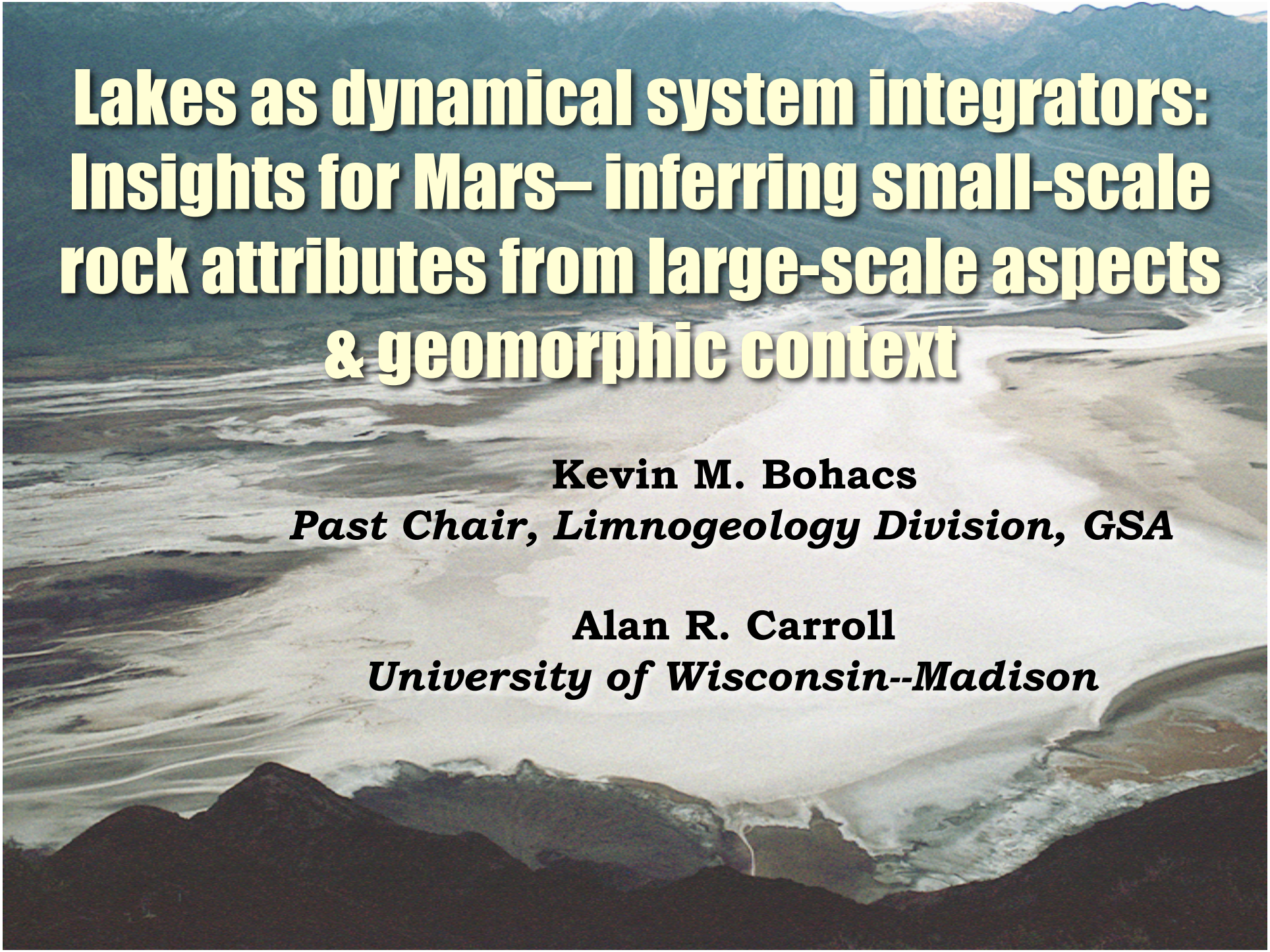


Lakes as dynamical system integrators: Insights for Mars– inferring small-scale rock attributes from large-scale aspects & geomorphic context

Kevin M. Bohacs
Past Chair, Limnogeology Division, GSA

Alan R. Carroll
University of Wisconsin--Madison

Lakes as dynamical system integrators: Insights for Mars

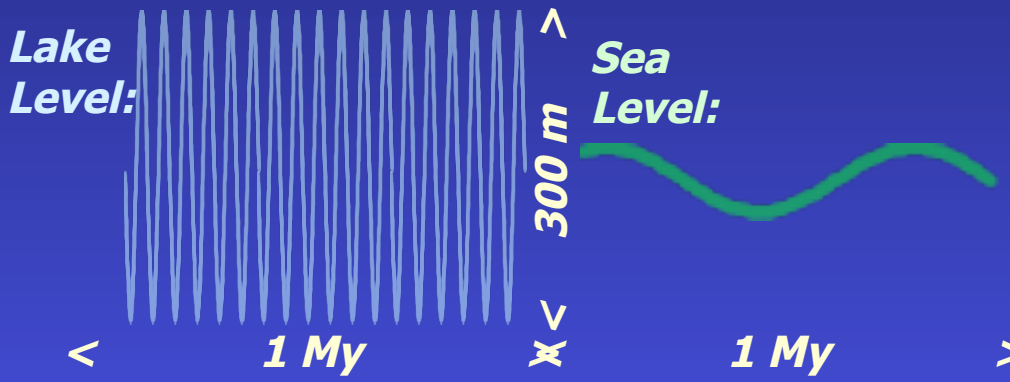
- **Lakes are highly integrated dynamical systems– this allows one to make very definite inferences about occurrence, character, & distribution of lithofacies and organic matter from large-scale stratigraphic patterns.**
- **The limnogeology community over the past 15 years has come to the conclusion that even very large lakes do not behave like small oceans, at least in the stratigraphic or geochemical sense** *(e.g., Carroll & Bohacs, 1999; Bohacs et al., 2000, 2003; Buoniconti, 2001).* **& therefore require different concepts/models.**
- **Lakes differ from oceans in several significant ways:**
  - **The very existence and character of a lake is fundamentally controlled by the existence of a spillpoint. This allows recognition from orbital imagery**
  - **Lake levels vary more widely and rapidly than sea level, hence, shoreline strata are commonly poorly developed and relatively thin,**
  - **Lake level, water supply, and sediment supply are often closely linked in lake systems (most marine models assume no linkage).**
  - **Lake water chemistry can vary widely and frequently**
  - **There are three distinct lake-basin types: overfilled, balanced-filled, and underfilled. Each has characteristic lithofacies & associated organic matter.**
- **Intermittently to persistently closed lake basins, on Earth, produce and preserve the largest concentrations of organic matter.**

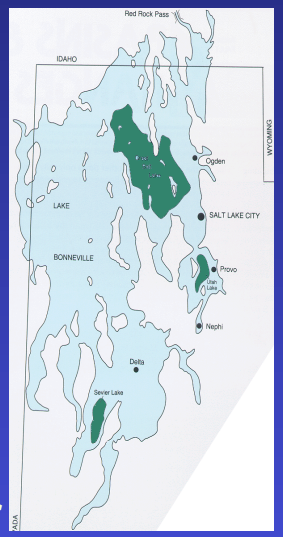
Bohacs & Carroll, 2011

Lakes NOT = Small Oceans, But <u>are</u> Sensitive Integrators

- **Sill (spillpoint) controls occurrence & character of lake**

- **Water Chemistry ∝ Lake Level *(hydrology, hx)***
- **Lake Level ∝ Water Supply ∝ Sediment Supply**
- **Bigger, Faster Changes**



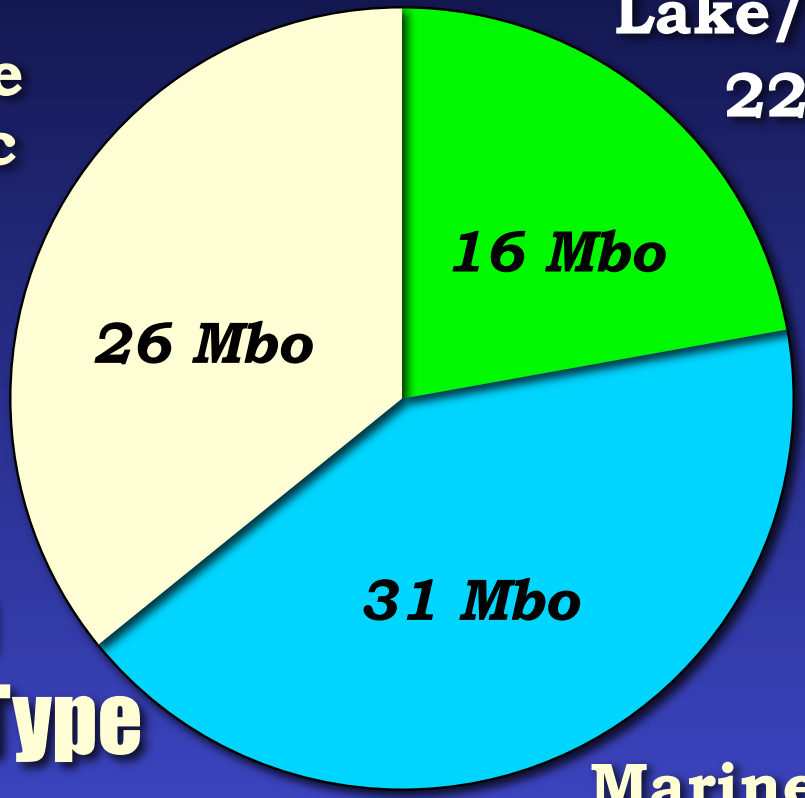


Lake Bonneville: = 300 m drop in 15,000 years

Bohacs & Carroll, 2011

Lakes Accumulate Significant Amounts of Organic Carbon

- More than 150,000 MBOE OOIP discovered:
  ≅ 68.9 Gbbls Oil, 49.3 TCf Gas, 85.7 Mbbl Condensate
- In more than 16 Countries *(China, Brazil, Indonesia)*



Daily Oil Production by Source Type

based on 2002 USGS, BP estimates

Bohacs & Carroll, 2011

Lakes as dynamical system integrators: Advantages from a exploration portfolio perspective

- **Lake-center environments are excellent sites for production and preservation of organic matter:**
  - ***Lakes are significant part of global organic C cycle on Earth***
  - ***Organic matter occurrence, character, and distribution is a strong function of lake basin type– enables tie of molecular geochemistry to ecosystem history to seismic/orbital imagery scale stratal patterns.***
- **Lake strata record details of paleoclimate (hydrology) evolution:**
  - ***Lake water chemistry and ecosystems = f (provenance lithotypes, hydrologic history)***
  - ***Persistently closed-hydrology lake basins = best 'rain gauge' (e.g. crater lake Bosumptwi, Ghana– Scholz et al.)***
- **Lake-center strata contain integrated record of provenance-terrane lithotypes and drainage basin history :**
  - ***Provides insights into a larger area beyond that physically visited***
  - ***Enables samples to be tied to landscape evolution across basin***

Bohacs & Carroll, 2011

Main Data Sources

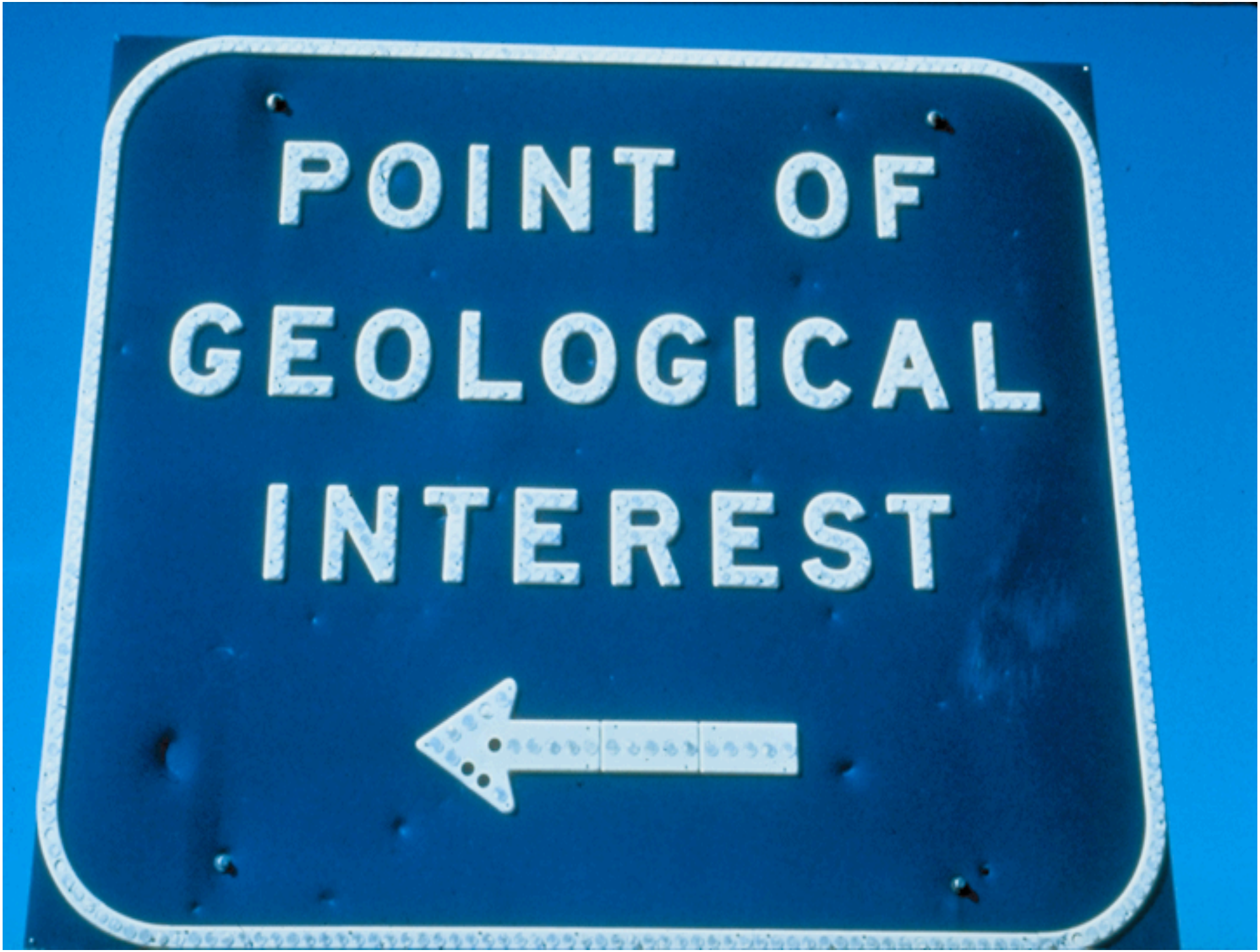
Ancient Lakes (224; Proterozoic-Pleistocene):

- **Gierlowski-Kordesch & Kelts, 1994**
- **Carroll & Bohacs, 1999; 2001**
- **Bohacs et al., 2000; Bohacs, 2011**

Modern Lakes (253; > 500 km^2):

- **Herdendorf, 1984** ***(digits in GSA Data Repository 9916)***

Bohacs & Carroll, 2011


POINT OF
GEOLOGICAL
INTEREST

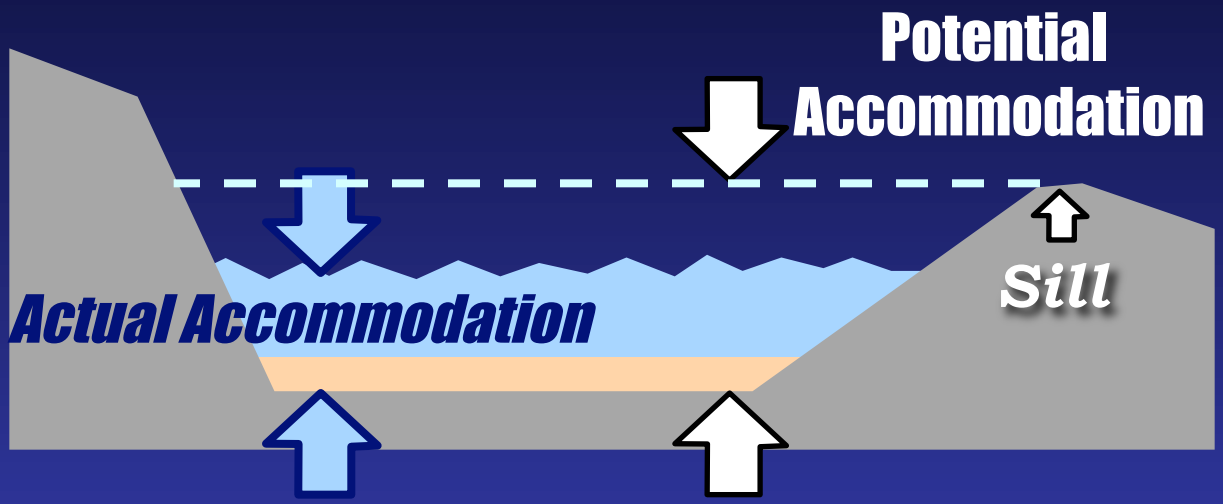
Lakes– Where & Why?

☑ H_2O

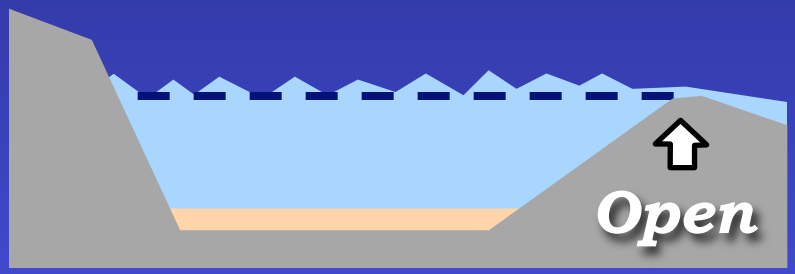
☑ Hole

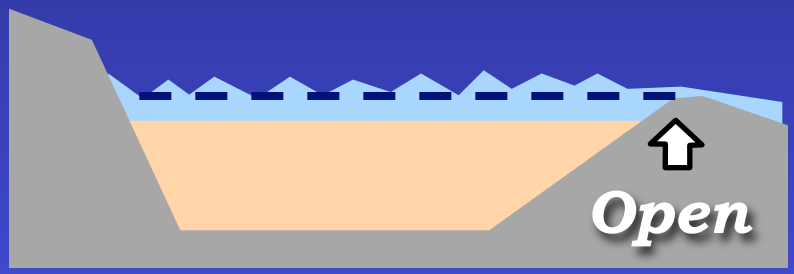
Sill Controls Existence & Nature of Lake

- **Potential Accommodation ≡ Space below Sill**



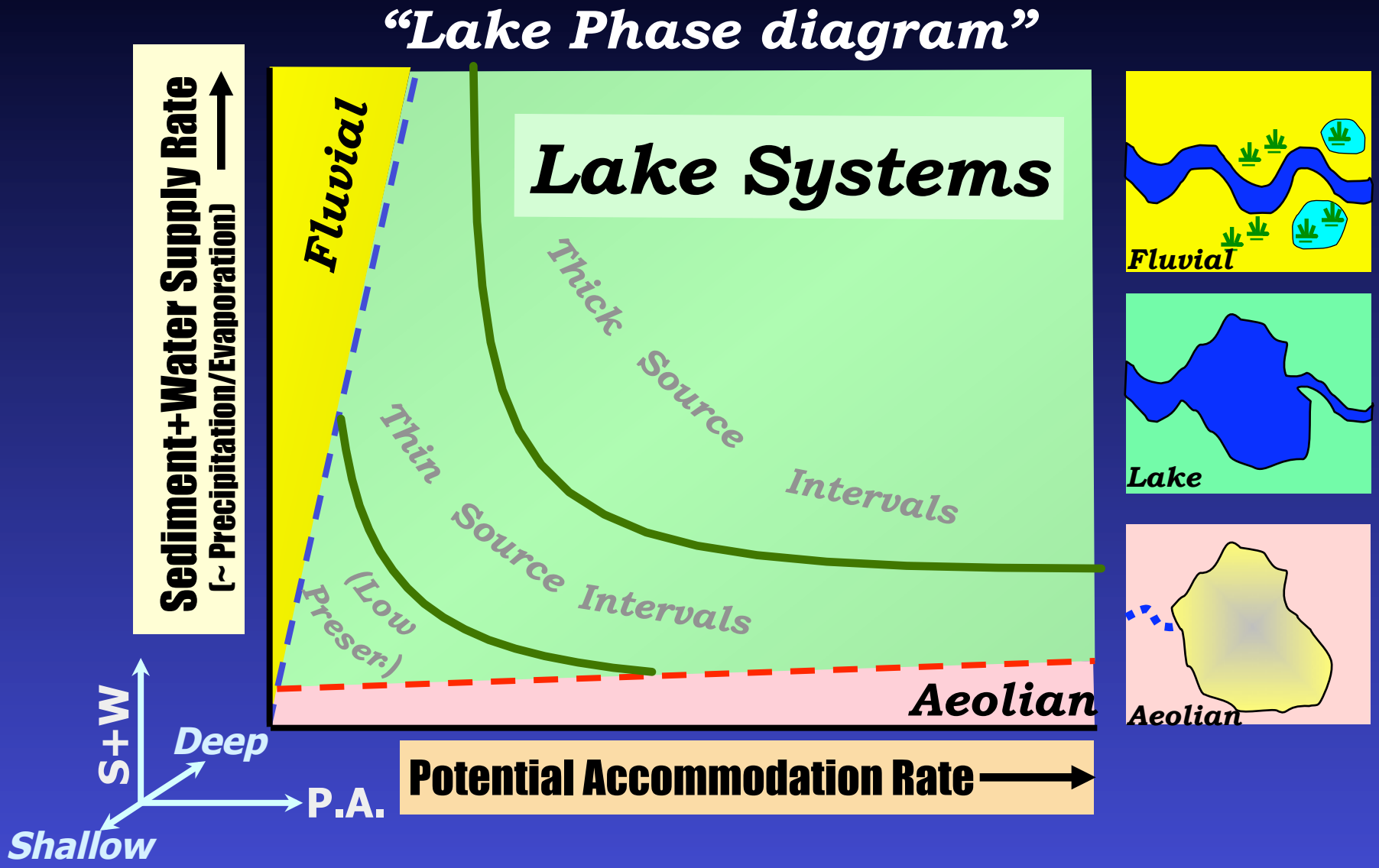
- ***Filled with <u>combination</u> of Sediment & Water:***





Bohacs & Carroll, 2011

Balance Controls Lake Occurrence



Lakes– Where & Why?

T F

- ☐ ☐ **Wide Variety of Modern Lakes = Wide Variety of Lake Facies Associations in Rocks ?**

Everybody sees ~ 3…

Lyell, 1830

- ☞ ***"Fluvial", "Deltaic", "Evaporitic" types***

Bradley, 1931

- ☞ ***Stable Freshwater, Expanding-Contracting Alkaline, strongly Alkaline playa-like***

Eugster & Kelts, 1983

- ☞ ***Open Freshwater, Perennial Saline, Ephemeral Salt Pan***

Olsen, 1990

- ☞ ***Richmond, Newark, Fundy types***

Mello, 1988

- ☞ ***Freshwater, Saline, Hypersaline***

Carroll & Bohacs, 1995

- ☞ ***Overfilled, Balanced-filled, Underfilled***

Carroll & Bohacs, 1999, 2001

- ☞ ***Fluvial-Lacustrine, Fluctuating Profundal, Evaporitic***

Lakes– Where & Why?

T F

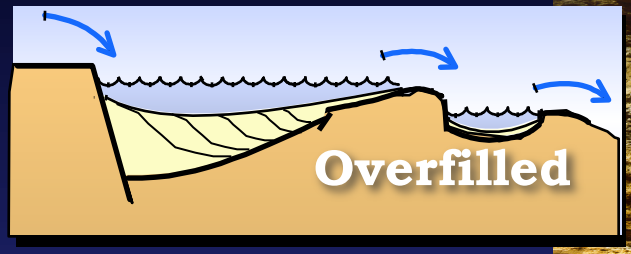
Wide Variety of Modern Lakes = Wide Variety of Lake Facies Associations in Rocks ?

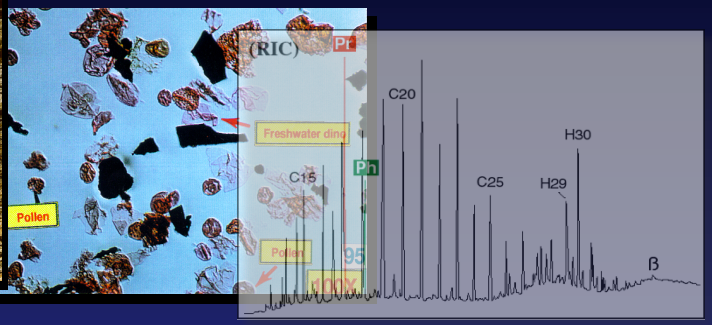
☞ **Despite Complexity of Modern Lake systems, Strata record only 3 major Facies Associations**

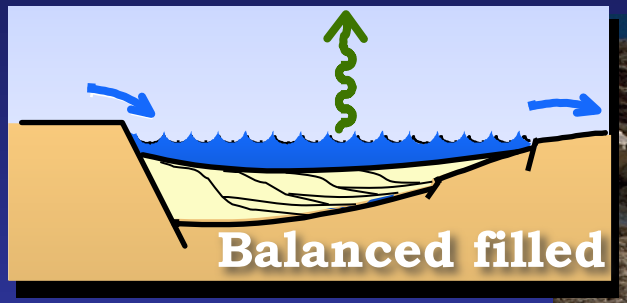
≅ "Geological Filter"

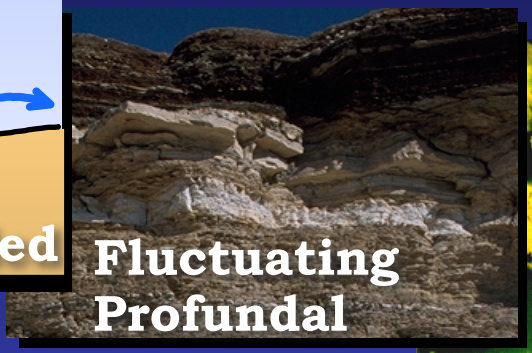
Bohacs & Carroll, 2011

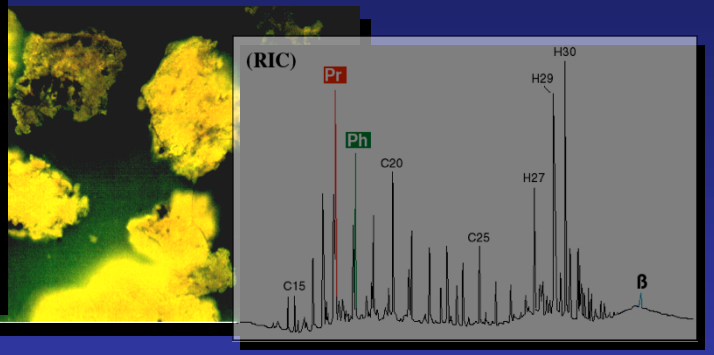
Only 3 Main Facies Associations Observed

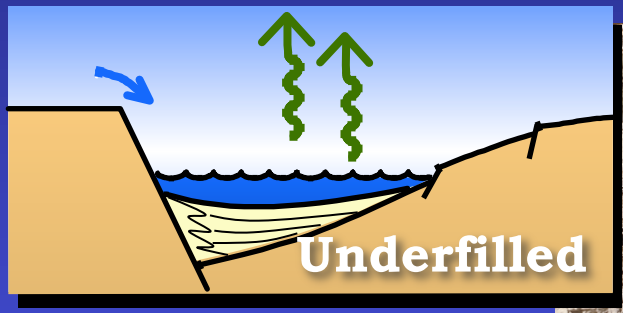


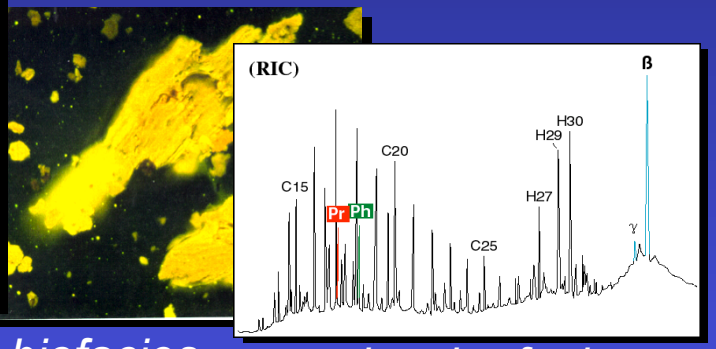












stratal patterns

lithofacies & bedding

biofacies

molecular facies

Bohacs & Carroll, 2011

Widely Observed Characteristics of Lake Facies Associations

Fluvial-Lacustrine:

- **Mostly Open Hydrology, Freshwater**
- **Dominated by Progradation, Clastics**

Fluctuating Profundal:

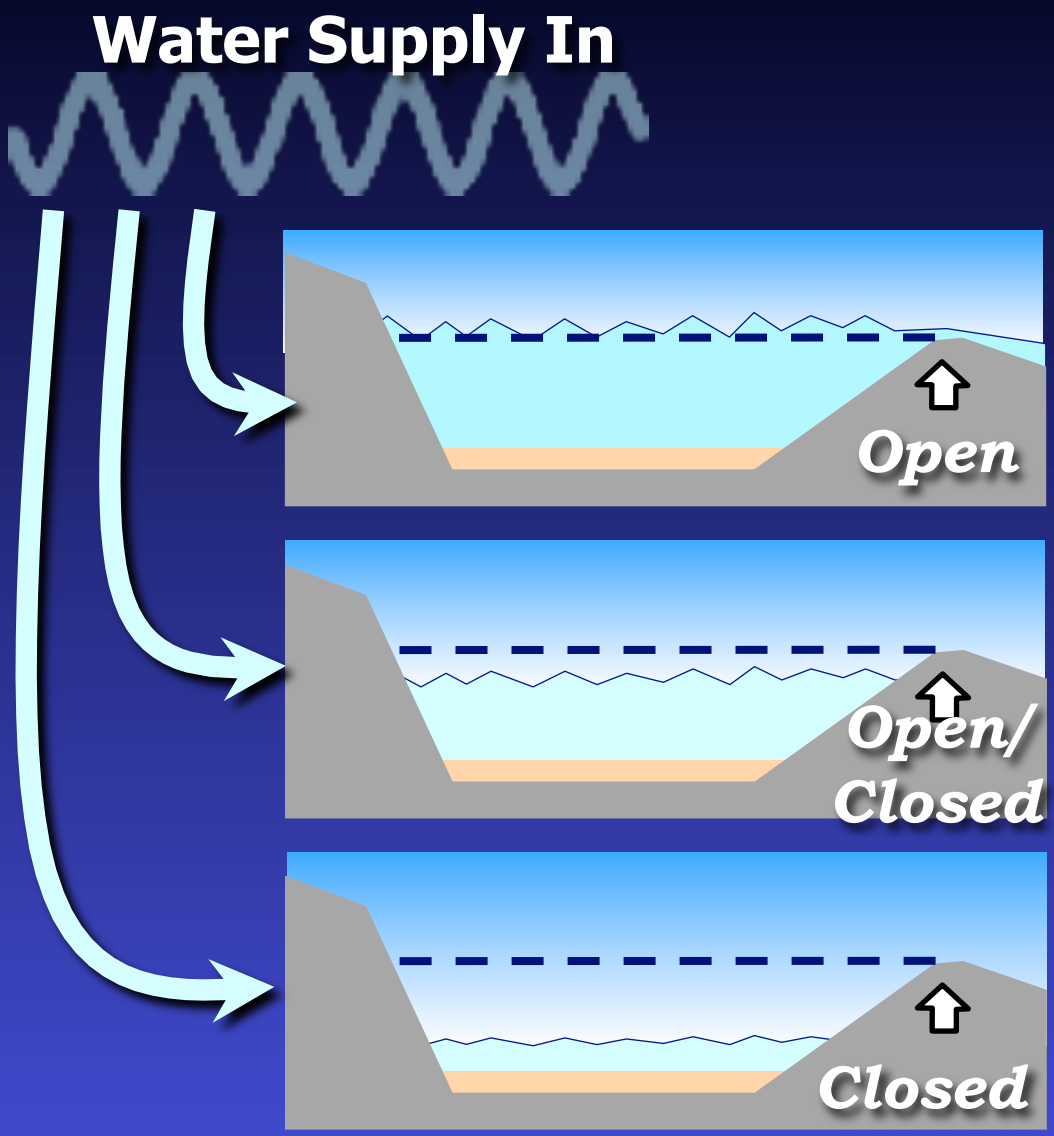
- **Open & Closed Hydrology, Alkaline-Saline**
- **Mixed Prograd'n & Aggrad'n, Clastic/Chemical**

Evaporative:

- **Mostly Closed Hydrology, Saline-Hypersaline**
- **Aggradational stacking, Evaporites/Chemical**

Bohacs & Carroll, 2011

Why ? -- 3 Modes of Hydrologic Response



Lake Level Response

Lake Level at sill
always overflowing

Lake Level near sill
intermittently overflowing

Lake Level below sill
never overflowing

Bohacs & Carroll, 2011

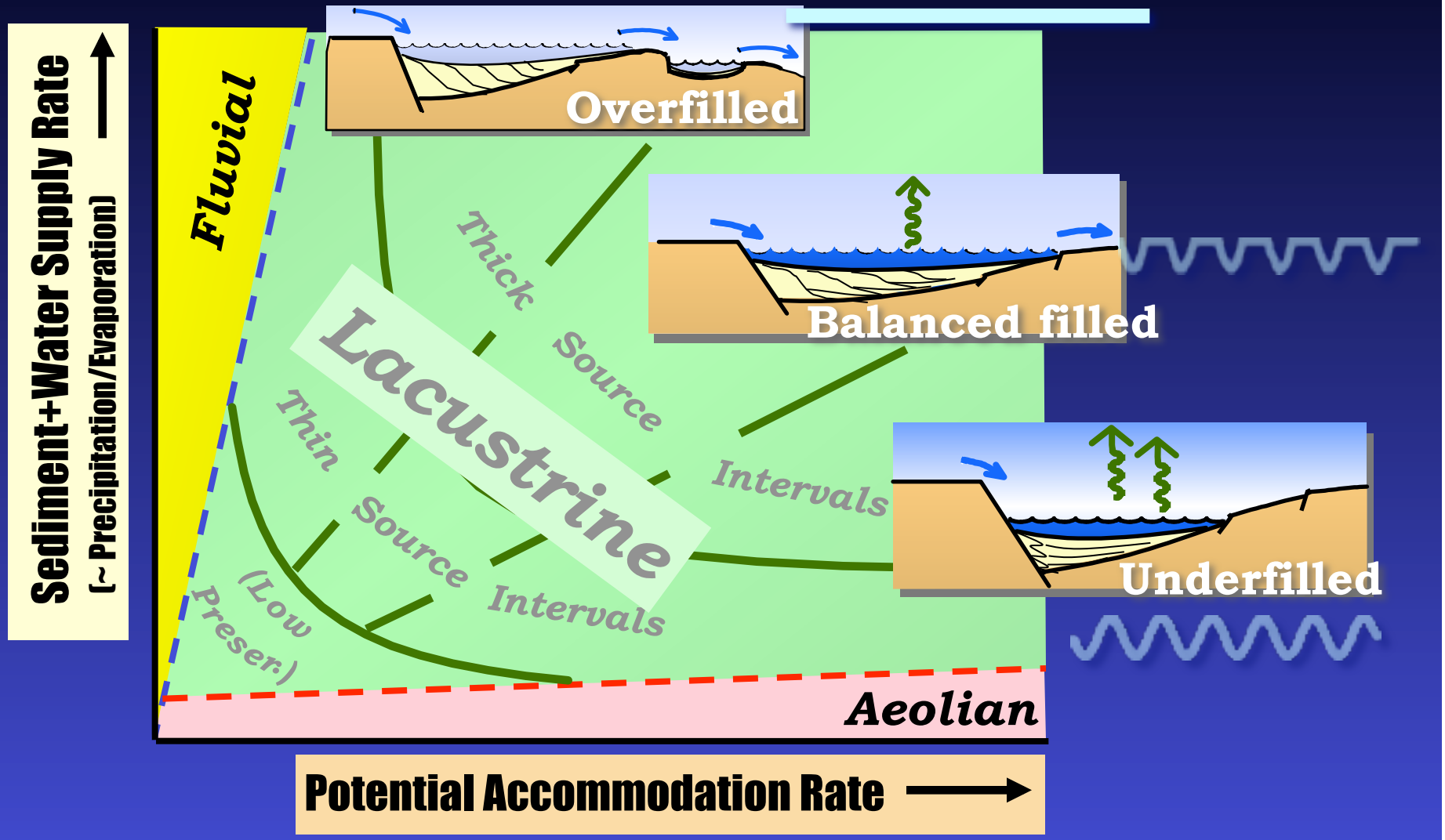
Lake Facies Associations– Controls

- ☑ **Stratal Record = Integrated History of Lake Hydrology**
- ☑ **Lake Hydrology = *f* (Pot'l Accommodation, Sediment+Water Supply)**

∴ **Pot'l Accommodation & Sed.+Water Supply Controls Stratal Record, Water Chemistry, & Rock Properties *(w/ provenance, ecology, age, basin shape as secondary controls)***

Bohacs & Carroll, 2011

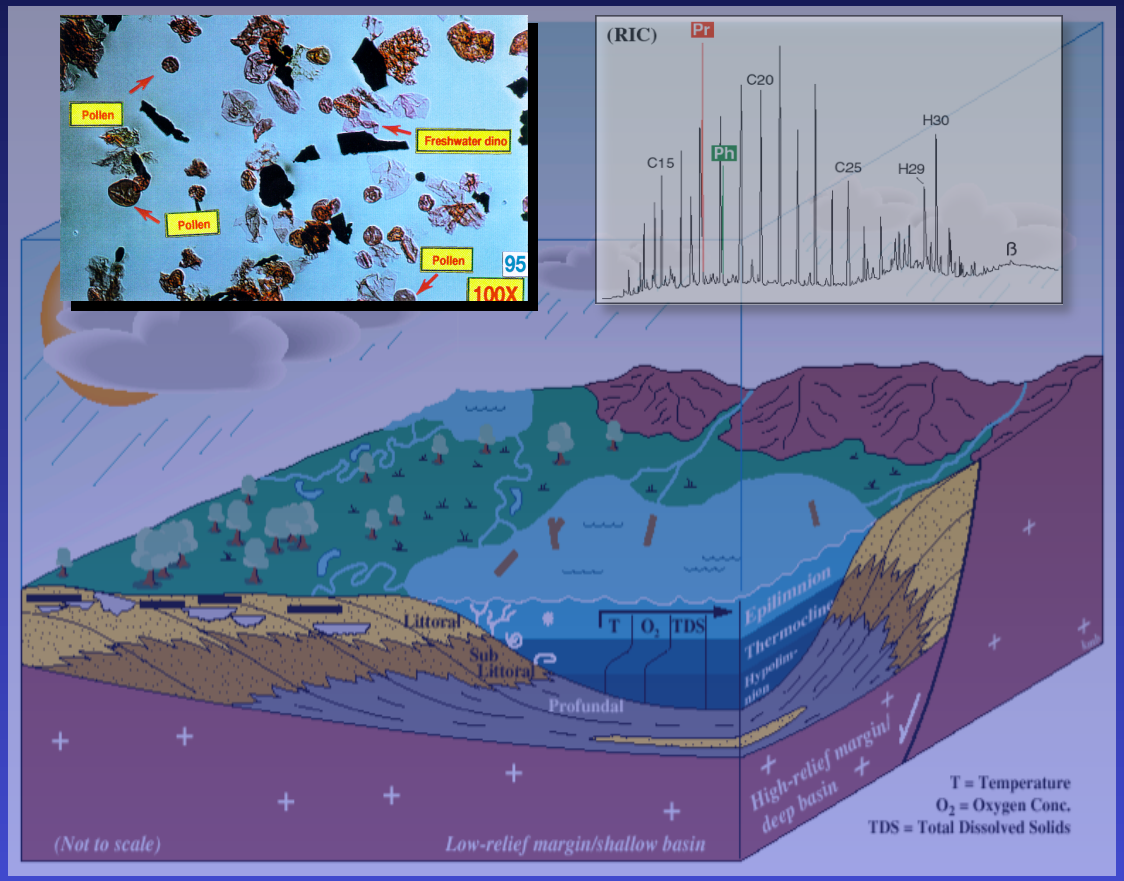
Lake-Basin Type ties Rock Properties to Proximate Controls



Bohacs & Carroll, 2011

Overfilled Lake Basin Systems- Summary

- Mostly Open Hydrology, Freshwater
- Fill Dominated by Progradation, Clastics



Organic Matter:

- Algal & land plant
- Mod. H content
- Long-chain waxes

Associated Strata:

- Progradational
- Shoreline Clastics
- Point-bar Ss

Overfilled Lake Basin map patterns

Persistent Lake Level =

- ✓ **Effective wave reworking**
- ✓ **Smooth shorelines**
- ✓ **Well-developed beach ridges**

Persistent influx =

- ✓ **Well-developed deltas**
- ✓ **Wave-dom'd deltas**

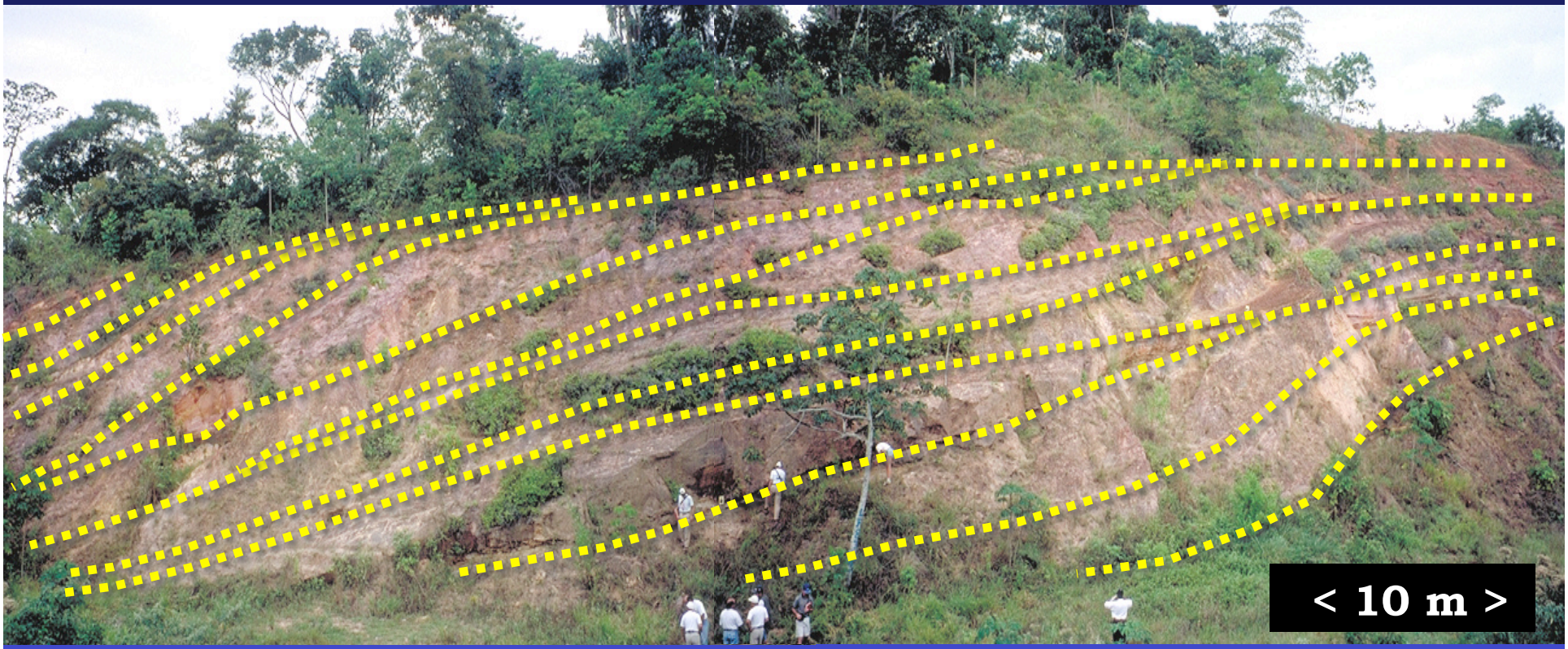
Bohacs & Carroll, 2011

Bohacs & Carroll, 2011

Overfilled Lake Basin Stratal Character:

(Marangalha Fm-- Cretaceous, Brazil)

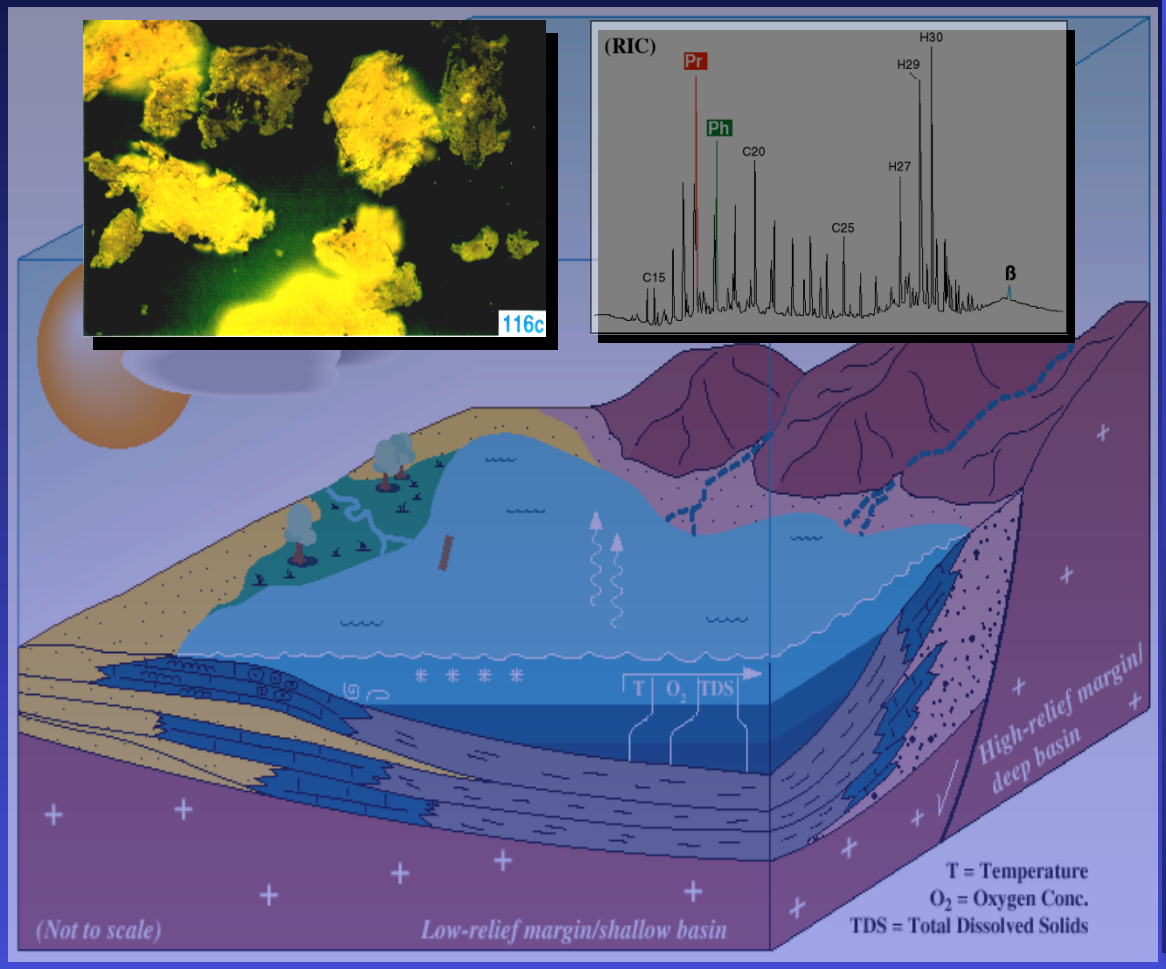
- » **Obliquely Prograding Deltas**
- » **Stable Lake Level**
- = **Laterally Extensive Shoreline Strata**



Bohacs & Carroll, 2011

Balanced-Filled Lake Basin System- Summary

- » Open & Closed Hydrology, Alkaline-Saline
- ≅ Mixed Prograd'n & Aggrad'n, Clastic/Chemical



Organic Matter:

- » Mostly 'Algae'
- » High H content
- » Paraffinic

Associated Strata:

- » Carbonates:
  - » Microbialites
  - » Grainstone
- » Clastics:
  - » Fluvial,
  - » Shoreline,
  - » Lake Floor

Bohacs & Carroll, 2011

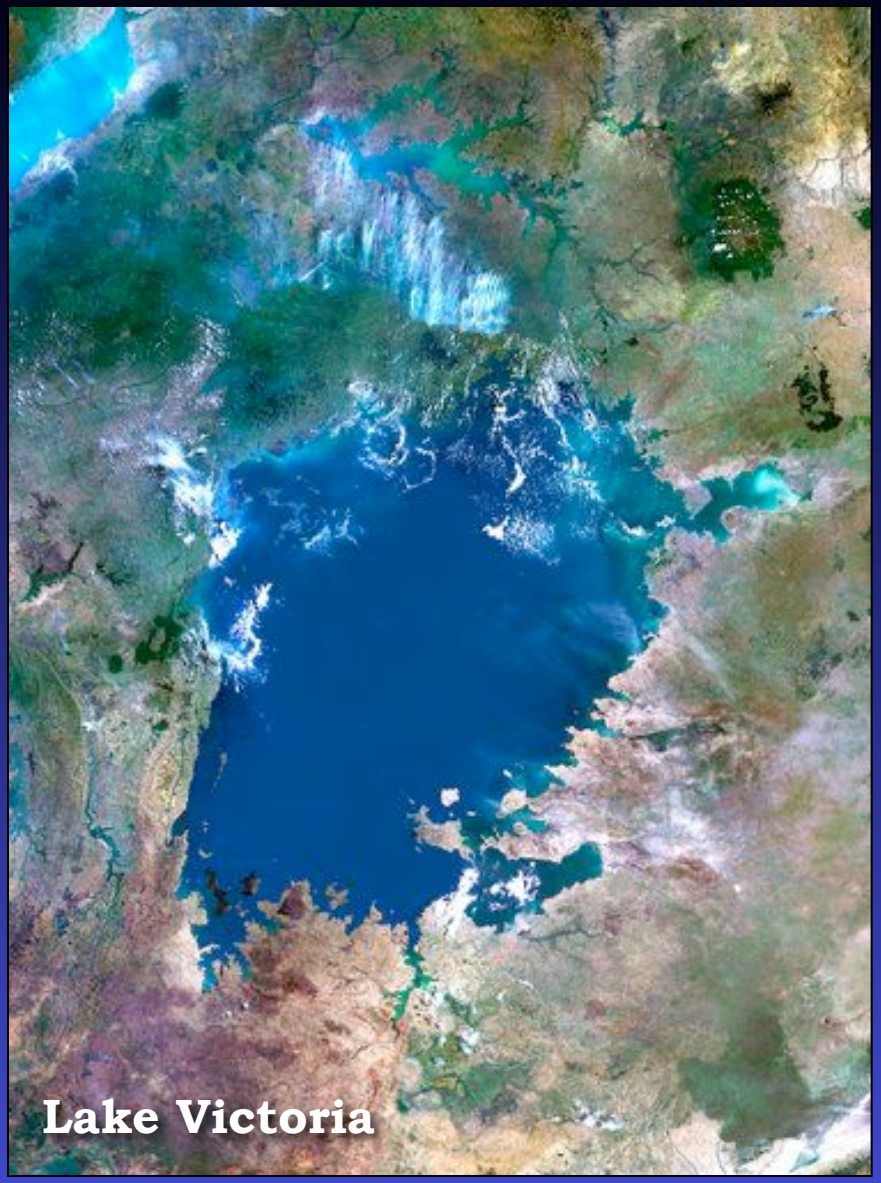
Balanced-filled Lake Basin map patterns

Fluctuating Lake Level =

- ✓ **Ineffective wave reworking**
- ✓ **Irregular shorelines**
- ✓ **Constructional & Erosional margins**

Intermittent influx =

- ✓ **Poorly developed deltas**
- ✓ **River dom'd deltas**



Bohacs & Carroll, 2011

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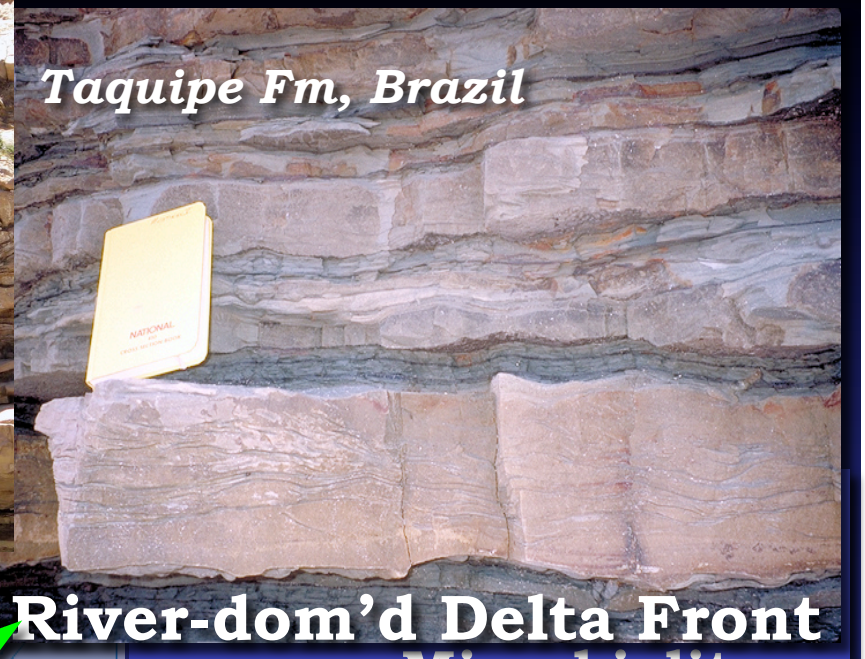


Taquipe Fm, Brazil

River-dom'd Delta Front

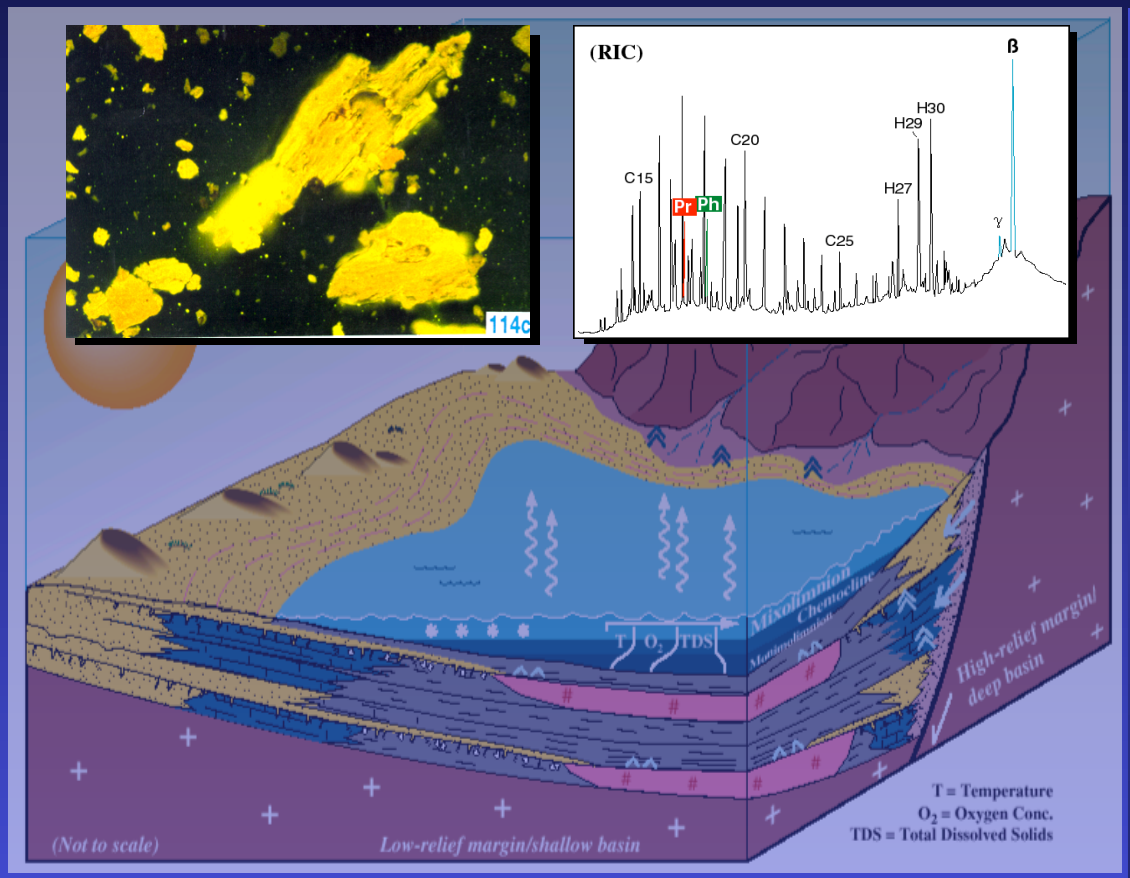
Taquipe Fm, Brazil

Lake Floor Fan

Bohacs & Carroll, 2011

Underfilled Lake Basin Sequence- Summary

- Mostly Closed Hydrology, Saline-Hypersaline
- Aggradational stacking, Evaporites/Chemical



Organic Matter:

- Only 'Algae'
- High H content
- Hypertonic tolerant

Associated Strata:

- Terminal Splays
- Shoreline CO_3
- Evaporites
- Aeolianites

Bohacs & Carroll, 2011

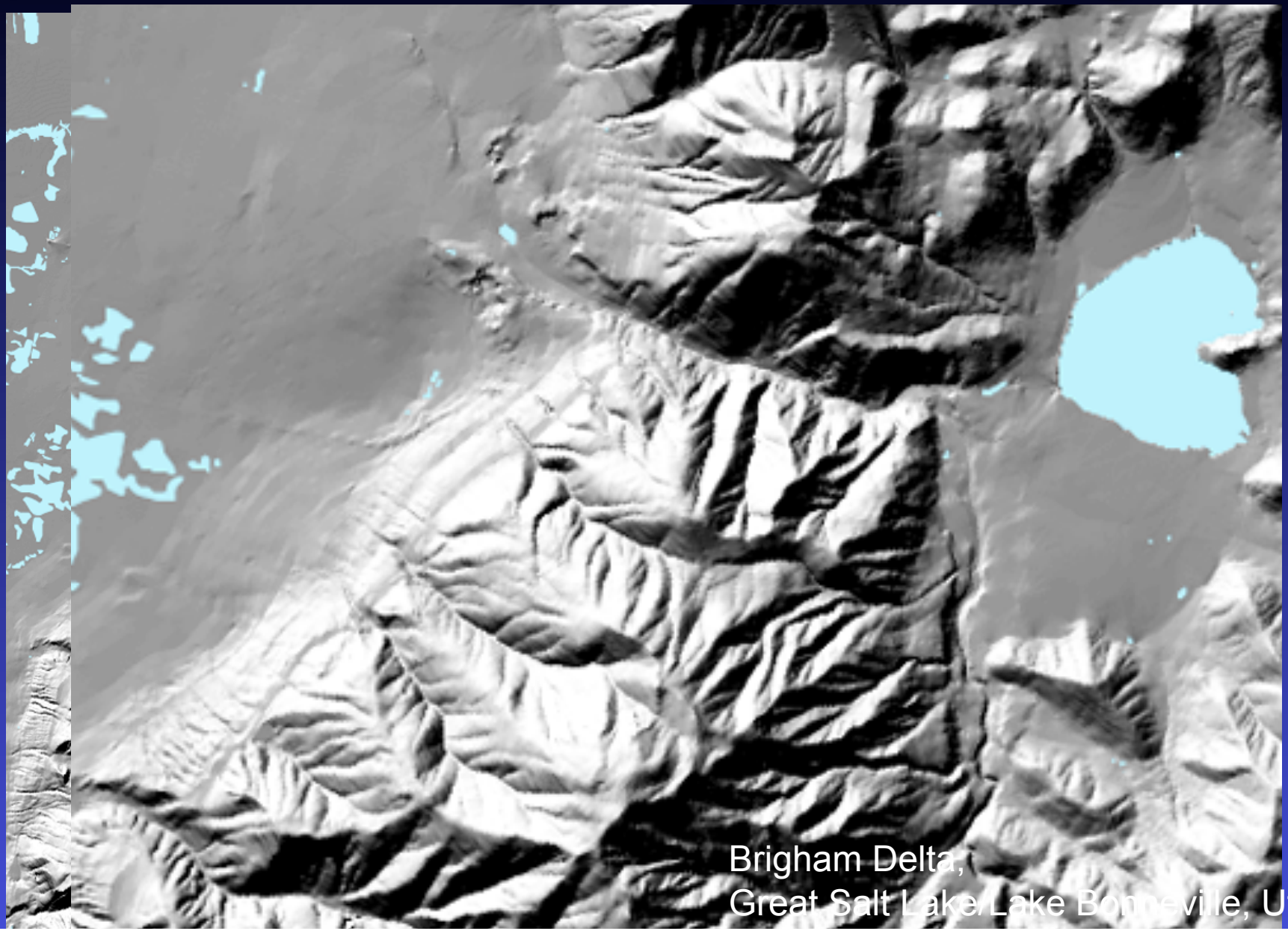
Underfilled Lake Basin– map patterns vary significantly with lake level…

- Wide diversity of shoreline types at lowstand
- Sheetflood/ Terminal Splays common during transgressions
- Deltas most active at highstand (esp Gilbert type…)

Volga River delta, northern Caspian Sea

Bohacs & Carroll, 2011

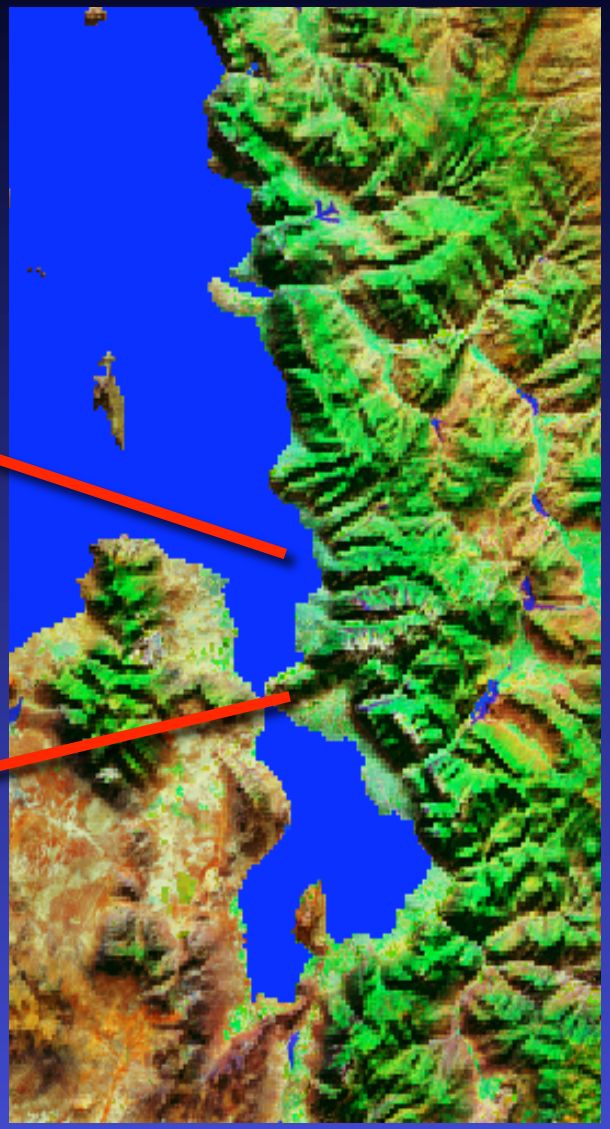
Underfilled Lake Basin– map patterns at Highstand



Brigham Delta,
Great Salt Lake/Lake Bonneville, Utah

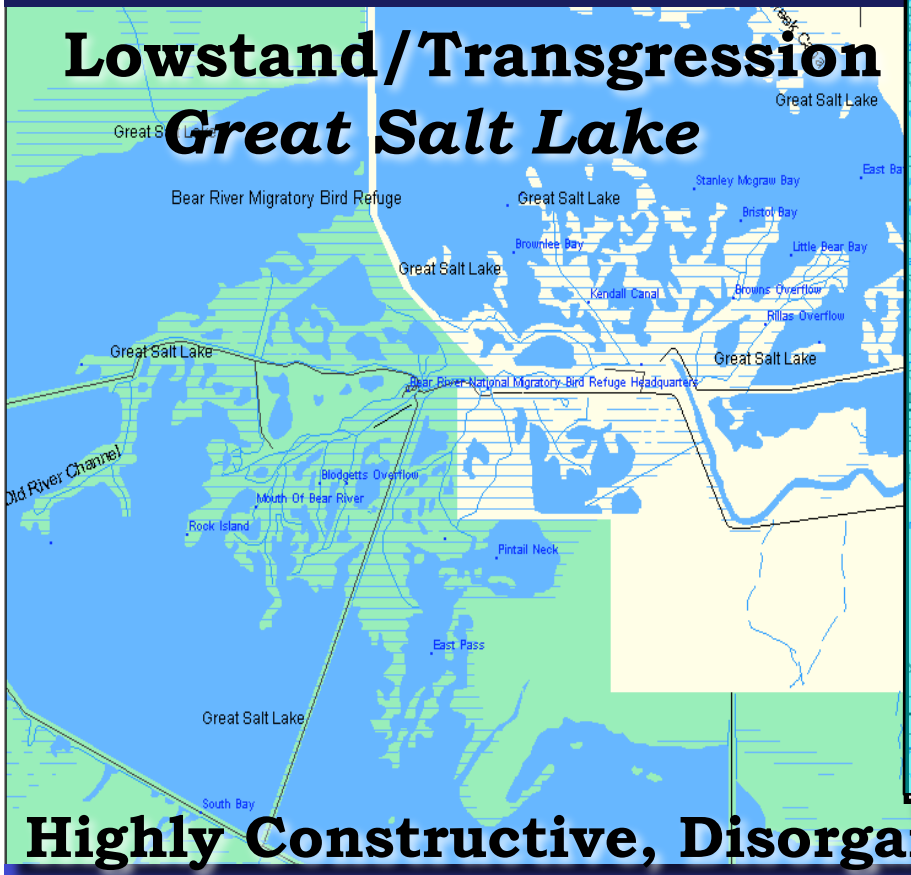
UFLB Shoreline Configurations-- Highstand

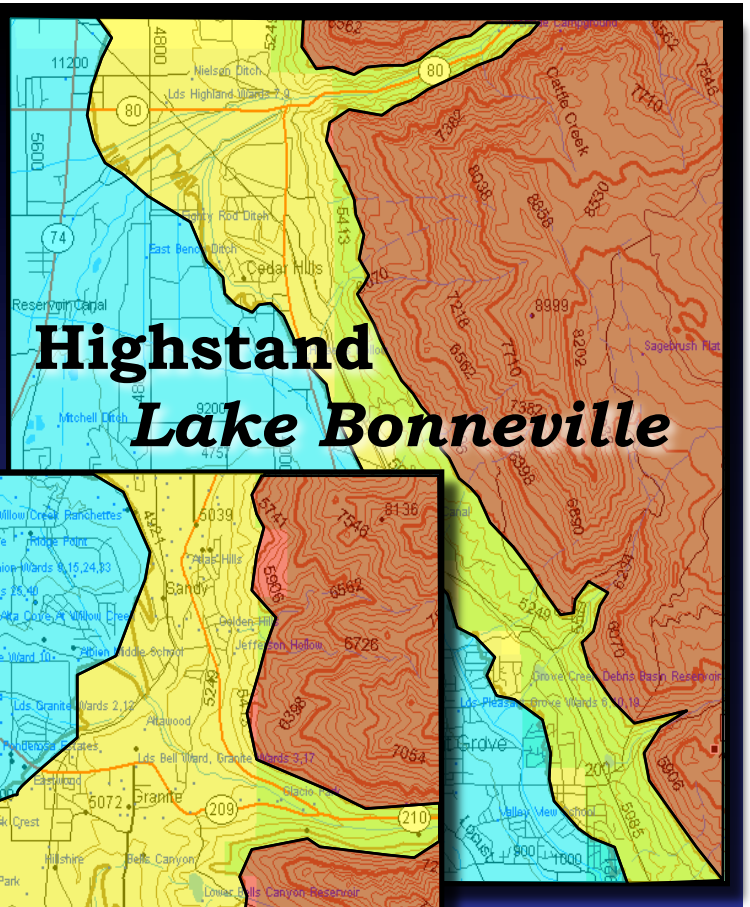
courtesy, M. Rhodes-Carson, GeoFuels, LLC

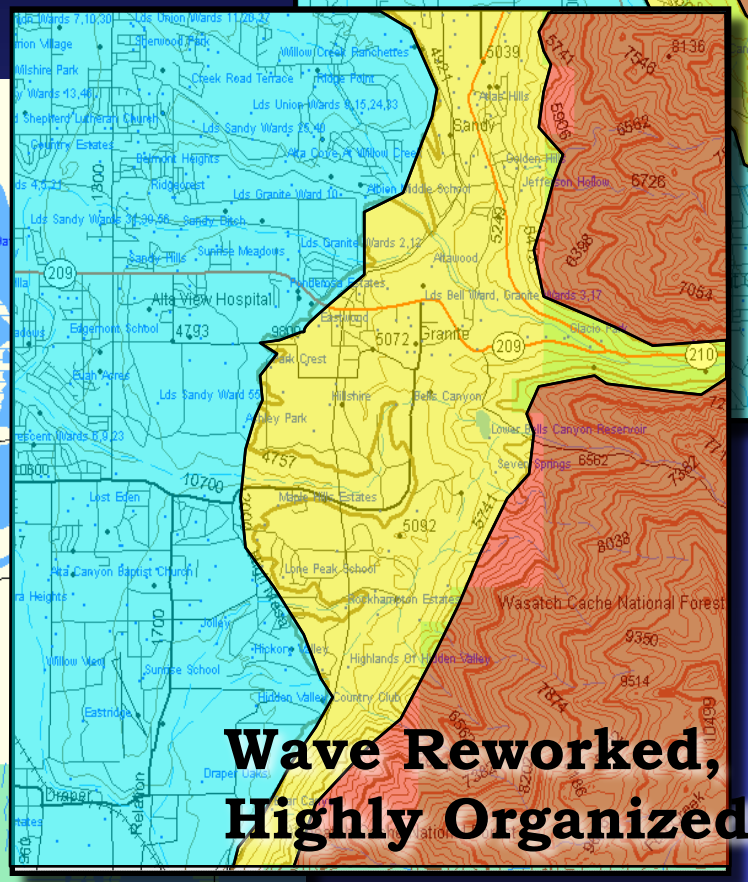


Bohacs & Carroll, 2011

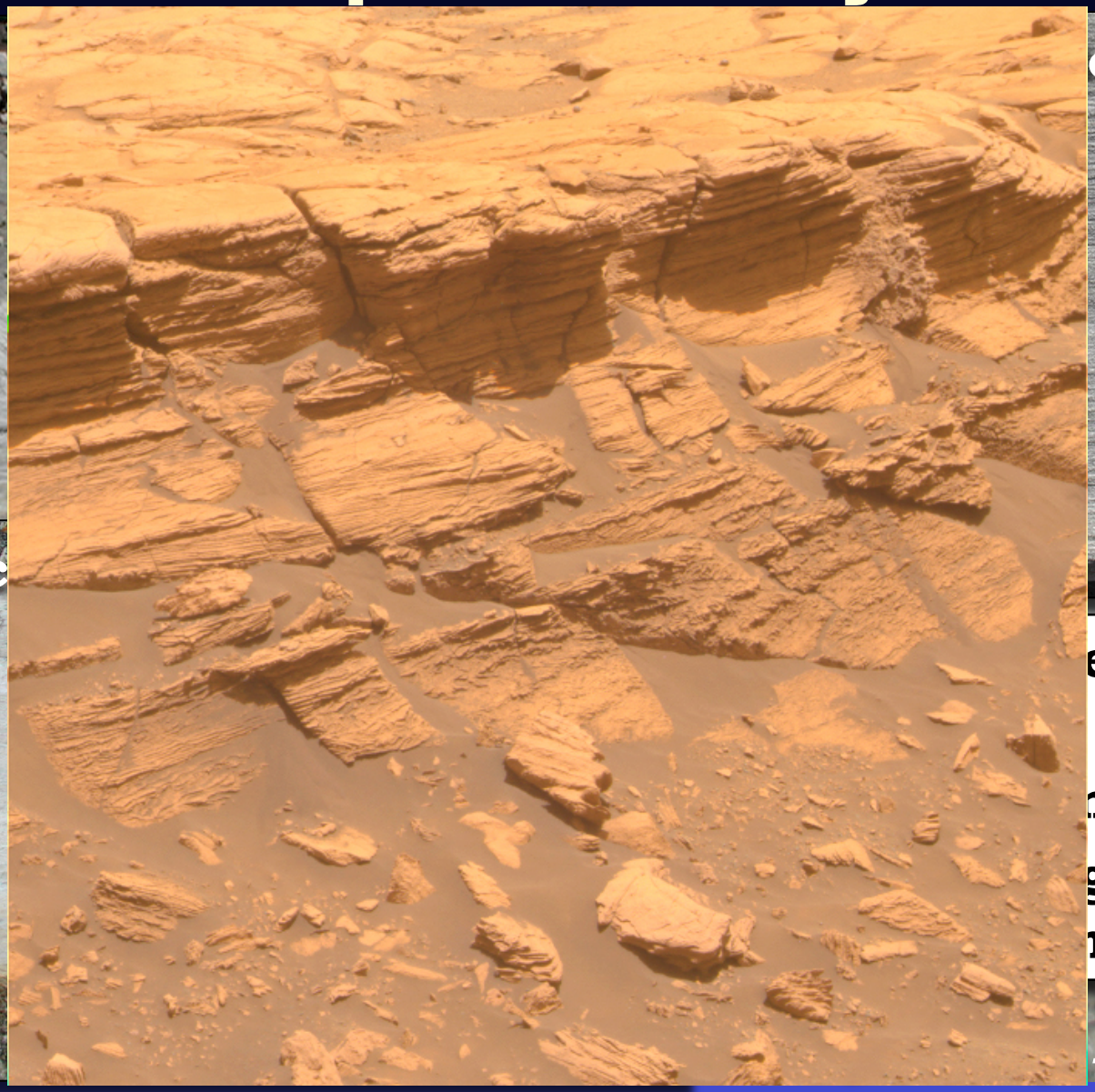
Shoreline Character Changes Greatly with Lake Level







UFLB: Apparently Parallel Strata Reveal Detailed Depositional History



ediment

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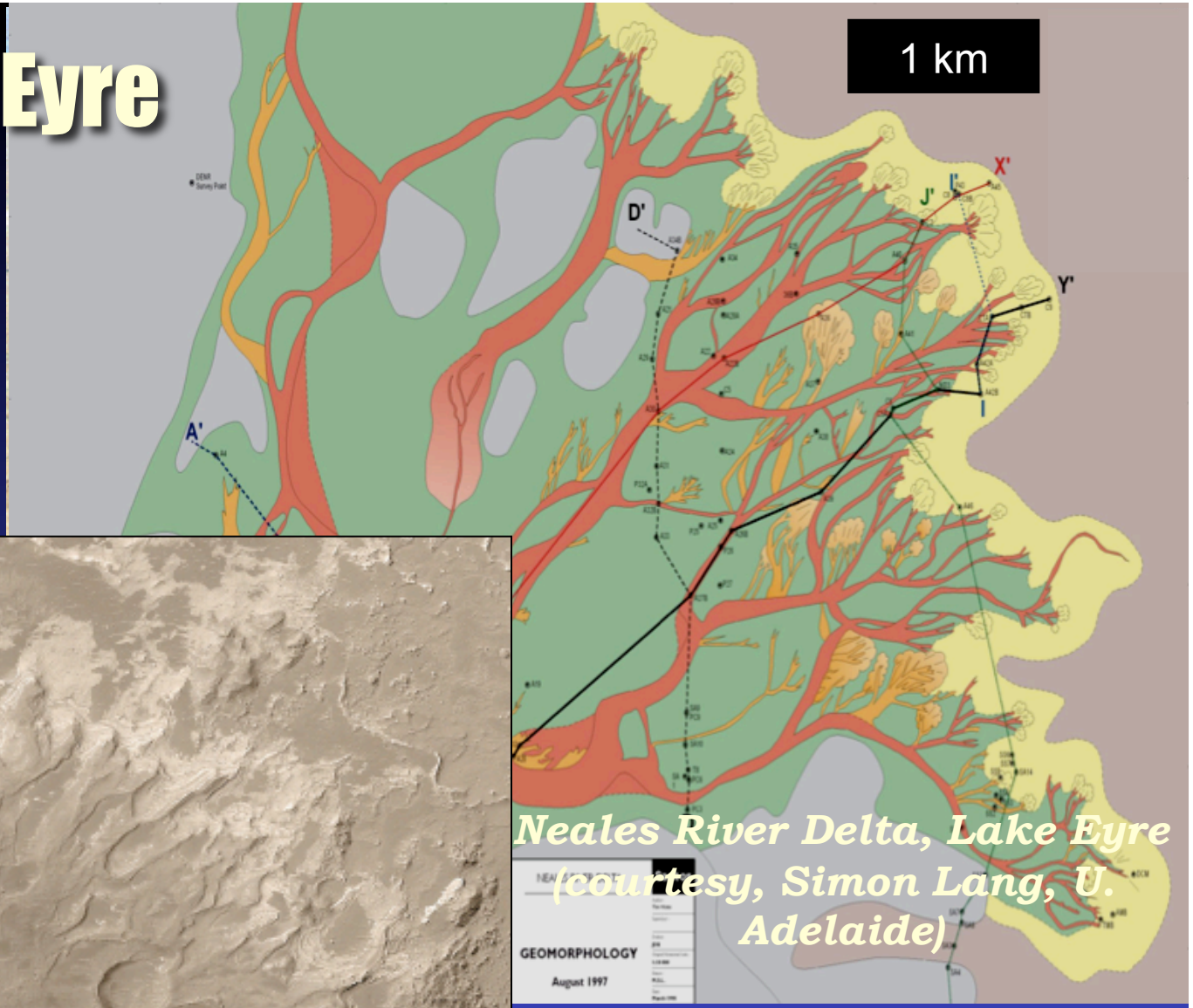
nal Flow

Azerbaijian

Bohacs & Carroll, 2011

UFLB-- Lake Eyre

Shoreline configuration & strata record rapidly decelerating sediment-laden flow under overall falling lake level



Neales River Delta, Lake Eyre (courtesy, Simon Lang, U. Adelaide)

Bohacs & Carroll, 2011

Bohacs & Carroll, 2011

Changing Lake Level/Water Chemistry Recorded in Evaporite Textures

- **Lowstand = Basin-center pond evaporite deposits**

Displacive texture (Intra Stratal)

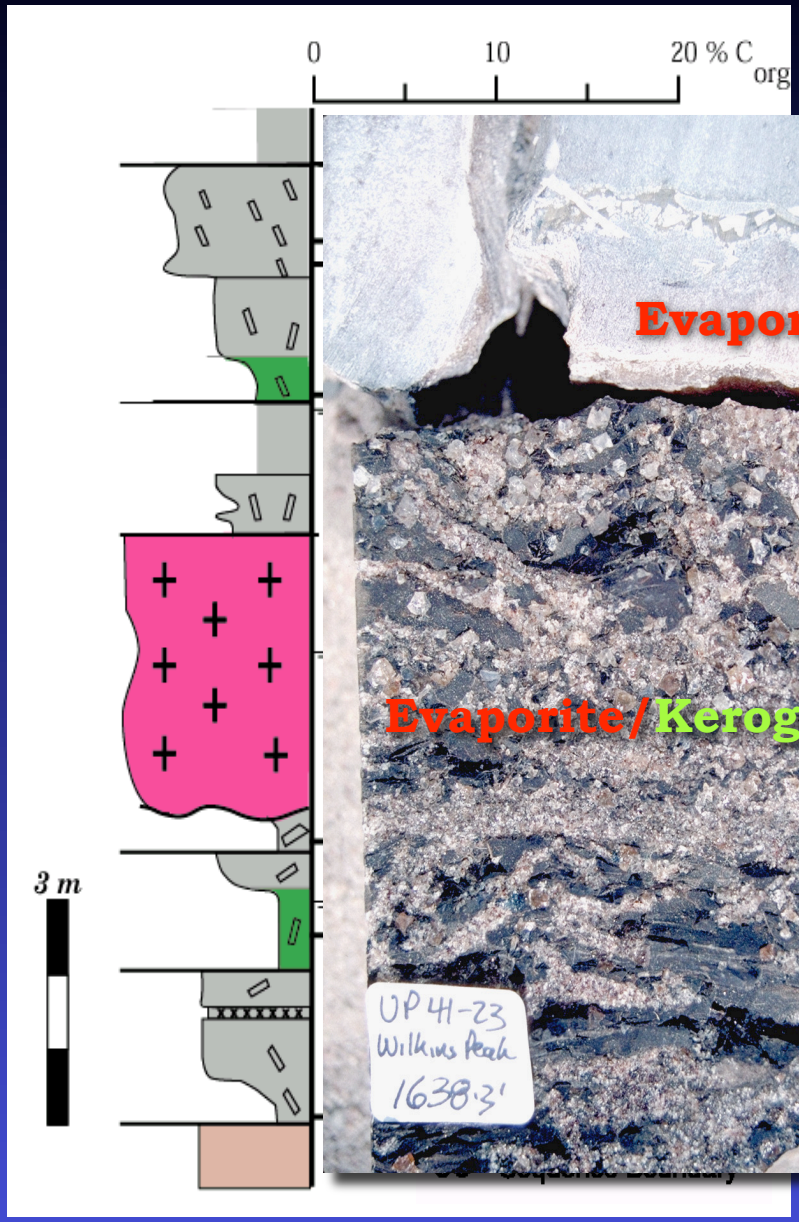
Cumulate texture (Sub Aqueous)

Green River Fm, Wilkins Peak mbr, Eocene

Badwater Basin, Death Valley, Pleistocene

Evaporite & Kerogenite Commonly Associated

Wilkins Peak mbr,, Green River Fm, Eocene



Bohacs & Carroll, 2011

Bohacs & Carroll, 2011

Organic Matter Accumulation Best in Intermittently Closed Hydrology Basins

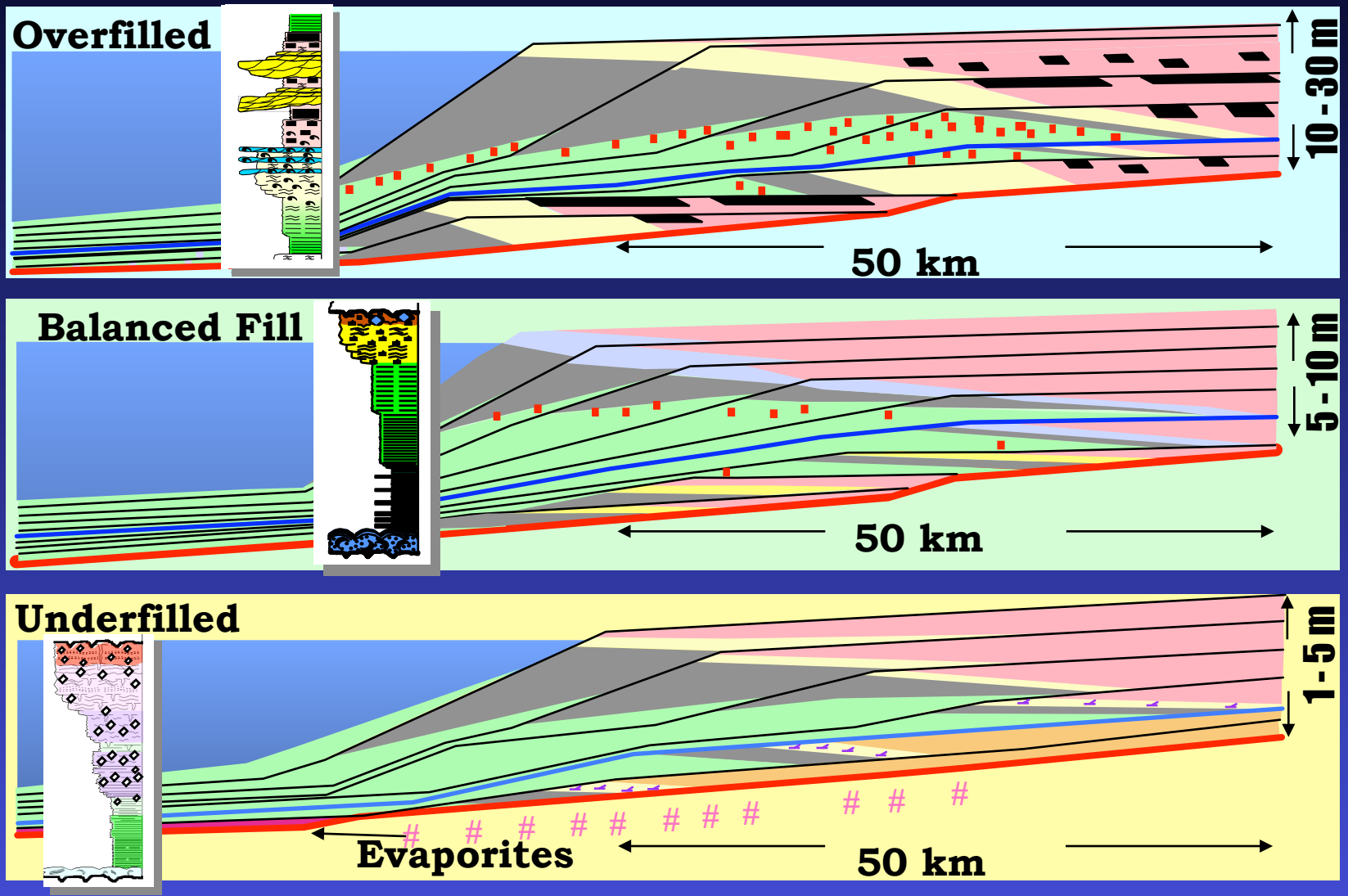
- **Production of organic matter fueled by:**
  - **episodic influx of nutrients during transgressions & highstands of lake level**
  - **concentration of nutrients by evaporation during closed hydrology periods**
- **Preservation enhanced by:**
  - **density stratification (evaporation during closed hydrology periods)**
  - **high rates of organic-matter production**
  - **close association with evaporite and clay minerals in lake center strata**
- **Concentration optimized by:**
  - **only intermittent influx of clastic sediments**
  - **minimal influx during most productive closed hydrology periods**

Bohacs & Carroll, 2011

Do these Differences Make a Difference ?

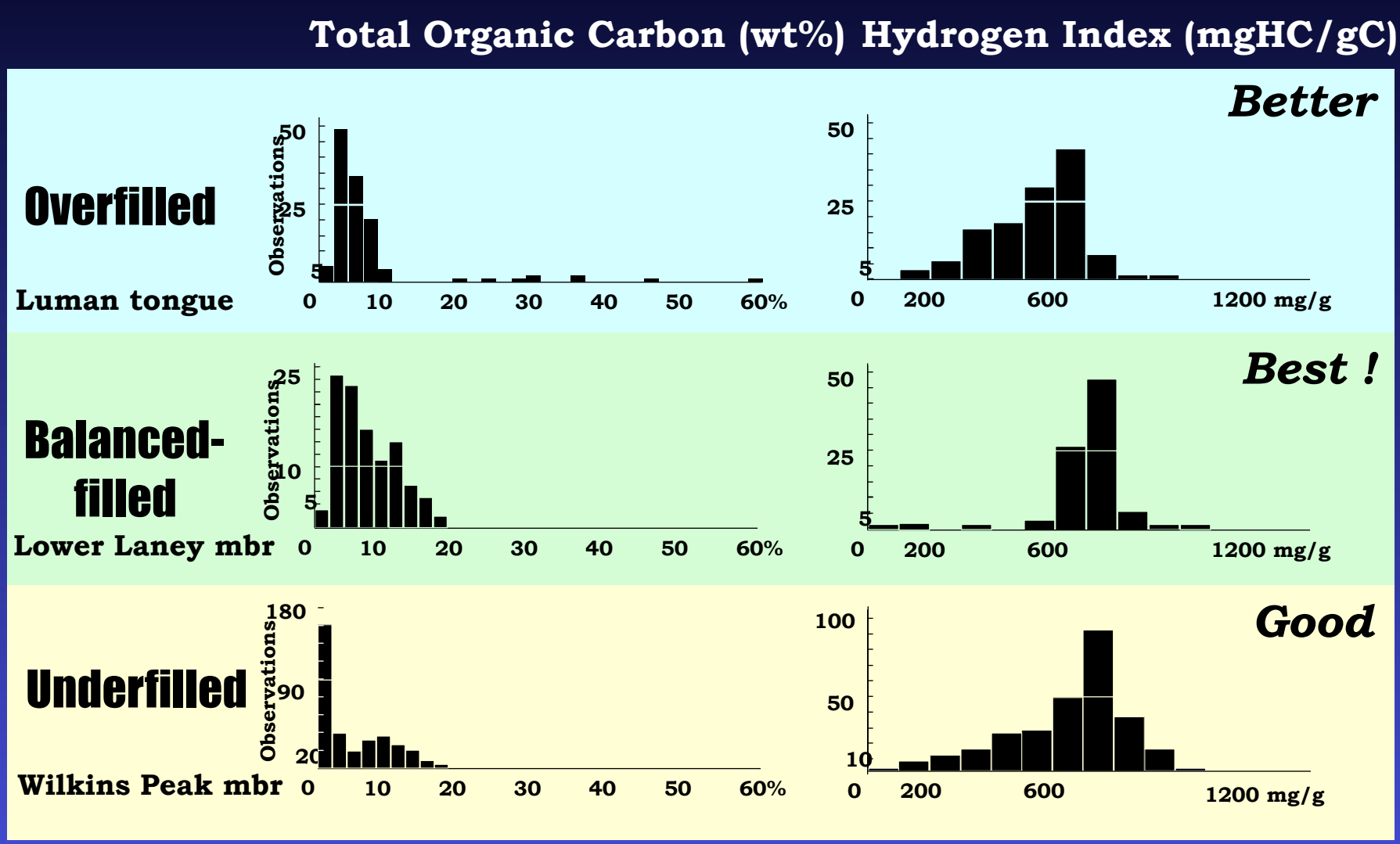
Bohacs & Carroll, 2011

Distinctive Expression of Dep' l Sequences: Lithofacies & Stratigraphy

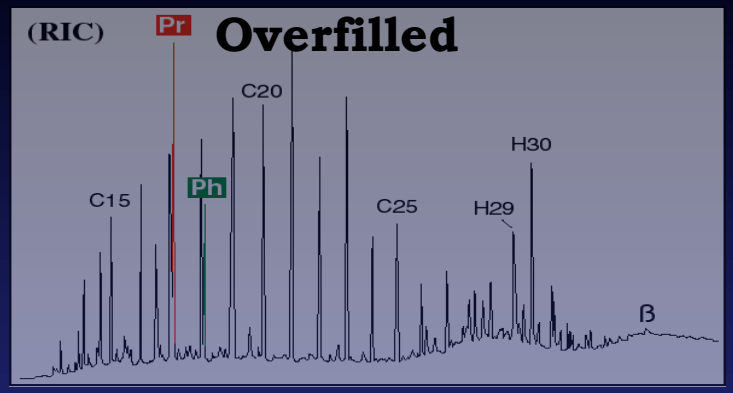


Bohacs & Carroll, 2011

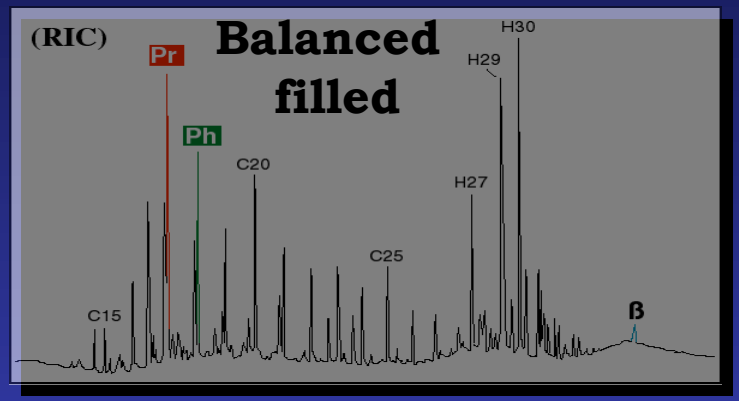
Each Lake-Basin Type Can Have Significant Source Rock Quality



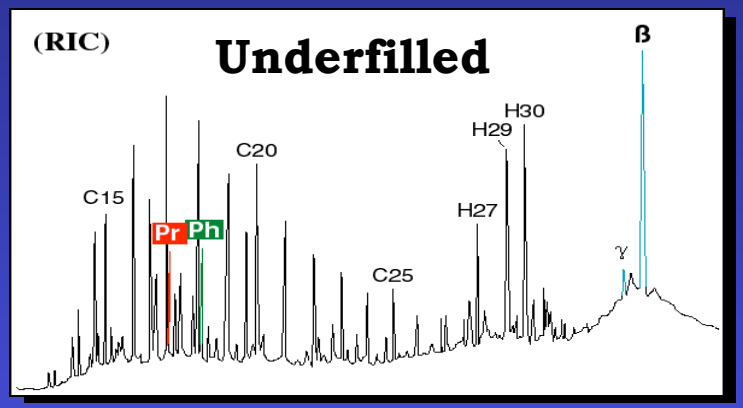
Distinctive Organic Geochemistry



- Pr/Ph high (1.5 - 5)
- Hop/Ster high (≤ 47)
- C_{29} desmethyl steranes
- S↓↓, β-carotane ↓↓, γ-cerane ↓



- Pr/Ph low (<1-2)
- Hop/Ster ≤ 15
- C_{29} steranes, Tricyclic terpanes
- S↓, β-carotane →, γ-cerane ↑



- Pr/Ph = v. low (<1)
- Hop/Ster ≤ 7
- Tricyclic terpanes ↑
- S↑, β-carotane ↑↑, γ-cerane ↑↑

after Bohacs et al, 2000; Carroll & Bohacs, 2001

Bohacs & Carroll, 2011

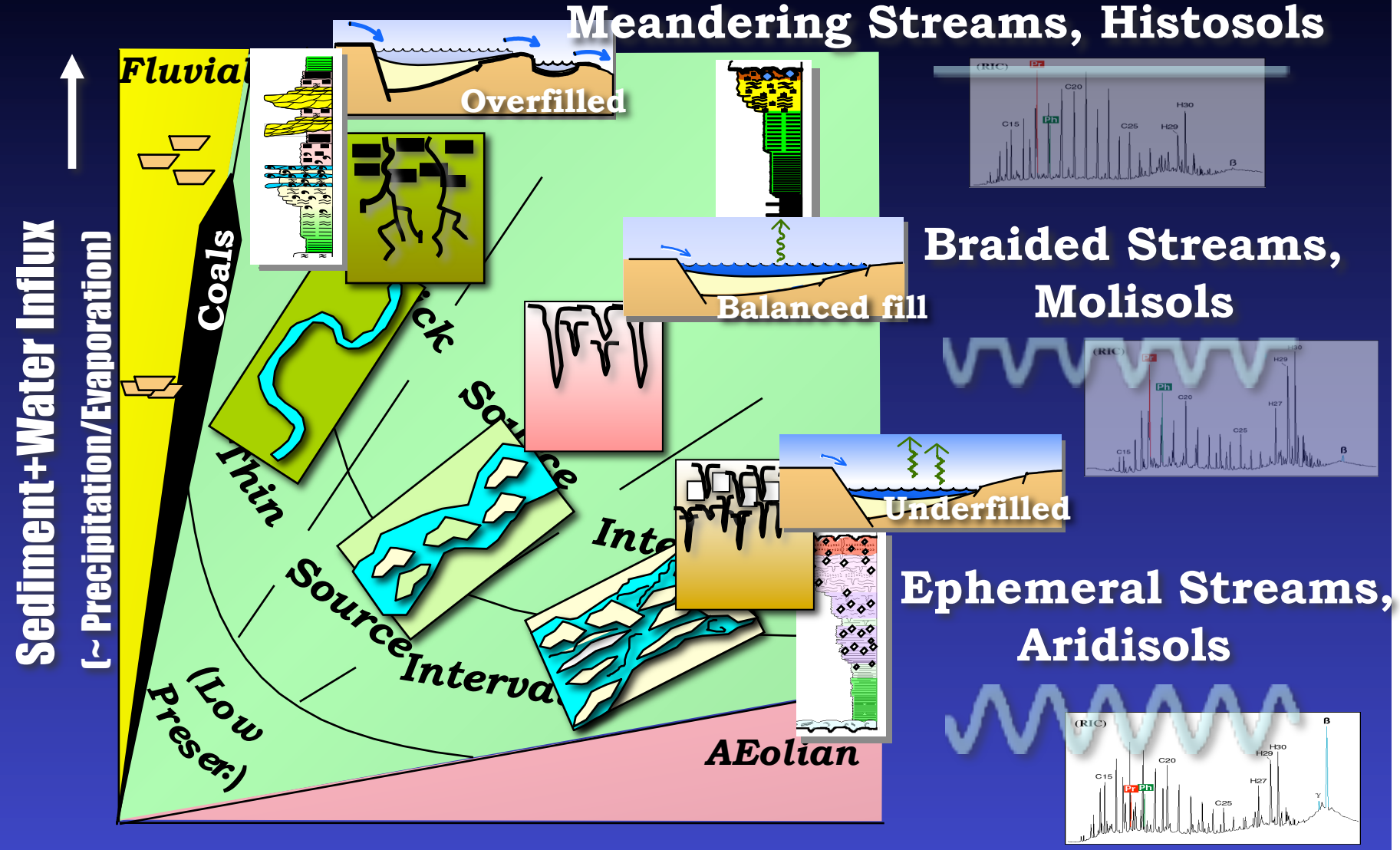
Bohacs & Carroll, 2011

So What??

- **Highly integrated nature of lake systems enables definitive, testable inferences about occurrence, character, & distribution of lithofacies and organic matter from large-scale stratigraphic patterns:**
  - **Lake water chemistry and ecosystems = *f* (provenance lithotypes, hydrologic history)**
  - **Persistently closed-hydrology lake basins = best 'rain gauge' & drainage-basin integrator**
  - **Lake-center environments are excellent sites for production and preservation of organic matter**
  - **Organic-matter character = *f* (Lake Basin Type)**

Bohacs & Carroll, 2011

Recurring Associations Enables Inversion Across Multiple Scales



Potentially useful insights for MSL

- **Optimal landing site to find balanced-filled to underfilled lake strata (intermittently to persistently closed hydrology) would have a large inlet and small outlet at high elevation above the basin floor.**
- **Holden appears to have had the most persistently closed hydrology and highest promise for original production of organic matter, but ... how well can the older lacustrine strata can be accessed, given the extensive development of the alluvial fan bajada?**
  - **Also, if the bajada progrades directly over the lacustrine center strata, the sedimentation rates may not have been sufficient to help preserve organic enrichment-- there may not have been sufficient stratal cover.**
- **The central portion of the Eberswalde delta complex could be problematic for concentrating organic matter, given the extensive clastic input, but those lake-margin strata could also have helped bury and preserve organic matter in older lacustrine center strata, below the master downlap surface under the clinothems.**
  - **If the underlying lacustrine center strata can be reached, especially older pre-delta units, at and below downlap surface, that would be very promising for organic matter and climate/hydrology records-- for it is the lake-center deposits that best integrate the full history of the basin.**

Bohacs & Carroll, 2011

Thank You!

Hope This Helps...

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- There has been a lot of good work on landing site selection, and a wide range of expertise has been brought to bear. It would appear, however, that insights from full consideration of the nature of lake systems and how they differ from global oceanic realms has not been incorporated, from what I can find quickly on the web.
- The limnogeology community over the past 15 years has come to the conclusion that even very large lakes do not behave like small oceans, at least in the stratigraphic or geochemical sense (e.g., Bohacs et al., 1999, 2000, 2003; Buoniconti, 2001). Lakes differ from oceans in several significant ways: 1. Lake levels vary more widely and rapidly than sea level, hence, shoreline strata are commonly poorly developed and relatively thin. 2. Lake level and sediment supply are often closely linked in lake systems (most marine models assume no linkage). 3. Lake shorelines commonly move basinward by a combination of by progradation and simple withdrawal of water. 4. The nature and very existence of a lake is fundamentally controlled by the relative rates of potential accommodation change and supply of sediment+water, giving rise to three distinct lake-basin types: overfilled, balanced-filled, and underfilled.
- One of the charms of the lake-basin-type approach is that it highlights the highly integrated nature of lake systems, that allow us to make very definite inferences about organic matter occurrence and character from large-scale stratigraphic patterns. We do this regularly using reflection seismic data and it can be done using remote sensing images of the Earth's surface. All of this is covered in great detail in the attached papers. The bottom line is that intermittently to persistently closed lake basins, on Earth, produce and preserve the largest concentration of organic matter. These systems also have the potential to contain the most accurate record of climate change (i.e., a good rain gauge-- see Scholz et al's work on crater Lake Bosumptwi, Africa; and Bohacs et al., 2003 for background).
- So, the optimal landing site would be the one with a large inlet and small outlet at high elevation above the basin floor. It would appear that Holden has the most persistent closed hydrology and highest promise for original production of organic matter, but I worry about how well the older lacustrine strata can be accessed, given the extensive and most excellent development of the alluvial fan bajada. Also, if the bajada progrades directly over the lacustrine center strata, the sedimentation rates may not have been sufficient to help preserve organic enrichment-- there may not have been sufficient stratal cover.
- The heart of the Eberswalde delta complex could be problematic for concentrating organic matter, given the extensive clastic input, but that pile of strata could also have helped bury and preserve organic matter in older lacustrine center, below the master downlap surface under the clinothems. If the underlying lacustrine center strata can be reached, especially older pre-delta units, that would be very promising for organic matter and climate/hydrology records-- for it is the lake-center deposits that best integrate the full history of the basin.

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