

# Application of Quantitative Facies Analysis to Sedimentology-Stratigraphy & Geochemistry of Unconventional Shale Resources

By Ariel Malicse, Ph.D.

President – Owner of Malletsee Holdings, LLC.

# OBJECTIVES

- To show the applications of Quantitative Facies Analysis (QFA) in sedimentology, stratigraphy, and geochemistry.
- To link geochemistry facies to Markov Chain Analysis.



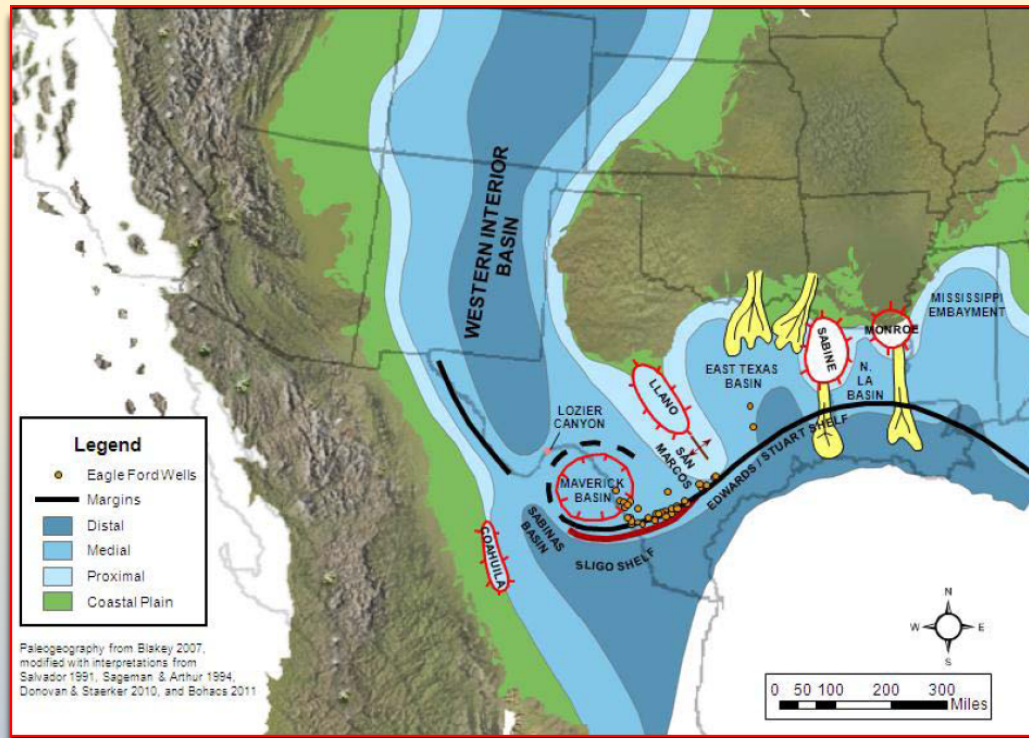
# COMMENTS & ACKNOWLEDGEMENTS

- The first part of the talk on Eagle Ford is from series of studies presented at the AAPG-ICE in 2013 (with J. G. Garcia, Shell) and AAPG, 2016 (with E. Van Dusen, B. Neff, D. Hurst, and H. McGarity-Beat). Data used was from the Core Lab Eagle Ford consortium.
- Geochemical data presented here are real data in the West Texas Permian Basin; however, location and actual depths are not shown.
- Thanks to John Ballmer (Sr. Petrophysicist, Oxy), Core Lab, Premiere Laboratory, Shell, and Murphy Exploration & Production.

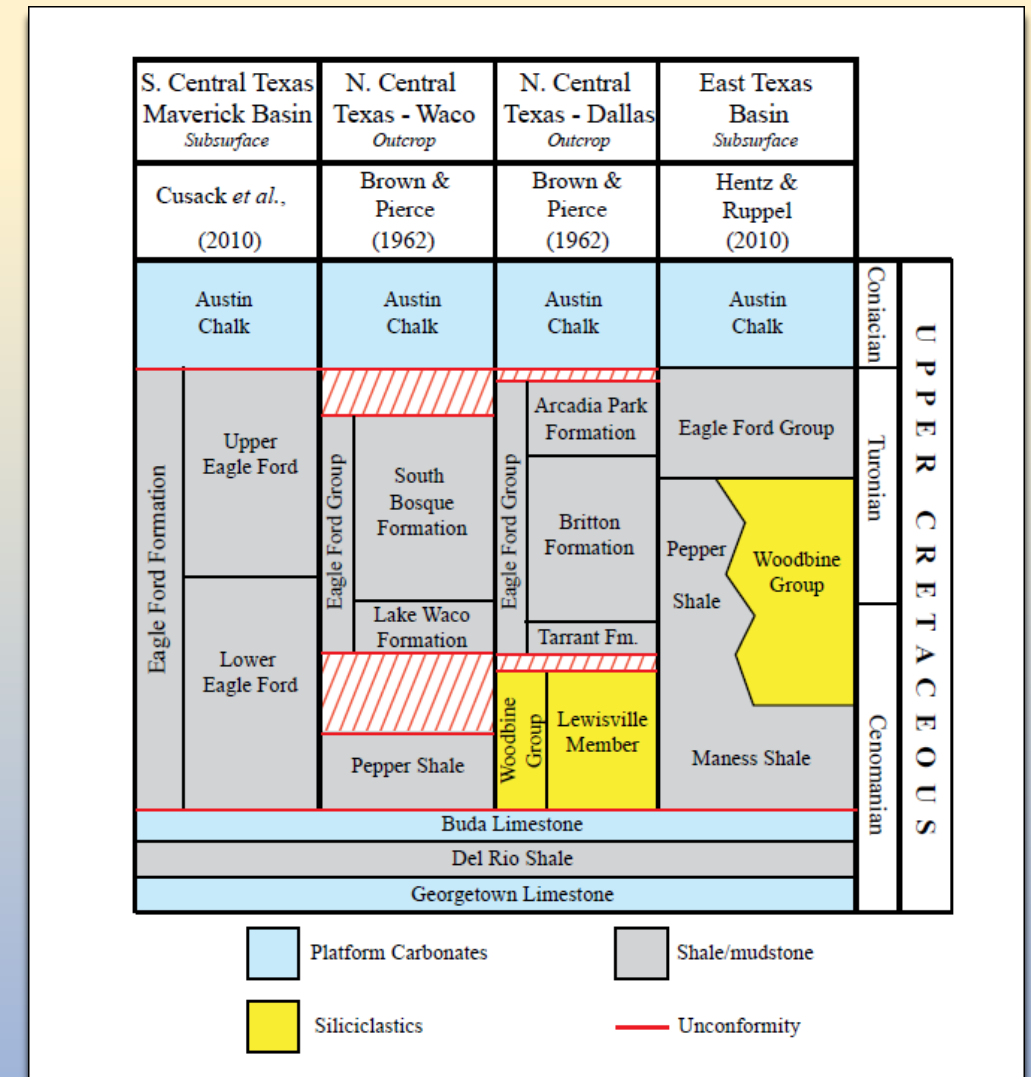
# TALK OUTLINE

1. QFA as it applies to sedimentary facies in the Eagle Ford in South Texas
  - What are the Eagle Ford sedimentary facies?
  - Methodology – What are the steps in QFA
  - What does the data mean? Iso-percent of different Eagle Facies at various stratigraphic slices
  - Application to mechanical stratigraphy
2. Application of QFA to ~ geochemical facies derived from 6,000+ data points
  - Variation of geochemical facies as a function of sequence stratigraphic units (no discussion on sequence stratigraphy)
  - Application of Markov Chain from QFA

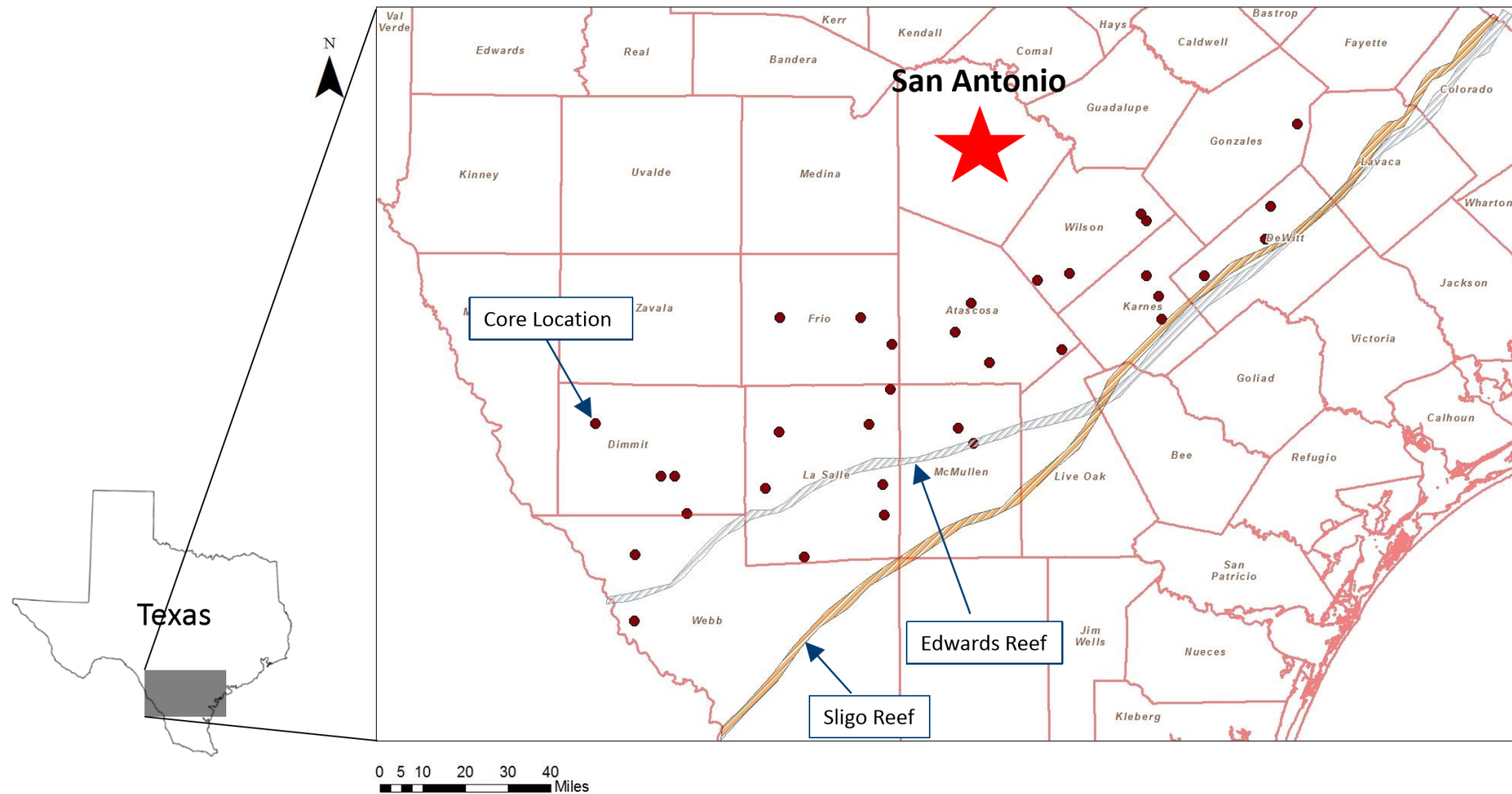
# GEOLOGIC SETTING & STRATIGRAPHY



- Eagle Ford was deposited around Texas during Late Cenomanian to Turonian time (Late Cretaceous, 97 to 89.8 Ma)
- Deposition of the Eagle Ford Formation is coeval with oceanic anoxic event 2 (OAE 2).
- SW of the San Marcos Arch, Eagle Ford is primarily composed of organic-rich marls with interbedded with lean, lime mudstone.
- SE of the San Marcos Arch, Eagle is shaly, organic-rich marls and lime mudstones.



# Study Area and Location of Cores – Eagle Ford Shale



37 cores



1457 1458 1459 1460 1461 1462

1B 1C 1B 1C 1B 1C

1C 1B 1C 1B 1C 1B

1B 1C 1A 1B 1C 1B

1C 1C 1B 1C 1A 1B

1B 1C 1C 1A 1C 1C

ft. .5 1 2 .5 3

1C 1A 1B 1C 1B 1C

1C 1B 1C 1A 1C 1C

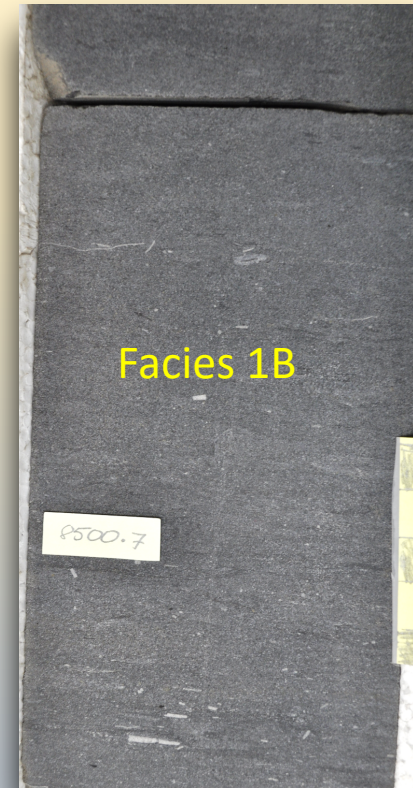
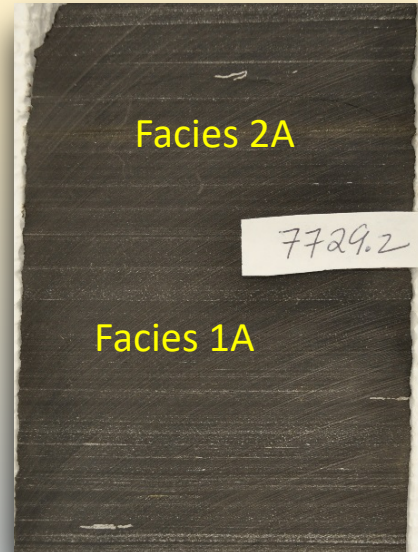
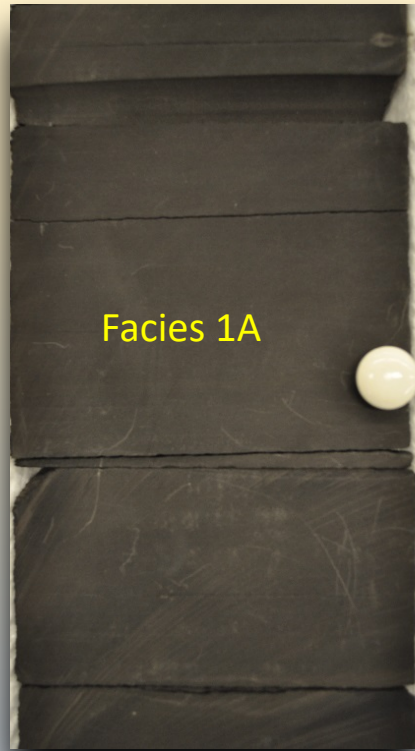
1B 1C 1B 1A 1C 1C

1C 1B 1C 1A 1C 1C

- **Subdivided cores into distinct sedimentary facies**
  - Initially divided: color, sedimentary structures, bioturbation
  - Enhance with XRD analysis: calcite content, TOC
- **Recorded:**
  - Color
  - The top and bottom depths of each facies
  - Sedimentary features
  - Nature of upper and lower contacts
  - Other features (faults, fractures, etc).
- **Incorporated other data**
  - Biostratigraphy
  - XRD
  - Rock mechanical data

# FACIES TYPES 1

Core Diameter = 3.5"



## **Facies 1A/2A**

### **Description**

- Black to dark gray
- Thin laminations in 2A

### **Composition**

- TOC = 3-8% (highest)
- Calcite = 40-70%

### **Interpretation**

- Lowest energy suspension deposits
- Facies 2A occasional ripples

## **Facies 1B**

### **Description**

- Dark gray
- Thin laminations. Bioturbated (BI 2-5)

### **Composition**

- TOC = 1-3%
- Calcite = 70-80%

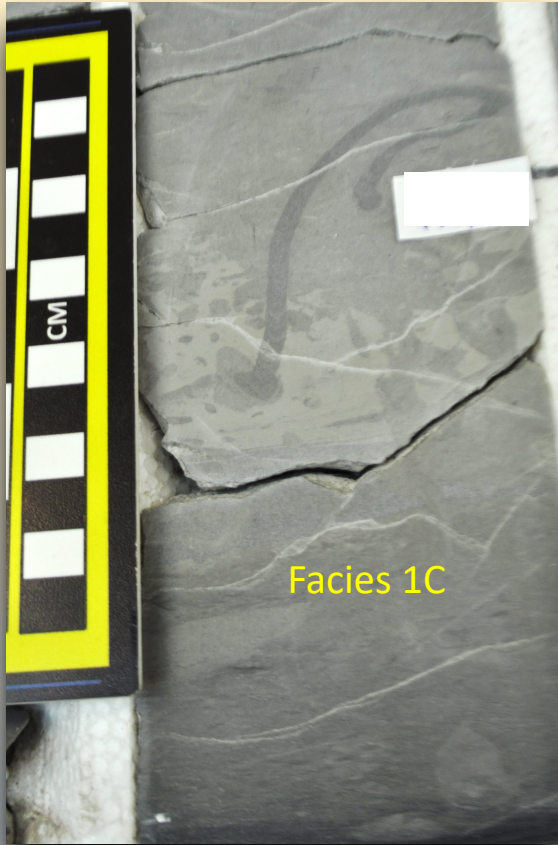
### **Interpretation**

- Suspension to ripple regime deposits
- Oxidic to suboxic conditions



# FACIES TYPES 1C, 2B, 2C

Core Diameter = 3.5"



## Facies 1C

### Description

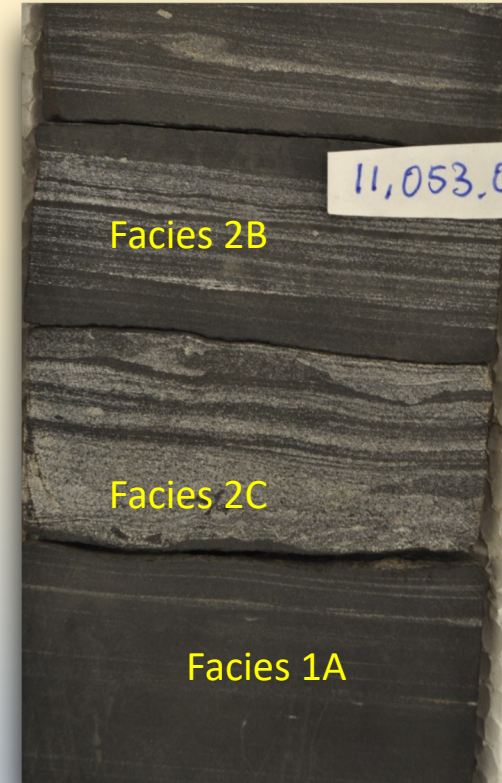
- Light gray to cream
- Bioturbated (BI 4-5)

### Composition

- TOC = <2%
- Calcite = 80-95%

### Interpretation

- Suspension to ripple regime deposits
- Oxic condition



## Facies 2B/2C

### Description

- Alternating light & dark layers
- Ripple cross laminations in 2C

### Composition

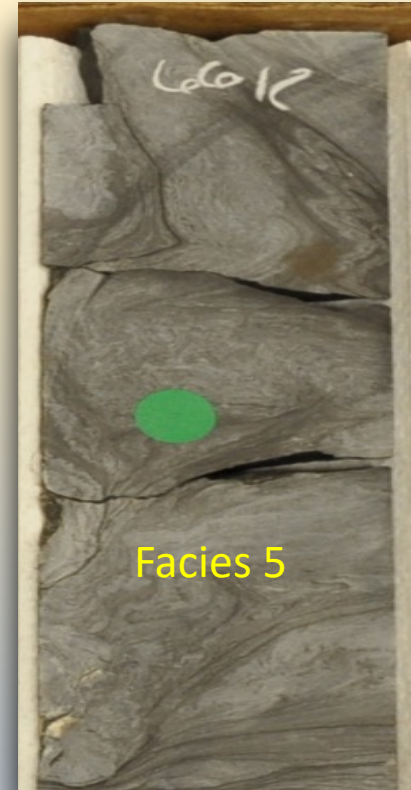
- TOC: 2B = 1-3%; 2C <2%
- Calcite = 70-80%

### Interpretation

- Variable ripple regime conditions
- Alternating suspension-traction deposition

# FACIES TYPES 3,5, 6

Core Diameter = 3.5"



## Facies 3

### Description

- Light gray
- Horizontal to low angle, cross-stratified

### Composition

- TOC = <1%
- Calcite = 80-95%

### Interpretation

- High energy traction deposits – storm/ turbidites

## Facies 5/6

### Description

- Dark to light gray
- Convoluted laminae (Facies 5)
- Matrix-supported clasts (Facies 6)

### Composition

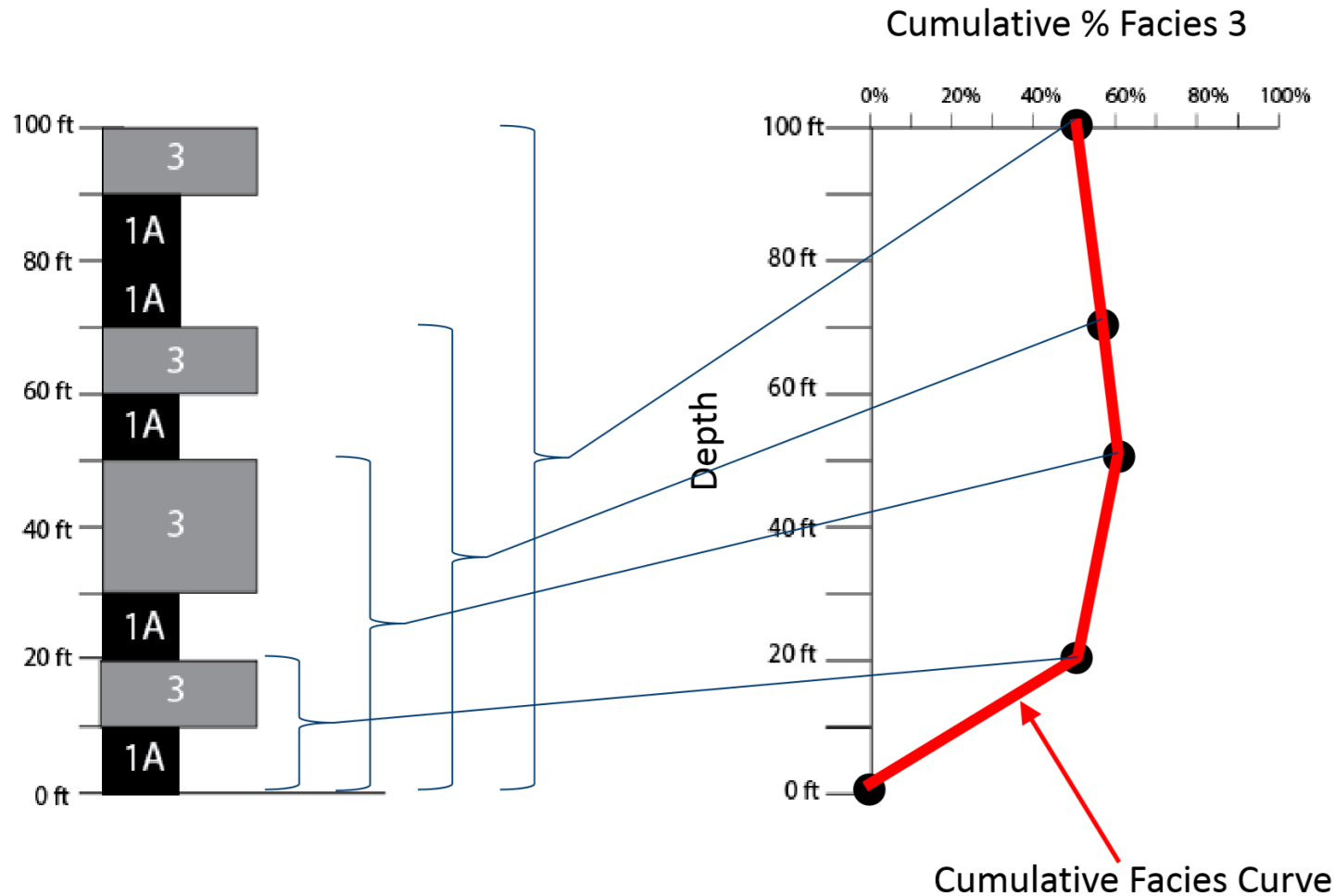
- Variable composition

### Interpretation

- Slumps & debris flow structures



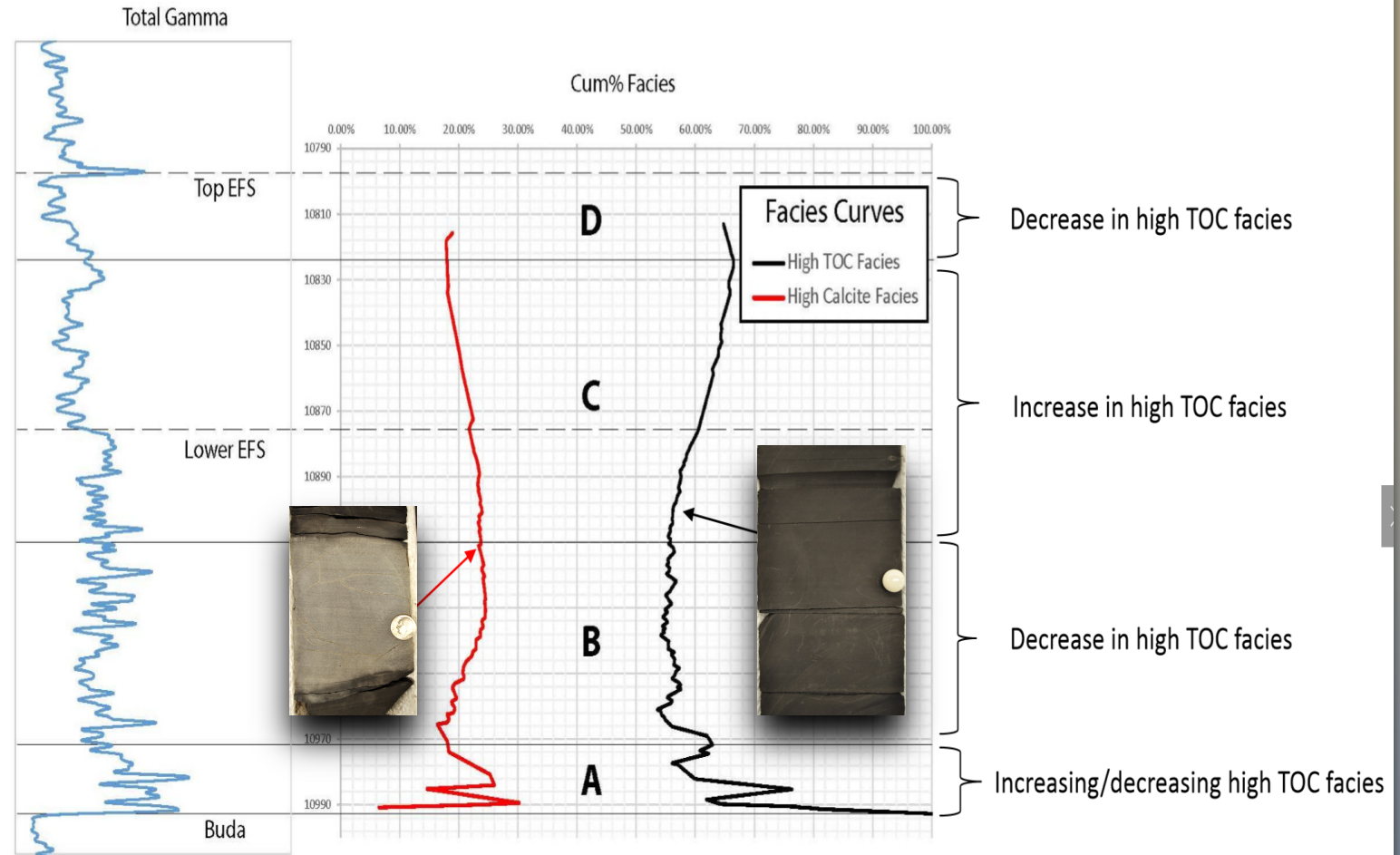
# Quantitative Facies Methodology (QFM)



- **QFM is a running net-to-gross calculation**
  - Isolate facies type/group
  - Measure facies thickness over given interval
    - Calculate cumulative %
  - Incrementally expand interval
- **Generate a cumulative percentage curve**
  - Observed changes in facies abundance
    - Increasing cumulative % = higher abundance
  - Different curves for different facies types.

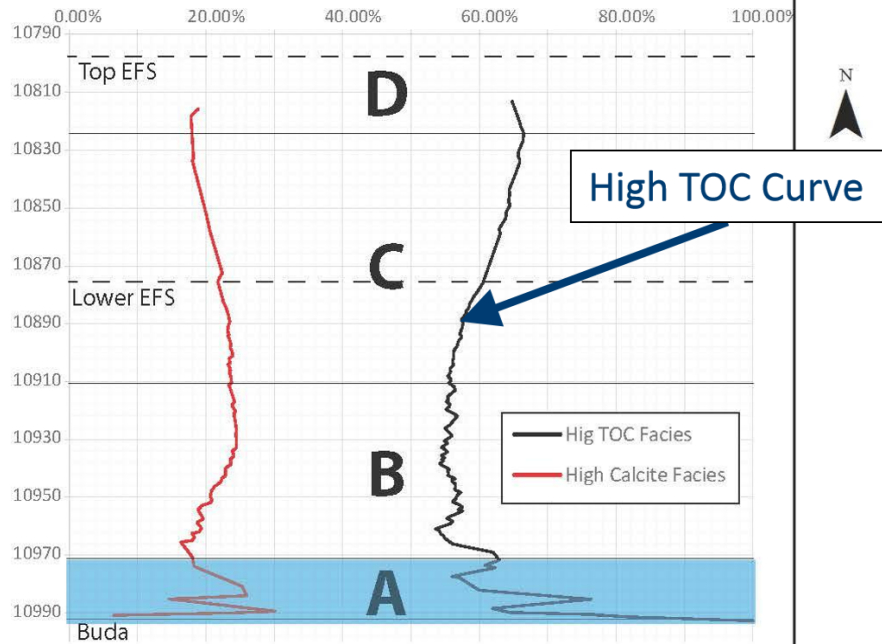
# Cumulative Facies Curves: Eagle Ford

- High TOC Facies:
  - 1A, 2A
- High Calcite Facies:
  - 2C, 3

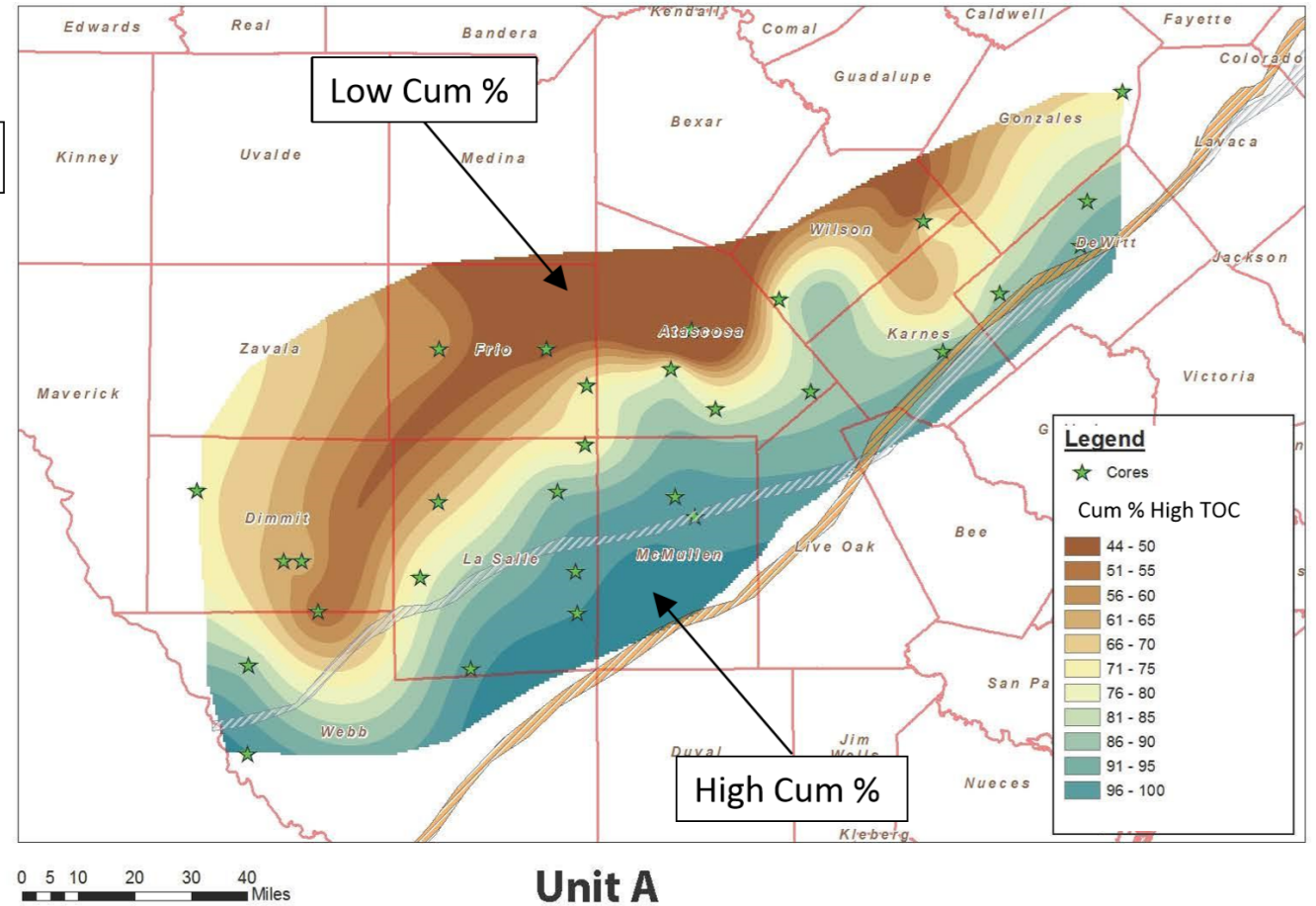


- Curves represent high calcite facies (red) and high TOC facies (black) – not all facies represented with displayed curves
- Curves subdivided by increases and decreases in cumulative %
- Pattern of cum% curves are controlled by sea level changes
- Cum% curve patterns change across the Eagle Ford Shale

# Eagle Ford Facies Distribution

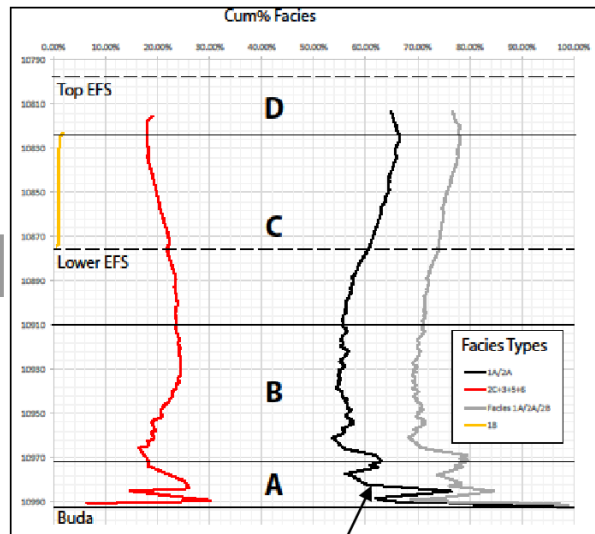


- Cum % map: high TOC facies
  - Top of Unit A
  - Brown = Low Cum%
  - Blue = High Cum%
- Illustrates changes in facies abundancies across EFS

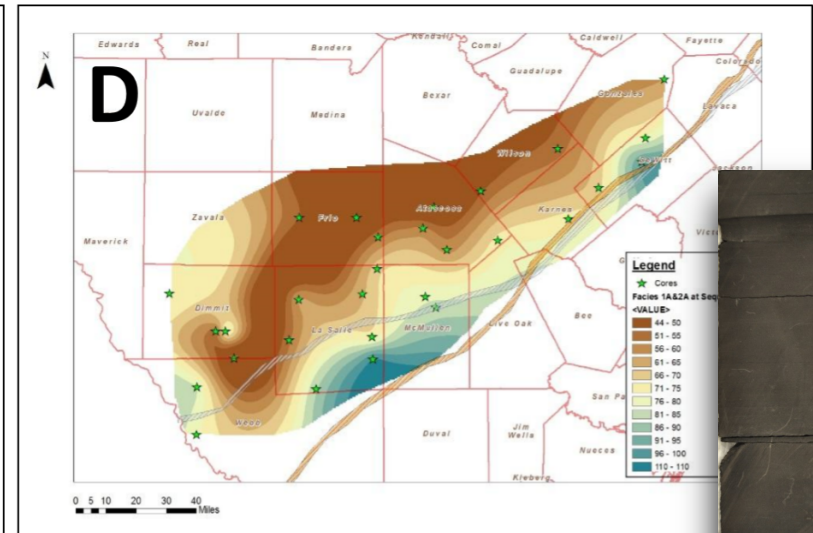
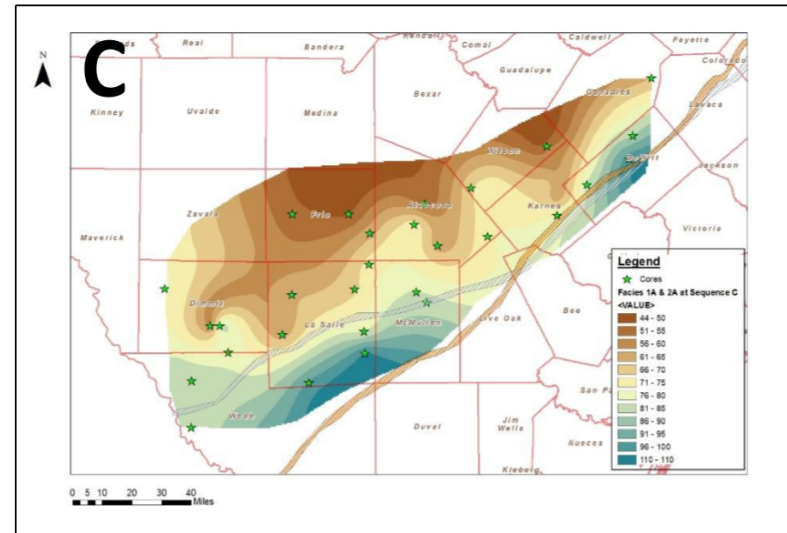
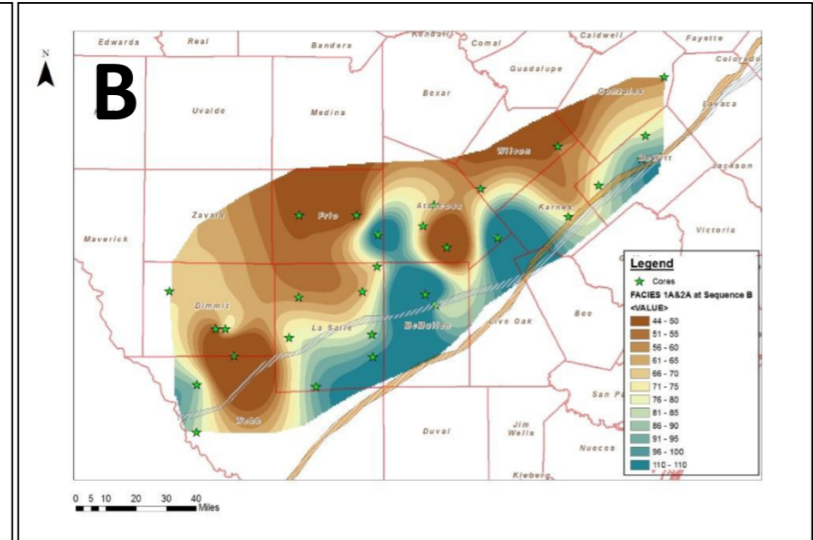
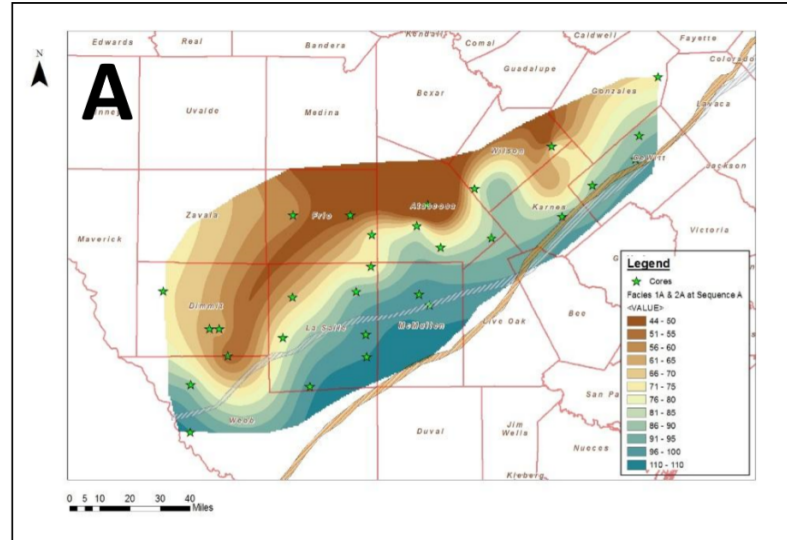


Cumulative Percent: High TOC Facies

# Eagle Ford Facies Distribution (High TOC)



1A/2A Cumulative Facies Percent





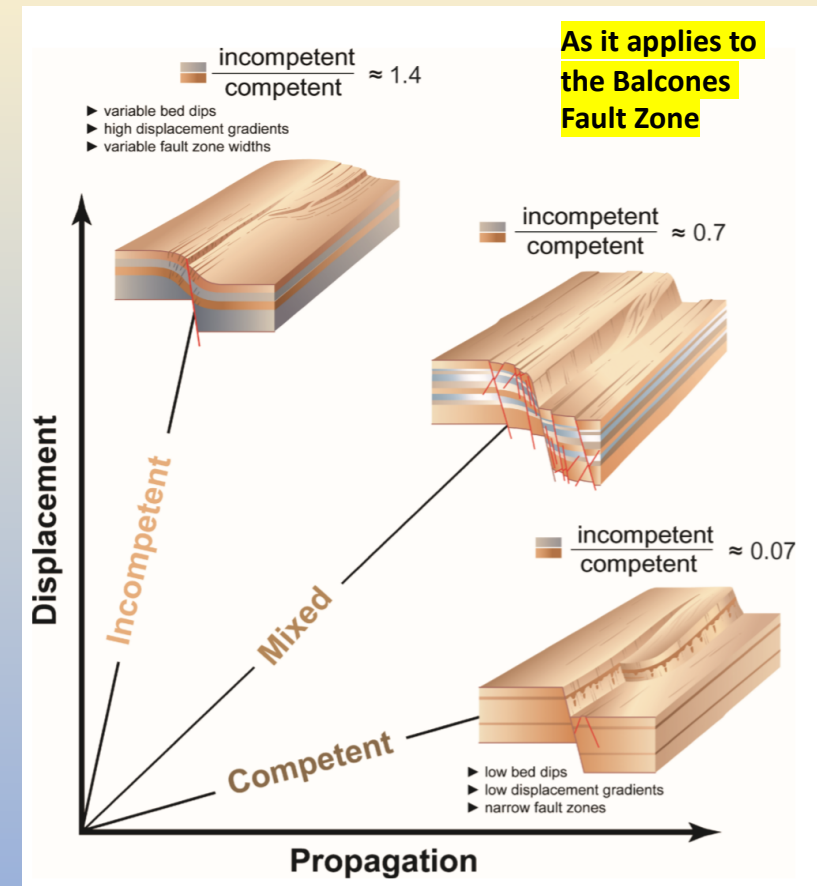
# Ratio of Incompetent and Competent Facies

(Modified after Ferrill and Morris, 2008 & Smart et al., 2014)



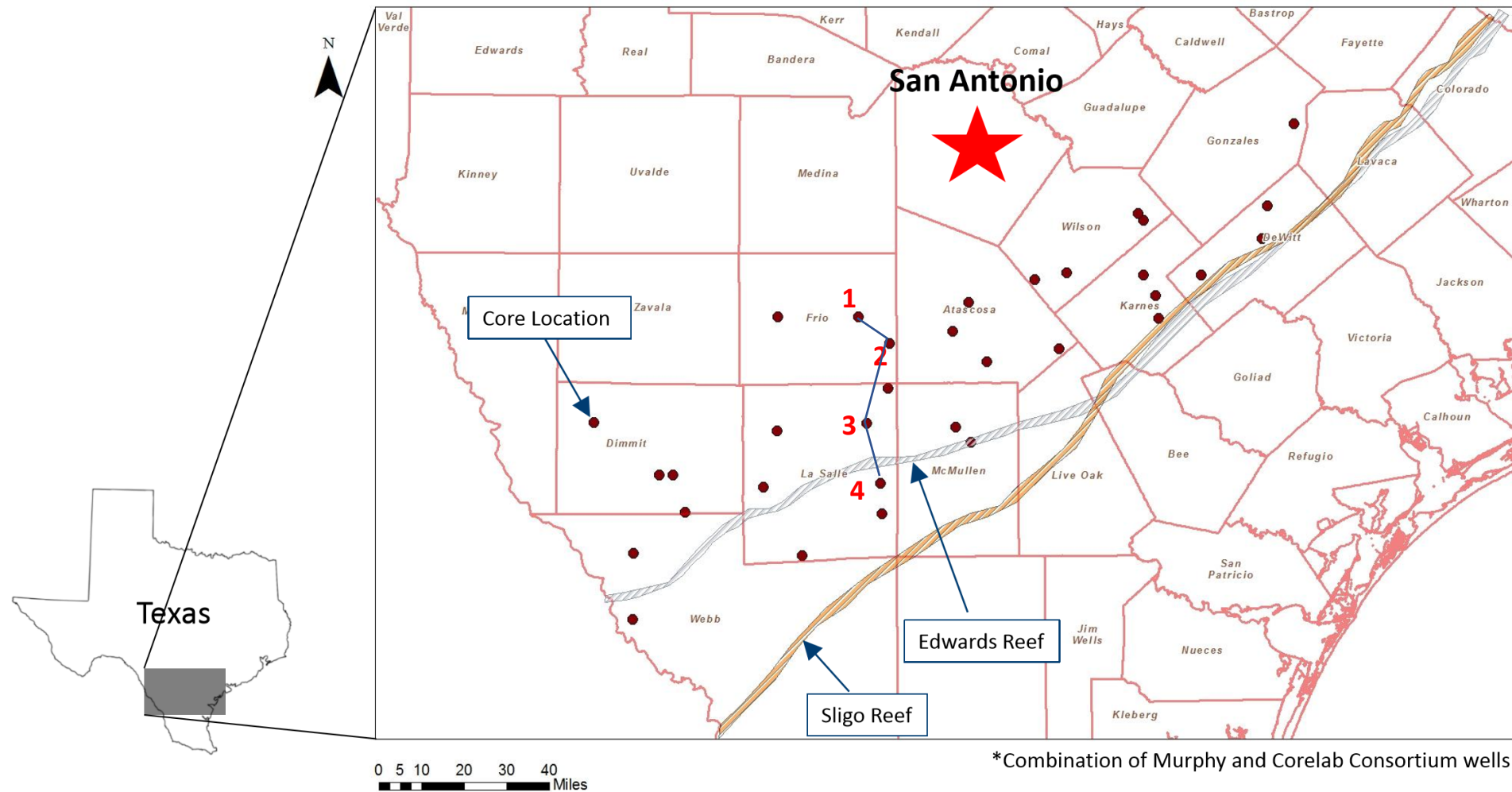
## Fracture Patterns

- Incompetent Facies: Facies 1A, 2A, 2B, 1B, and Ash
- Competent Facies (Calcite-Rich): Facies 2C, and 3

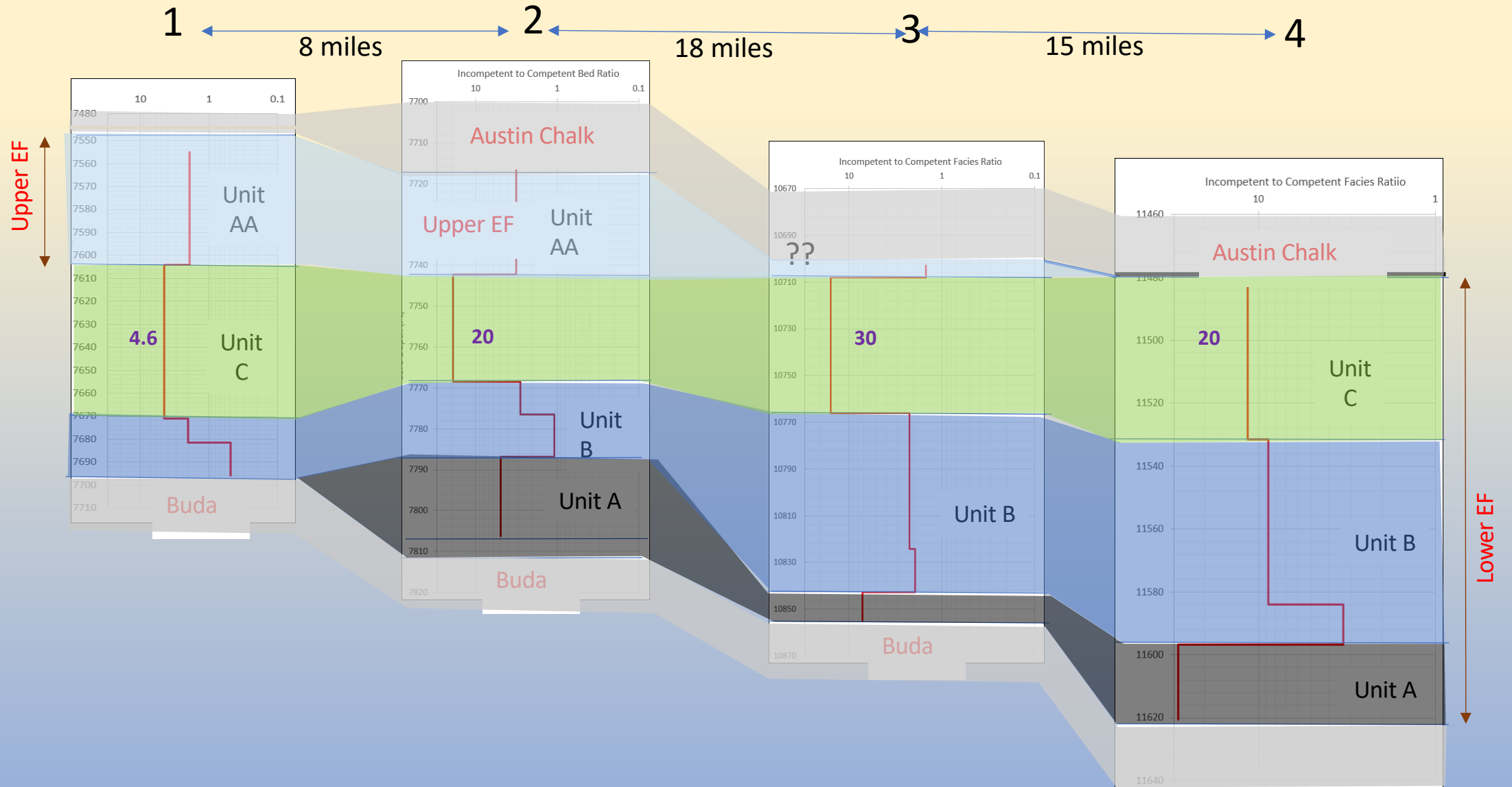


Ferrill and Morris, 2008

# Study Area and Location of Cores – Eagle Ford Shale



# CROSS-SECTION OF INCOMPETENT TO COMPETENT BEDS PER DEFINED EAGLE FORD UNITS



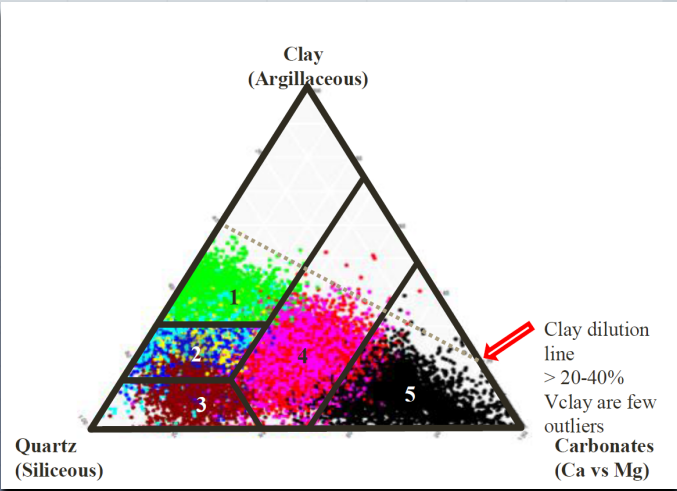
Major Elements											Trace Elements																
SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	Total <sup>3</sup>	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Y	Zr	Nb			
wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %								ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm		
68.46	0.65	7.25	3.02	0.05	0.56	1.88	1.61	2.27	0.13	2.49	88.37	111	119	7	31	8	52	13	6	80	135	17	241	16			
72.35	0.54	6.99	2.28	0.03	0.38	1.41	1.73	1.94	0.12	2.32	90.09	80	107	7	32	10	29	10	8	75	147	20	233	16			
70.43	0.63	7.77	2.61	0.03	0.66	1.49	1.48	2.10	0.11	2.58	89.89	101	117	7	32	13	32	11	7	76	162	21	224	15			
72.25	0.52	6.84	2.34	0.03	0.65	1.60	1.28	1.88	0.12	2.51	90.03	148	90	7	28	9	28	10	7	72	154	18	226	15			
72.48	0.51	6.81	2.28	0.03	0.58	1.54	1.35	1.82	0.10	2.45	89.96	111	100	7	31	14	37	11	6	75	144	17	222	15			
72.76	0.47	6.76	2.22	0.03	0.53	1.42	1.27	1.84	0.10	2.44	89.92	102	92	6	29	11	2559	12	15	73	154	20	216	15			
72.74	0.42	6.77	2.24	0.03	0.71	1.46	1.09	1.84	0.12	2.44	89.86	101	100	6	29	11	31	10	6	69	137	15	189	13			
74.18	0.42	6.27	2.01	0.02	0.49	1.31	1.23	1.75	0.11	2.25	90.18	101	100	7	28	16	36	11	7	73	150	15	223	15			
68.42	0.75	7.04	3.16	0.04	0.60	1.58	1.57	2.22	0.11	2.67	88.43	125	118	7	30	10	44	12	8	81	141	18	229	16			
67.68	0.76	7.83	3.19	0.03	0.71	1.84	1.29	2.33	0.11	3.06	88.83	138	136	8	36	19	39	11	7	79	139	18	253	17			
61.39	0.88	10.64	3.27	0.03	1.26	2.08	1.33	2.94	0.08	4.45	89.67	226	145	13	61	36	47	16	15	111	126	24	265	19			
61.65	0.81	11.06	4.67	0.04	1.51	1.67	1.21	2.98	0.12	4.37	90.10	204	127	14	57	47	46	15	13	116	112	29	258	19			
65.82	0.85	10.41	3.51	0.04	1.10	1.32	1.34	2.79	0.10	3.22	90.51	133	129	9	43	28	40	13	8	107	120	25	296	19			
66.16	0.93	10.26	3.45	0.04	1.10	1.32	1.21	2.71	0.10	3.17	90.55	117	129	11	49	24	56	16	9	122	119	26	293	20			
66.93	0.77	9.32	3.22	0.04	1.11	1.29	1.23	2.61	0.11	3.11	90.7	117	129	10	47	24	27	13	9	102	119	23	278	19			
65.02	0.85	10.14	3.63	0.04	1.29	1.64	1.33	2.69	0.10	3.39	90.12	114	129	8	36	17	31	14	8	109	108	25	275	19			
74.43	0.22	6.44	0.94	0.04	0.54	1.64	1.33	2.69	0.23	1.62	87.23	132	35	8	31	5	31	6	4	43	216	25	182	13			
66.83	0.85	9.84	3.31	0.04	1.06	1.44	1.36	2.59	0.09	2.95	90.34	127	124	11	44	25	39	14	9	105	125	22	289	19			
64.25	0.86	10.05	3.90	0.03	1.19	1.87	1.39	2.67	0.10	3.61	89.93	175	132	12	50	22	60	15	10	103	126	21	254	17			
60.87	0.77	9.09	3.93	0.04	1.07	3.98	1.43	2.47	0.48	3.86	87.98	190	130	13	53	28	28	12	10	89	193	43	281	20			
65.19	0.74	9.90	3.75	0.06	1.26	1.59	1.28	2.60	0.08	3.43	89.89	150	109	15	50	32	28	17	11	124	134	21	272	18			
65.09	0.75	9.79	3.9	0.10	1.14	1.44	1.26	2.60	0.08	3.38	89.83	143	109	13	49	28	24	14	8	101	139	20	267	18			
66.54	0.59	8.62	3.68	0.03	0.90	1.76	1.41	2.31	0.09	3.87	89.80	163	113	11	53	29	27	14	10	94	118	18	223	16			
71.96	0.55	7.16	3.7	0.03	0.7	1.6	1.3	2.3	0.08	3.8	89.78	137	118	10	48	18	19										
65.55	0.74	9.18	3.75	0.03	1.08	1.67	1.36	2.57	0.08	3.57	89.58	135	131	11	50	34	26										
53.98	1.23	7.27	3.38	0.01	0.63	1.33	1.23	2.25	0.13	3.55	89.33	177	106	10	45	31	43										
59.15	1.14	7.57	4.81	0.09	0.59	3.26	1.83	2.94	0.12	3.13	84.42	109	162	8	38	21	38										
67.12	0.78	9.22	3.01	0.04	0.94	1.81	1.45	2.15	0.15	2.51	89.47	98	129	7	32	15	34										
71.98	0.59	7.94	3.12	0.03	0.8	1.37	1.17	2.17	0.1	2.6	89.59	109	109	6	29	13	30										
75.12	0.50	6.67	1.65	0.03	0.49	1.08	1.13	1.82	0.16	1.81	90.46	88	101	4	25	1	44										
76.54	0.46	6.14	1.4	0.03	0.46	0.9	1.06	1.68	0.14	1.75	90.88	73	94	4	23	3	49										
75.90	0.58	6.27	1.56	0.03	0.31	1.03	1.30	1.71	0.15	1.74	90.58	40	103	4	26	1	40										
78.15	0.40	5.34	1.29	0.03	0.29	0.86	1.12	1.44	0.16	1.59	90.66	56	92	4	21	0	46										
71.31	0.33	4.42	2.35	0.07	0.81	3.13	1.39	1.12	0.13	1.55	86.59	155	41	11	21	4	22										
52.84	0.27	3.88	5.11	0.14	2.27	10.24	1.74	0.92	0.13	1.58	79.11	207	0	35	21	7	32										
42.01	0.24	3.49	5.45	0.15	2.25	17.37	1.53	0.91	0.14	1.60	75.14	224	0	44	21	8	21										
44.55	0.26	3.80	6.19	0.17	3.24	14.16	1.19	0.93	0.10	1.56	76.16	204	0	46	22	7	20										
43.86	0.25	3.54	6.25	0.17	2.98	14.87	1.29	0.92	0.10	1.57	75.79	208	0	47	18	9	18										
43.77	0.25	3.69	6.19	0.18	2.85	14.98	1.56	0.93	0.13	1.56	76.09	220	0	47	18	11	20	8	5	33	270	33	195	12			

# Materials - Objectives

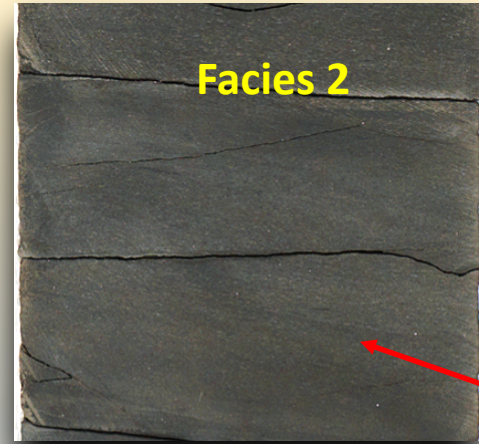
- 6,000 plus XRF data from 305m of cores taken every 5 cm
  - Brueker handheld XRF, calibrated, rock surface cleaned, and avoid clasts
- Create a geochemical facies using the XRF mineral models:
  - Quartz – Clay – Carbonates
- Apply Quantitative Facies Analysis (QFA) to determine:
  - How much geochemical facies per stratigraphic units?
  - How do geochemical facies vary vertically?
  - Can we predict vertical geochemical facies transition using Markov Chain?

# Materials - Objectives

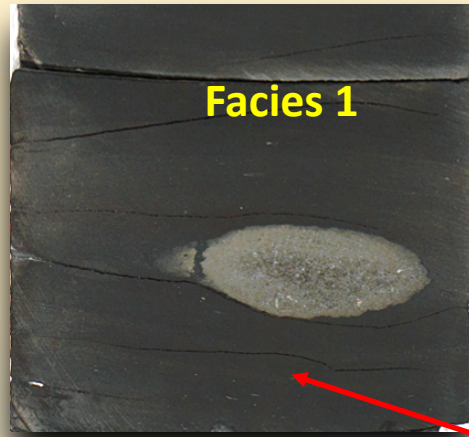
- 6,000 plus XRF data from 305m of cores taken every 5 cm
  - Bruker handheld XRF, calibrated, rock surface cleaned, and avoid clasts
- Create a geochemical facies using the XRF mineral models:  
Quartz – Clay – Carbonates
- Apply Quantitative Facies Analysis (QFA) to determine:
  - How much geochemical facies per stratigraphic units?
  - How do geochemical facies vary vertically?
  - Can we predict vertical geochemical facies transition using Markov Chain?







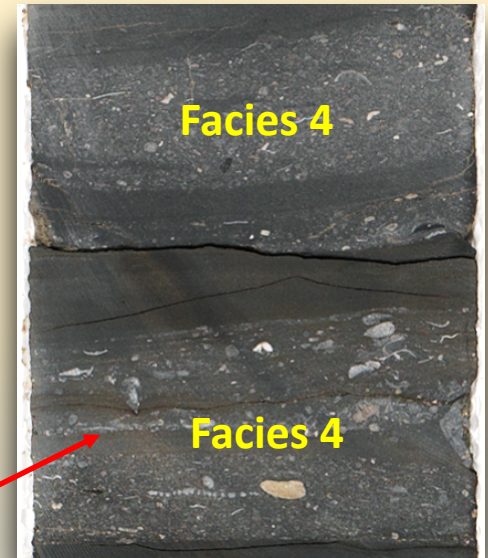
**Facies 2**



**Facies 1**

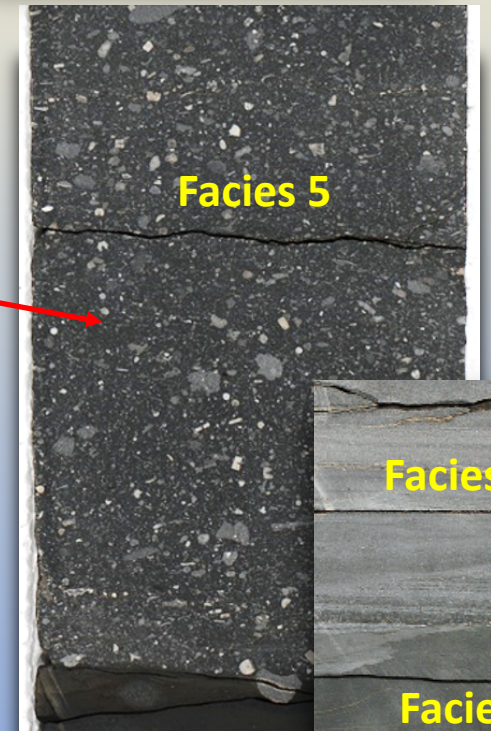


**Facies 3**

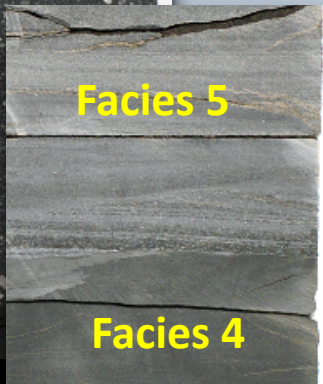


**Facies 4**

**Facies 4**

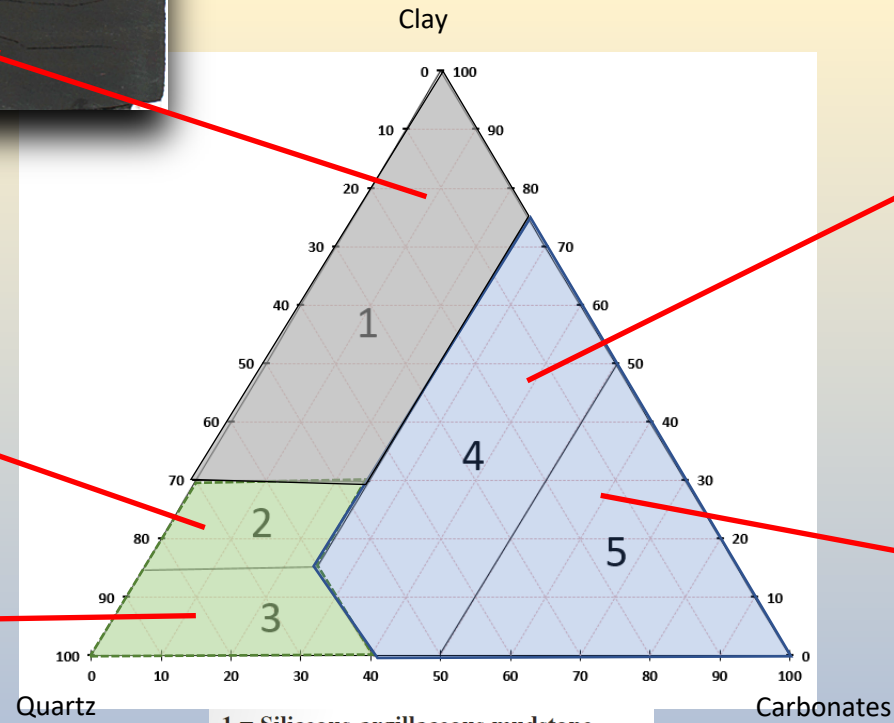


**Facies 5**



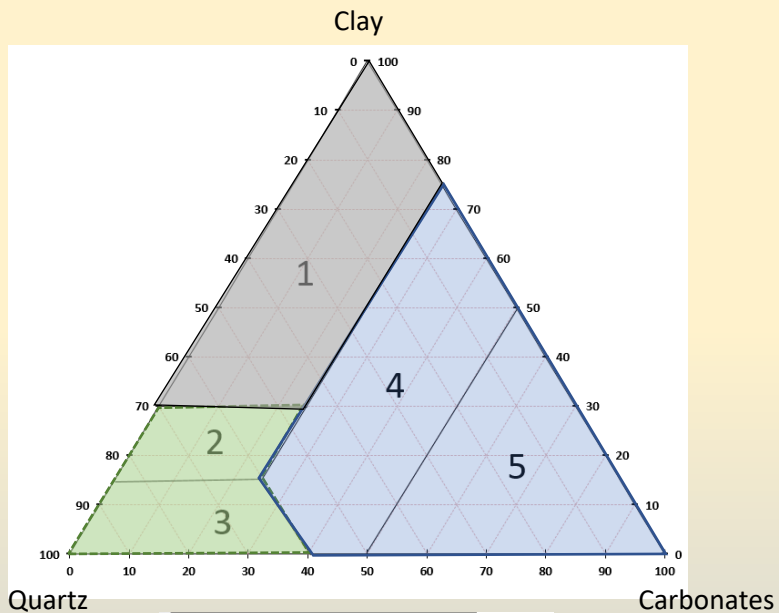
**Facies 5**

**Facies 4**



- 1 = Siliceous-argillaceous mudstone
- 2 = Siliceous mudstone
- 3 = Quartz-rich-siliceous mudstone
- 4 = Siliceous-calcareous mudstone
- 5 = Calcareous mudstone / Lmstn

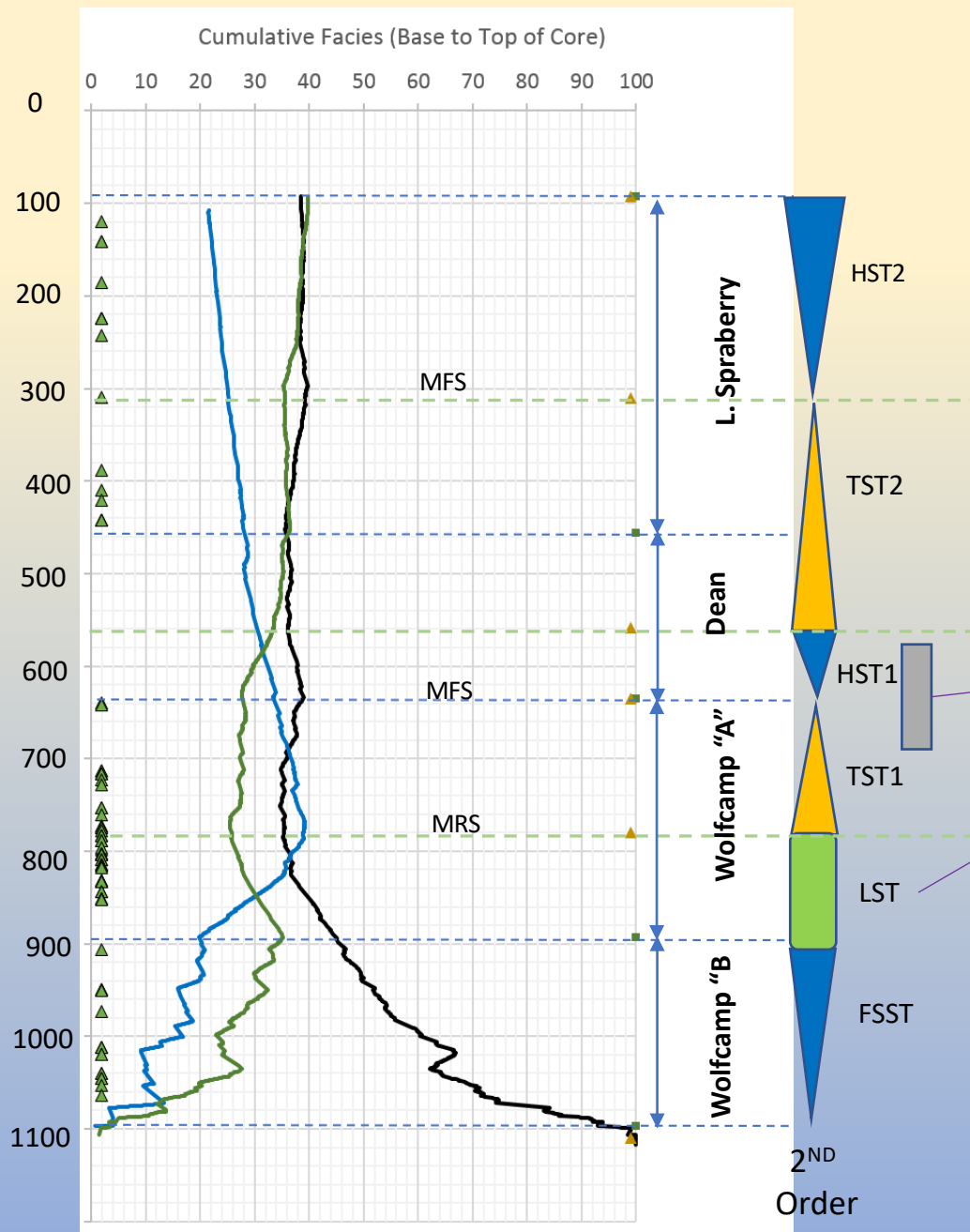
Core Diameter = 9 cm



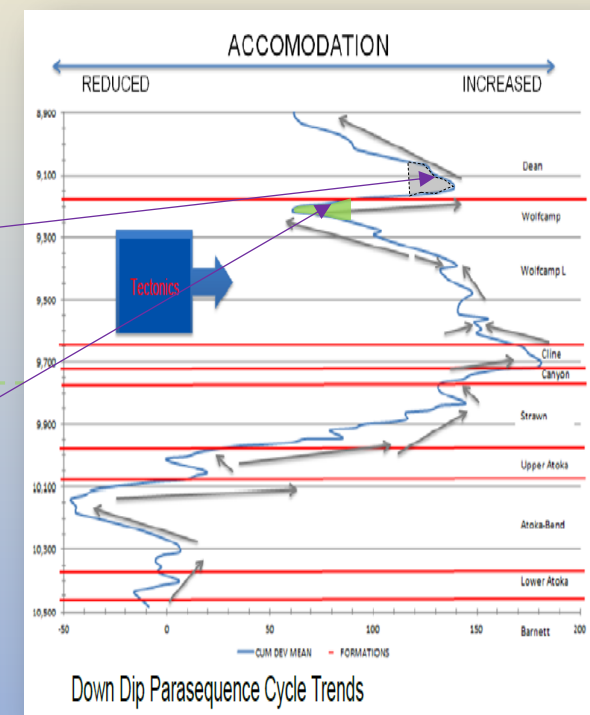
- 1 = Siliceous-argillaceous mudstone
- 2 = Siliceous mudstone
- 3 = Quartz-rich-siliceous mudstone
- 4 = Siliceous-calcareous mudstone
- 5 = Calcareous mudstone / Lmstn

- Facies 1
- Facies 4 & 5
- Facies 2 & 3

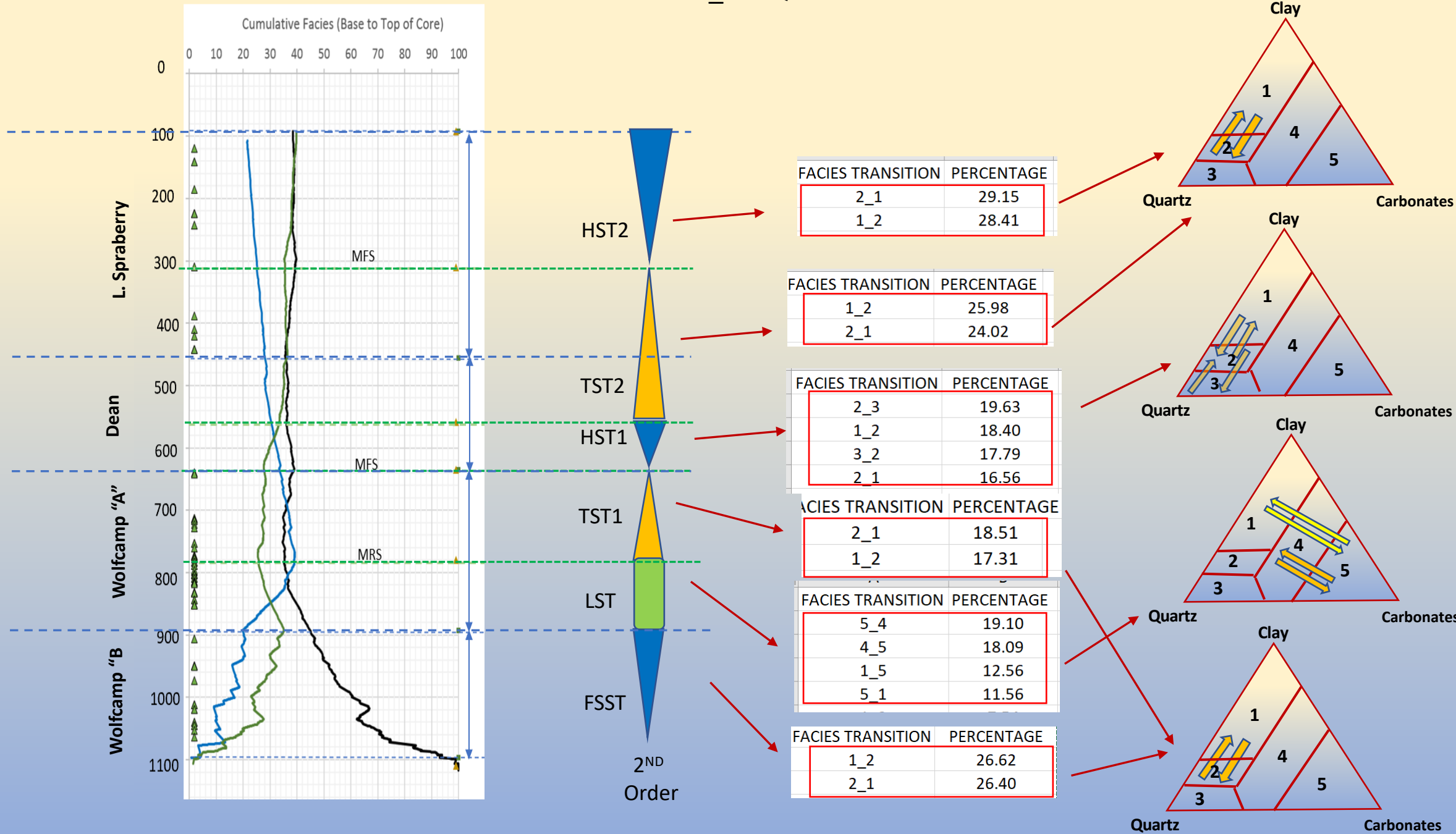
Legend (After, Catuneanu, 2006)  
 FSST= Falling Stage Systems Tract  
 LST = Low Stand Systems Tract  
 TST = Transgressive Systems Tract  
 HST = High Stands Systems Tract



Sequence stratigraphy was based on a combination of seismic data from basin to shelf (Prochnow and Hinterlong, 2014 AAPG) combined with XRF data set.

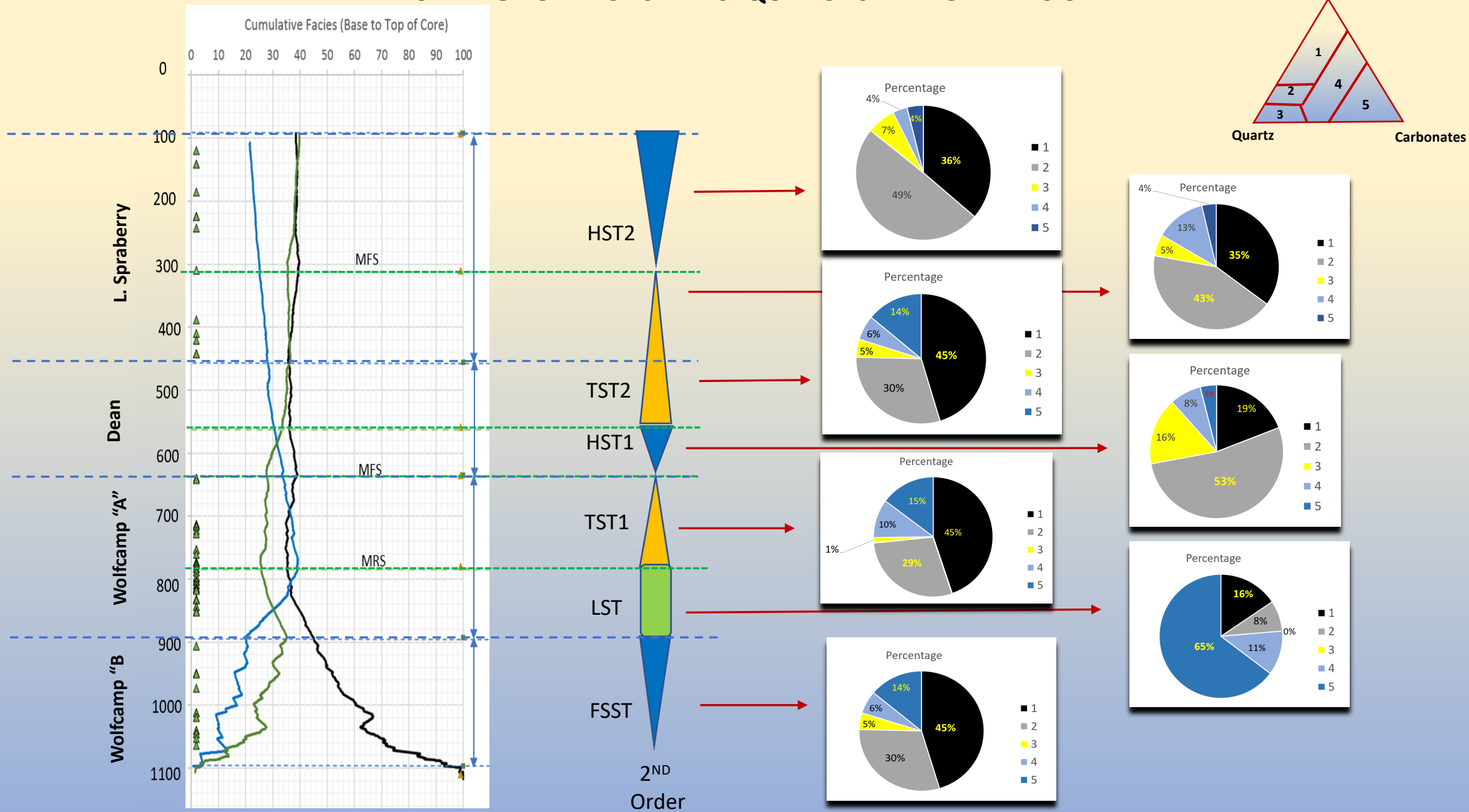


# FACIES TRANSITION\_FREQUENCY DISTRIBUTION





# PERCENTAGE OF FACIES PER SEQUENCE STRATIGRAPHIC UNIT



# WHAT IS MARKOV CHAIN?

- Is a stochastic (*having a random probability distribution*) model that describes the sequence of possible events where the probability of each event is dependent on the state attained in previous event (see Gingerich, 1969; Graham, 1988; Gagniuc, P.A., 2017).
- Markov Chain answers general questions: 1) is the vertical order of sequence random or ordered?; 2) in which way is it ordered? (Graham, 1988)

$$\textbf{Next State} = (\text{Matrix of Transition of Probabilities}) \times (\text{Current State})$$

# MARKOV CHAIN MATRIX

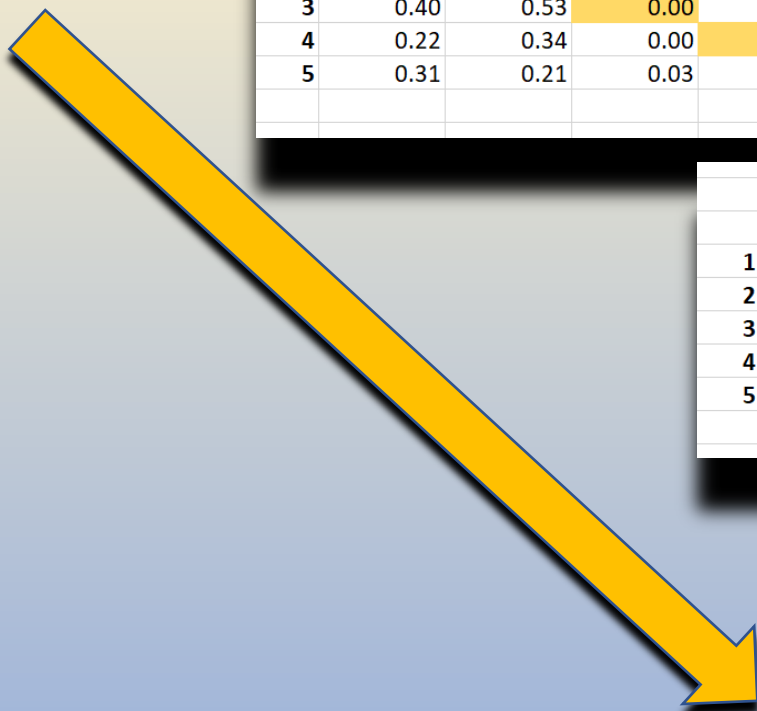
(After Gingerich, 1969)

	Transition Count Matrix				
	1	2	3	4	5
1	0	119	17	9	13
2	118	0	27	13	6
3	18	24	0	1	2
4	9	14	0	0	18
5	12	8	1	18	0

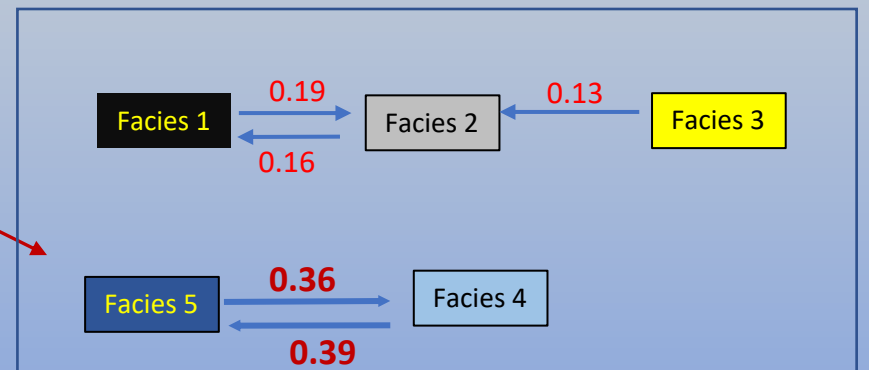
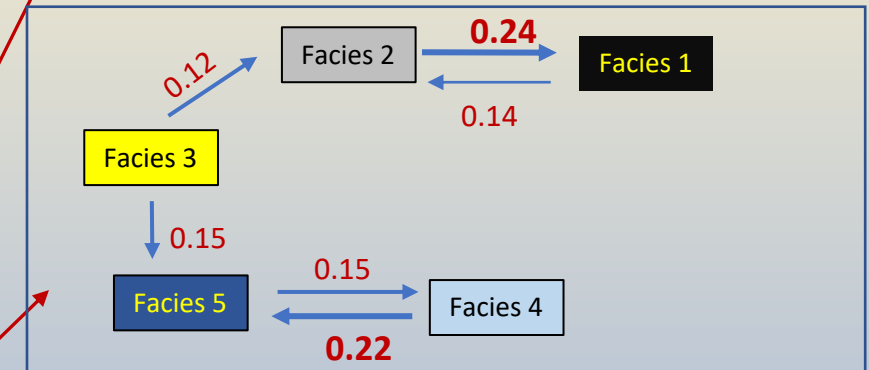
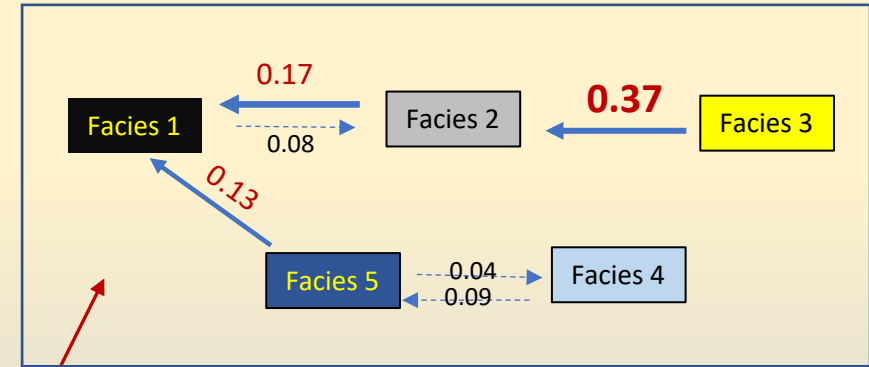
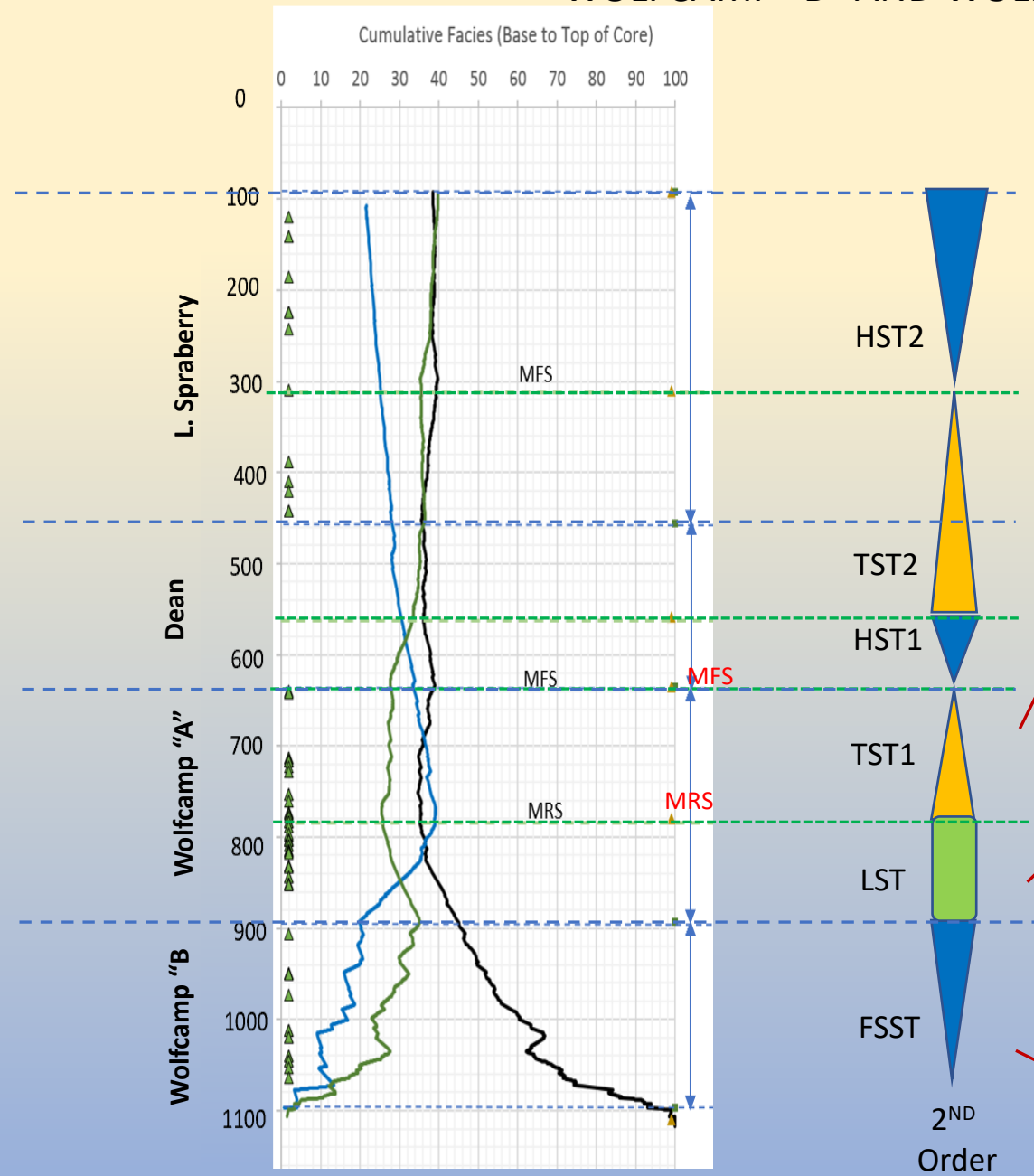
	Transitional Probability Matrix				
	1	2	3	4	5
1	0.00	0.75	0.11	0.06	0.08
2	0.72	0.00	0.16	0.08	0.04
3	0.40	0.53	0.00	0.02	0.04
4	0.22	0.34	0.00	0.00	0.44
5	0.31	0.21	0.03	0.46	0.00

	Independent Trial Matrix				
	1	2	3	4	5
1	0.00	0.57	0.16	0.00	0.13
2	0.56	0.00	0.16	0.14	0.14
3	0.39	0.41	0.00	0.10	0.10
4	0.39	0.40	0.11	0.00	0.04
5	0.39	0.40	0.11	0.10	0.00

	Difference Matrix (TPMx - ITMx)				
	1	2	3	4	5
1	0.00	0.19	-0.05	0.06	-0.05
2	0.16	0.00	0.01	-0.07	-0.10
3	0.01	0.13	0.00	-0.08	-0.05
4	-0.17	-0.06	-0.11	0.00	0.39
5	-0.08	-0.20	-0.08	0.36	0.00

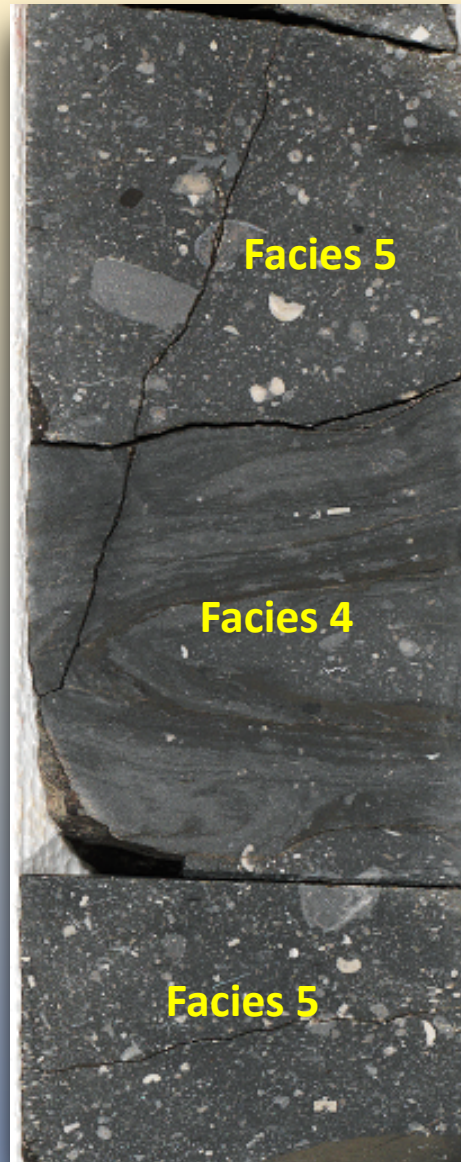
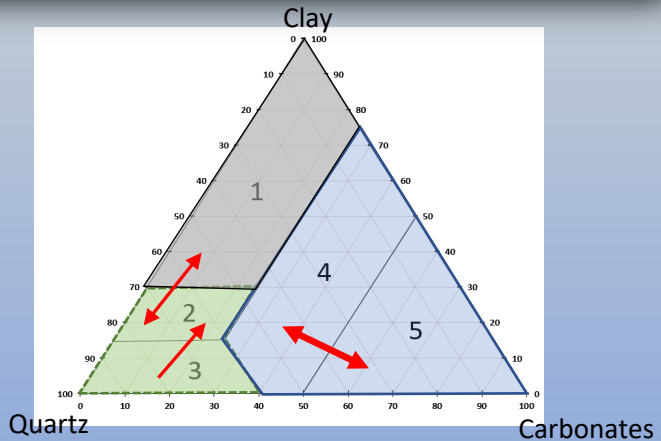
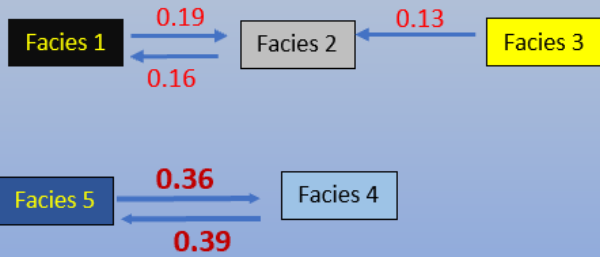
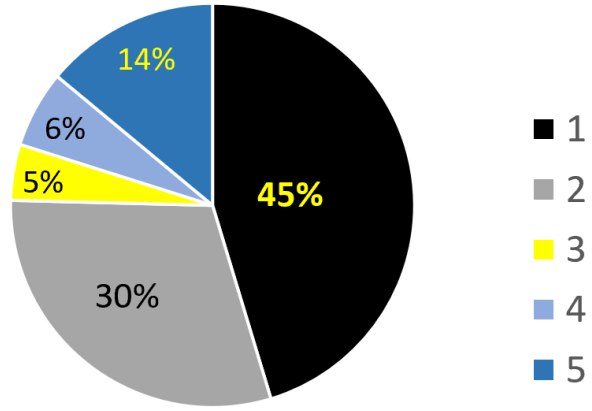


# WOLFCAMP "B" AND WOLFCAMP "A" FACIES TRANSITION\_MARKOV CHAIN



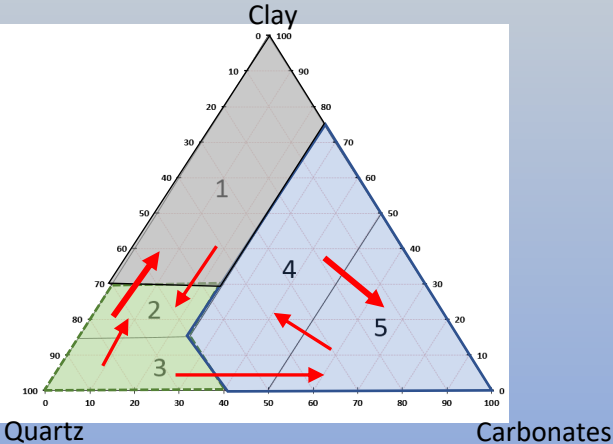
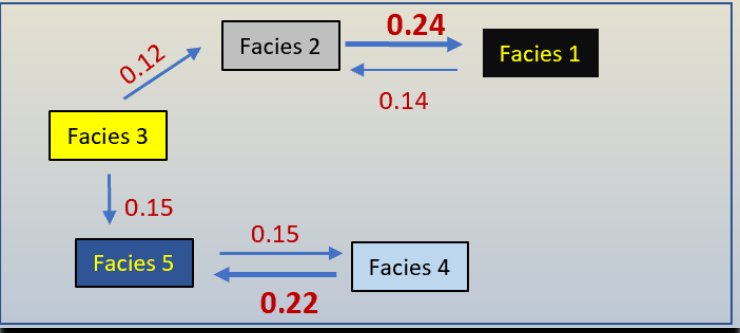
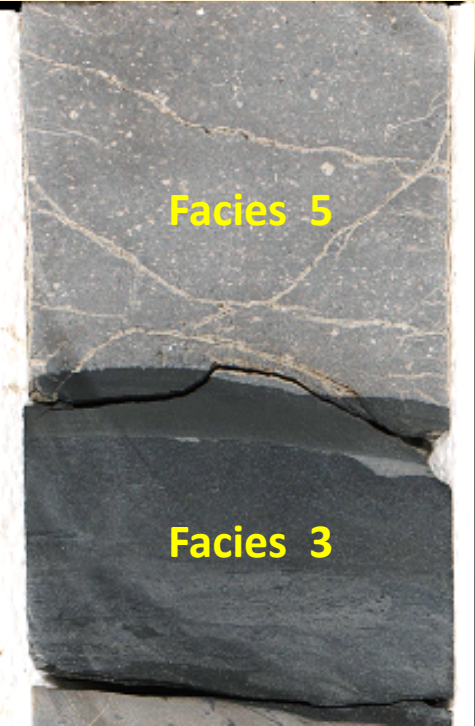
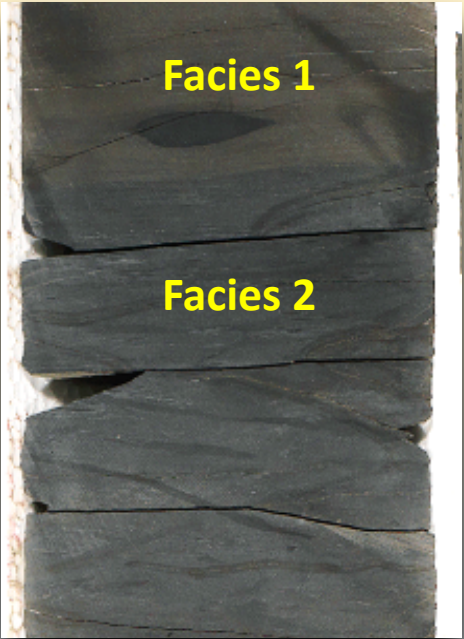
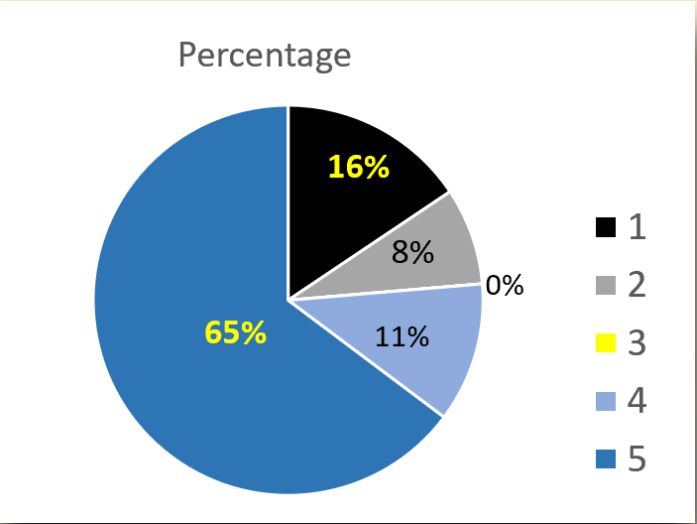
# Wolfcamp "B" FSST FACIES TRANSITION \_MARKOV CHAIN

Percentage





Wolfcamp "A" LST FACIES TRANSITION \_MARKOV CHAIN



# SUMMARY

- Quantitative Facies Analysis (QFA), either sedimentary- or geochemically- facies, provide various statistical methods to characterize each facies, e.g. mean, standard deviation, cumulative amounts, etc.
- QFA as applied to sedimentary facies allowed one to show how much facies (via iso-percent) at various stratigraphic slice. The amount of each facies per stratigraphic slice represents sedimentary condition at that particular stratigraphic interval.
- QFA can be used to translate the sedimentary facies to mechanical facies to show variability of stratigraphic units vertically or horizontally, i.e., incompetent- to competent facies ratio.
- QFA – Markov Chain as applied to geochemical facies allowed a predictive model for the “next state” vertical order of facies. This “next state” probability can be attributed to genetically related depositional process.

**The End**