Sandstone Composition Variation in Regressive to Transgressive Cycles in the Telegraph Creek and Eagle Formations in South-Central Montana*

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Search and Discovery Article #51415 (2017)**
Posted August 7, 2017

*Adapted from oral presentation given at AAPG Rocky Mountain Section Annual Meeting, Billings, Montana, June 25-28, 2017

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Abstract

The Upper Cretaceous Telegraph Creek and Eagle formations in south-central Montana contain a series of regressive to transgressive cycles deposited on the western margin of the Cretaceous Interior Seaway. This study focuses on sandstone mineralogy/provenance and sandstone clay composition. Four cycles have been identified and mapped regionally using outcrop and subsurface data. Each cycle left behind an upward-coarsening shoreface and/or deltaic sandstone body, capped by either a transgressive sand, an erosional top, or maximum flooding surface. Each successive cycle stepped further basinward creating a larger progradational wedge. The lowest cycle studied, the Telegraph Creek Formation, contains a single regressive sandstone topped by a transgressive ravinement surface and pebble lag. Petrographic composition modes average Qt/F/L 54/25/21 and clay content is primarily Fe chlorite and berthierine.

The Eagle Formation is composed of three cycles. The basal cycle is a detached low-stand delta capped by a ravinement surface, which is overlain by transgressive "green" marine sands. The regressive delta sandstones average Qt/F/L 59/17/24 and clays present are dominantly Fe chlorite and berthierine. The "green" sands are Qt/F/L 68/11/21 and the clays primarily smectite, Fe chlorite and glauconite. The middle cycle is a highstand normal regressive delta and a sharp-based forced regressive shoreface that are incised into. This is indicative of base-level fall and the incision surface represents a sequence boundary. The delta sandstones are Qt/F/L 66/17/17 and clays dominantly Fe chlorite and berthierine. The shoreface Qt/F/L is 68/17/15 and clays are primarily kaolinite and Fe chlorite. This is transgressed by a tidally-influenced valley-fill, shoreface, and marine "green" sand.

The valley fill is Qt/F/L 73/14/13 with clays primarily kaolinite and Fe chlorite in the lower part. Smectite and glauconite become abundant in the upper part. The shoreface is Qt/F/L 68/15/17 with clays primarily smectite, Fe chlorite, and glauconite. The “green” sand is Qt/F/L 70/10/20 and clays are primarily smectite and glauconite. The top cycle is normal regressive shoreface and delta deposits capped by a transgressive ravinement surface with a black chert-pebble lag, representing the Claggett transgression. The delta deposits are Qt/F/L 72/13/15 and the shoreface is Qt/F/L 81/8/11. Clays in this cycle are dominantly Fe chlorite and berthierine.

Petrographic data indicate that all cycles are sourced from a recycled orogen setting with a trend of increasing quartz content up-section. Potassium to plagioclase feldspar ratios are ~1 to 1 in the Telegraph Creek, basal Eagle cycle, and the incised valley fill/transgressive shoreface part of the middle Eagle cycle; otherwise the ratios are ~2 to 1. The lower ratios are coincident with the presence of bentonite beds, indicating active volcanism. The dominate clays in regressive sandstones represent a verdine facies (Fe chlorite ~35% and berthierine ~25%) indicating deposition in a shallow warm- water nearshore setting with substantial fresh water input. Transgressive clays are dominated by smectite (~25%), Fe chlorite (~20%), and glauconite (~15%), similar to a glaucony facies suggesting a dominance of marine shelf processes. The preponderance of kaolinite (~30%) in forced regression shoreface and valley fill sediments is thought to be the result of delta plain incision.

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Sandstone composition variation in regressive to transgressive cycles in the Telegraphy Creek and Eagle formations in south-central Montana

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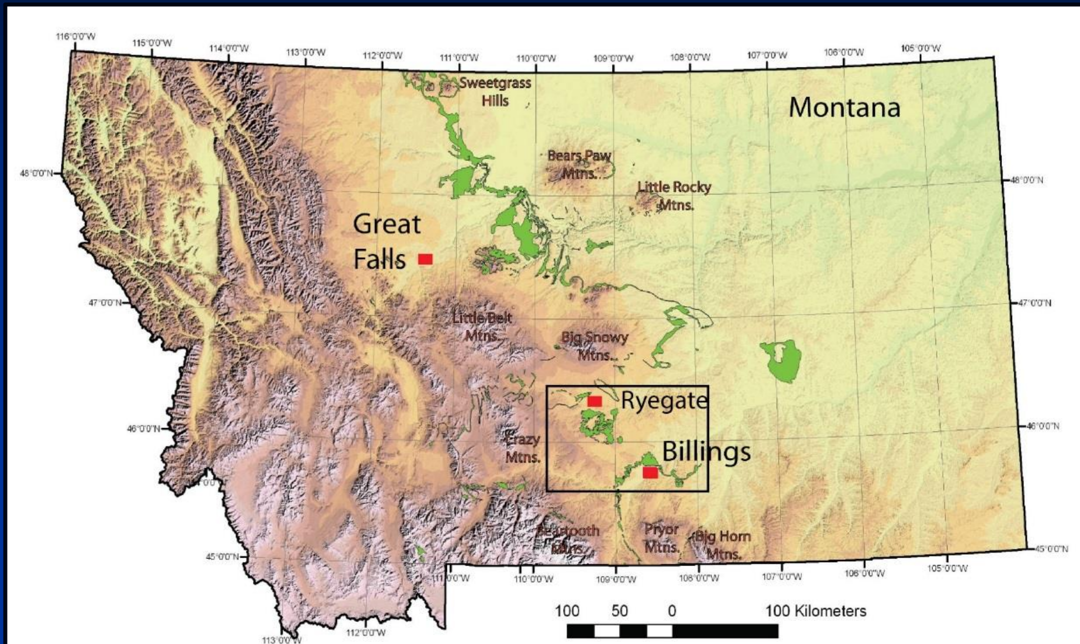
Location and Generalized Stratigraphy



PERIOD	STAGE	SOUTH_CENTRAL MONTANA	
UPPER CRETACEOUS	CAMPANIAN	BEARPAW	
		JUDITH RIVER	
		CLAGGETT	
		EAGLE	Upper Member
			Middle Member
	SANTONIAN		Lower Member
		TELEGRAPH CREEK	
		NIOBRARA	

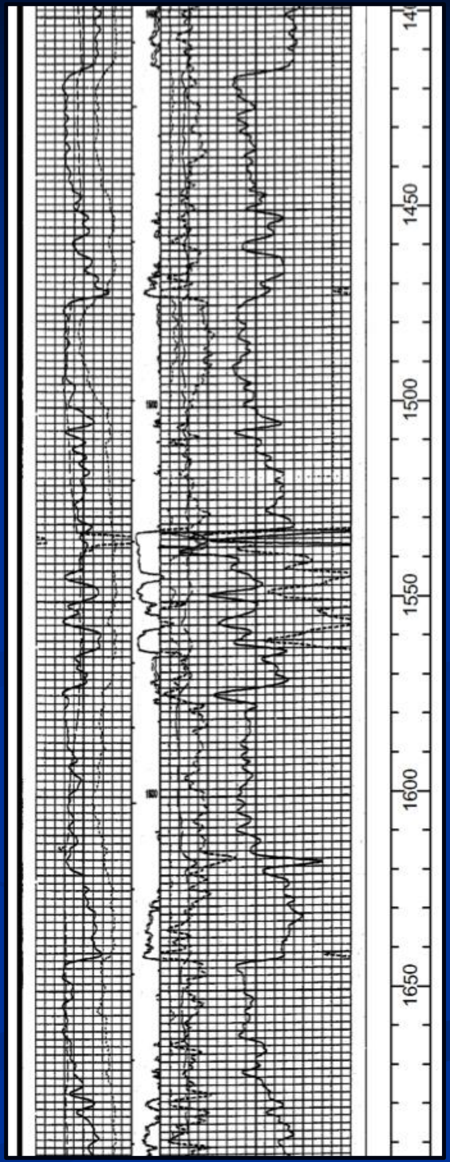
(from Spangler, 2012)

Sandstone framework grain composition can be used to determine provenance. When this data is combined with the clay mineral assemblage present it can be used refine depositional setting in a sequence stratigraphic context. While studies of this type have been done for the Milk River Formation in Alberta and northern Montana, this has not been done for the Eagle and Telegraph Creek formations in south-central Montana. This type of study aids in reservoir characterization and can be used to refine depositional environments in similar reservoir sandstones.

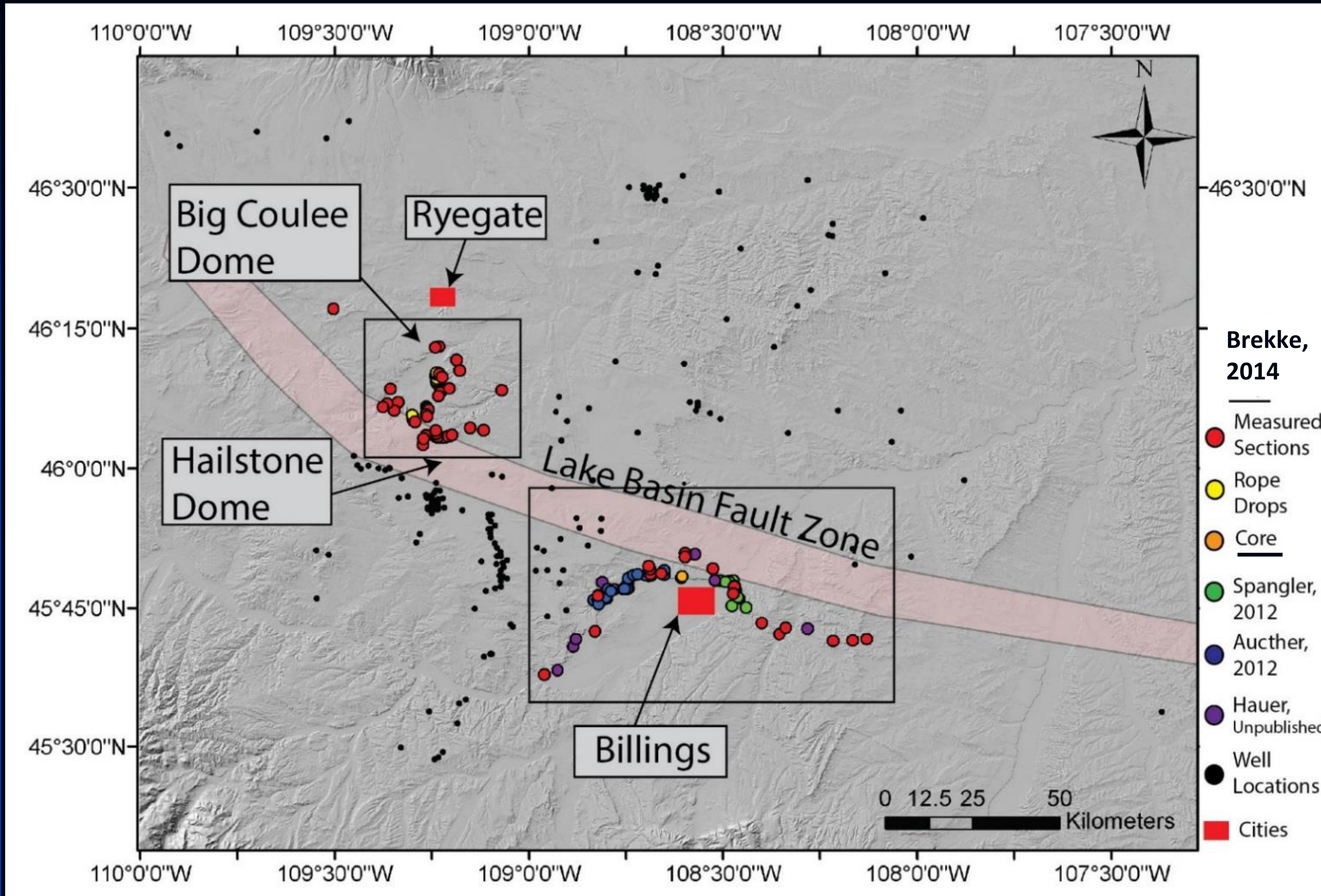
Field Methods

- 212 Stratigraphic Sections
  - 177 Measured sections
  - 35 “Rope drop” sections
- 1 HQ (6.35 cm diameter) core (122 m depth)
- 171 well logs
- ~250 km of high resolution photomosaics examined
- Petra data integration
- ArcGIS modeling
- Samples selected for petrographic and clay analyses were obtained from 14 measured sections and the core
  - 9 measured sections were located in the ‘Rim Rocks’ (Park City to Pryor Creek Valley), 3 in Big Coulee Dome, and 2 in Hailstone Dome

Colgrove 31-18



GR Density

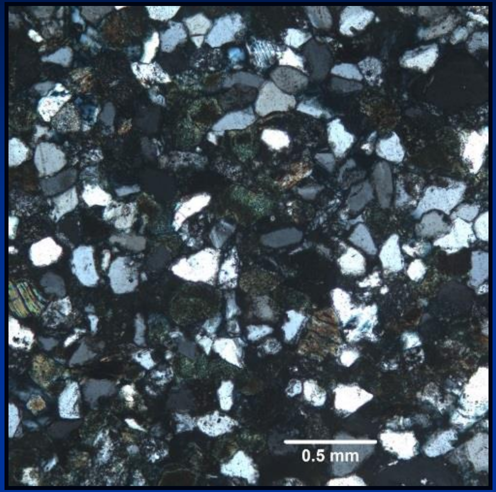


Locations of Measured Sections and Wells

(modified from Brekke, 2014)

In south-central Montana a localized package of en-echelon stacked normal faults is known as the **Lake Basin Fault Zone** (LBFZ) (Sears, 2006; Sears and Hendrix, 2004). This structural feature traverses the study area (**pink shaded area**) (Lopez, 2000; Wilde and Porter, 2001). Hanson and Little (1989) suggested that reactivation along the LBFZ localized sedimentation depositing anomalously high amounts of sediment in the Billings area.

Petrographic Methods



Quartzose grains	
Qmu	Monocrystalline quartz - undulatory
Qmn	Monocrystalline quartz - nonundulatory
Qp	Polycrystalline quartz
Chert	Chert
Q	Total quartz for Folk's composition classification (= Qmu + Qmn + Qp)
Qt	Total quartzose grains (= Qmu + Qmn + Qp + Chert)
Qm	Total monocrystalline quartz (= Qmu + Qmn)
Feldspar grains	
K	Potassium Feldspar (Sanidine, Orthoclase, Microcline)
P	Plagioclase Feldspar (Albite, Oligoclase)
F	Total feldspar grains (= K + P)
Lithic grains	
Lv	Volcanic lithic grains (volcanic glass, tuff, felsic volcanic grains)
Lm	Metamorphic grains (phyllite, schist)
Ls	Sedimentary grains (mudstone, siltstone, sandstone, shale)
Lime	Limestone
Lu	Unknown lithic
L	Total unstable lithic grains (= Lv + Lm + Ls + Lime + Chert)
Lt	Total lithic grains including quartzose lithics (= Lv + Lm + Ls + Lime + Chert + Qp)
Lnq	Total non-quartzose lithic grains (= Lv + Lm + Ls + Lime)

Accessory minerals: biotite, muscovite, green pellets, zircon, tourmaline, opaque grains, rhodochrosite
Cements: calcite cement, chlorite, clay, iron oxide cement, opal, silt/mud, opaque cement
Void space was also counted

- A total of **94** sandstone samples (**86 thin sections from field samples** and **8 thin sections from core**) were examined petrographically.
- Petrographic characteristics included grain composition and texture.
- Thin sections were point-counted via transmitted light microscopy using a modified Gazzi (1966) – Dickinson (1970) method to determine overall sandstone composition.
  - A minimum of 500 framework grains (quartz, feldspar, and lithics) were counted for each sample.
  - The percentage of accessory minerals, clay, cement, and void space were also counted but not included in the 500 framework grain counts per sample.

Clay X-ray Diffraction Methods

- Clays were obtained from **46** sandstone samples (**42 field samples** and **4 core samples**) from the Telegraph Creek and Eagle formations for X-ray diffraction (XRD) analyses. The <2 µm clay fraction was extracted from each sample by gentle hand crushing, ultrasonic dispersion, and centrifuged as described by Moore and Reynolds (1997).
- Oriented samples were prepared and analyzed under conditions of air dried, ethylene glycolated, and heated to 300°C, then to 550°C for one hour. Oriented samples were used for identification of the clay mineral assemblage.
- For quantitative analysis, randomly oriented powders were prepared following the methodology of Eberl (2003). Triplicate diffractograms were collected for all samples and summed to increase signal to noise ratio.
- Diffraction patterns were collected on a PANalytical X'Pert PRO X-ray diffractometer with CuKα radiation using X'Pert Data Collector software.
- PANalytical's X'Pert HighScore Plus was used for mineral identification. RockJock (Eberl, 2003) was used for quantitative analysis.

Results and Interpretations

- Sedimentologic and stratigraphic attributes
  - 16 facies
  - 9 facies associations
  - 6 significant surface types
  - 7 facies successions
- Sequence stratigraphic systems tracts
  - 8 systems tracts
- Tectonics vs. Eustacy
  - Both are factors
- Sandstone lithology
  - Composed primarily of felspathic litharenites
- Provenance analysis
  - Recycled orogen
- Clay mineral analysis
  - Glaucony and verdine facies identified

Facies Associations

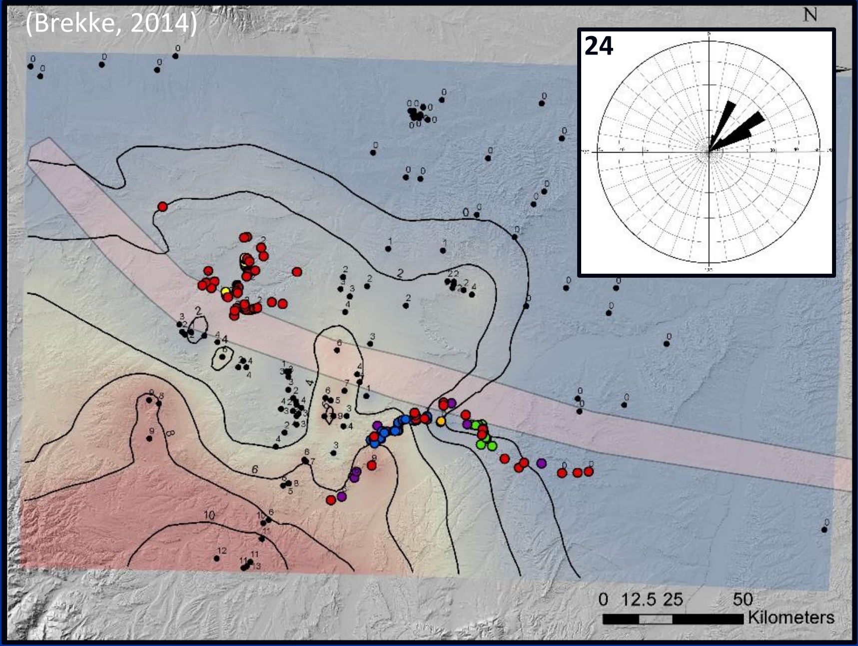
Facies Association	Facies	Interpretation	Characteristics
FA1	Facies 3A: Light gray hummocky cross-stratified sandstone Facies 2: Interbedded mudstone and ripple cross-laminated siltstone and sandstone Facies 1: Laminated mudstone with ripple laminated siltstone and sandstone	Inner marine shelf to offshore transition	Coarsening upward succession of laminated to interbedded mudstone, siltstone and very fine sandstone.
FA2	Facies 8: Inclined graded, planar laminated, planar bedded, and ripple laminated sandstone Facies 6: Massive to planar laminated and ripple laminated sandstone	Fluvial dominated delta front	Coarsening upward succession of clinoforms consisting of hyperpycnal flow deposits.
FA3	Facies 4: Cross-stratified sandstone	Shoreface	Coarsening upward succession of cross stratified high energy sandstones.
FA4	Facies 4: Cross-stratified sandstone	Erosional based shoreface	Cross stratified high energy sandstone erosionally overlying more proximal (F14 or F16) or distal facies (F1).
FA5	Facies 15: Coal Facies 14: Paleosol Facies 12: Laminated and bedded sandstone, heterolithic strata, and mudstone Facies 10: Inclined heterolithic strata with unidirectional cross-stratified and laminated sandstone Facies 9: Low angle stratified sandstone and cross-stratified sandstone	Delta plain	Fining upward succession consisting of distributary channels, fluvial channels, overbank deposits, paleosols, and coal.
FA6	Facies 12: Laminated and bedded sandstone, heterolithic strata, Facies 9: Low angle stratified sandstone and cross-stratified sandstone	Fluvial channels	Fining upward, erosionally based, concave upward, channel forms with lateral accretion deposits, and overbank deposits.
FA7	Facies 7: Graded, planar laminated and ripple laminated sandstone and siltstone	Overwash deposits	Stacked hyperpycnal flow deposits with combined flow sedimentary structures.
FA8	Facies 16: Bioturbated blue-green muddy sandstone Facies 15: Coal Facies 13: Carbonaceous mudstone Facies 12: Laminated and bedded sandstone, heterolithic strata, and mudstone Facies 11: Inclined heterolithic strata with bidirectional cross-stratified and laminated sandstone	Estuary to bay	Fining upward deposits consisting of tidally influenced channels, overbank deposits, coal, bioturbated blue green muddy sandstone.
FA9	Facies 1: Laminated mudstone with ripple laminated siltstone and sandstone Facies 2: Interbedded mudstone and ripple cross-laminated siltstone and sandstone Facies 3B: Gray-green hummocky cross-stratified sandstone Facies 5: Massive to laminated green muddy sandstone	Marginal marine to marine shelf	Fining upward succession of cross stratified sandstones, bioturbated sandstones, HCS, sandstones, and interbedded and laminated mudstone with siltstone and sandstone.

(modified from Brekke, 2014)

Facies Succession 1:

Telegraph Creek: Sandstone 1

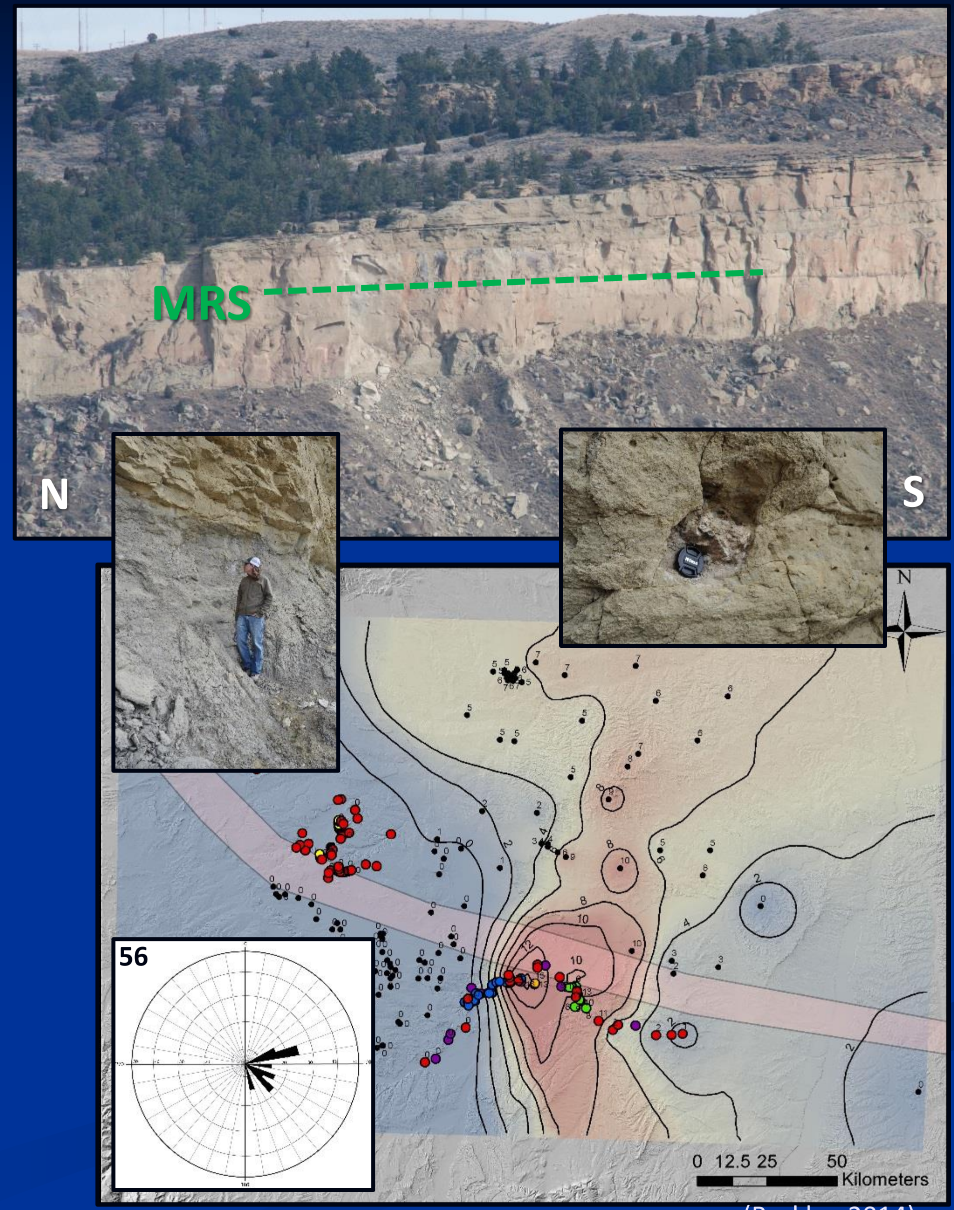
- Regressive coarsening upward package
  - Marine shelf (FA1)to delta front (FA2)
- Up to ~40 m thick in the southwest
- Prograded to the NE
- Base is **MFS** at the top of the Niobrara
- Top truncated by a **TRS**



Sandstone Isopach

Facies Succession 2:
Eagle: Sandstone 2a

- Regressive coarsening upward package
  - Marine mudstones (FA1) to delta front (FA2)
  - Up to ~30 m thick
  - Detached system that prograded from NW to E/SE
  - Base is **MFS**
  - Top is **MRS**



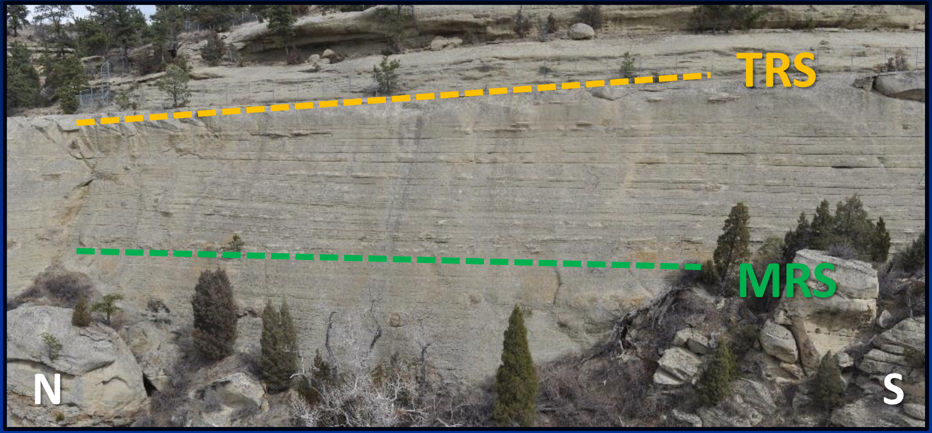
(Brekke, 2014)

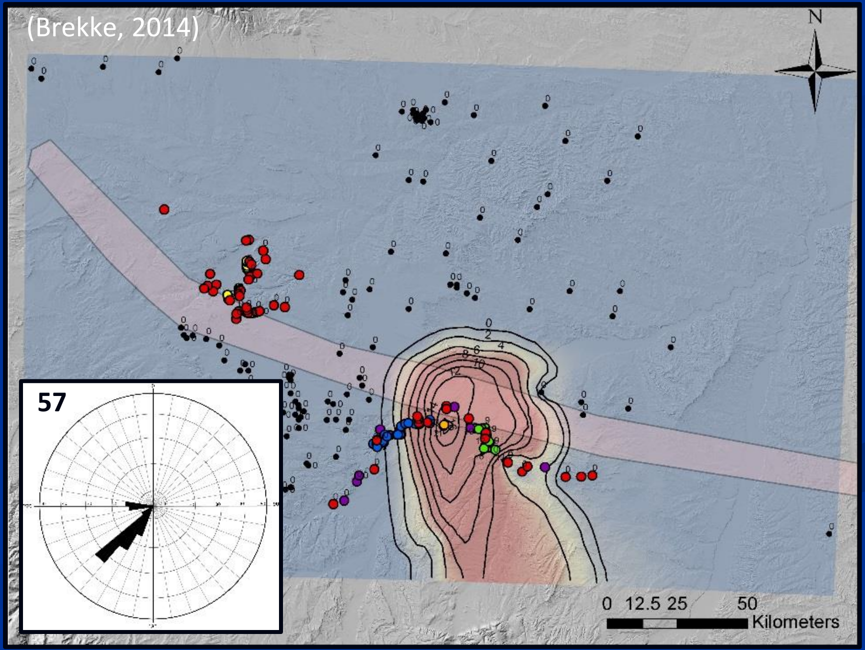
Sandstone Isopach

Facies Succession 2:

Eagle: Sandstone 2b

- Transgressive package
  - Overwash fan complex (FA7)
    - Reworked deltaic sediments moved landward through storm and wave action
  - Up to ~20 m thick
  - Retrograde migration landward (to the SW)
  - Base is **MRS**
  - Top truncated by **TRS**



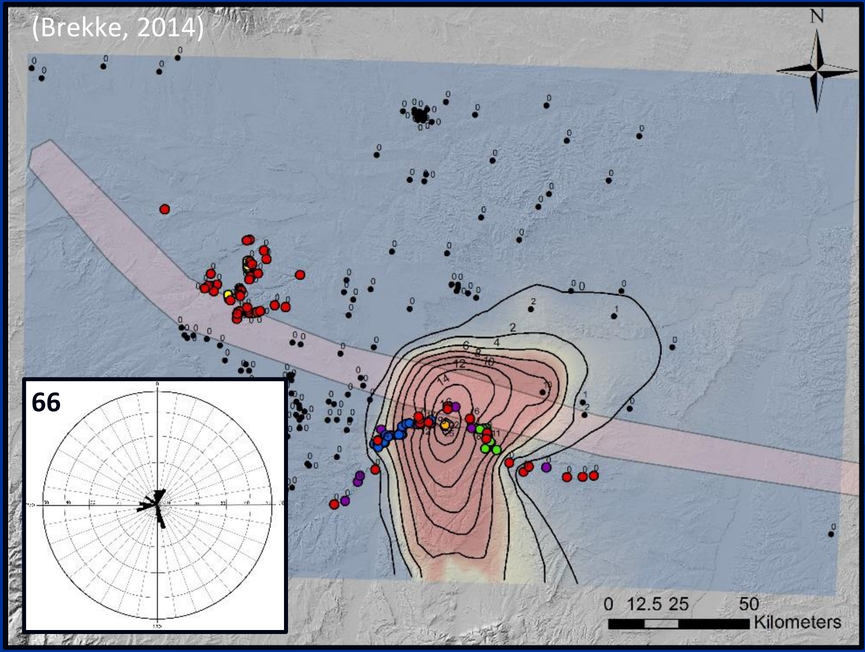


Sandstone Isopach

Facies Succession 3:

Eagle: Green Sandstone Transgression

- Transgressive fining upward package
  - Offshore transition to marine shelf (FA9)
  - Up to ~30 m thick
  - Retrograde migration landward in the Billings area
  - Thickest south of the LBFZ
  - Base is **TRS**
  - Top is **MFS**

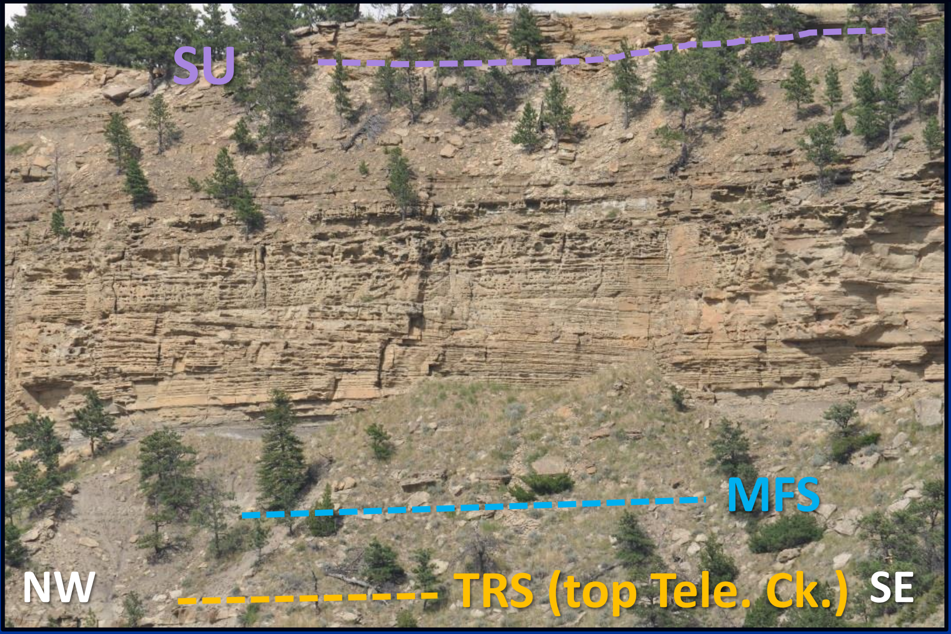


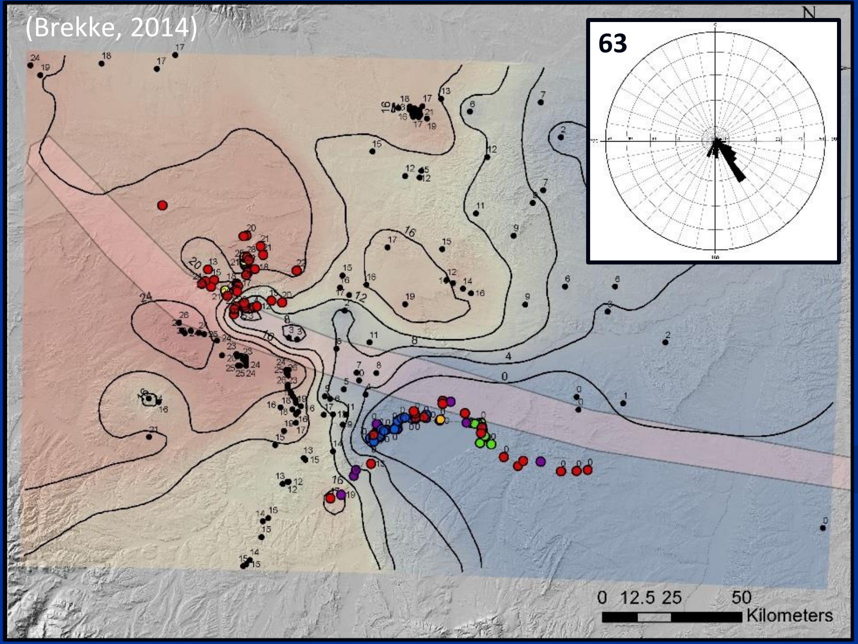
Sandstone Isopach

Facies Succession 4:

Eagle: Sandstone 3

- Regressive coarsening upward to fining upward succession
  - Marine mudstones (FA1) to delta front sandstones (FA2) to delta plain (FA5)
  - Up to ~70 m thick in the NW
  - Prograded from the NW to the SE
  - Thickens across the LBFZ along paleostrike (to the S/SW)
  - Base is MFS
  - Top truncated by a SU or RSME



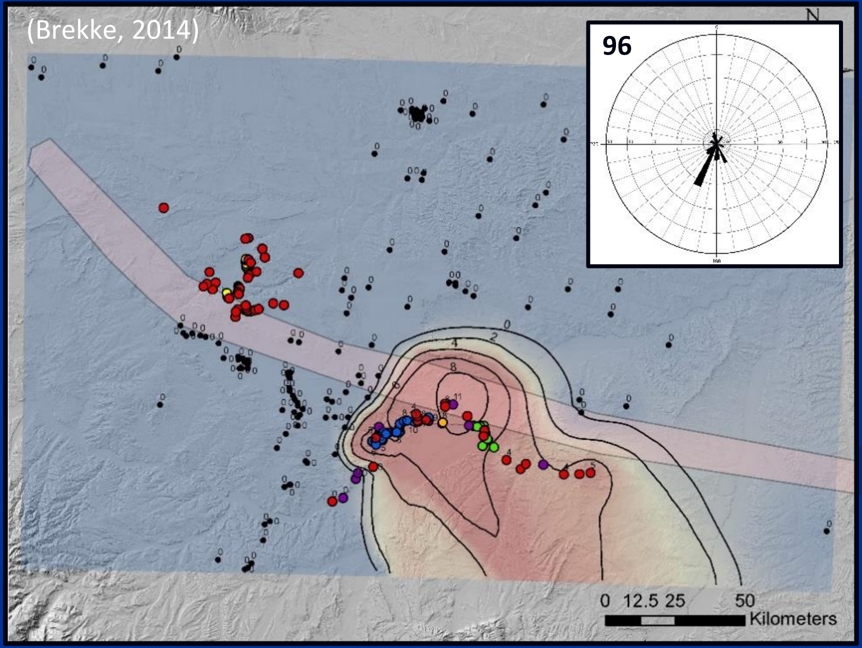


Sandstone Isopach

Facies Succession 5:

Eagle: Sharp based shoreface

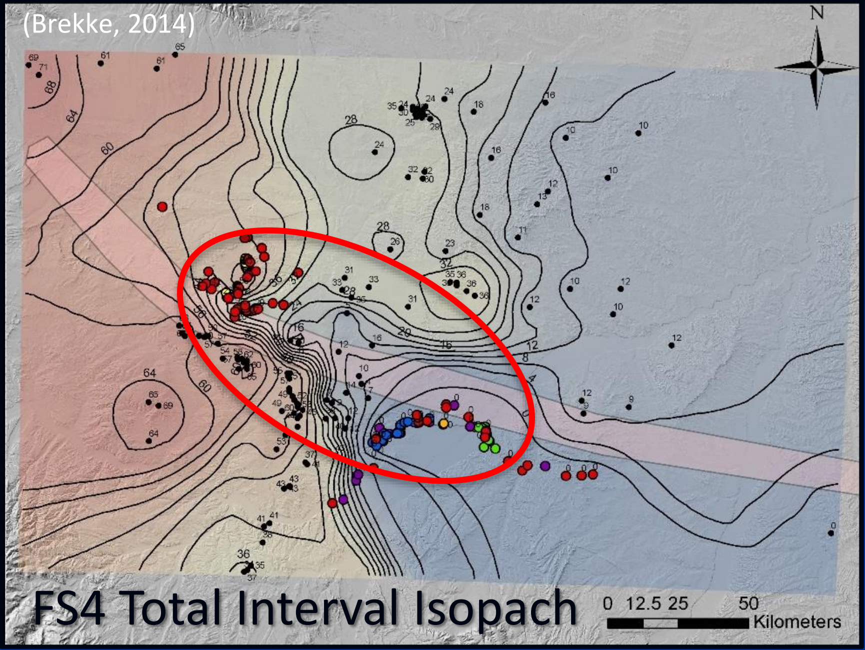
- Forced regressive shoreface
  - Erosionally based shoreface (FA4)
  - Up to ~10 m thick
  - Prograded to the S/SE
  - Base is **RMSE**
  - Truncated by either fluvial channels or tidally influenced channels creating a **SU** or **TSE**



Sandstone Isopach

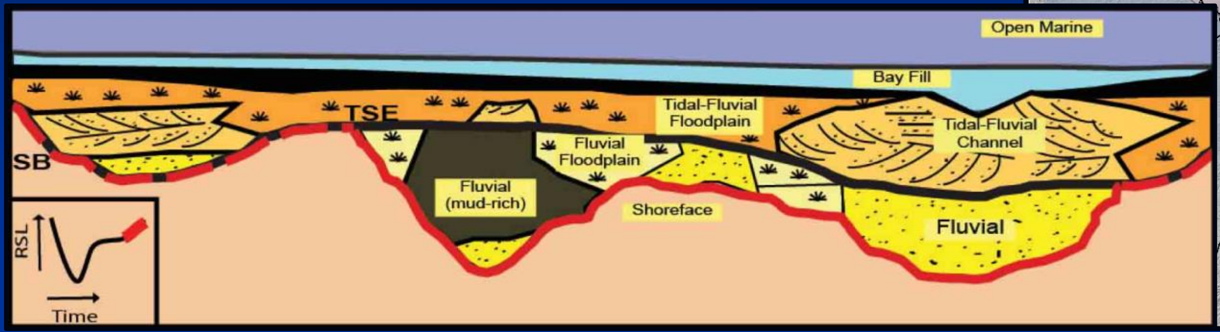
Fluvial Incision

- During base level fall channel gradients are increased, resulting in increased stream power and fluvial incision
  - This resulted in the development of an Incised Valley eroding into FS4 and FS5
  - Up to ~40 m of incision

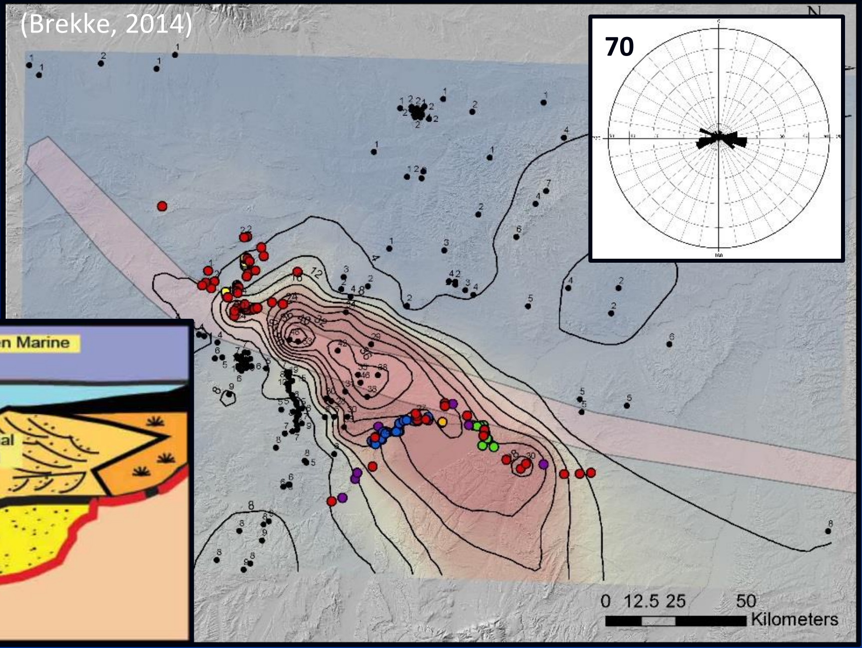


Facies Succession 6:

Eagle: Incised valley fill to marine shelf



(Auchter, 2012)

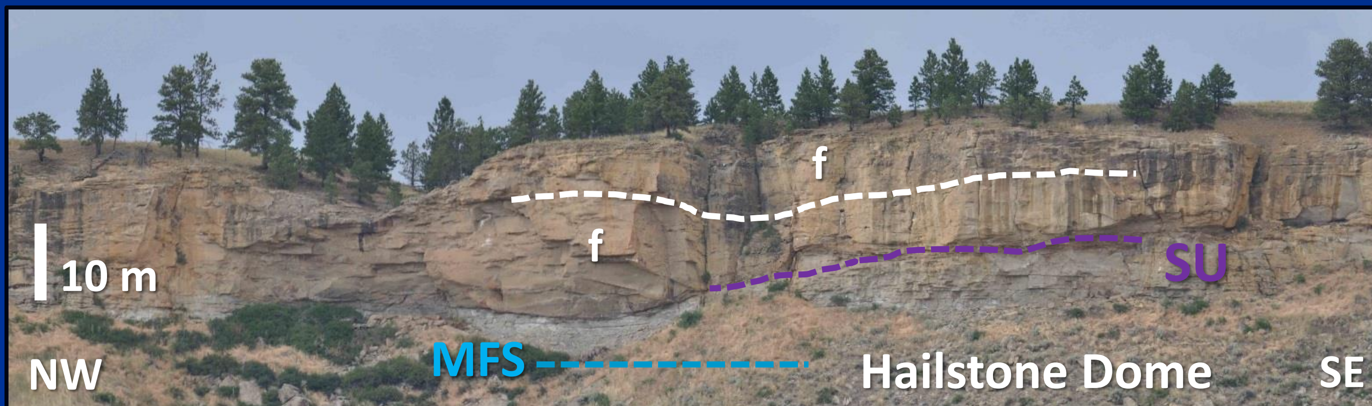


Total Interval Isopach

- Transgressive fining upward succession
  - Fluvial channels (FA6) to estuary to bay (FA8) to shoreface (FA4) to offshore transition to marine (FA9)

- Up to ~40 m thick
- FA8 retrograded and filled much the Incised Valley
- Base is incision surface **SU**
- Top is **MFS**


10 m
f
d
N
Big Coulee Dome
'Typical' Single Story Fluvial Channel
S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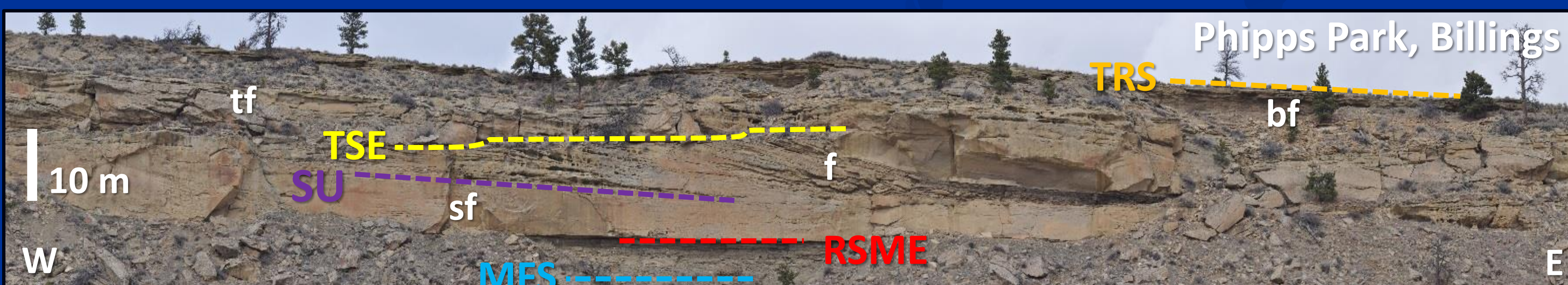
Hailstone Dome
SE


Phipps Park, Billings
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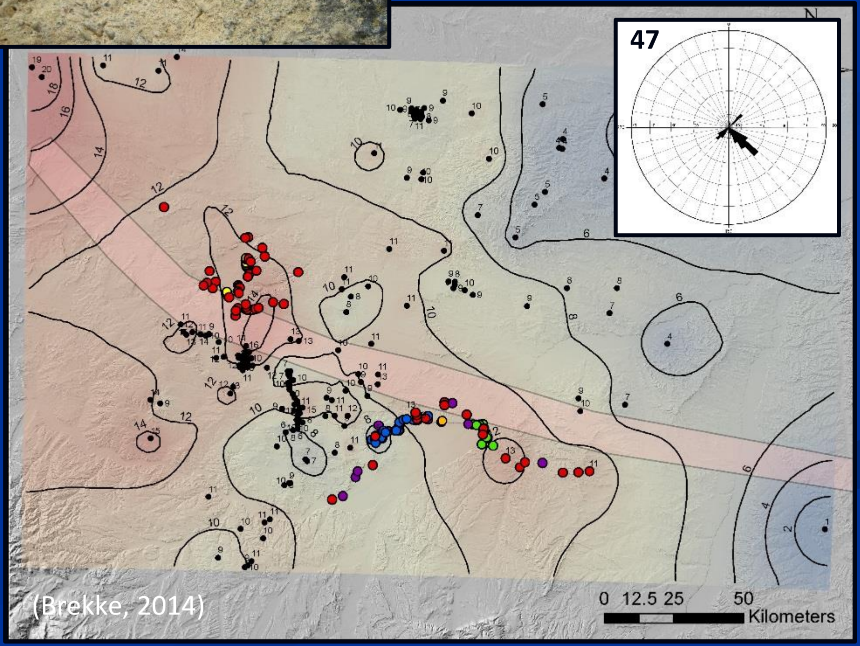
Facies Succession 7:
Eagle: Sandstone 4

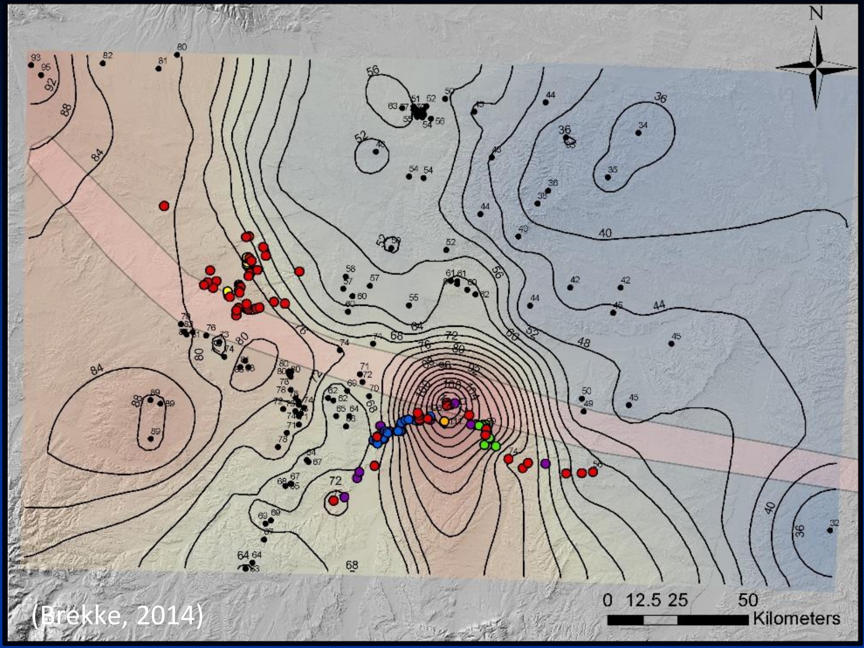
- Regressive coarsening upward succession
  - Shelf to offshore transition (FA1), delta front(FA2), and shoreface (FA3) deposits.
  - Up to ~20 m thick
  - Prograded to the SE
  - Base is **MFS**
  - Truncated by a regional **TRS** associated with the Claggett transgression



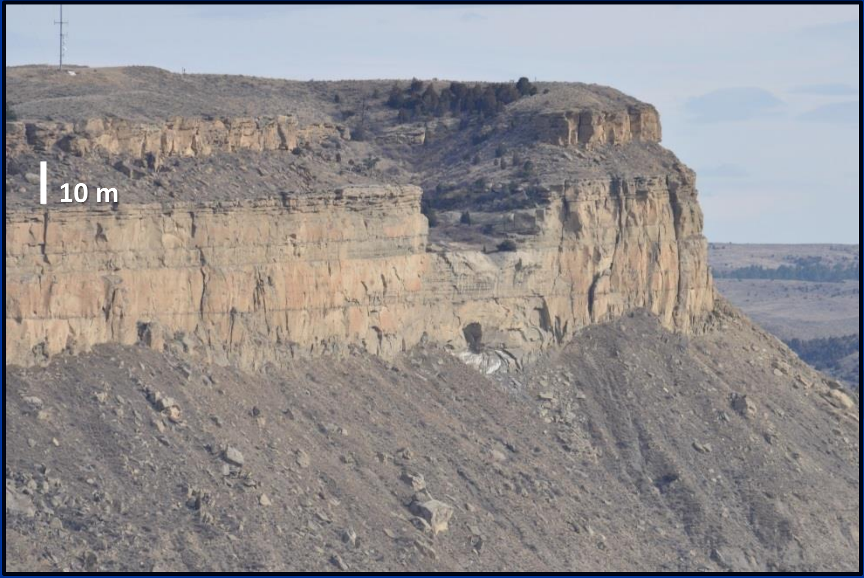
Sandstone Isopach

Significance of the LBFZ

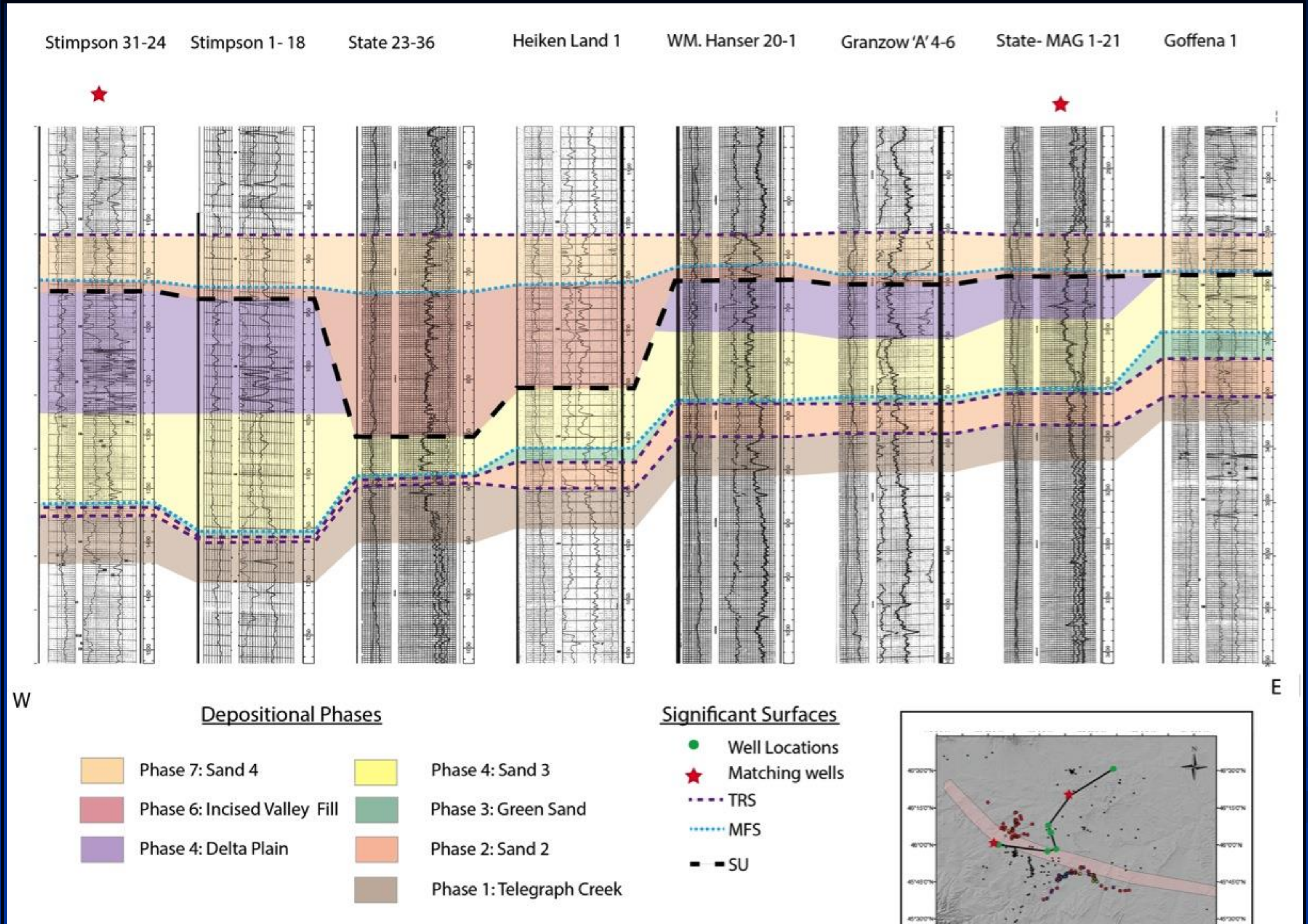
- Syndepositional faulting along the Lake Basin Fault Zone creates the paleostrike variability of the sediment packages, affecting sediment distribution throughout the deposition of the Telegraph Creek and Eagle formations.
- Accommodation generation within and to the south of the LBFZ has a three-fold history : 1) low activity (FS1) , 2) high activity (FS2-5), and 3) decreased activity (FS 6-7).



Eagle Total Interval Isopach



Significance of the LBFZ



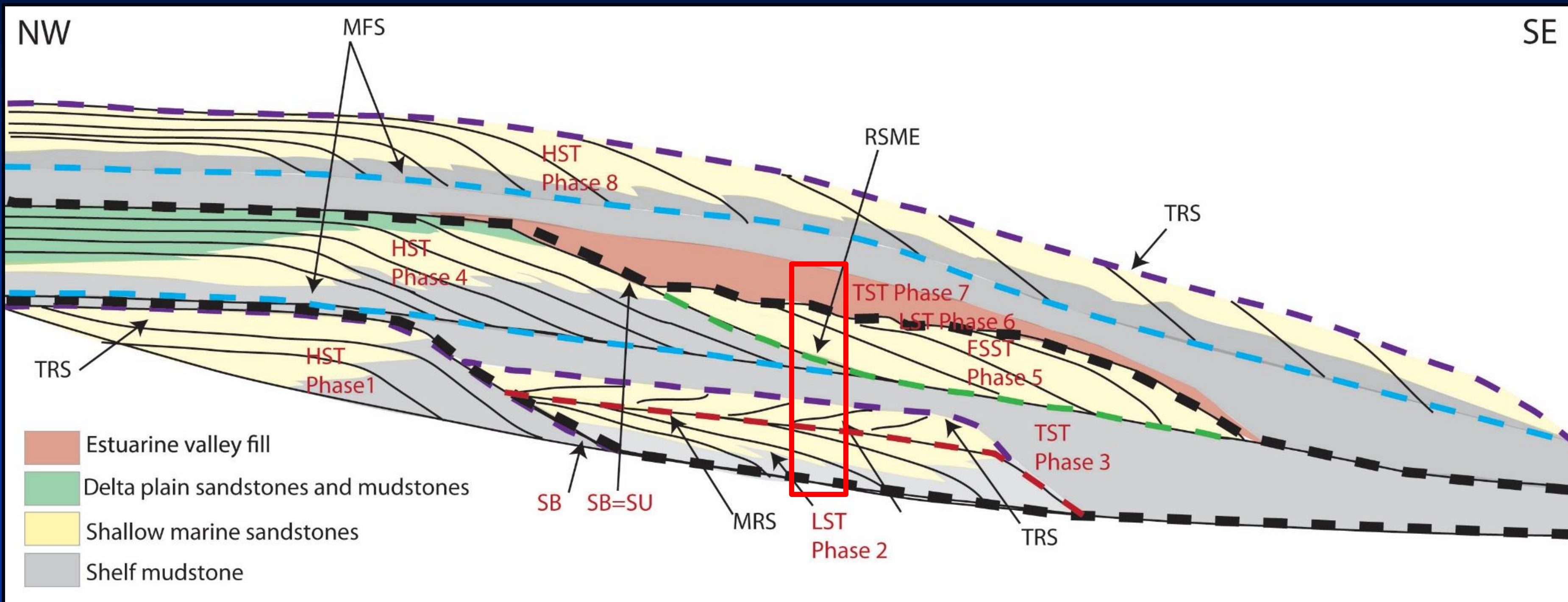
(Brekke, 2014)

Sequence Stratigraphy

- The Telegraph Creek and Eagle formations consist of 8 system tracts:
  - 8) Highstand (Upper Eagle deltaics and shoreface)
  - 7) Transgressive (Estuary/Bay/Shoreface/Green Sands)
  - 6) Lowstand (Fluvial channels)
  - 5) Falling stage (Sharp based shoreface and fluvial incision)
  - 4) Highstand (Middle Eagle deltaics)
  - 3) Transgression (Overwash fans and green sands)
  - 2) Lowstand (Lower Eagle deltaics)
  - 1) Highstand (Telegraph Creek deltaics)

Dip Section Schematic

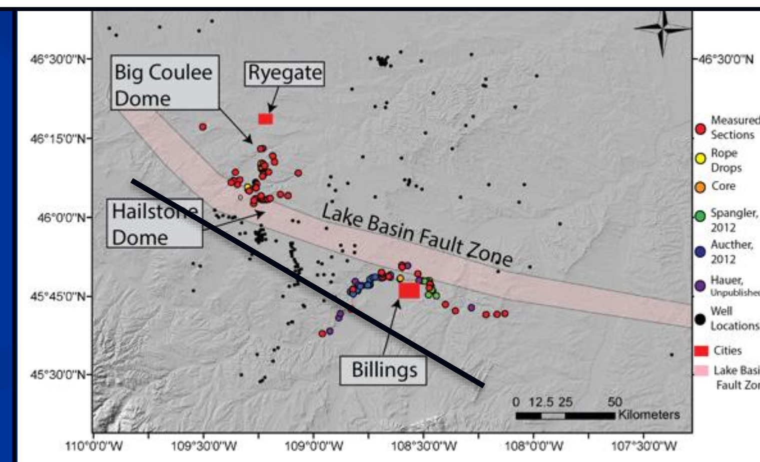
(modified from Brekke, 2014)



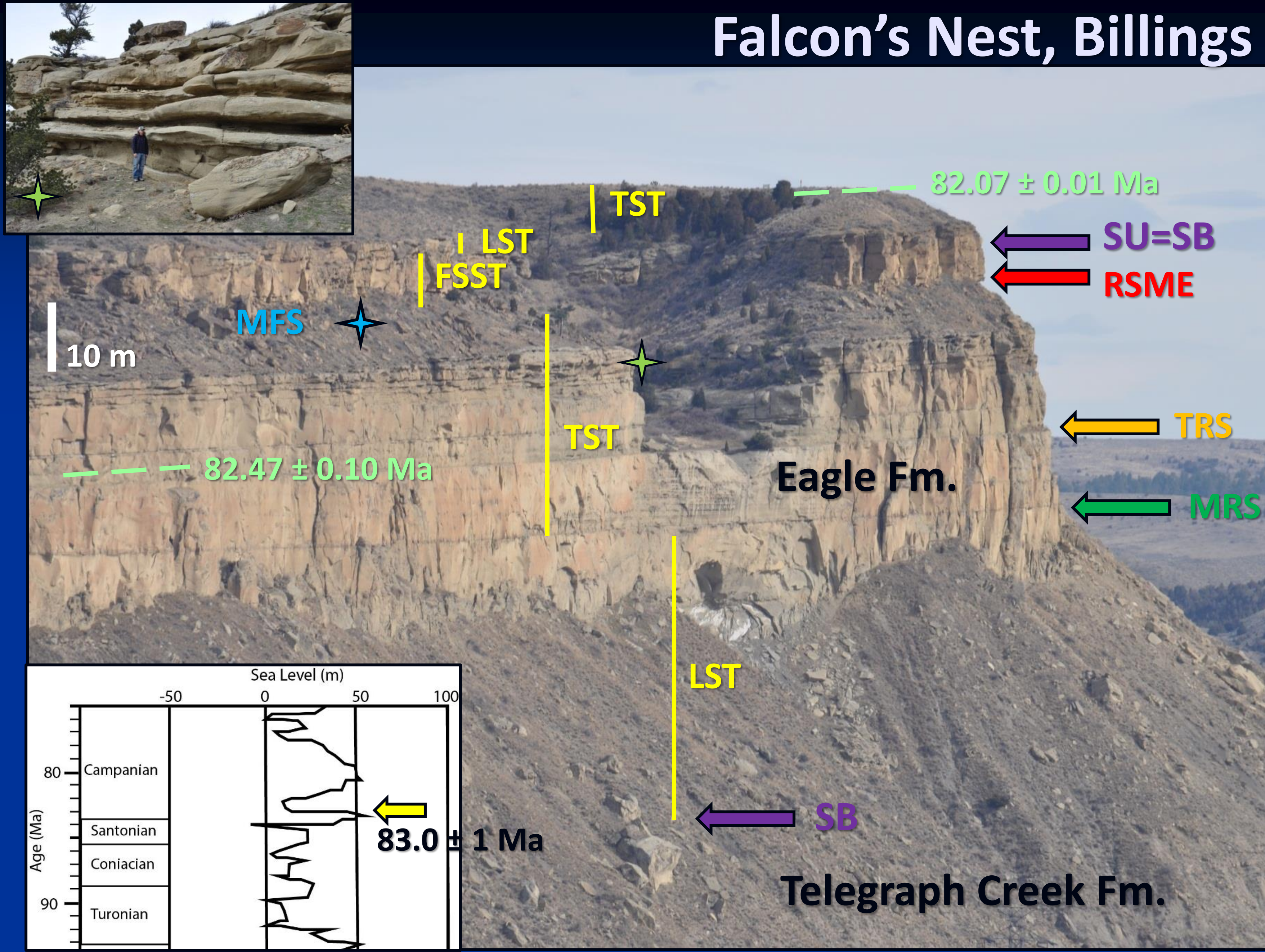
Two bentonites were dated using U/Pb ID-TMS method on zircons. These bentonites are located in successive transgressive system tracts.

The date from the **Lower Eagle** is **82.47 ± 0.10 Ma** and the date from the **Middle Eagle** is **82.07 ± 0.01 Ma**.

This represents a **400 ka periodicity** between transgressions indicating **orbital forcing**.



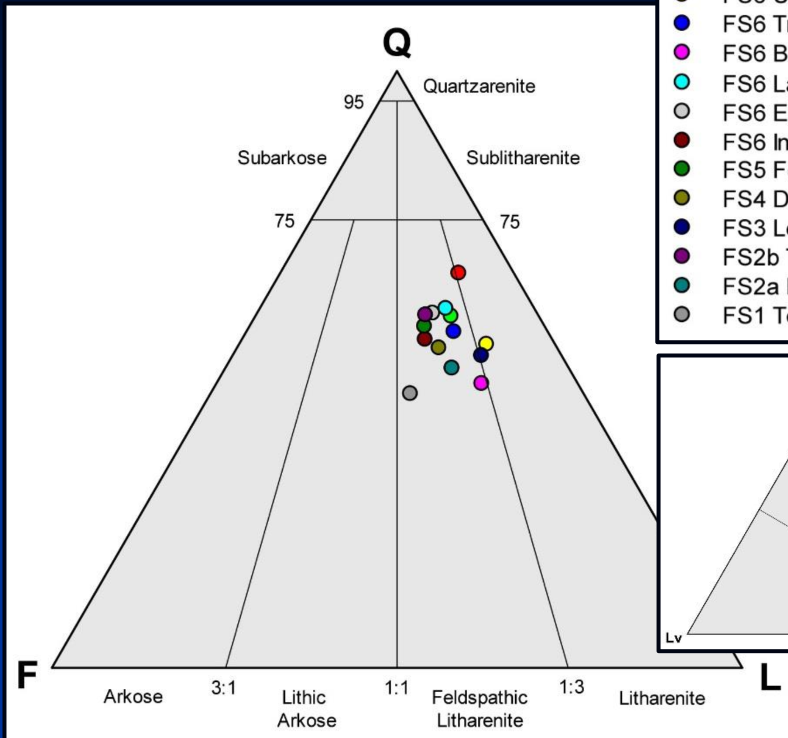
Falcon's Nest, Billings

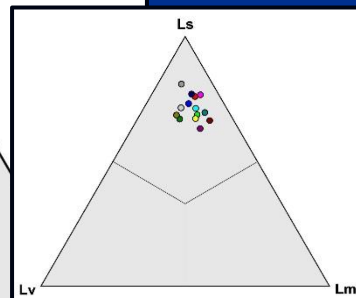


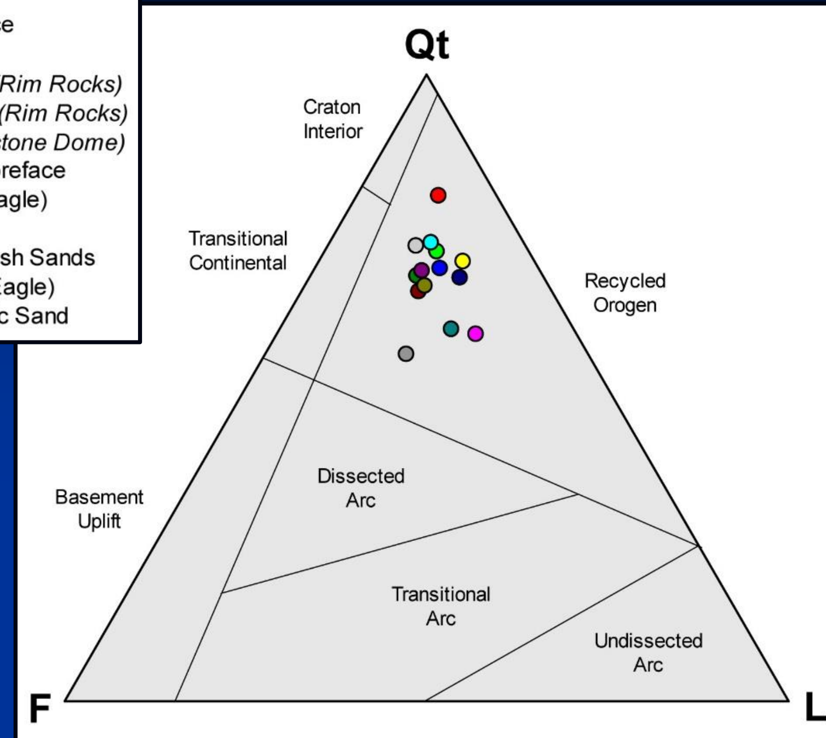
(modified from Miller et al., 2005)

Lithology

Provenance



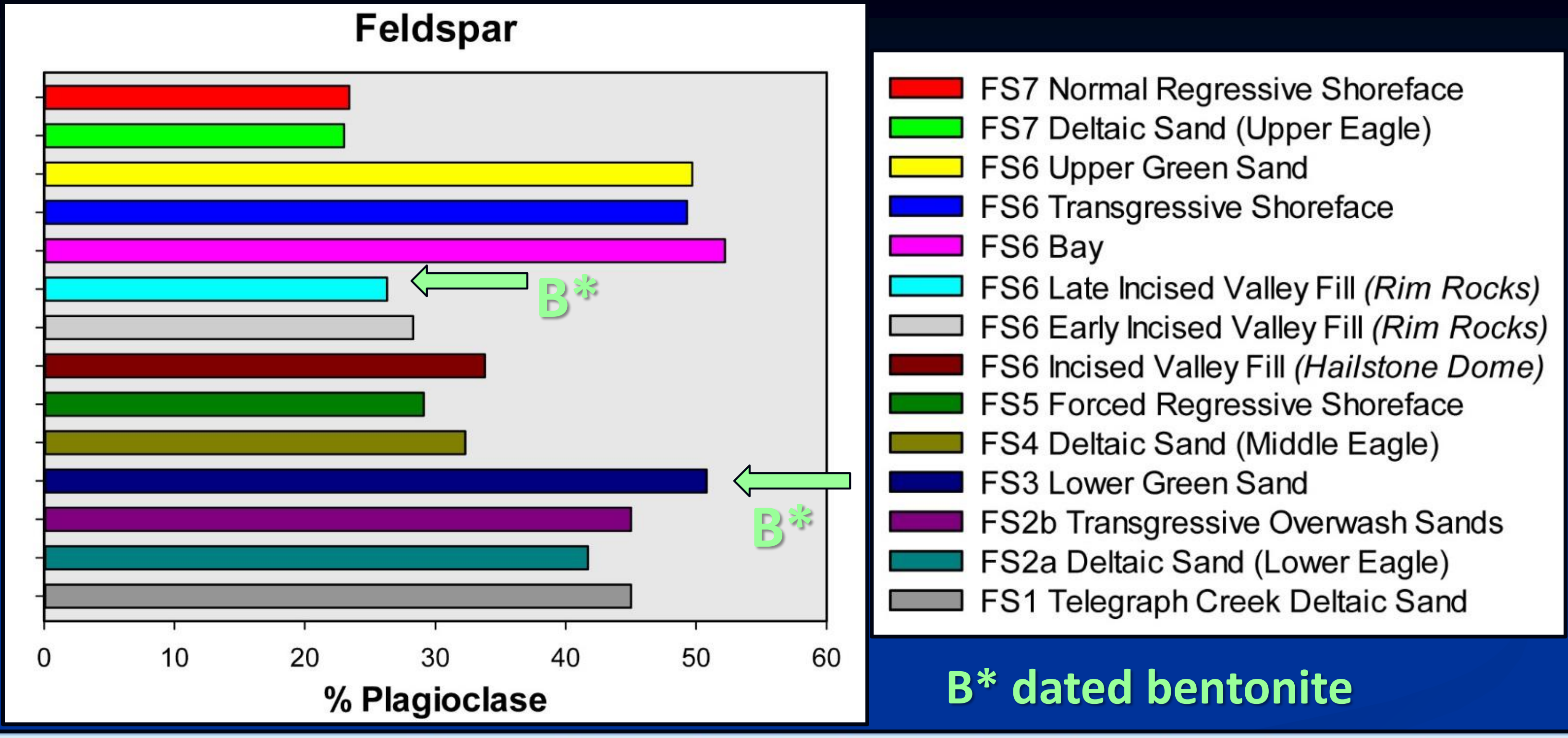




(after Folk, 1974)

(after Dickinson et al., 1983)

Sandstone	# Samples	QLF: Quartz	QLF: Lithics	QLF: Feldspar	QLF: Lm	QLF: Ls	QLF: Lv	QtFL: Quartzose	QtLF: Lithics	QtLF: Feldspar	Mean Phi
FS7 Normal Regressive Shoreface	5	66.1	25.9	8.0	15.6	75.8	8.6	80.6	11.4	8.0	2.29
FS7 Deltaic Sand (Upper Eagle)	8	58.9	28.3	12.7	20.0	68.5	11.5	71.7	15.6	12.7	2.63
FS6 Upper Green Sand	7	54.2	35.9	9.9	20.2	67.0	12.8	70.1	20.0	9.9	3.05
FS6 Transgressive Shoreface	5	56.3	30.1	13.6	14.8	73.0	12.2	69.0	17.4	13.6	2.27
FS6 Bay	5	47.6	38.5	13.9	17.1	76.5	6.4	58.5	27.6	13.9	2.78
FS6 Late Incised Valley Fill *(Rim Rocks)*	5	60.2	27.0	12.8	18.2	71.1	10.7	73.1	14.1	12.8	2.42
FS6 Early Incised Valley Fill *(Rim Rocks)*	5 (2c)	59.4	25.5	15.1	13.0	71.3	15.7	72.6	12.3	15.1	2.16
FS6 Incised Valley Fill *(Hailstone Dome)*	5	55.1	26.6	18.4	25.5	66.2	8.3	65.3	16.3	18.4	2.25
FS5 Forced Regressive Shoreface	5	57.3	25.4	17.4	14.8	66.8	18.4	67.8	14.8	17.4	2.32
FS4 Deltaic Sand (Middle Eagle)	10	53.6	29.3	17.1	12.9	68.4	18.7	66.2	16.7	17.1	2.58
FS3 Lower Green Sand	7 (2c)	52.3	36.1	11.6	13.9	76.8	9.3	67.5	20.9	11.6	3.11
FS2b Transgressive Overwash Sands	5 (2c)	59.1	24.6	16.3	23.8	63.0	13.2	68.6	15.1	16.3	2.52
FS2a Deltaic Sand (Lower Eagle)	6 (2c)	50.2	32.9	16.9	22.2	69.4	8.4	59.3	23.8	16.9	2.79
FS1 Telegraph Creek Deltaic Sand	8	45.9	29.0	25.1	8.4	80.8	10.8	55.3	19.6	25.1	2.71



B* dated bentonite

Sandstone	# Samples	Sanidine	Orthoclase	Microcline	Total K Spar	Albite	Oligoclase	Total Plag	QLF: Feldspar
FS7 Normal Regressive Shoreface	5	8.8	63.4	4.4	76.6	12.0	11.4	23.4	8.0
FS7 Deltaic Sand (Upper Eagle)	8	10.7	62.7	3.6	77.0	10.2	12.8	23.0	12.7
FS6 Upper Green Sand	7	14.0	34.8	1.5	50.3	26.5	24.2	49.7	9.9
FS6 Transgressive Shoreface	5	14.9	33.8	2.0	50.7	25.0	24.3	49.3	13.6
FS6 Bay	5	10.4	34.3	3.1	47.8	28.8	23.4	52.2	13.9
FS6 Late Incised Valley Fill (Rim Rocks)	5	13.2	55.6	4.9	73.7	1.1	25.2	26.3	12.8
FS6 Early Incised Valley Fill (Rim Rocks)	5 (2c)	23.6	44.5	3.6	71.7	1.9	26.4	28.3	15.1
FS6 Incised Valley Fill (Hailstone Dome)	5	22.3	40.1	3.8	66.2	2.5	31.3	33.8	18.4
FS5 Forced Regressive Shoreface	5	22.6	44.3	4.0	70.9	1.2	27.9	29.1	17.4
FS4 Deltaic Sand (Middle Eagle)	10	23.7	40.9	3.1	67.7	2.6	29.7	32.3	17.1
FS3 Lower Green Sand	7 (2c)	13.4	31.4	4.4	49.2	13.5	37.3	50.8	11.6
FS2b Transgressive Overwash Sands	5 (2c)	8.3	41.7	5.0	55.0	12.2	31.8	45.0	16.3
FS2a Deltaic Sand (Lower Eagle)	6 (2c)	14.5	39.7	4.1	58.3	12.8	28.9	41.7	16.9
FS1 Telegraph Creek Deltaic Sand	8	18.8	32.4	3.8	55.0	22.0	23.0	45.0	25.1

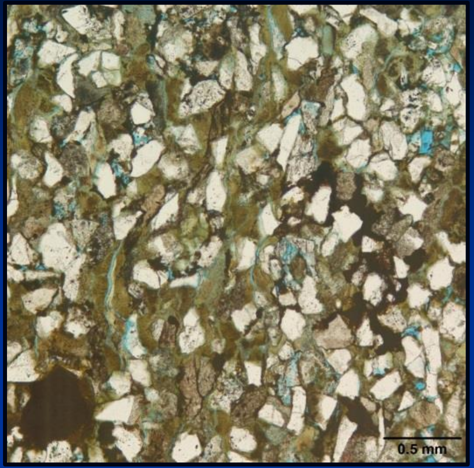
Feldspar types identified using the methods described by Gautier (1981).

Glaucony vs. Verdine

iron-rich clay minerals		non[1]-granular		granular: peloids[2]		granular: ooids	
		M	A	M	A	M	A
Glauconitic minerals	Glauconite		X	?	XX		
Glauconitic minerals	Glauconitic Smectite	x	X	XX	X		
Glauconitic minerals	Green Smectite[3]		x	X	X	x[4]	x
Chamositic minerals	Berthierine		x	XX	X	x[4]	XX
Chamositic minerals	Chamosite		x	x[5]	X		XX

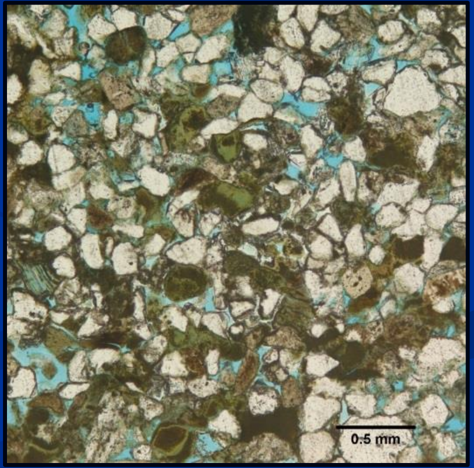
Glauconitic and chamositic iron rich clay minerals and their variability in form (modified from Van Houten & Purucker, 1984): M = modern environments and A = ancient environments. Numbers indicate as follows: 1 = film facies, including cement, thin crusts, and grain coating. 2 = some have single rims of radially arranged flakes. 3 = specific mineral seldom identified. 4 = proto-ooids with only a few laminae. 5 = sample from Barataria Bay, Louisiana.

Upper Green Sand



SHE1S21 GP1

Lower Green Sand



PHP1S1 GP1

Glaucony vs. Verdine

- **Glaucony Facies**
  - Iron-rich phyllosilicates (clays); variable potassium content; **K is the distinguishing / major cation**
    - Forms in water temperatures of 10-15°C and depths of 125-250 m
    - Thought to represent marine conditions and low sedimentation rates
  - **Green smectite** - specific mineral seldom identified; includes nontronite
  - **Mixed-layer glauconitic smectite** – K_2O content < 6%
    - Glauconitic mineral grains with lower (< 6%) K_2O are iron-rich mixed-layered illite/smectite
    - Many consider iron-rich, mixed-layered illite/smectite to simply be glaucony (e.g. Kazerouni et al., 2013; Thompson and Hower, 1975)
    - Most common in Mesozoic rocks
  - **Glauconite** – high K_2O content (> 6%); micaeous clay

Glaucony vs. Verdine

- **Verdine Facies**
  - Iron-rich phyllosilicates (clays); **Fe is the distinguishing / major cation**
    - Forms in water temperatures of > 20^{o}C and < 60 m depth
    - Forms in close proximity to river mouths and other sources of fresh water input
  - **Odinite** – 7Å green iron-rich clay; forms in modern settings at sediment surface
    - Odinite reduces to berthierine at temperatures of < 60^{o}C
  - **Berthierine** – serpentine group; 7Å chamositic clay mineral
    - Berthierine diagenetically alters to chamosite
  - **Chamosite** – 14Å mineral of the Fe-rich chlorite group
    - Fe^{2+} end member
- When chamosite forms a framework grain coating, it can inhibit quartz cementation, preserving anomalously high porosity in sandstone reservoirs (> 20%) at great burial depths, such as 4-5 km (e.g., Bahlis and De Ros, 2013; Pe-Piper and Weir-Murphy, 2008).

Glaucony vs. Verdine

Sandstone	# Samples	Kaolinite	Illite	Smectite	Glauconite	Chlorite	Berthierine	% Clay
FS7 Normal Regressive Shoreface	3	7.5	13.1	16.9	6.3	32.1	24.1	3.7
FS7 Deltaic Sand (Upper Eagle)	3	6.8	16.0	16.7	2.5	32.1	25.9	4.1
FS6 Upper Green Sand	3	8.4	15.5	31.8	15.6	25.6	3.1	8.7
FS6 Transgressive Shoreface	3	8.4	15.5	31.8	15.6	25.6	3.1	4.6
FS6 Bay	3	6.4	18.2	23.9	17.9	24.7	8.9	12.6
FS6 Late Incised Valley Fill *(Rim Rocks)*	3	26.4	14.1	22.1	5.1	28.3	4.0	5.4
FS6 Early Incised Valley Fill *(Rim Rocks)*	3 (1c)	32.1	13.9	18.0	4.0	28.0	4.0	3.8
FS6 Incised Valley Fill *(Hailstone Dome)*	3	30.7	13.0	11.7	0.9	35.7	8.0	4.8
FS5 Forced Regressive Shoreface	3	33.6	14.1	16.8	5.0	28.5	2.0	3.4
FS4 Deltaic Sand (Middle Eagle)	3	12.0	13.4	11.2	0.7	37.6	25.1	3.9
FS3 Lower Green Sand	3 (1c)	8.3	12.1	28.5	20.0	29.6	1.5	9.8
FS2b Transgressive Overwash Sands	3 (1c)	9.0	13.6	27.0	12.4	30.0	8.0	3.6
FS2a Deltaic Sand (Lower Eagle)	3 (1c)	6.5	15.5	14.2	2.4	33.1	28.3	4.2
FS1 Telegraph Creek Deltaic Sand	3	11.1	12.8	14.0	2.3	37.8	22.0	4.8

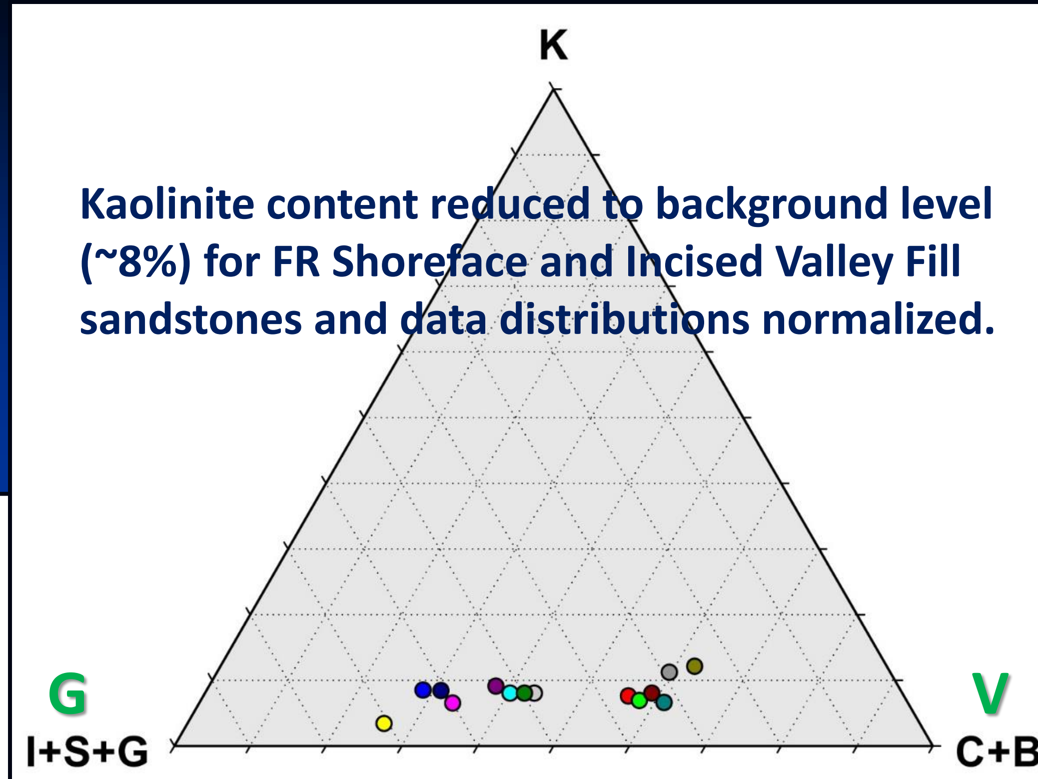
Upper Green Sand

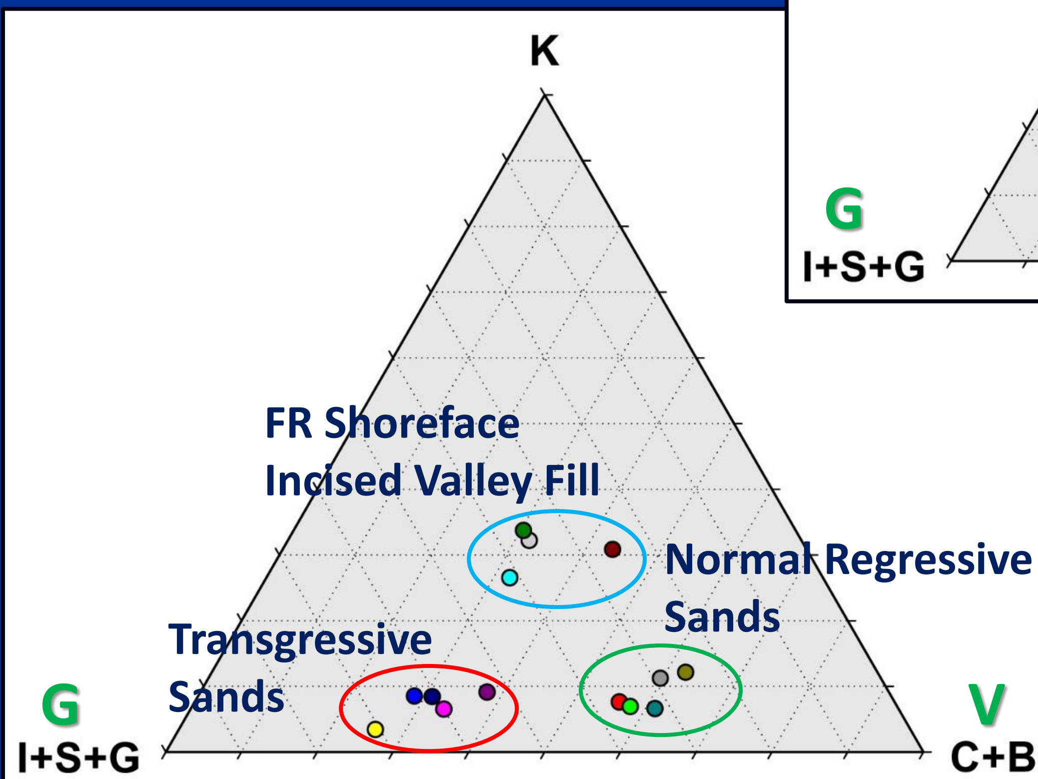
Lower Green Sand HCS

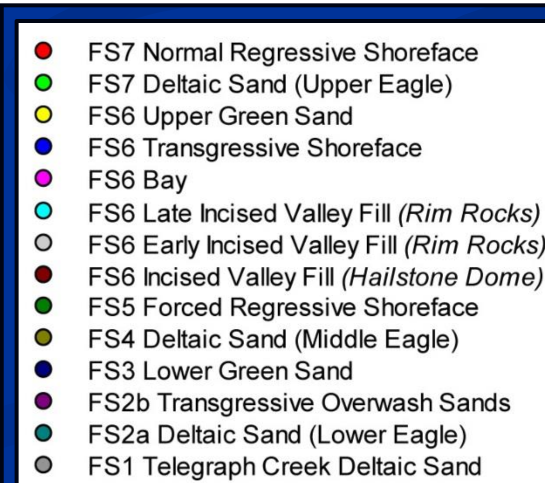
Glaucony vs. Verdine

Anomalously high kaolinite content is the result of base-level fall and fluvial incision into weathered delta plain sediments.

Kaolinite content reduced to background level (~8%) for FR Shoreface and Incised Valley Fill sandstones and data distributions normalized.







Conclusions – Summary

- Sydepositional fault displacement (down to the south) in the LBFZ controlled paleostrike sediment distribution patterns and the location of valley incision
- Base-level fluctuations controlled by orbital forcing (400 ka eccentricity) lead to system tract cyclicity
- Plagioclase feldspar content generally decreases up-section with two exceptions that are coincident with bentonites (Elkhorn Mountain Volcanics?)
- Glaucony facies clays (illite + glauconite + smectite) dominate transgressive system tract sandstones
- Verdine facies clays (chlorite + berthierine) dominate regressive system tract sandstones
- Increased kaolinite content is associated with the forced regression and incised valley fill sandstones

Acknowledgments

- Students: Neal Auchter, Alexander Brekke, Ryan Carter, Joern Hauer, Elyse Rector, Eleanor Spangler, and Jennifer Torres
- Colleagues: Marc Hendrix, Michael Hofmann, and Graham Thompson
- Financial Support
  - American Association of Petroleum Geologists
  - Ballard Petroleum Holdings, LLC
  - Billings Geophysical Society
  - Geological Society of America
  - Patrick McDonough Memorial Fund: UM Foundation
  - Rocky Mountain Association of Geologists
  - Tobacco Root Geological Society