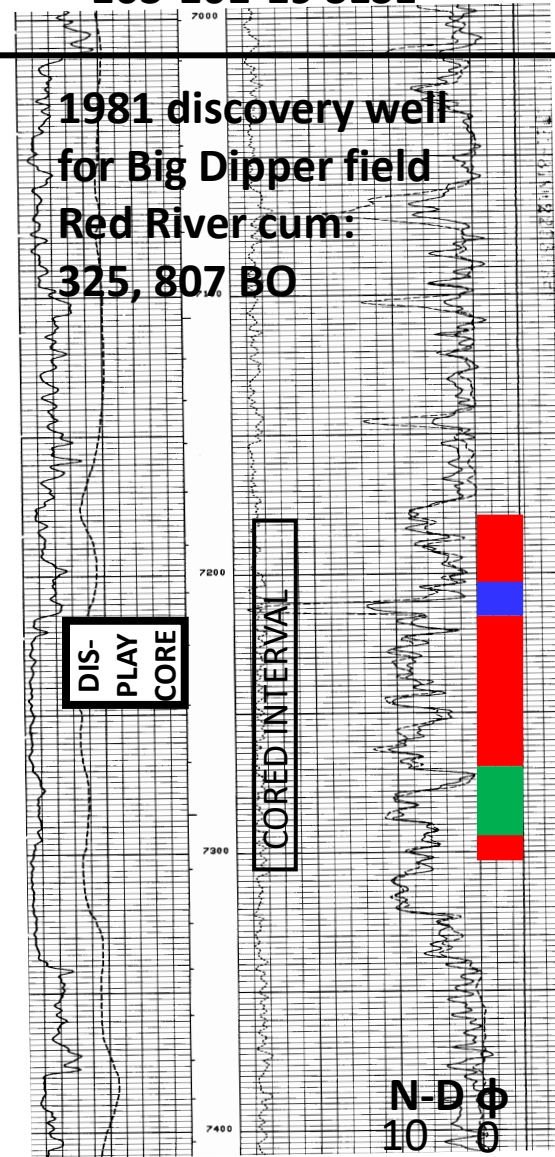
#9482 Carter 1-5

163-101-5 SENE



#8721 Wehrman 1-19

163-101-19 SESE

**G'**

**1981 discovery well
for Big Dipper field
Red River cum:
325, 807 BO**

[Red Bar] = Dominantly skeletal grainstone;

[Blue Bar] = Microcrystalline Dolostone

[Green Bar] = Cherty Packstone & Wackestone

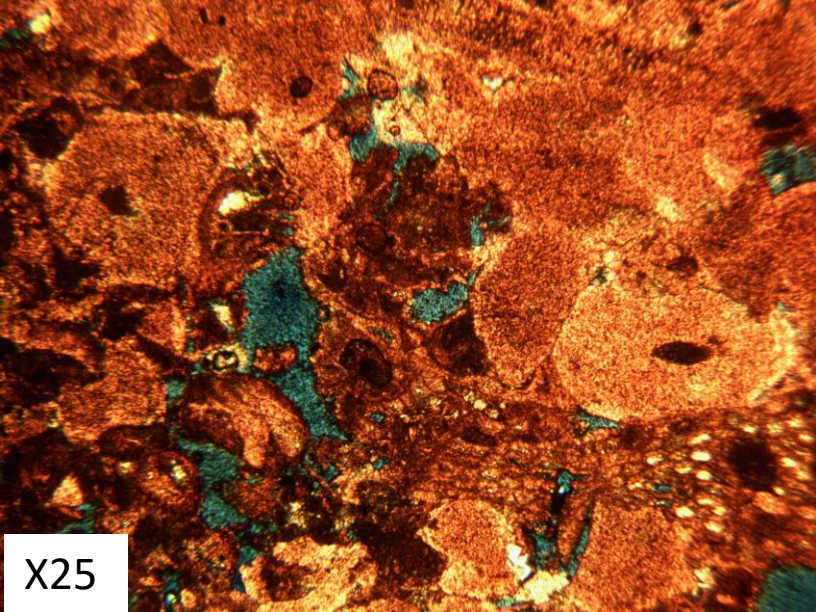
Core depths 7216-7246' in the Wehrman #1-19 core (NDIC #8721) consists dominantly of crinoid-bryozoan grainstone with good visible interparticle porosity

TENNECO OIL COMPANY

NO. 1-19 WEHRMAN	FORMATION : MISSION CANYON	DATE : 6-20-81
WILDCAT	ORLG. FLUID: SALT GEL--NO OIL	FILE NO. : 3805-2952
DIVIDE COUNTY	LOCATION : SE SE SEC 19 T163N R101W	ANALYSTS : R. MOHL
	STATE : NORTH DAKOTA	ELEVATION: 2292 KB

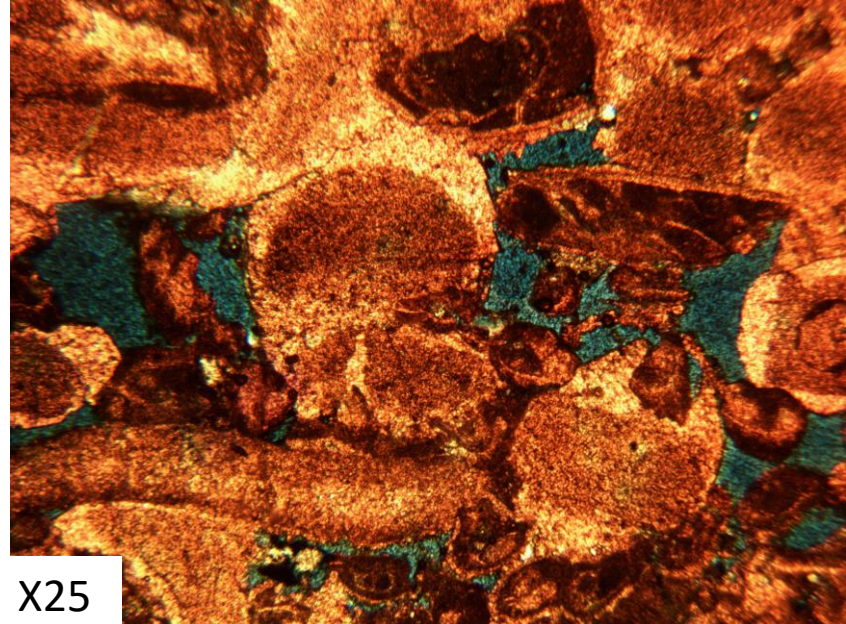
SAMP. NO.	DEPTH	PERM. TO AIR (MD)	POR.	FLUID SATS.	GR. DNS.	DESCRIPTION
		HORZ. VERTICAL	FLD.	OIL WATER		
37	7216-17	22	9.1	7.7 32.9	2.68	LM V/FN-XLN ALGAL FOSS FRAG
38	7217-18	1.2	10.2	8.7 34.7	2.69	LM V/FN-XLN ALGAL FOSS FRAG
39	7218-19	0.60	9.4	0.0 50.9	2.69	LM V/FN-XLN ALGAL FOSS FRAG
40	7219-20	0.71	8.5	0.0 47.8	2.69	LM V/FN-XLN ALGAL FOSS FRAG
41	7220-21	0.04	2.1	5.0 69.9	2.74	LM V/FN-XLN
42	7221-22	15	7.6	0.0 55.8	2.68	LM FN-XLN ALGAL FOSS FRAG
43	7222-23	19	9.3	9.5 29.4	2.69	LM FN-XLN ALGAL FOSS FRAG
44	7223-24	4.3	9.9	0.0 47.5	2.68	LM FN-XLN ALGAL FOSS FRAG
45	7224-25	9.4	11.3	0.0 66.3	2.68	LM FN-XLN ALGAL FOSS FRAG
46	7225-26	1.7	9.9	1.0 56.2	2.68	LM FN-XLN ALGAL FOSS FRAG
47	7226-27	40	10.4	8.5 34.0	2.68	LM FN-XLN ALGAL FOSS FRAG
48	7227-28	4.9	12.0	8.0 55.9	2.68	LM FN-XLN ALGAL FOSS FRAG
49	7228-29	5.5	10.8	0.0 75.3	2.68	LM FN-XLN ALGAL FOSS FRAG
50	7229-30	5.3	11.9	0.0 76.1	2.68	LM FN-XLN ALGAL FOSS FRAG
51	7230-31	0.54	6.5	0.0 43.4	2.68	LM FN-XLN ALGAL FOSS FRAG
52	7231-32	82	12.4	7.0 37.2	2.68	LM FN-XLN ALGAL FOSS FRAG
53	7232-33	36	12.2	0.0 52.7	2.68	LM FN-XLN ALGAL FOSS FRAG
54	7233-34	21	12.0	0.0 61.9	2.68	LM FN-XLN ALGAL FOSS FRAG
55	7234-35	1.7	11.8	0.8 64.4	2.68	LM FN-XLN ALGAL FOSS FRAG
56	7235-36	6.5	9.9	1.0 57.1	2.68	LM FN-XLN ALGAL FOSS FRAG
57	7236-37	18	10.7	6.5 37.2	2.69	LM FN-XLN ALGAL FOSS FRAG
58	7237-38	21	11.5	1.7 37.2	2.68	LM FN-XLN ALGAL FOSS FRAG
59	7238-39	16	10.6	0.9 52.5	2.68	LM FN-XLN ALGAL FOSS FRAG
60	7239-40	1.5	8.1	2.5 29.8	2.69	LM FN-XLN ALGAL FOSS FRAG
61	7240-41	7.1	8.9	2.3 38.3	2.68	LM FN-XLN ALGAL FOSS FRAG
62	7241-42	123	11.2	4.4 38.3	2.68	LM FN-XLN ALGAL FOSS FRAG
63	7242-43	89	12.0	0.8 59.8	2.68	LM FN-XLN ALGAL FOSS FRAG
64	7243-44	46	12.6	0.8 64.6	2.68	LM FN-XLN ALGAL FOSS FRAG
65	7244-45	21	13.2	0.8 76.7	2.68	LM FN-XLN ALGAL FOSS FRAG
66	7245-46	13	12.5	0.0 70.6	2.68	LM FN-XLN ALGAL FOSS FRAG

DVF
CVF



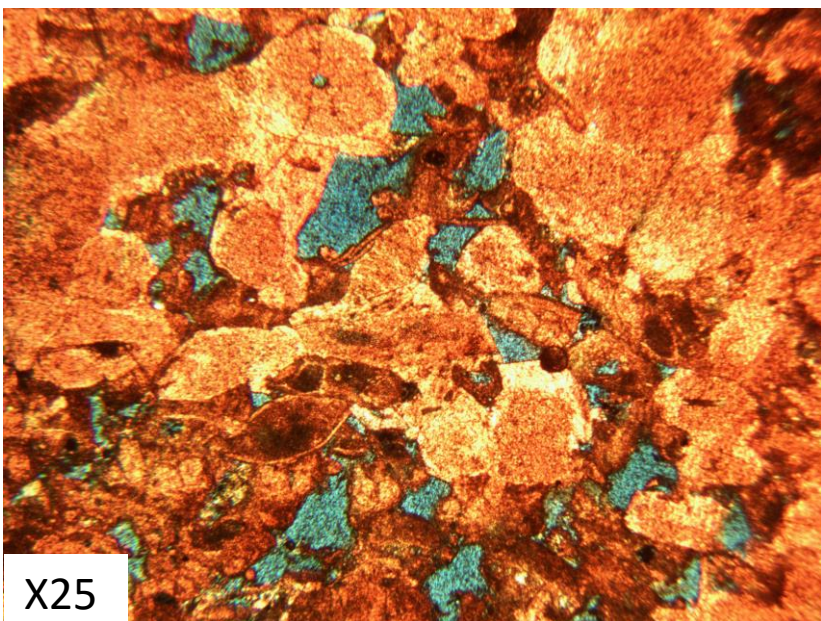
X25

Wehrman 1-19, 163-101-19 SESE
7241'; $\emptyset = 11.0\%$, $K_a = 123$ md



X25

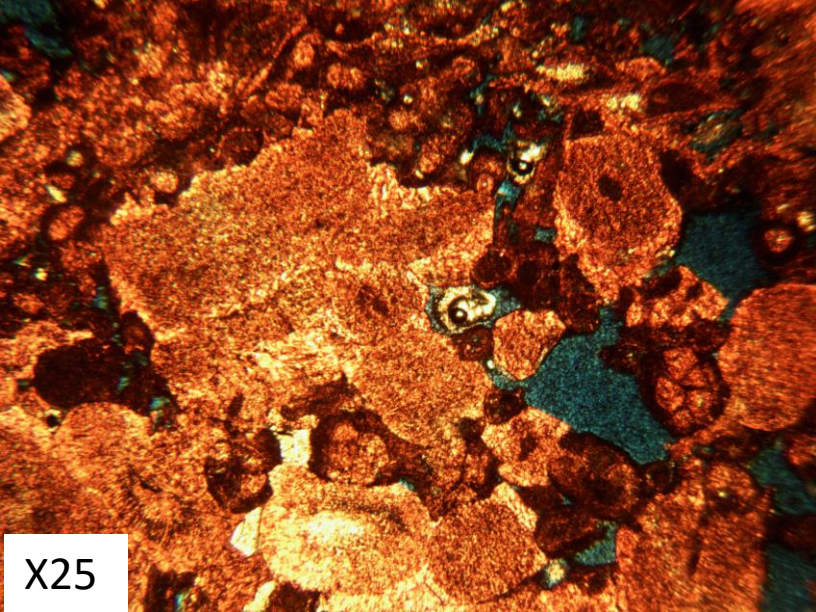
Wehrman 1-19, 163-101-19 SESE
7241'; $\emptyset = 11.0\%$, $K_a = 123$ md



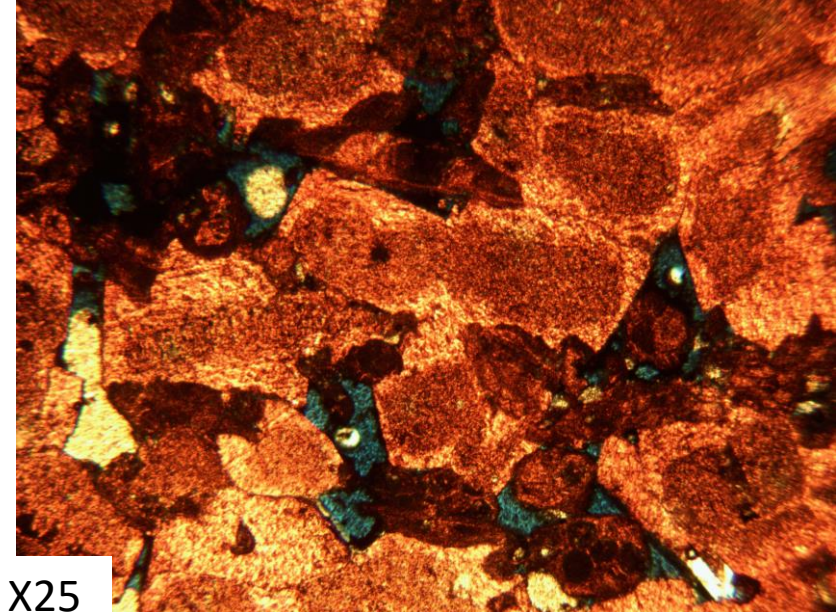
X25

Wehrman 1-19, 163-101-19 SESE
7242'; $\emptyset = 12.0\%$, $K_a = 89$ md

**Facies VI: Crinoid-Bryozoan
Grainstones with Good
Interparticle Porosity and
Good Permeability**

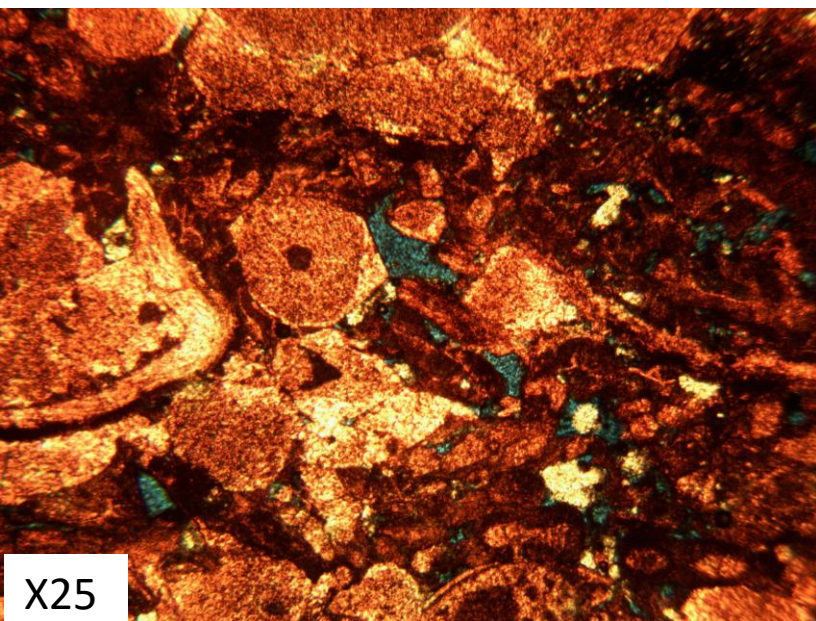


**Wehrman 1-19, 163-101-19 SESE
7244'; \emptyset = 12.6%, Ka = 46 md**



X25

**Wehrman 1-19, 163-101-19 SESE
7244'; \emptyset = 12.6%, Ka = 46 md**



X25

**Wehrman 1-19, 163-101-19 SESE
7244'; \emptyset = 12.6%, Ka = 46 md**

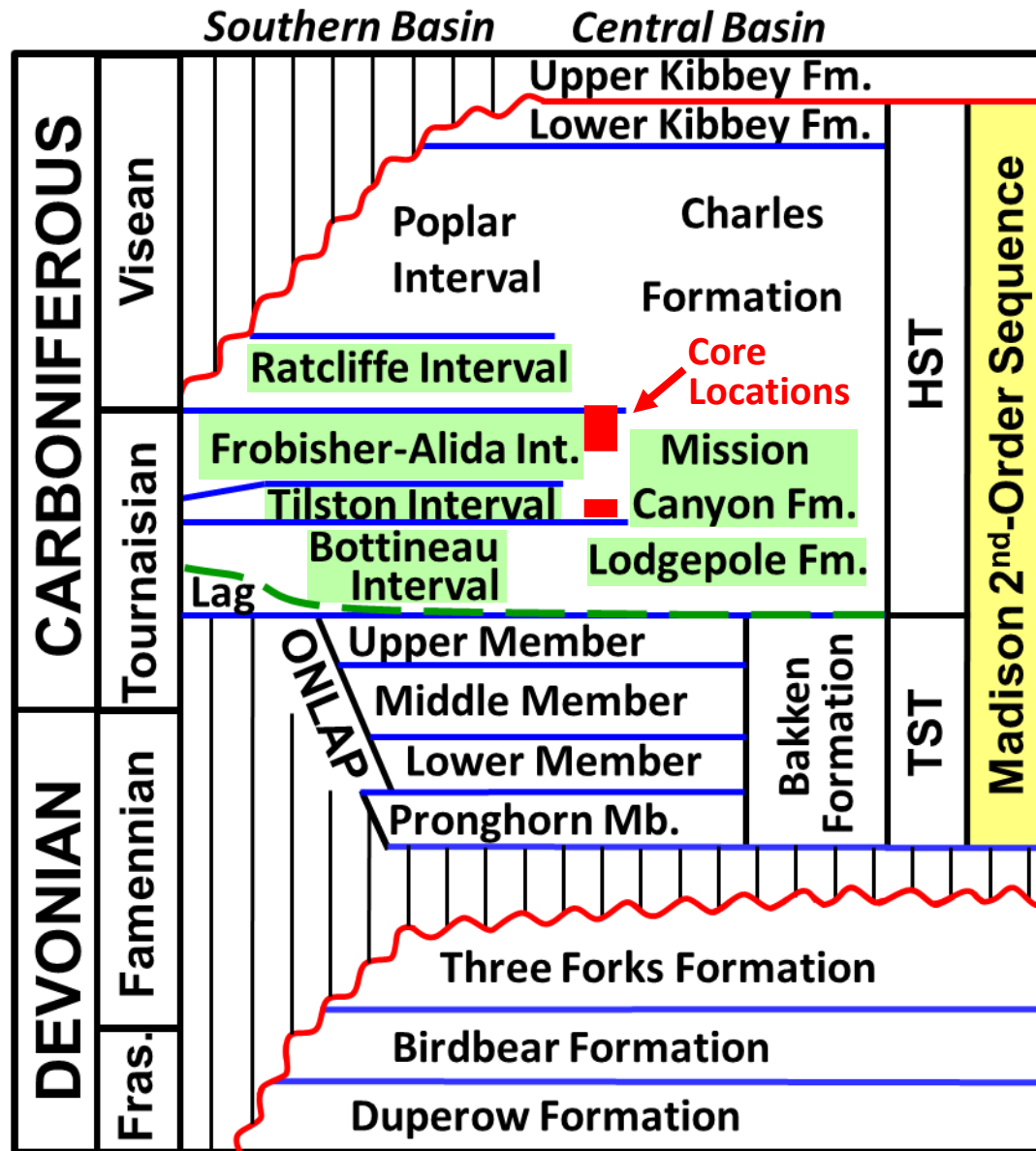
**Facies VI: Crinoid-Bryozoan
Grainstones with Good
Interparticle Porosity and
Good Permeability**

Tilston
Oolite Shoal Facies
Oolitic Grainstone and
Skeletal-Oolitic Grainstone

Limestone Flow Unit

Cores
Jacobs #F14-24-P; 134-96-24 SWSW (NDIC #511): 8051-8110'

Williston Basin Stratigraphic Column



Major Basin Margin Unconformity

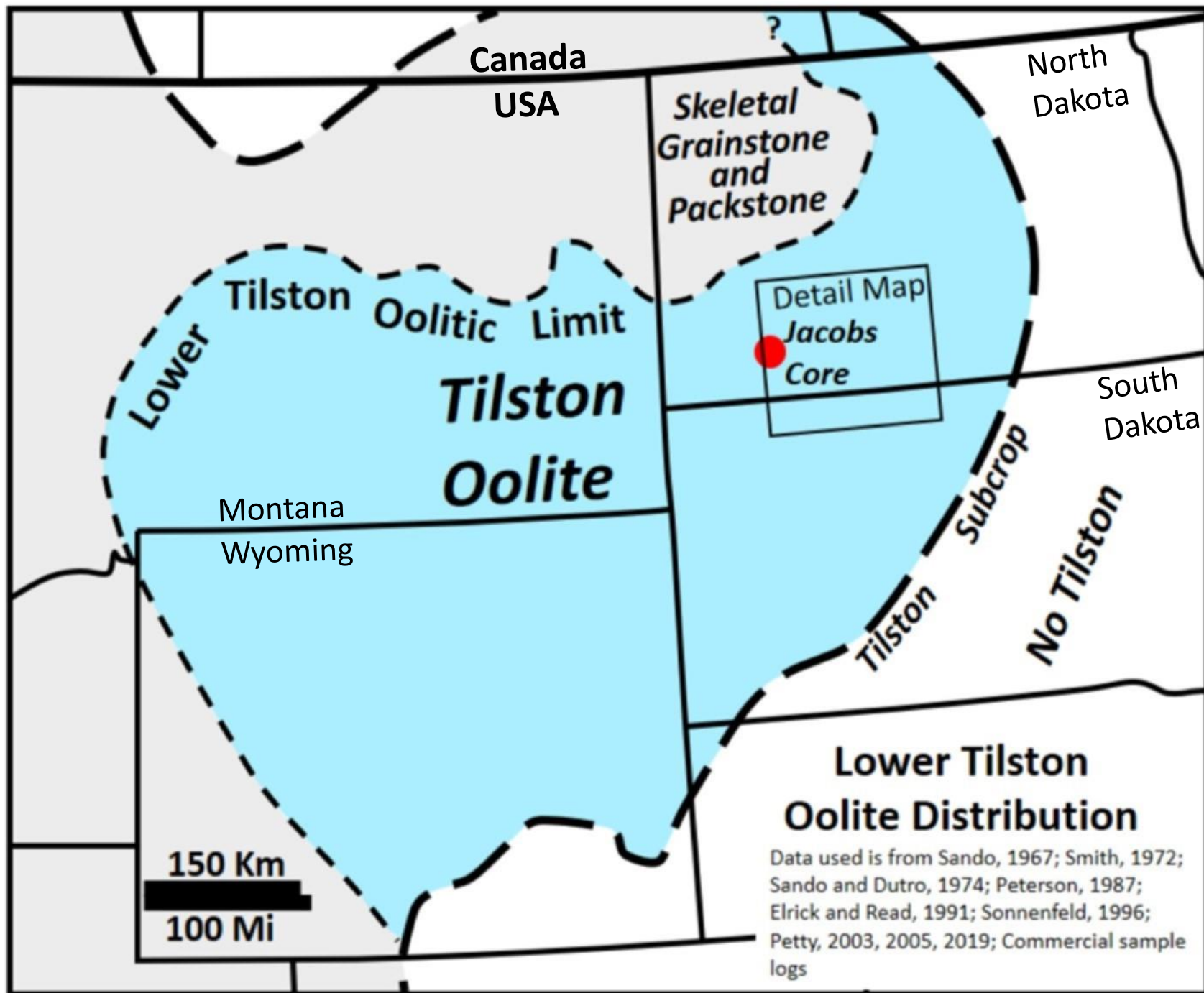
Original Madison sequence definition in Wyoming by Sonnenfeld (1996).
Williston basin usage by Petty (2006, 2010, 2017, 2019a)

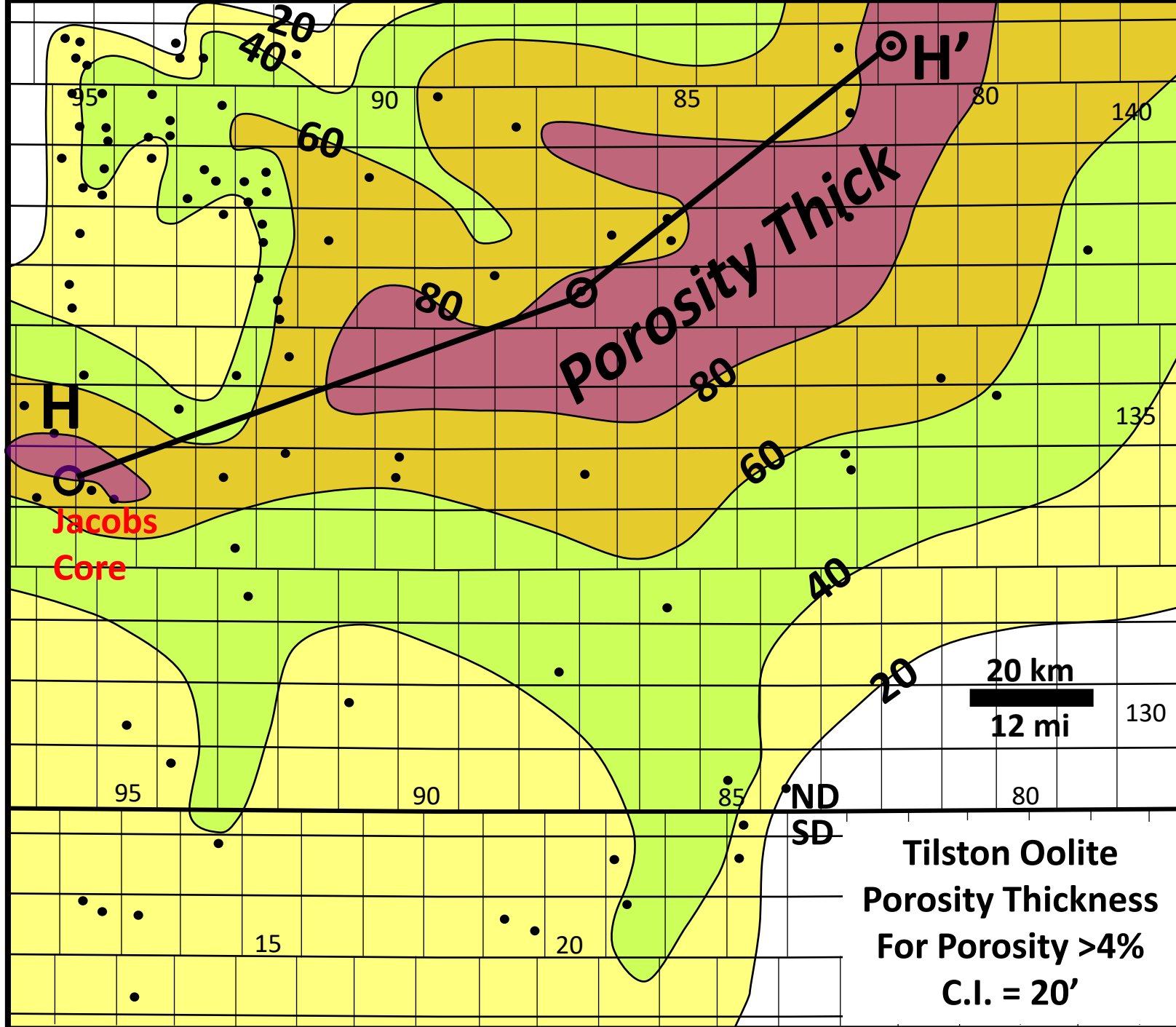
28 m.y.

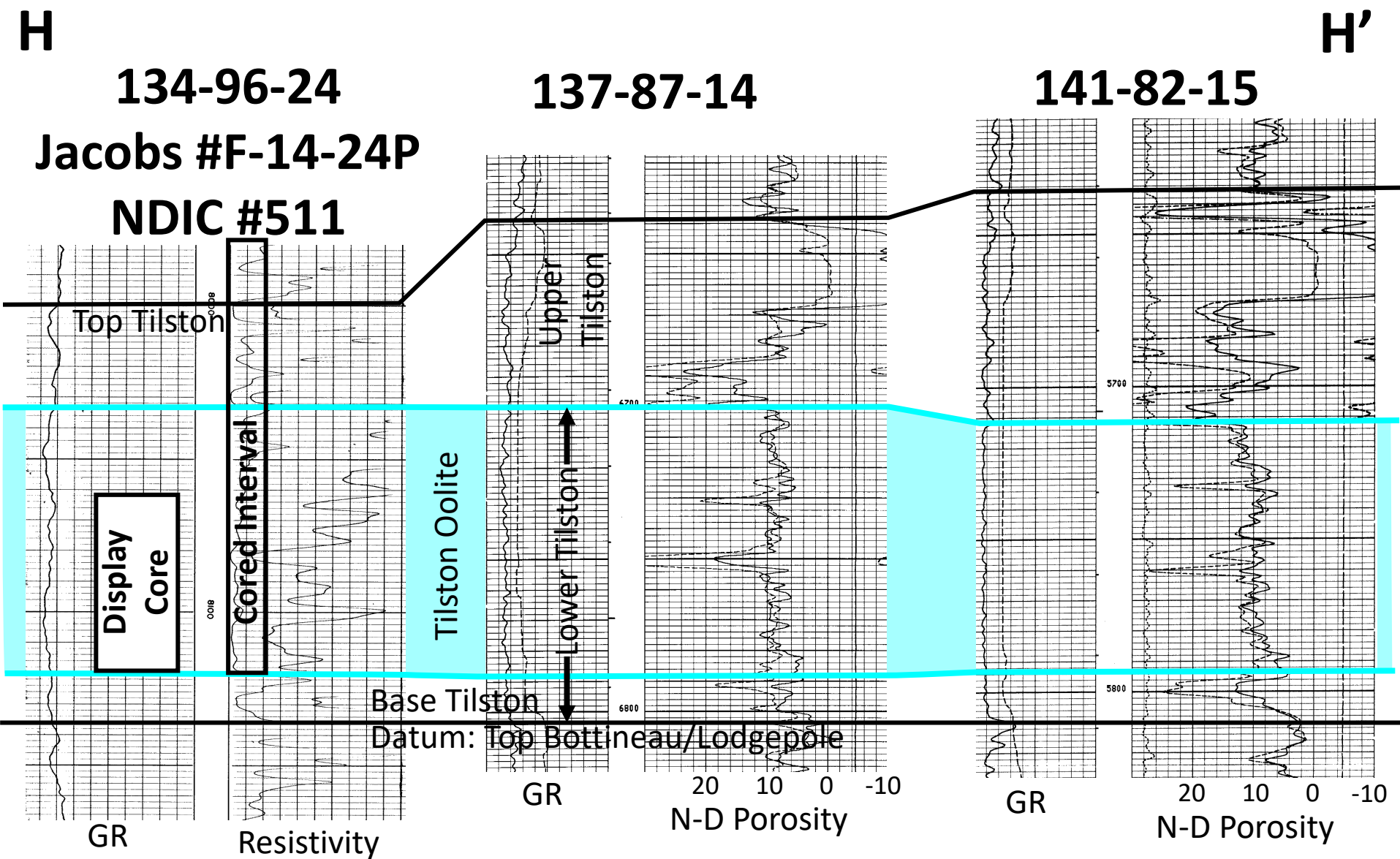
Madison 2nd-order MFS

Acadian Unconformity

Intervals are marker-defined units (Carlson and LeFever, 1987) that parallel biostratigraphic zones (Petty, 2005, 2010, 2019b). Formations are lithology-defined units that may be diachronous.







Note: the base-Tilston log marker corresponds exactly with the biozone boundary between Mamet foraminifer zone 8 and zone 9. This is the best-constrained biozone boundary within the Madison (Petty, 2005).

134-96-24 SWSW

Jacobs F-14-24 NDIC #511

GR

Top Lower Tilston

8050 Log Depth

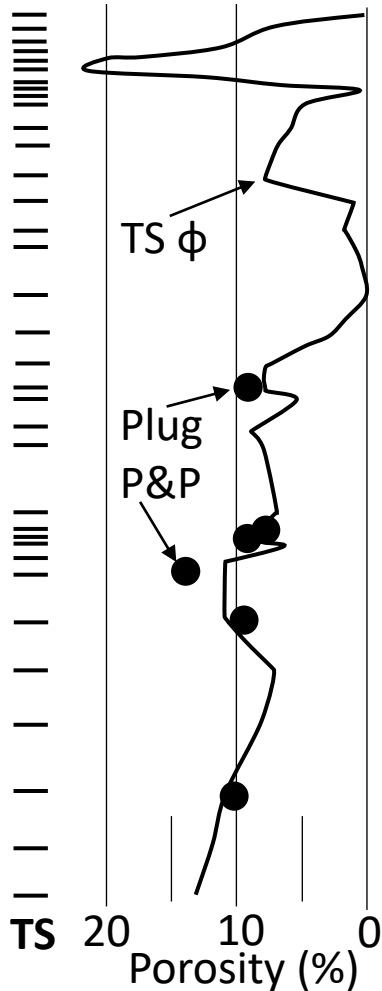
8050 Core Depth

10 meters

8100 Log Depth

8100 Core Depth

Tilston Oolite



8018-23: Dolostone; burrowed skeletal mudstone

8023-26: Cherty grainstone (base) to packstone (top)

8026-35: Limestone; porous oolitic grainstone

8035-51: Limestone; calcite-cemented oolitic grainstone

8051-83: Limestone; porous oolitic grainstone with 10% skeletal grains and preserved interparticle porosity

8056'	8.9%	38 md	8076'	14.4%	130 md
8071'	8.4%	33 md	8081'	9.4%	22 md
8072'	8.9%	73 md			

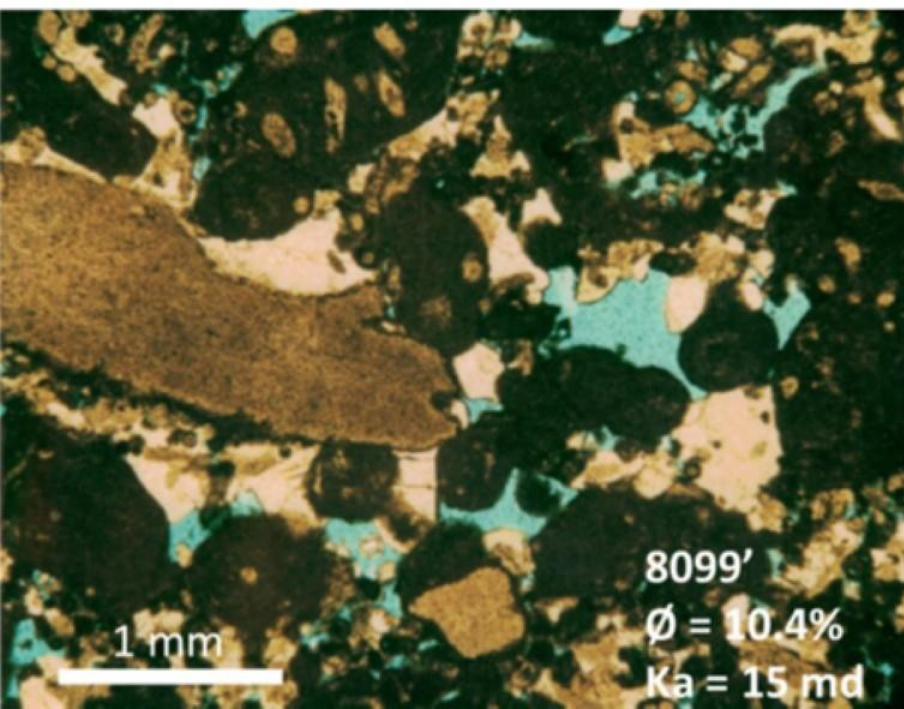
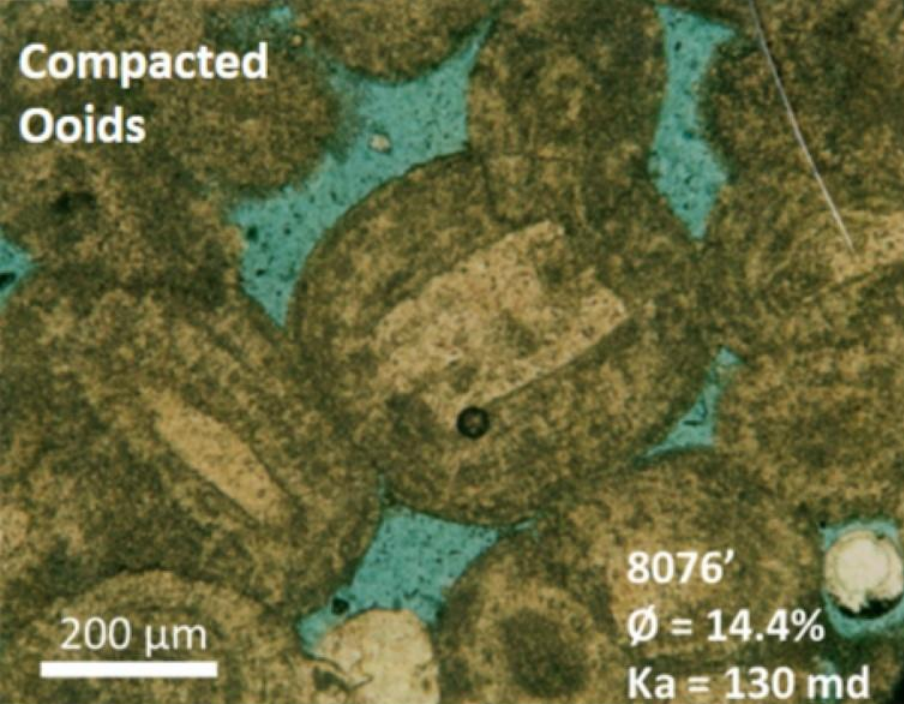
8083-8110: Limestone; porous, skeletal-oolitic grainstone, with 17% skeletal grains and preserved interparticle porosity

8099'	10.4%	15 md
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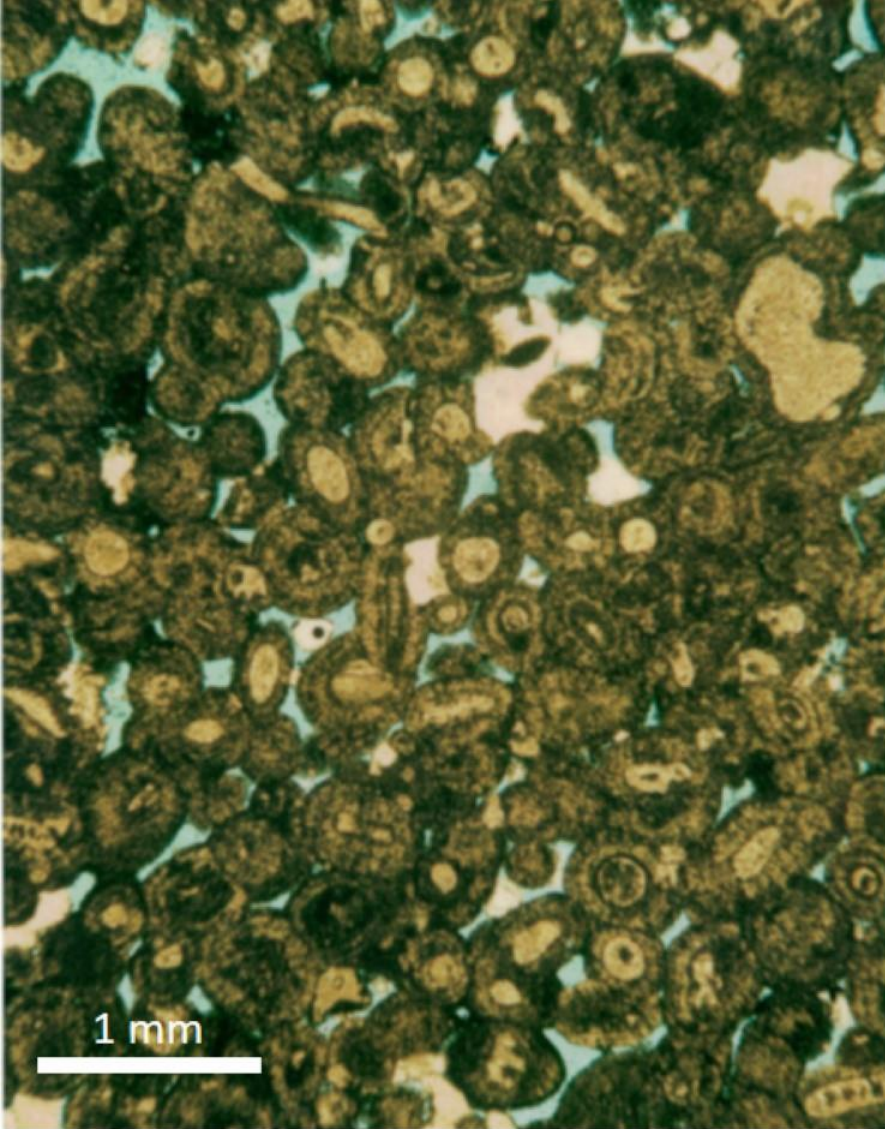
Base core

Base Lower Tilston Interval= base Frobisher-Alida = base Mission Canyon Formation

Top Bottineau Interval = Top Lodgepole Formation



**Tilston Oolitic and
Skeletal-Oolitic
Grainstone
Jacobs #F-14**



Jacobs #F14-24-P; 8076'
 $\phi = 14.4\%$, $K_a = 130\text{md}$

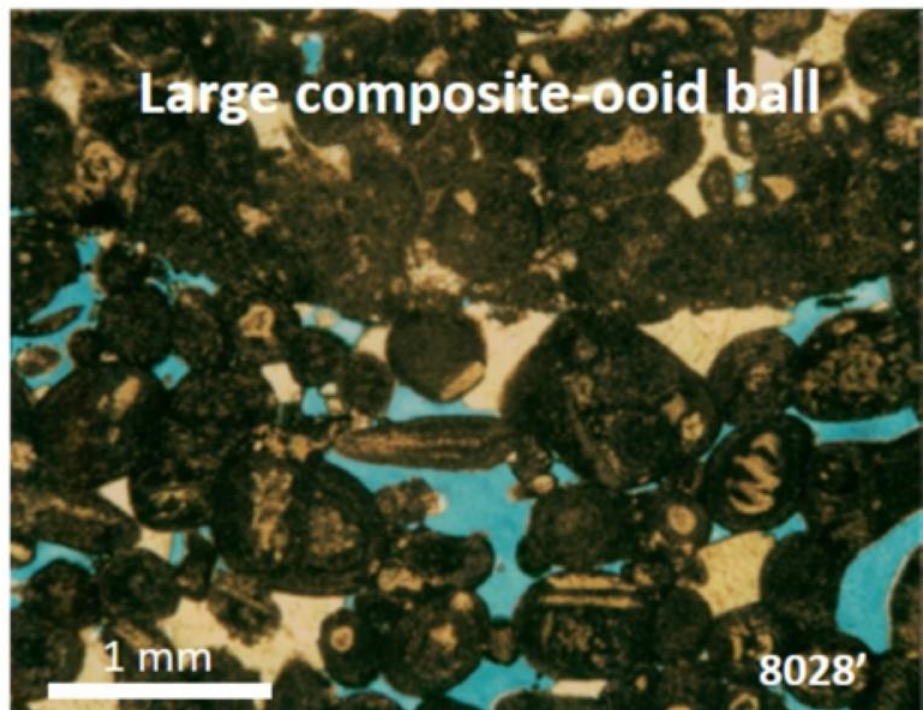
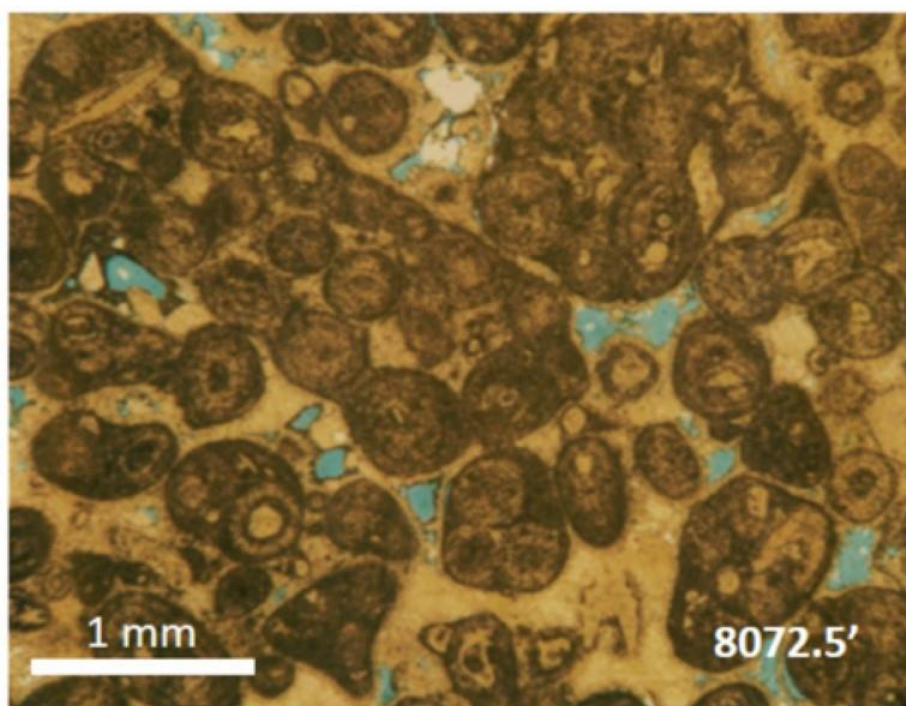
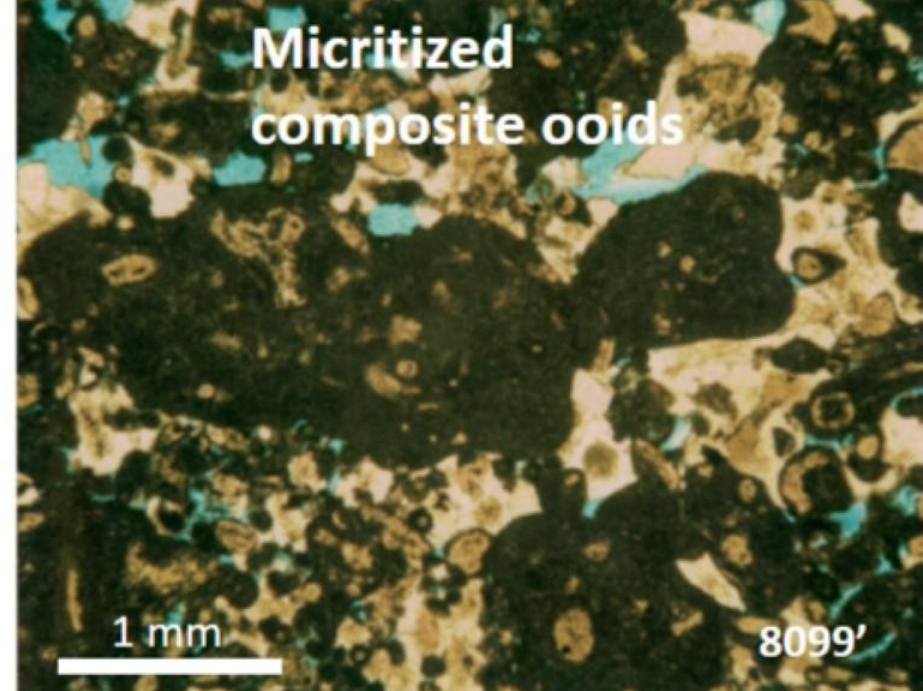


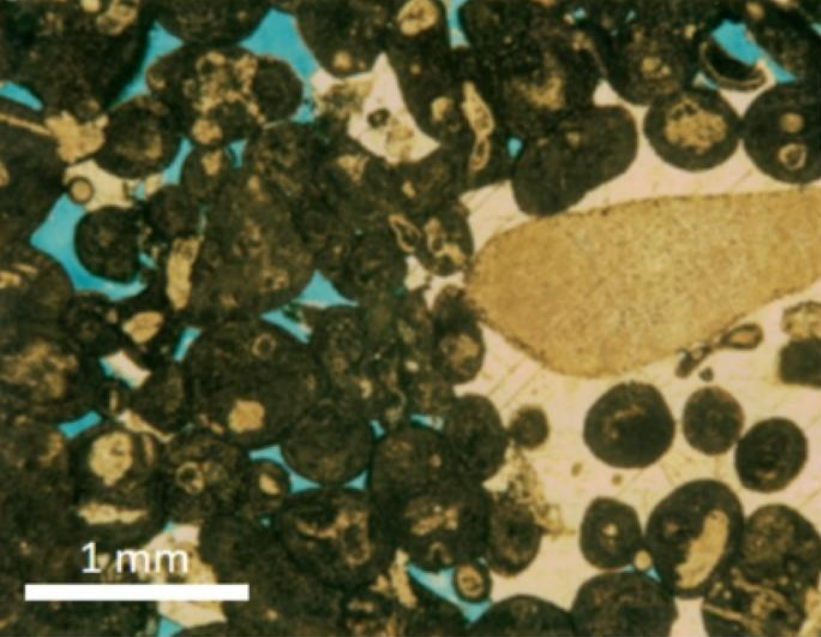
Jacobs #F14-24-P; 8028'

Tilston

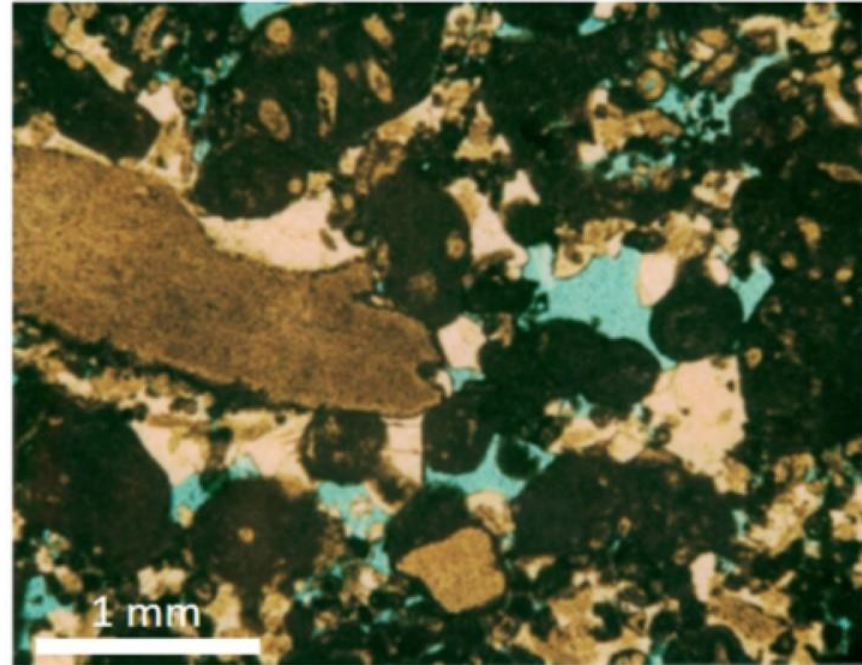
Composite Ooids

Jacobs #F-14

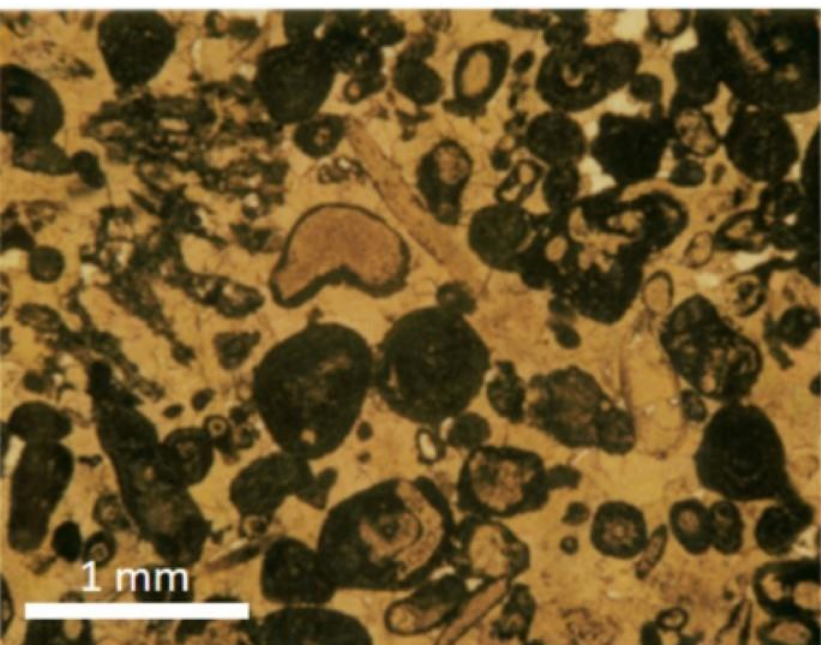




Jacobs #F14-24-P; 8028'



**Jacobs #F14-24-P; 8099';
 $\phi = 10.4\%$, $K_a = 15$ md**



Jacobs #F14-24-P; 8041'

**Skeletal-Oolitic
 Grainstone with Pre-
 Compaction Calcite
 Cement
 Jacobs #F-14**

Production Summaries for Facies

Facies II Production and Petrophysics

- **Production**
 - **Dolostone**
 - **Flow units transition landward into facies I anhydrite**
 - **Producing examples:**
 - **Big Stick, Elkhorn Ranch, Tree Top, Little Knife**
 - **Flow units can be successfully developed with horizontal wells**
- **Petrophysics**
 - **Most facies II flow units are thin; commonly about 4'**
 - **Thin-bed effect can be an issue with petrophysical evaluation**
 - **Best reservoir quality in burrowed dolostone**
 - **Laminated dolostone can be porous but with low permeability**

Rival Facies III

Glass Bluff-Elk & Indian Hill Fields

Production & Petrophysics

- **15 productive, cored wells**
 - **Water Saturation**
 - **Average Log S_w = 68% ($m=n=2.0$ & $R_w = 0.018$)**
 - **Average Core S_w = 51**
 - **Some Rival accumulations in northwest ND were overlooked originally due to high S_w**
 - **Mud-log oil shows are essential for proper evaluation of untested areas with porosity**
 - **Production**
 - **Average vertical oil cum from cored, Rival-only productive wells = 189 MBO (160 acre spacing)**

Facies IV Production and Petrophysics

- **Production**
 - **Dolostone**
 - **Dominantly in southwest ND and southern Nesson anticline**
 - **Blue Buttes, Antelope, Big Stick, Elkhorn Ranch, TR, Tree Top, Whiskey Joe, Little Knife, Fryburg, Medora**
- **Petrophysics**
 - **Individual flow units may have uniform petrophysical properties due to uniform regional distribution of dolomite crystal size relationships**

Facies V Production and Petrophysics

- **Production**
 - Dolomitic limestone & calcareous dolostone
 - Areas with thick oil column
 - Dominantly in southwest ND and southern Nesson anticline
 - Southern Little Knife field, southern TR-Whiskey Joe area, Medora-Fryburg area, Blue Buttes, Antelope
- **Petrophysics**
 - Fryburg-Medora-TR-Whiskey Joe area vertical and lateral R_w variability complicates log S_w
 - With constant R_w , this facies can calculate high S_w (40+%) with $m = n = 2.0$ in oil-productive areas