EVAPORITE DEPOSITION and DOLOMITIZATION in a DYNAMIC LACUSTRINE SETTING, GREEN RIVER FORMATION (EOCENE), PICEANCE/UNITA BASINS, COLORADO/UTAH, USA

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The Green River Lake System

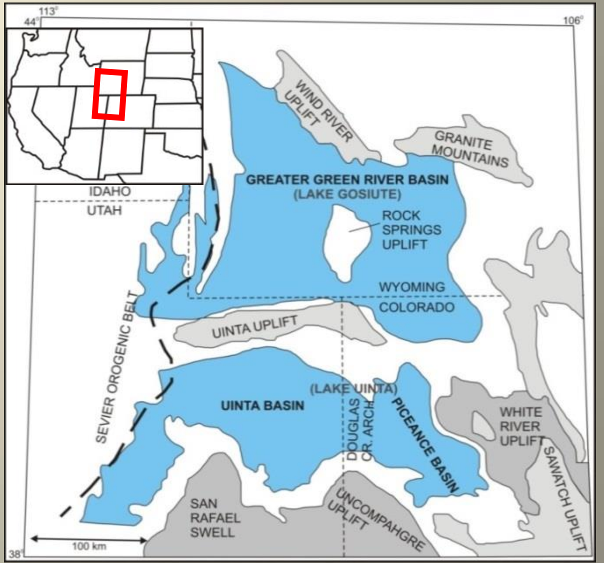
- Deposition during and immediately after *Eocene climate optimum* (~54-44 Ma). Mid-latitudes and continental interior intermountain setting. Period of slow subsidence. Climate varied from arid to humid.

- *Perennial, varyingly stratified lakes* with fluctuating lake levels. Each basin has a unique history, but basins connected at times during their history. Stable isotopes co-vary suggesting closed lake system.

- *Lakes alkaline, high in Na and HCO3.* Evaporite minerals include primary dawsonite, nahcolite, trona, and halite. Precipitation occurs in shallow water, at chemocline, and within bottom sediment.

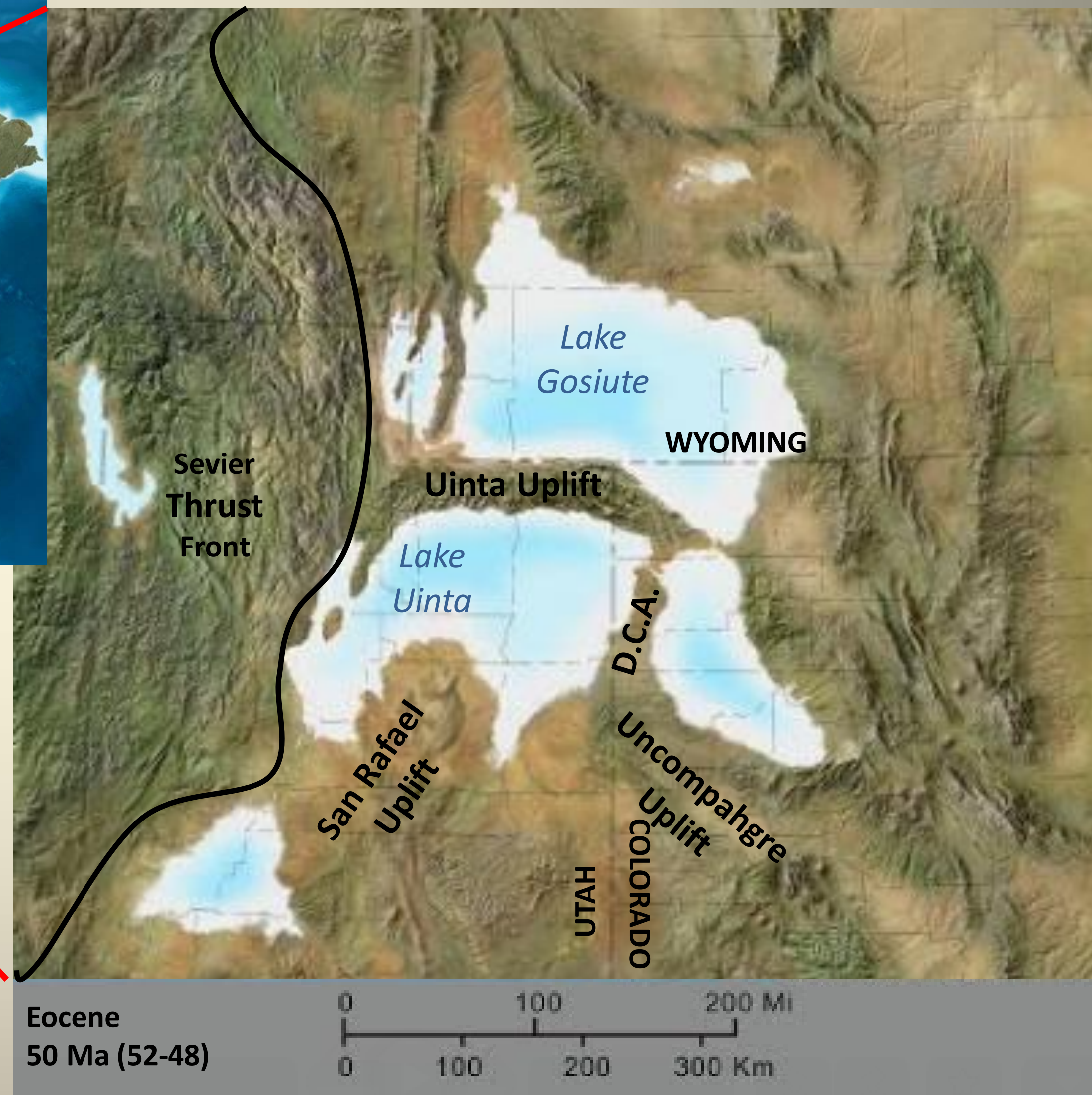
- *Dolomite* occurs as (1) early replacement of lake-margin lime sediments, and (2) in sublittoral-profundal oil shale (replacement or direct precipitate?)

- Preservation of *high amounts of organic matter* in lake center mud rocks suggests dysoxic to anoxic bottom waters. Microbial mediation of dolomitization?



Green River Paleogeography

Eocene (50 Ma)

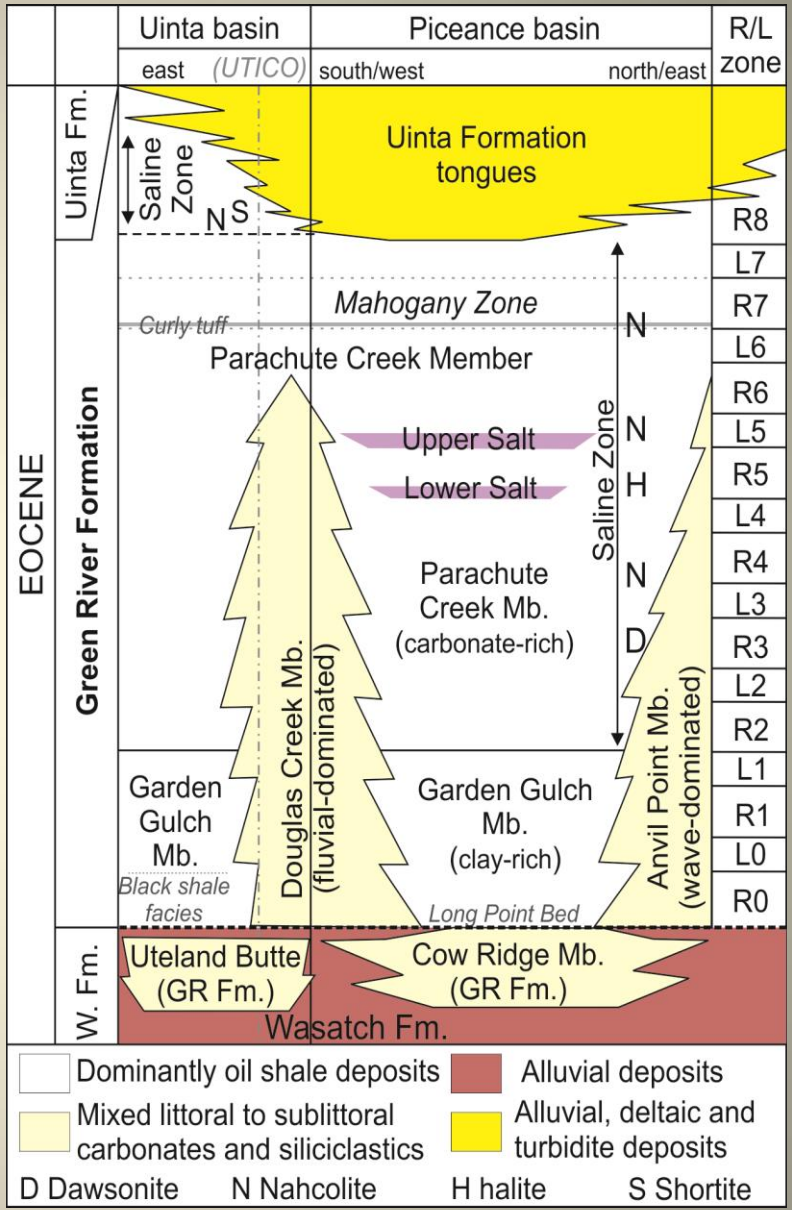


- **World's largest known oil shale resources occur in:** lake sediments of Green River Formation Western Colorado, Utah, & Wyoming
- **Each basin has a unique history**
- **Major basins connected at times during history**
- **All have periods of evaporite deposition**

Stratigraphy

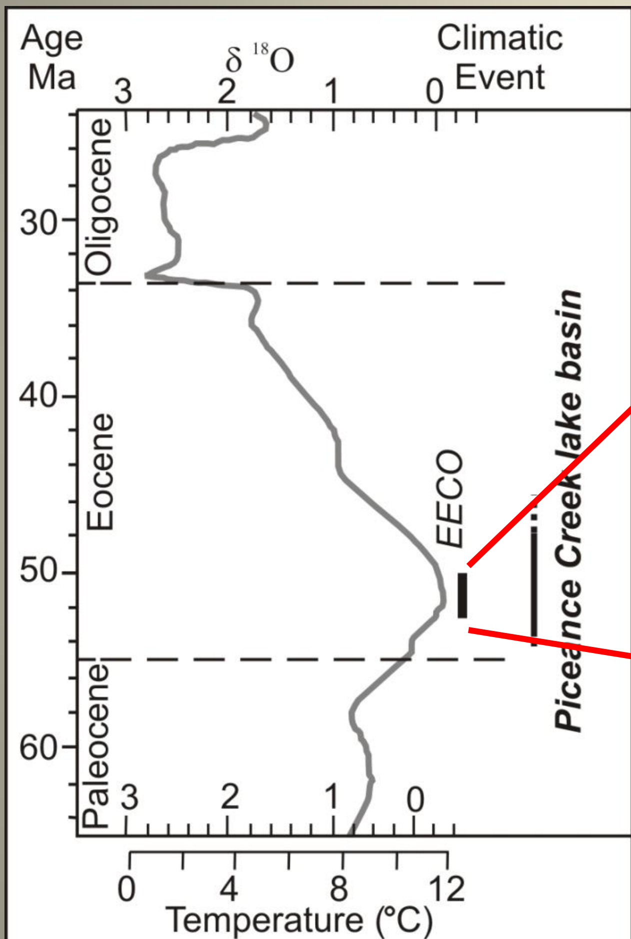
- **Duration: *Eocene Optimum***
- **Piceance basin (~54 to ~48 Ma)**
- **Uinta basin (~54 to ~44 Ma)**
- **Divided into:**
  1. **Members, based on lithofacies**
  2. **Rich and lean zones (R/L), based on kerogen content**

■	Alluvial, deltaic, and turbidite deposits
■	Dominantly oil shale deposits
■	Dominantly mixed littoral to sublittoral carbonates and siliciclastics
■	Alluvial deposits

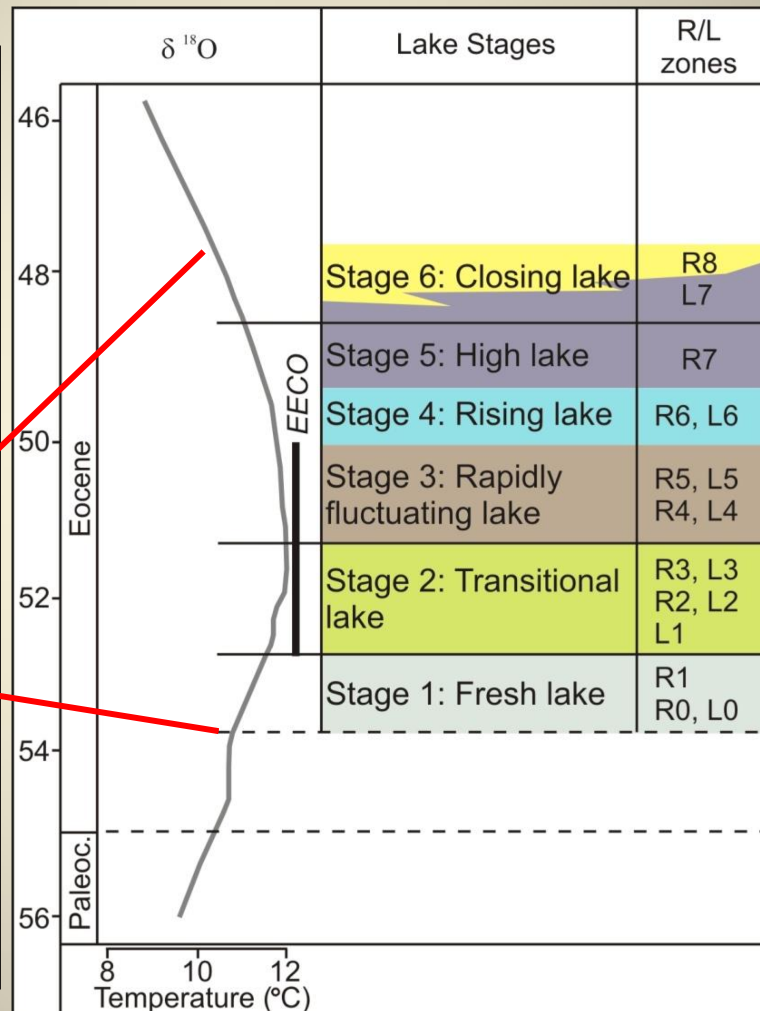


Modified after Vanden Berg 2008; Self et al. 2010; Tänavsuu-Milkeviciene and Sarg 2012

Eocene Climate & Lake Uinta



After Zachos et al. 2001
Age data after Smith et al. 2008, 2010



EECO – Early Eocene Climatic Optimum

Clastic flood

Deepest, stratified

Increasing runoff, nahcolite

Nahcolite, halite

Dawsonite, Nahcolite + clastics

Stratified, fresh to mesosaline, no evaporites

Green River Lake Waters: Brine Evolution and Chemical Divides

Green River Inflow Waters: **Low temperature chemical weathering:** Minerals + dissolved atmospheric CO_2 produce ions **Na**, Ca, Mg, K, Cl **HCO_3**, SO_4 which then form chemical sediments in closed basin lakes.

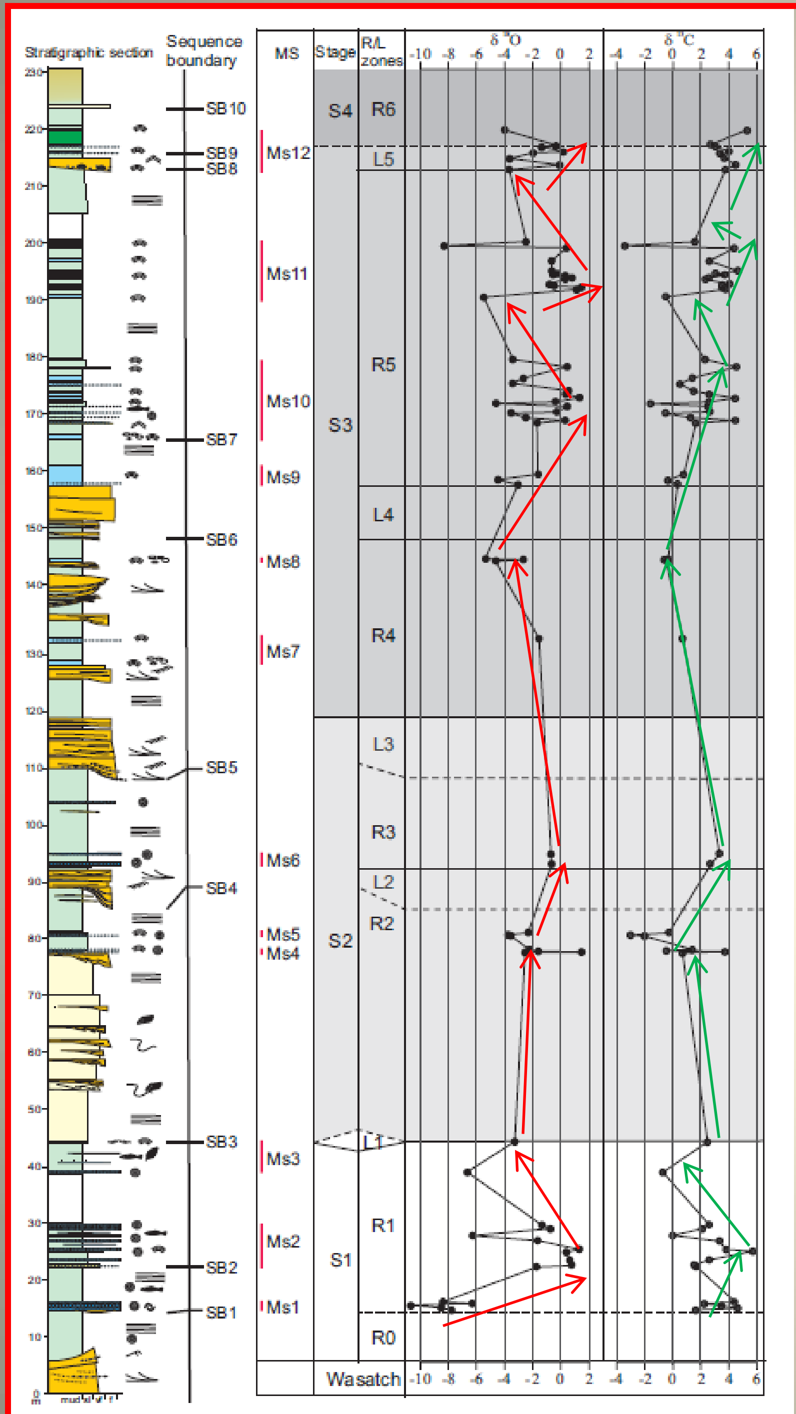
$HCO_3 + CO_3 > Ca$

$CaCO_3$ Precipitation, use up Ca, Mg; extra $HCO_3 + CO_3$ forms alkaline (pH 9-10) brines.

Precipitation of Na-carbonates, i.e., dawsonite, nahcolite, trona, and halite

Accelerated chemical weathering with elevated atmospheric CO_2 in the Eocene (Smith et al., 2008)

Lake Stable Isotopes Co-vary A Closed System



Incr. Evap. – Higher Salinity

Incr. Inflow - Freshening

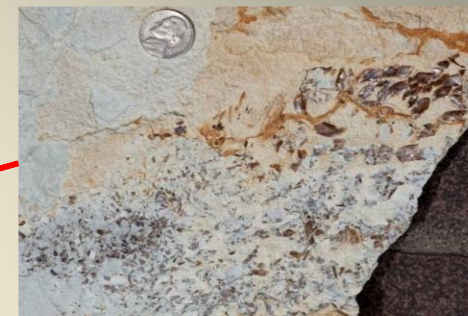
Incr. Photosyn. – High Productivity

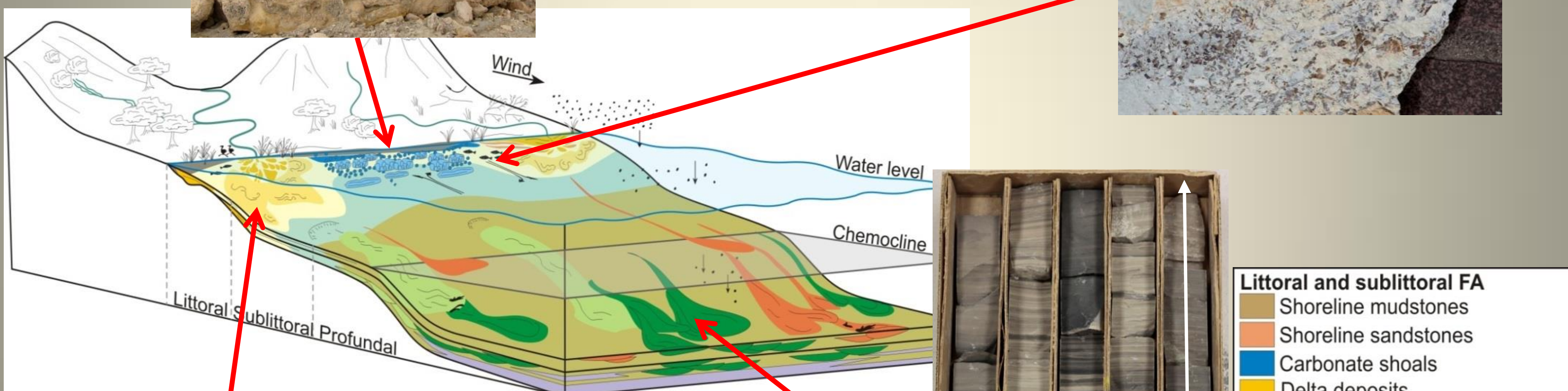
Incr. CO2 uptake - Oxic

- Shoreline intraclastic mud deposits
- Carbonate shoal deposits
- Microbial carbonates
- Delta deposits
- Littoral, sublittoral siliciclastics
- Littoral, sublittoral oil shale
- Profundal laminated oil shale
- Profundal oil shale breccia

Lake Depositional System

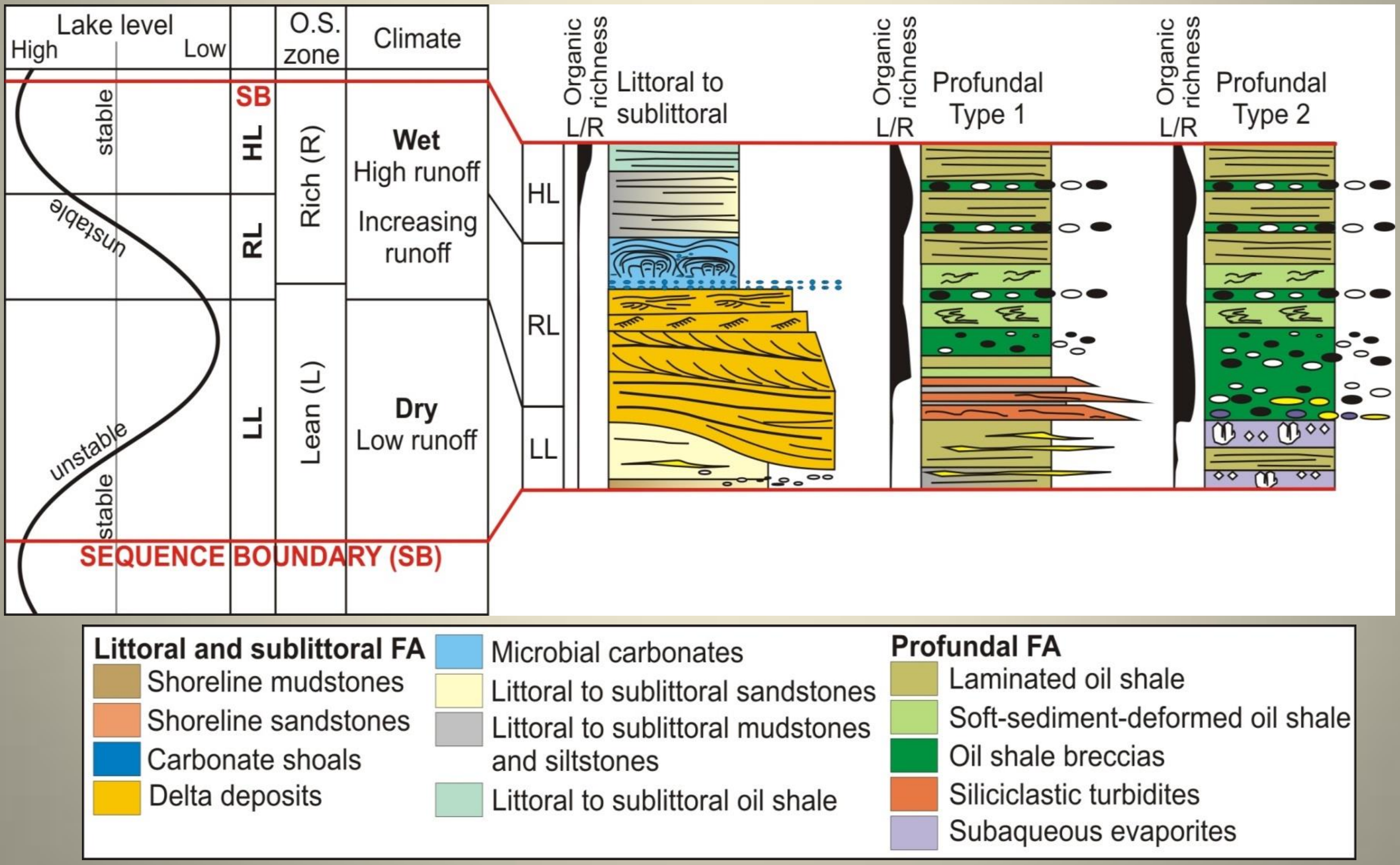
- *Higher frequency compared with marine systems.*
- *Prone to rapid fluctuations caused by the combination of autocyclic and allocyclic changes.*



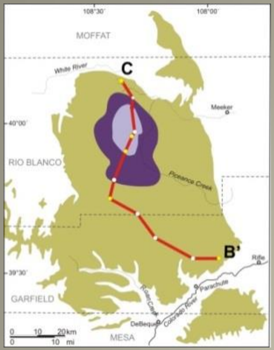


Sequence Stratigraphy and Climate

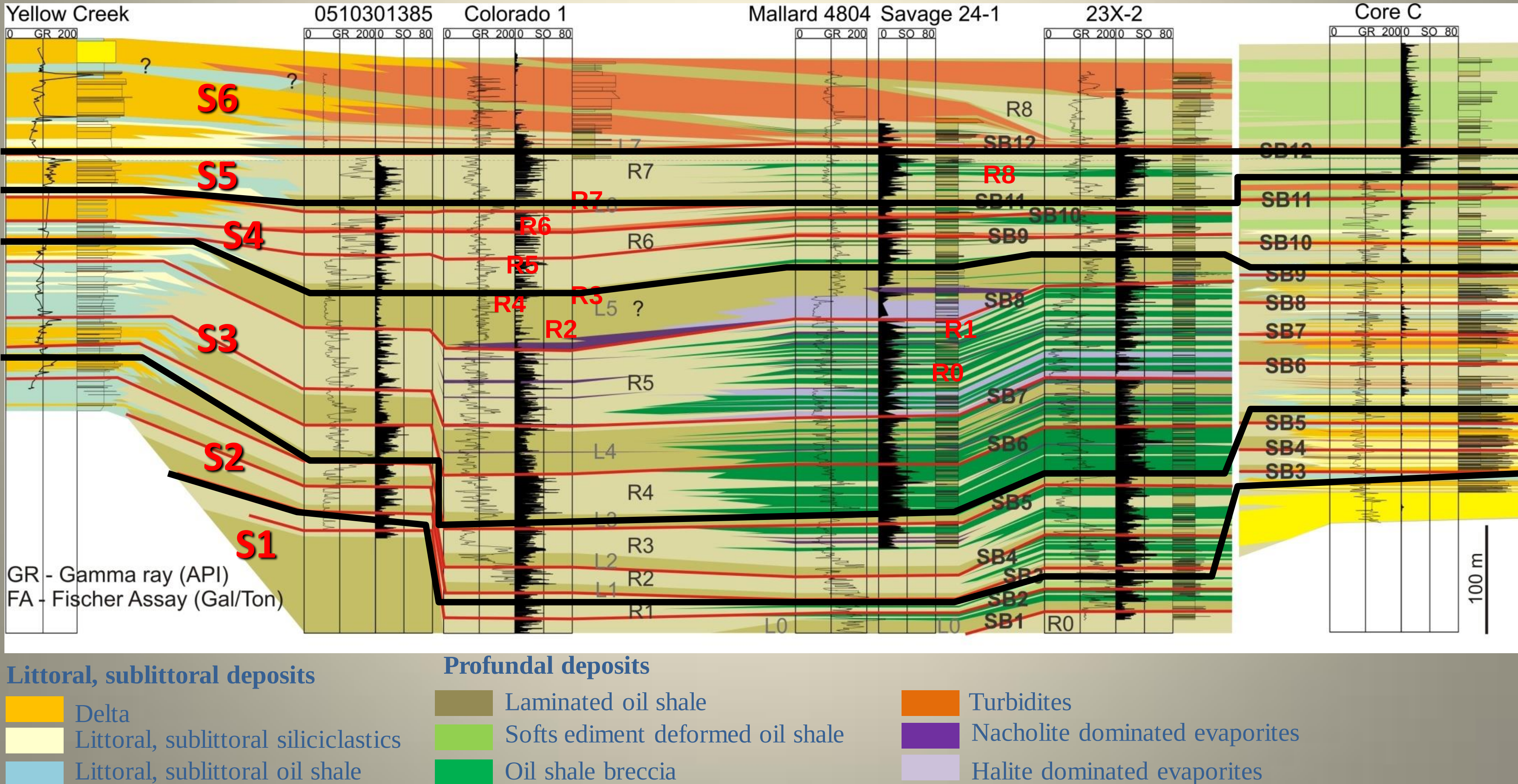
- Deepening-upward cycles
- Cyclicity is controlled by runoff and vegetation



Depositional Model - Lake Stages



Stage 6. Closing lake
Stage 5. High lake
Stage 4. Rising lake
Stage 3. Highly fluctuating lake
Stage 2. Transitional lake
Stage 1. Fresh lake



Green River Fm. Deep Lake Center Evaporites

Green River Fm. Deep Lake Center Evaporites

(F) Evaporite breccia - debrite

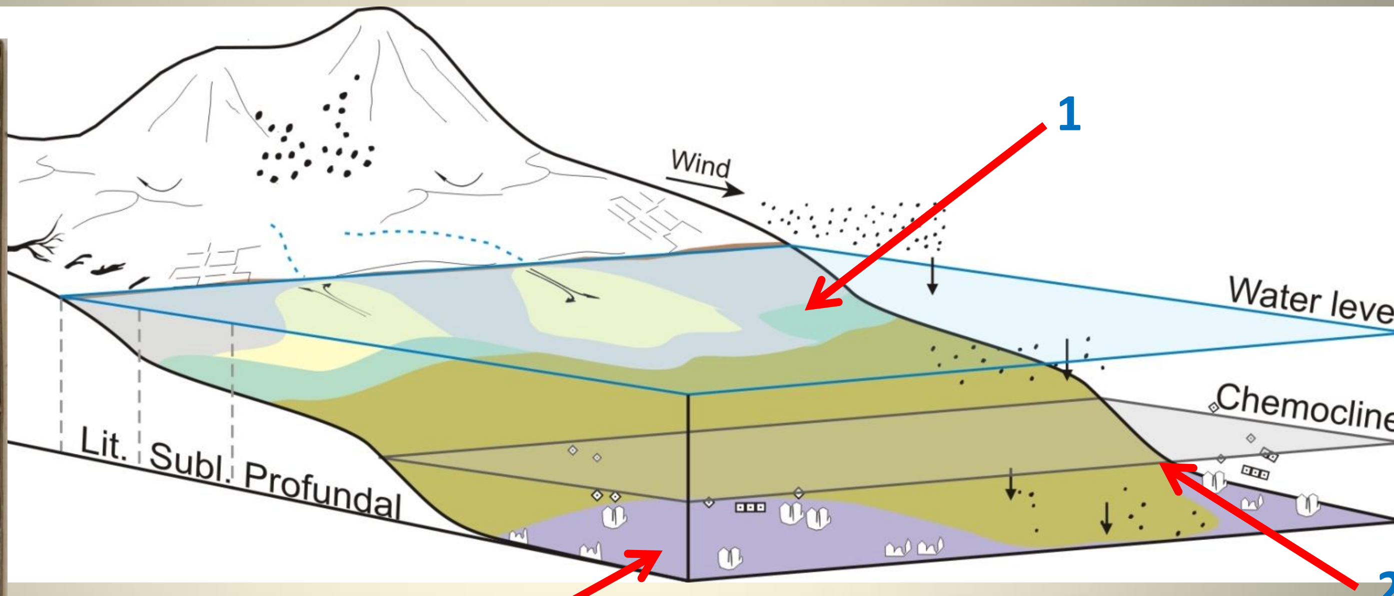
(G) Halite bottom growth and halite to nahcolite laminites

(H) Nahcolite nodules & crystals on bedding plane

Tänavsuu-Milkeviciene and Sarg, 2013, in press

Arid climate → Low runoff → Low lake level

Perennial Stratified Saline Lake



Littoral to sublittoral sandstones
Littoral to sublittoral mudstone and siltstone
Littoral to sublittoral oil shale
Laminated oil shale
Evaporites (halite, nahcolite)

Possible Environments of Precipitation:

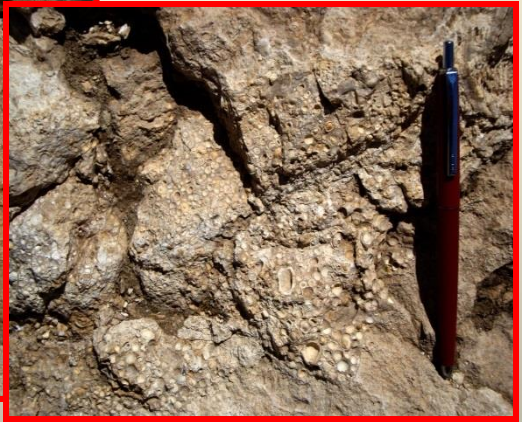
1. **Brine formation in shallow surface layer**
2. **Precipitation at chemocline due to mixing/turbulence**
3. **Bottom growth & displacive growth within sediment**

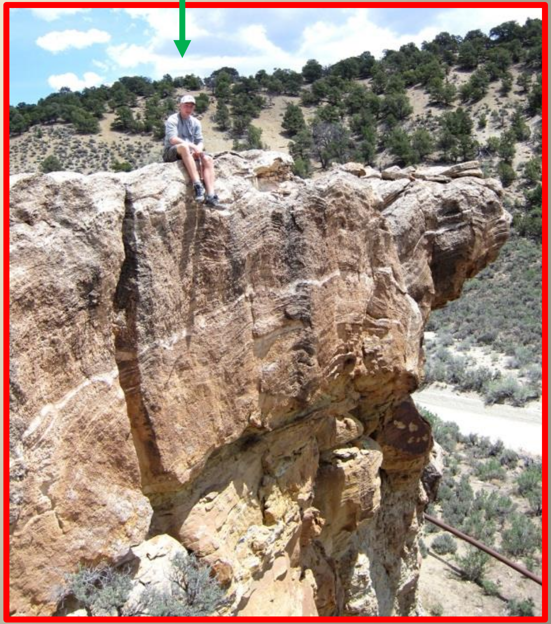
Dolomite and the Lake

Two Groups:

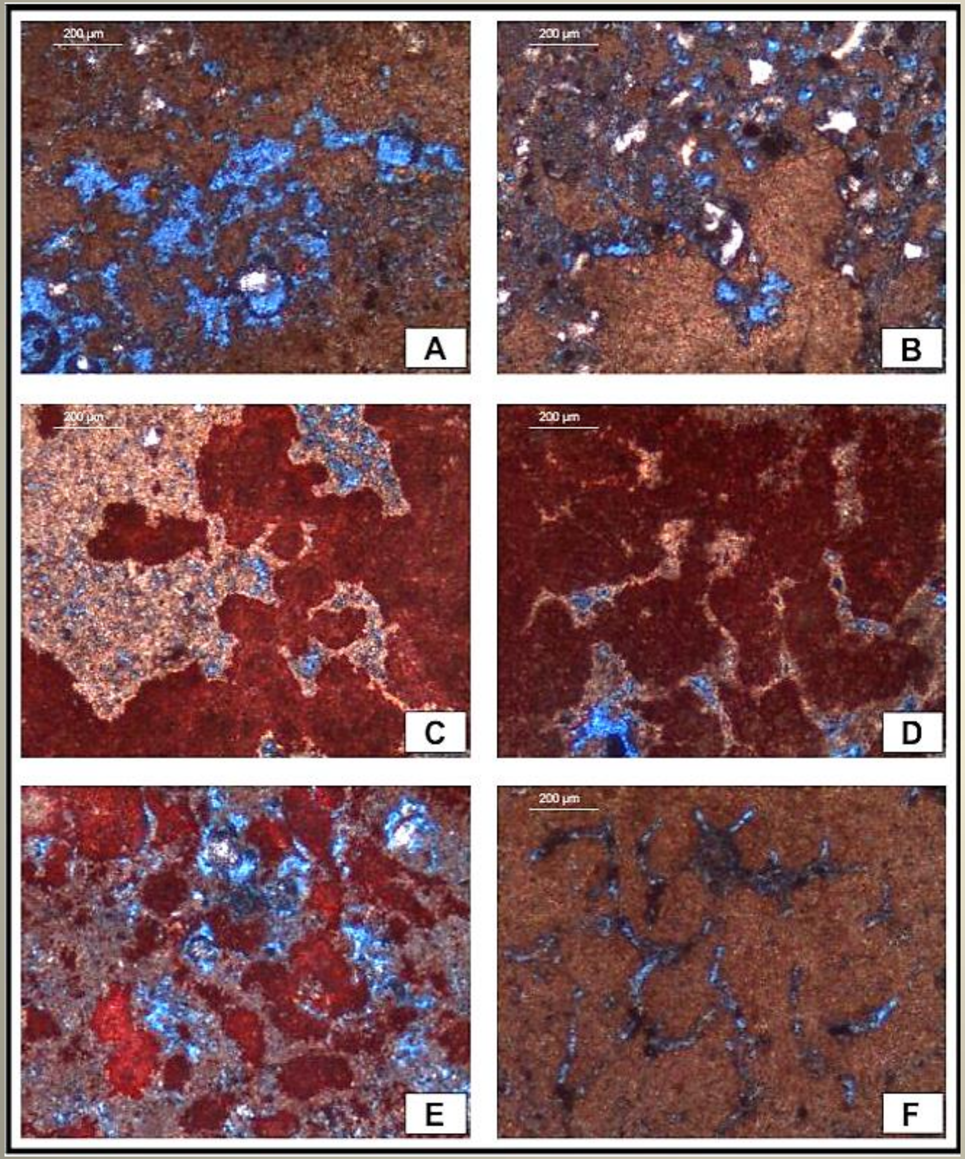
1) The Lakeshore
2) The Offshore Lake

Littoral Microbialite Deposits



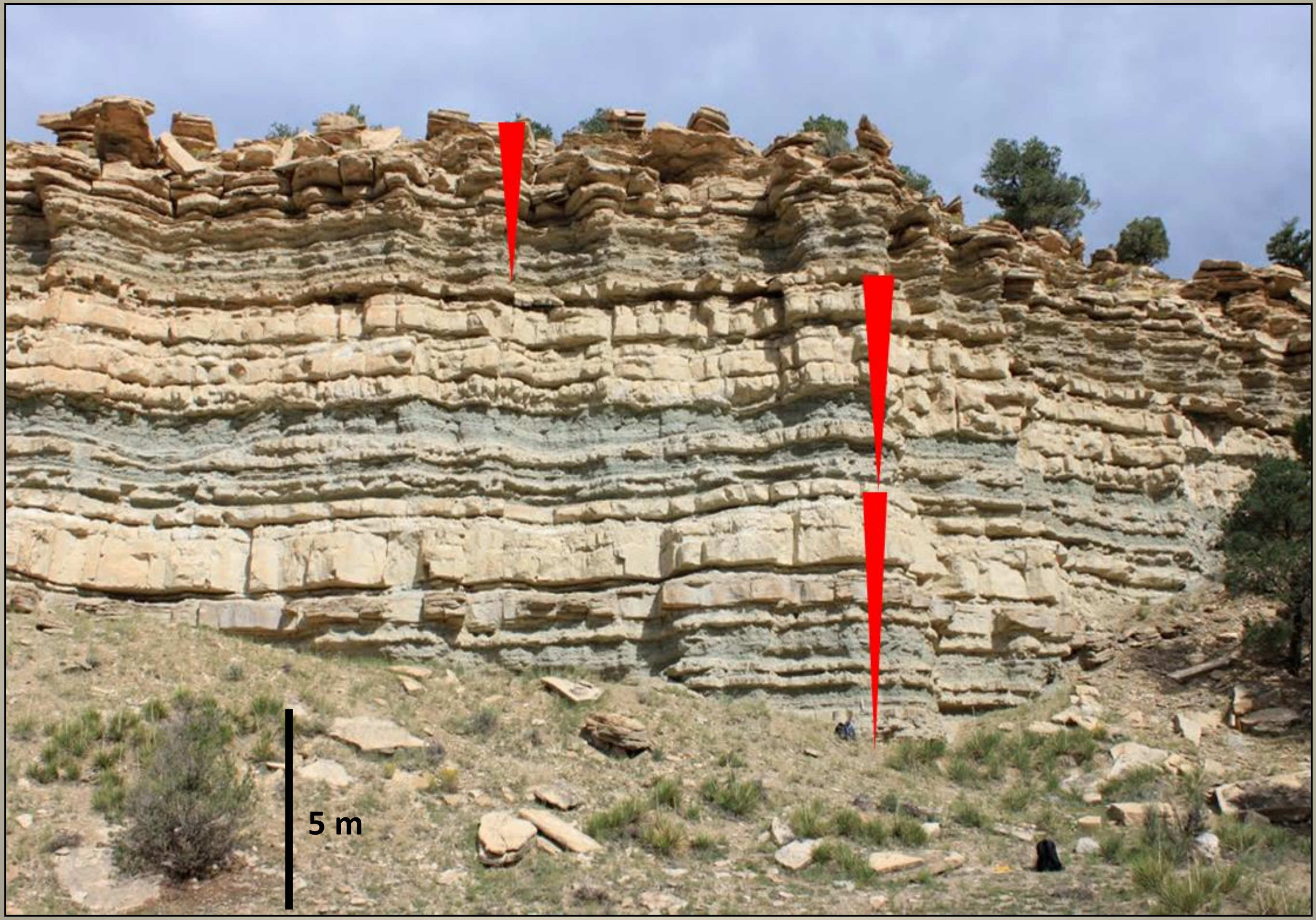


Thrombolite Microtexture

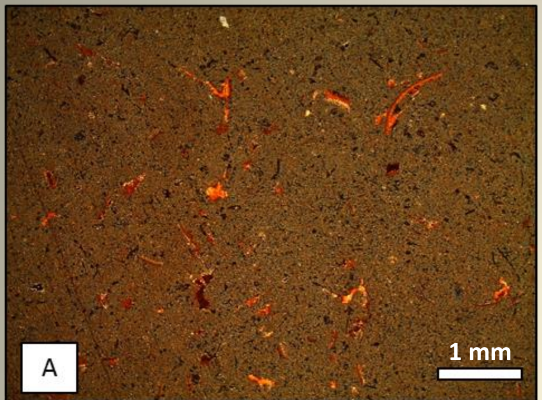


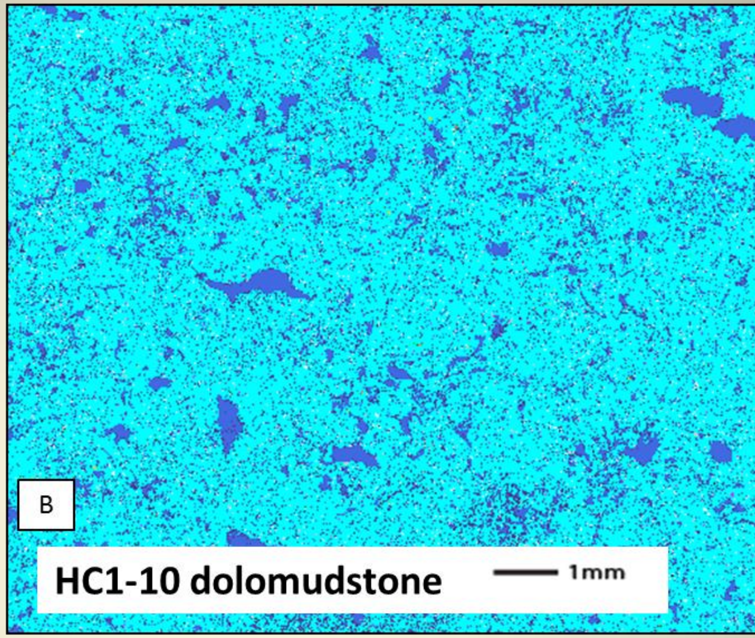
A. Dolomitic thrombolite
B. Arborescent dolomitized thrombolite
C. Calcitic thrombolite with interstitial mud
D. Calcitic thrombolite
E. Partially dolomitized thrombolite clots
F. Fully dolomitized thrombolite

Lakeshore Shallowing Upward Cycles – Mudstones to Grainstones

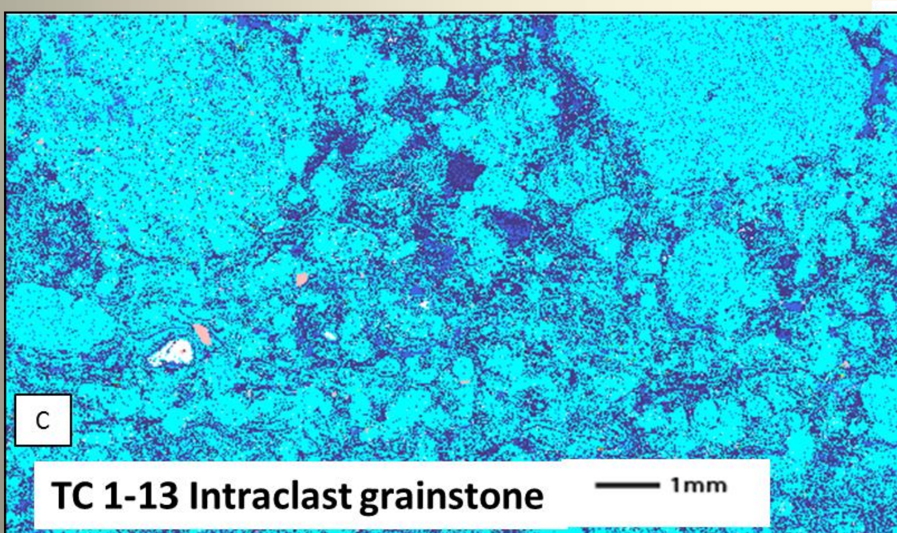


QEMSCAN images of Littoral-Sublittoral Mudrocks





Mineral Name	Area Percent
Background	1.37
Quartz	0.31
Biotite/Phlogopite	0.00
Illite	0.04
Illite-Smectite	0.00
Smectite	0.00
Chlorite	0.01
Muscovite/Kaolinite	0.00
Plagioclase	0.02
K-feldspar	0.01
Calcite	9.69
Calcite (Mg-Bearing)	10.60
Dolomite	79.10
Fe Oxide/Hydroxide	0.00
Apatite	0.12
Other Minerals	0.02
Others	0.08



Mineral Name	Area Percent
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Illite	0.01
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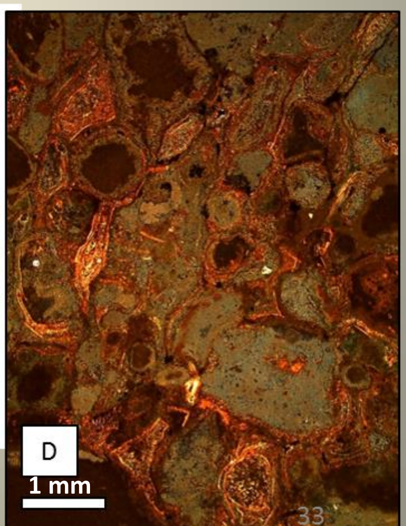
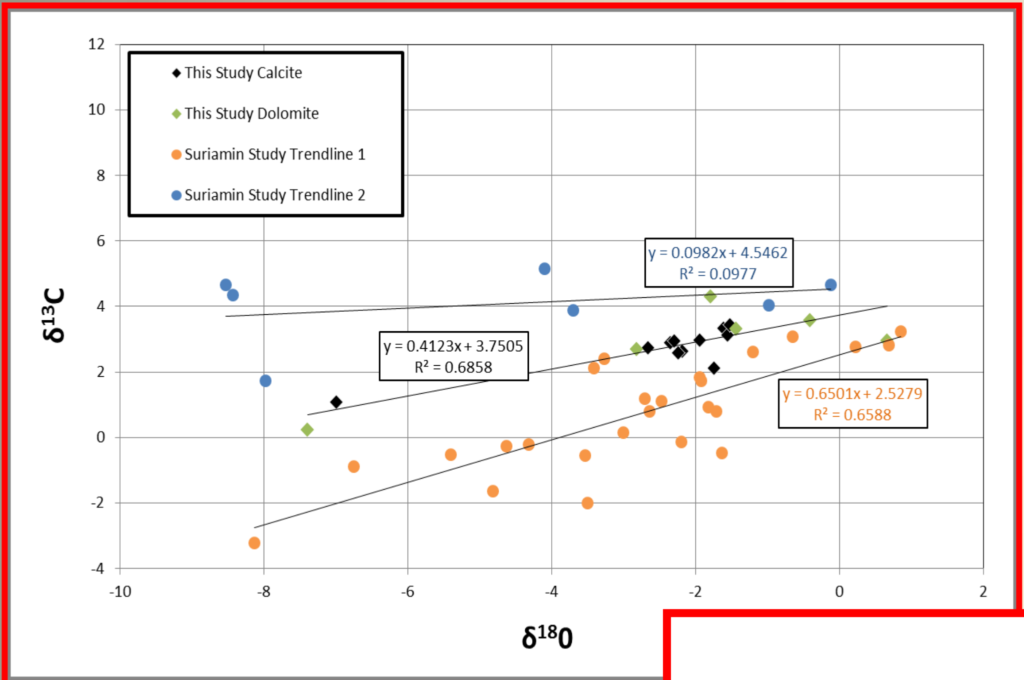
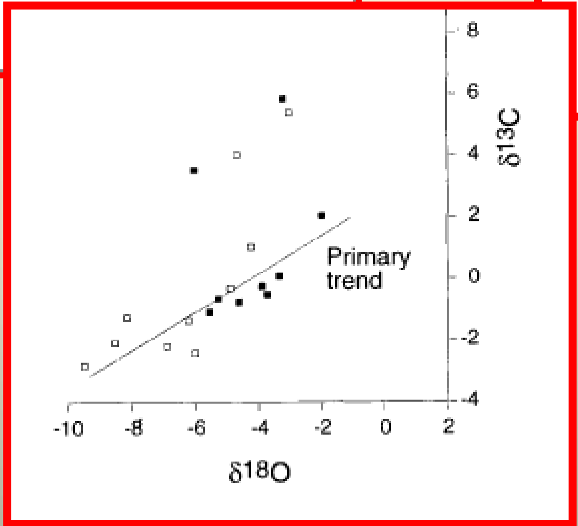
Smectite	0.00
Chlorite	0.01
Muscovite/Kaolinite	0.00
Plagioclase	0.01
K-feldspar	0.01
Calcite	9.71
Calcite (Mg-Bearing)	23.54
Dolomite	66.02
Fe Oxide/Hydroxide	0.23
Apatite	0.04
Other Minerals	0.02
Others	0.17

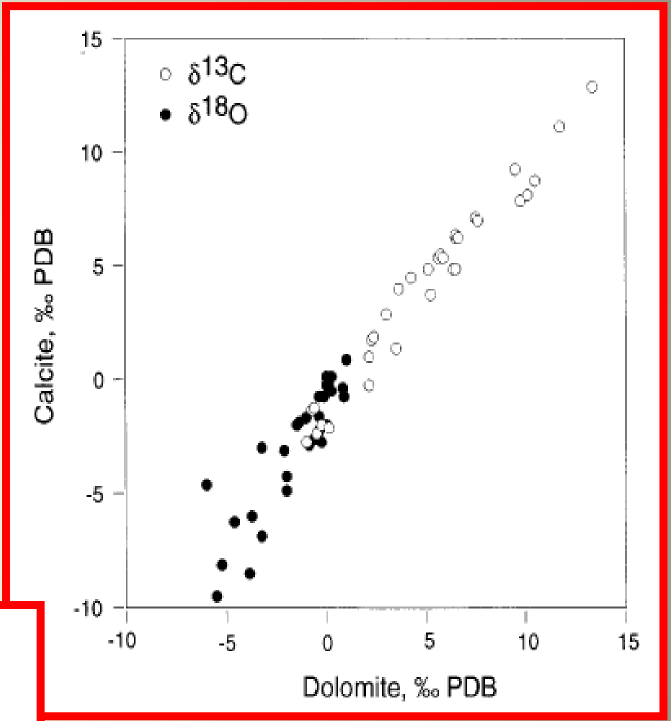


Lakeshore Stable Isotopes - Dolomite & Calcite



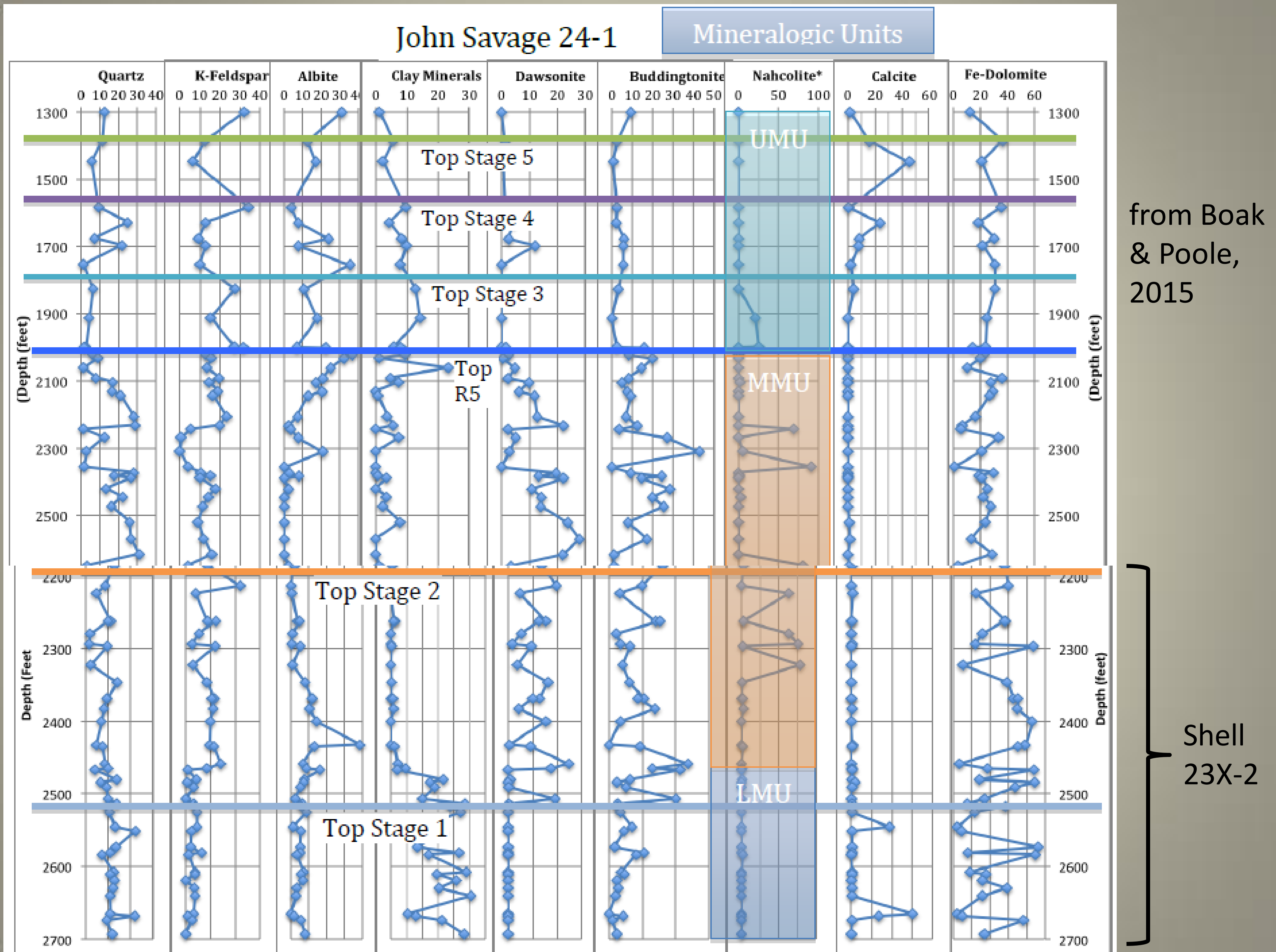
from Swierenga, Sarg, & Tänavsuu-Milkeviciene 2015





USGS Coyote Wash 1

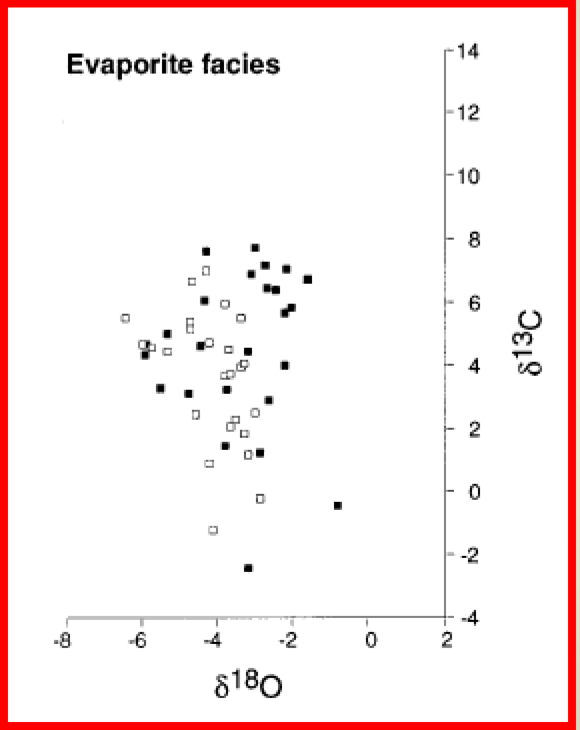
from Pitman, 1996

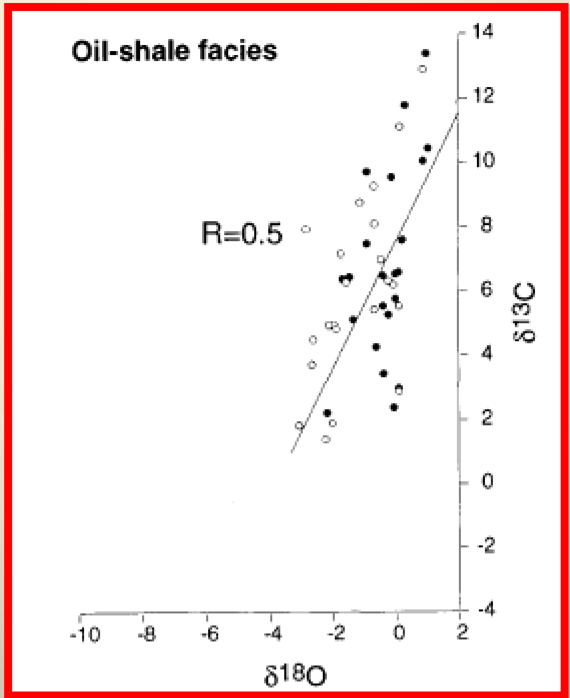


John Savage 24-1
Mineralogic Units
Quartz
K-Feldspar
Albite
Clay Minerals
Dawsonite
Buddingtonite
Nahcolite*
Calcite
Fe-Dolomite
(Depth (feet)
Depth (feet)
Depth (Feet
UMU
MMU
LMU
Top Stage 5
Top Stage 4
Top Stage 3
Top R5
Top Stage 2
Top Stage 1
from Boak & Poole, 2015
Shell 23X-2

Offshore Lake Stable Isotopes – Dolomite & Calcite

Nahcolite





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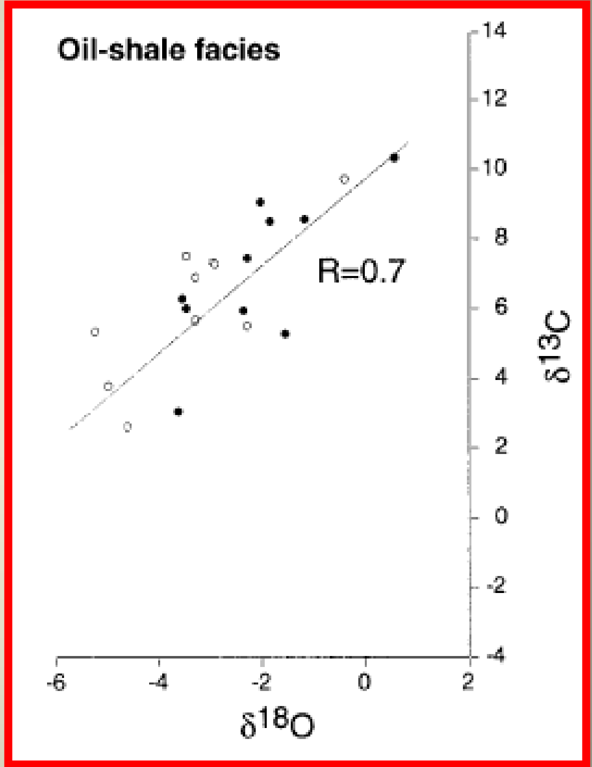

USBM O1A

from Pitman, 1996

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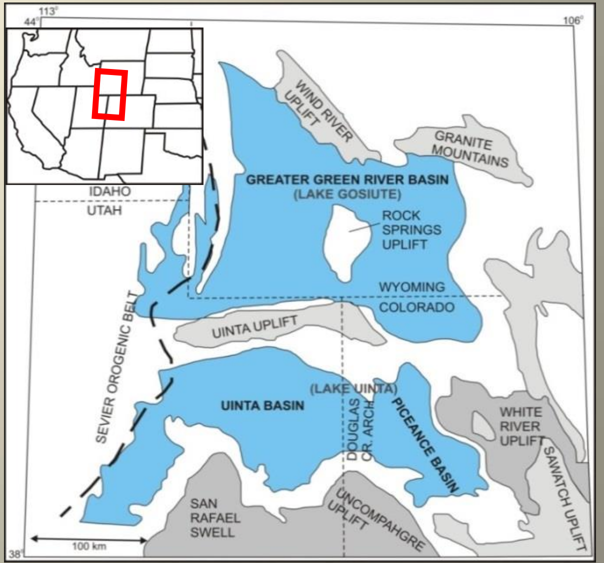
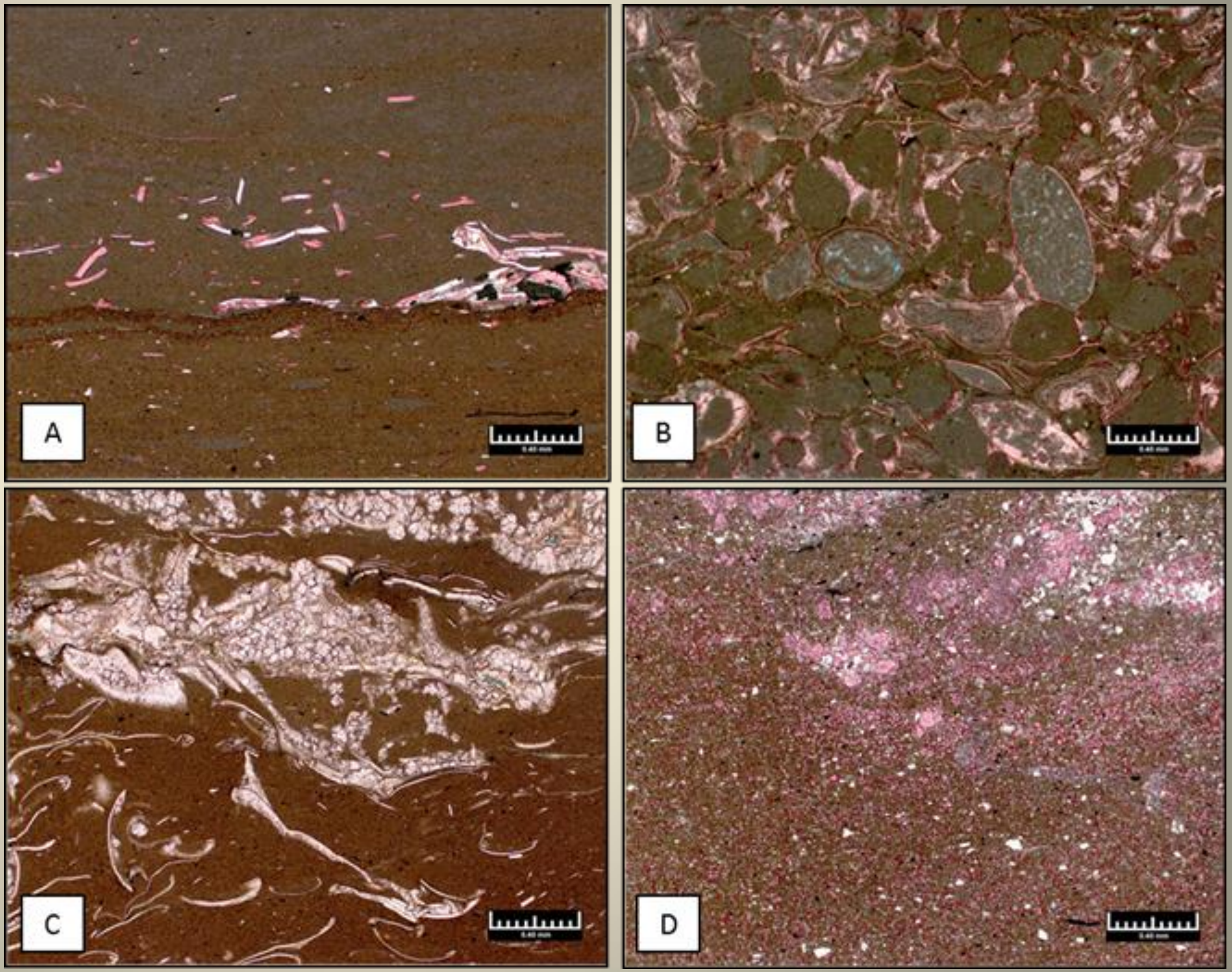


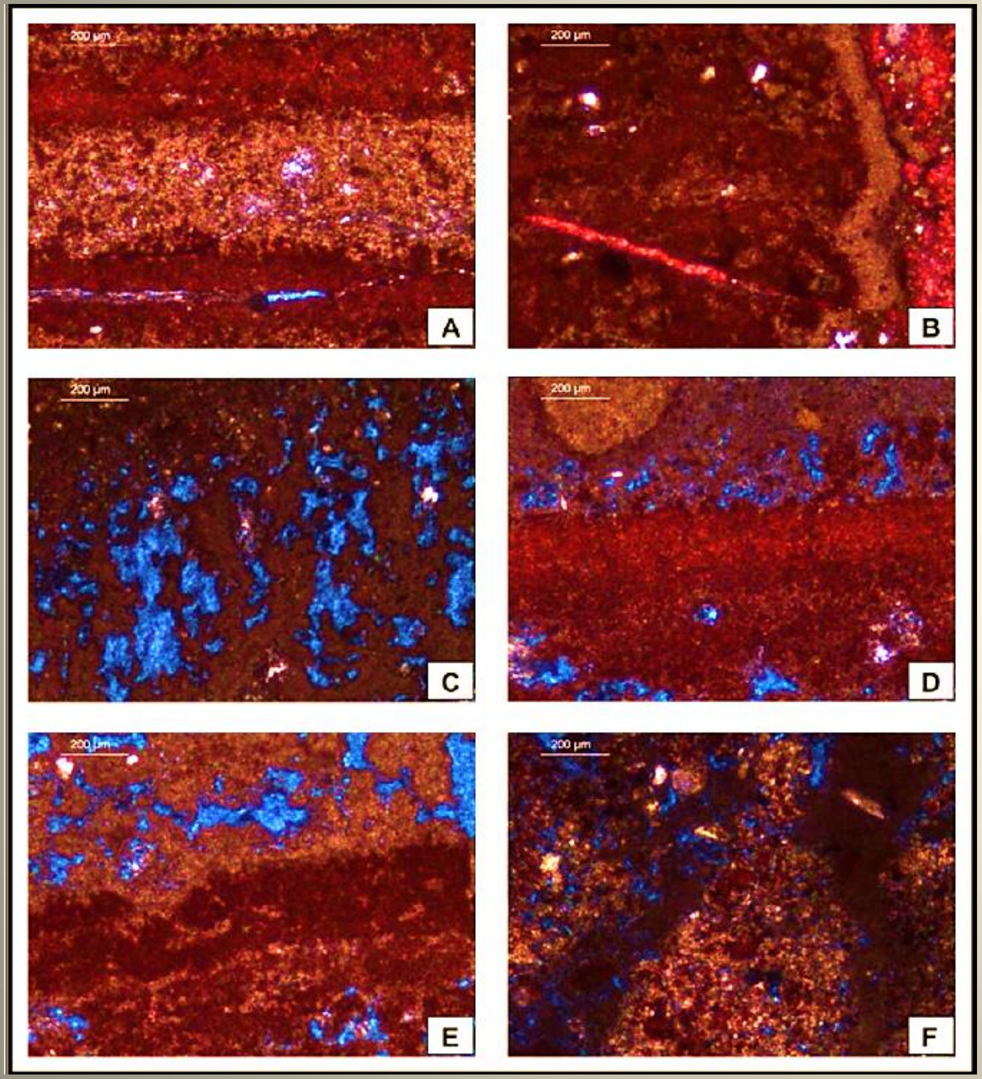
Littoral-Sublittoral Mudrocks and Grainstones

A) ostracod dolomitic mudstone-wackestone;
B) ostracod lime packstone-grainstone, brown-green peloids are dolomitized;
C) molluscan lime dolomitic wackestone-packstone, mud is dolomitic & bioclasts are calcite;
D) Laminated dolomitic oil shale

Black scale bar is 0.40 mm.

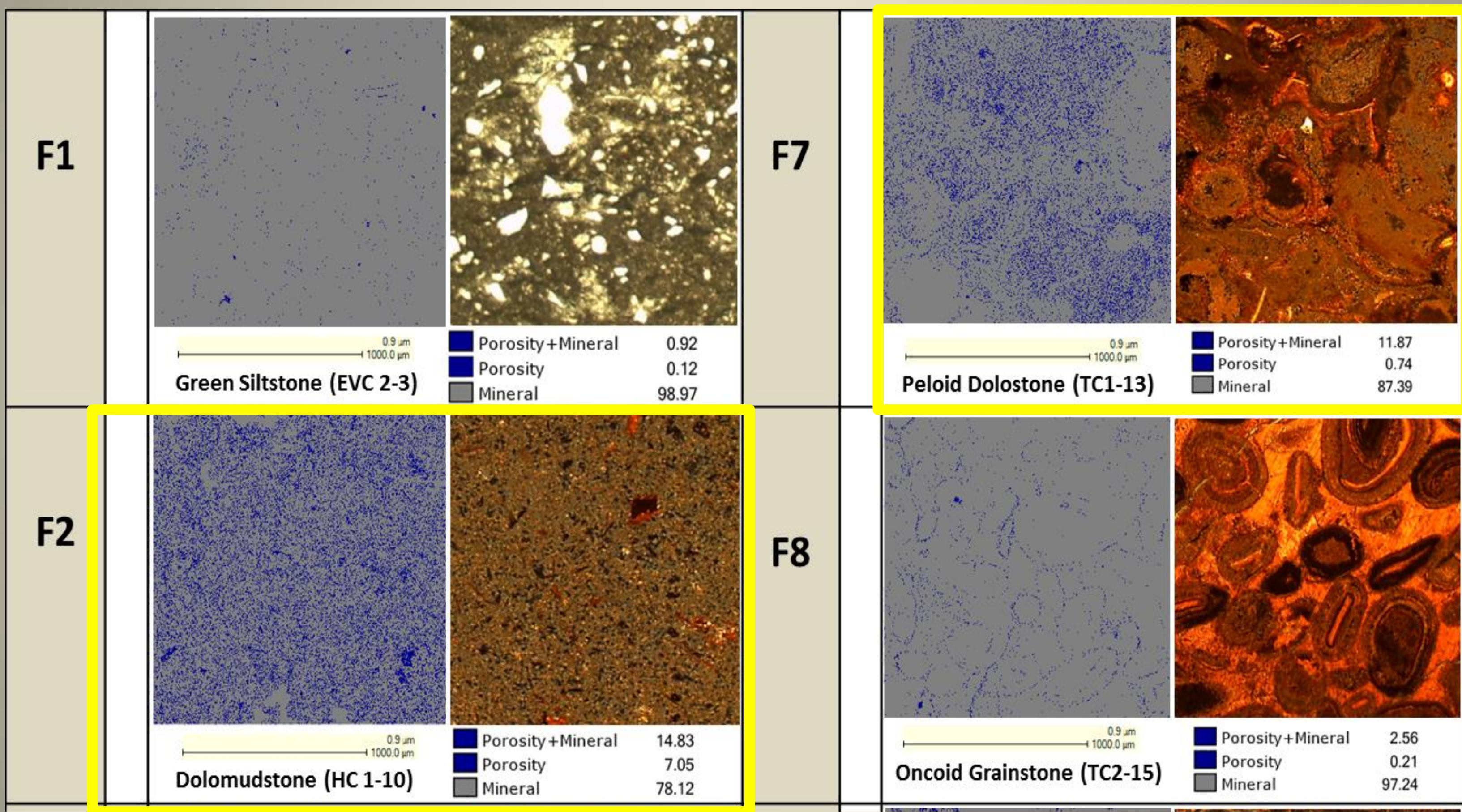


Stromatolite Microtextures

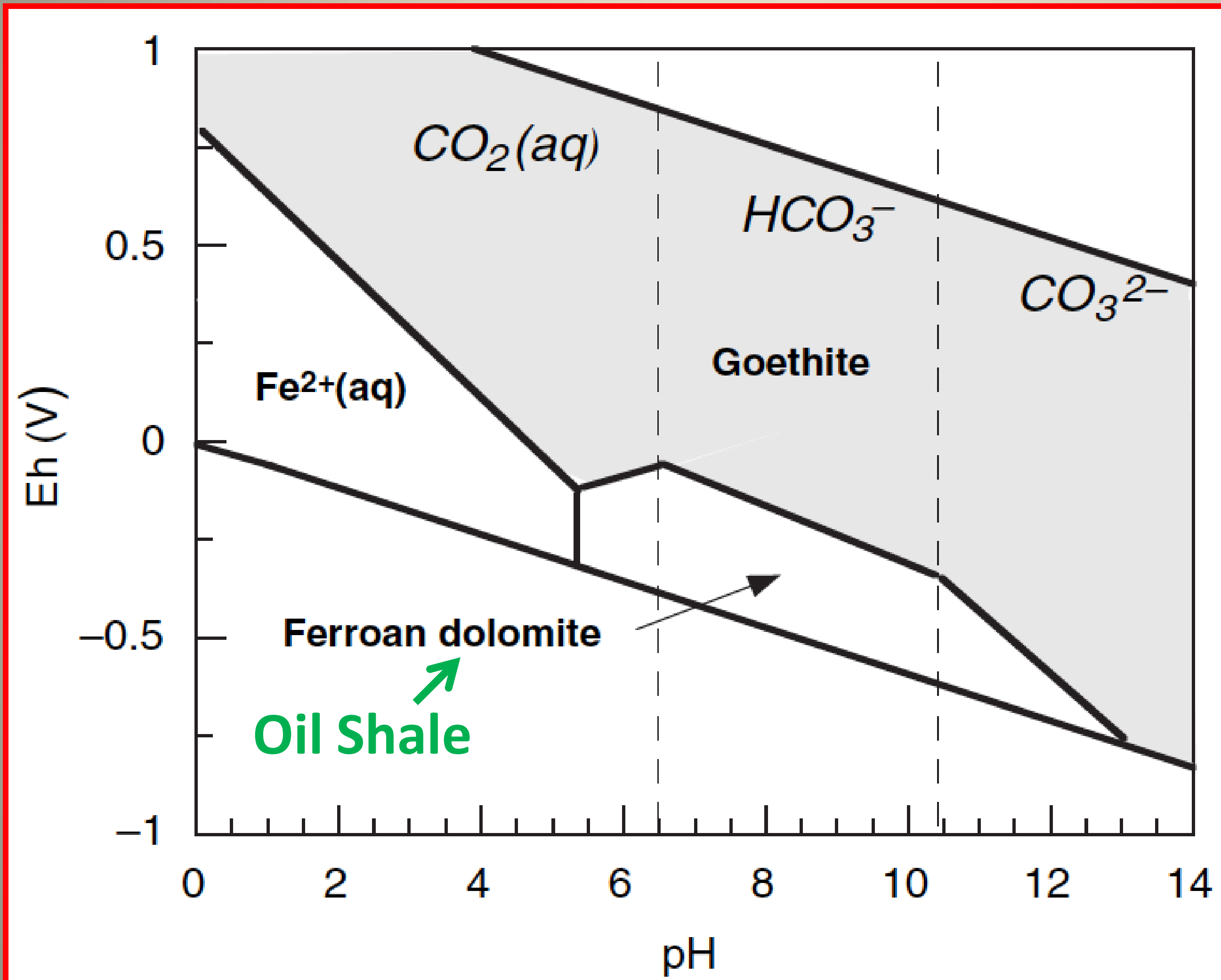


A. **Fine-grained stromatolite with alternating dolomite and calcite lamina**
B. **Columnar stromatolite with dolomitized outer coating**
C. **Dendrolite layer**
D. **Agglutinated stromatolite with alternating dolomite and calcite lamina**
E. **Agglutinated stromatolite with dolomite and calcite lamina**
F. **Agglutinated stromatolite with irregular laminations**

Dolomudstone Porosity



Redox Conditions for Ferroan Dolomite



a (ankerite) = 0.1;

[Fe(II) aq] = 10^{-4}

Inorganic C conc. = $10^{-2.7}$

Grosz et al. (2006)
Geofluids 6, 137-153