# Geologic Framework of Pennsylvanian – Early Permian of the Permian Basin

Baylor University
Geosciences Seminar Series

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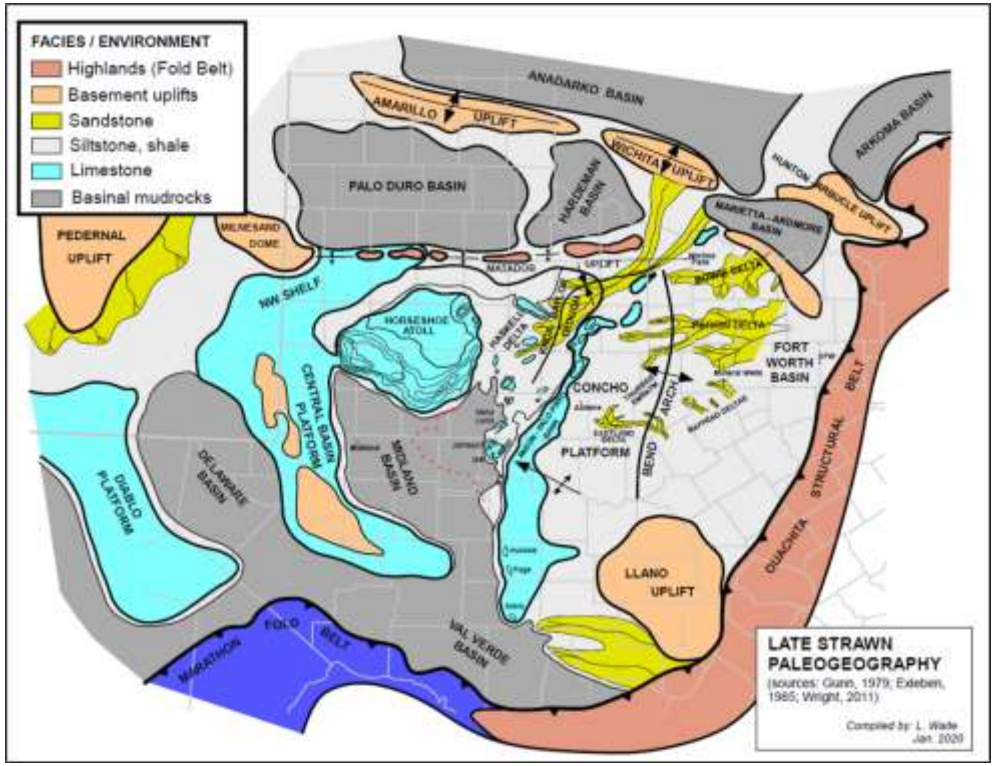


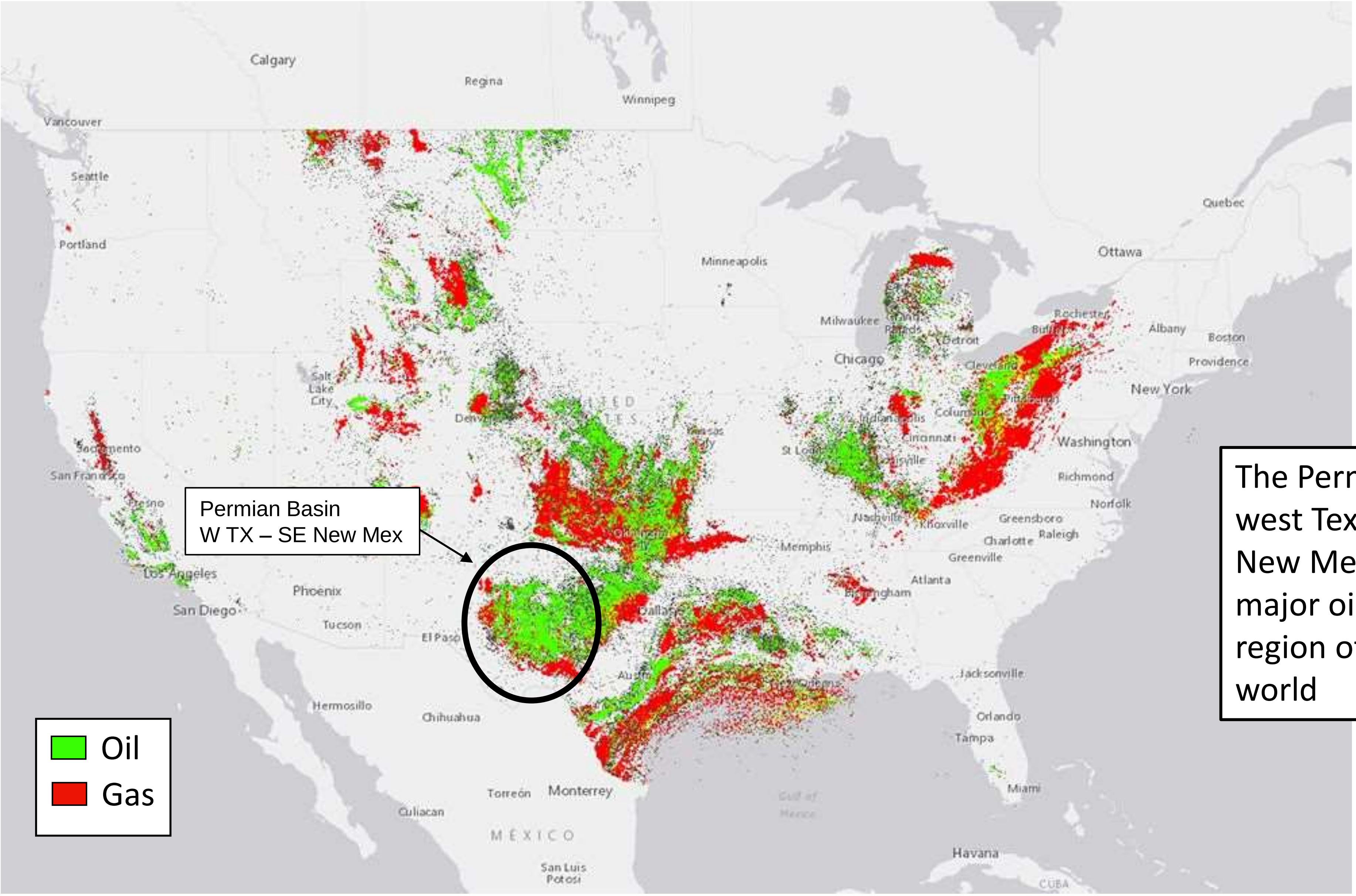
# Geologic framework of Penn – lower Permian of Permian Basin: Outline

- Introduction
  - Location of U.S. Permian Basin
  - Pennsylvanian-early Permian themes
  - Global sea-level framework for the Paleozoic (Sloss megacycles)

- Pennsylvanian – lower Permian basin fill / stratigraphic units

- Why it matters: economic importance

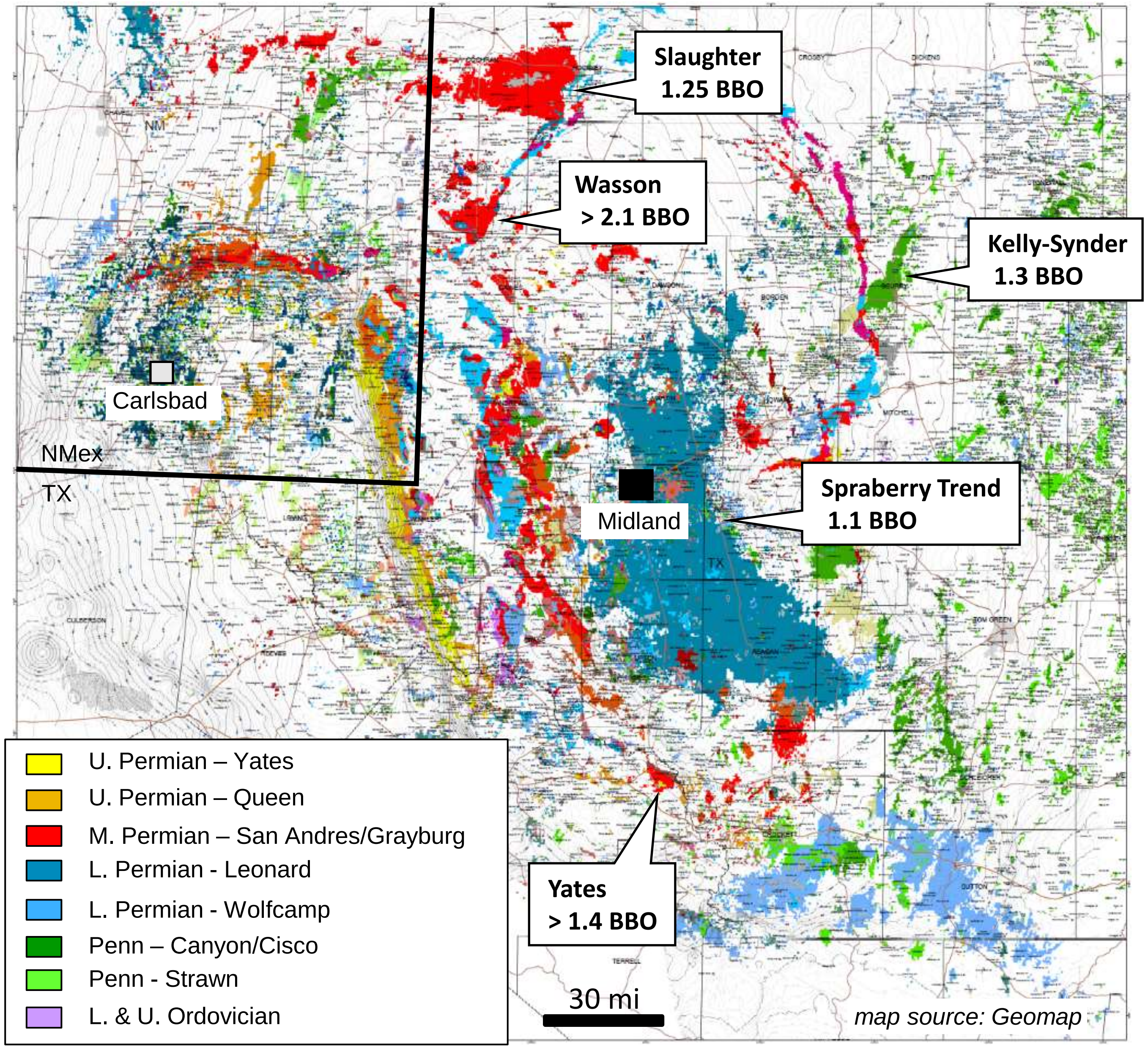
# Oil and gas fields of the Lower 48 U.S.




The Permian Basin of west Texas and SE New Mexico is a major oil producing region of the U.S. and world

# Permian Basin, West Texas

Conventional oil and gas fields colored by age of reservoir




- Cumulative oil production ~ 36.5 billion barrels of oil + 109 trillion cubic ft. gas
- 51 oil fields with “giant” status (>100 million barrels of oil cumulative production), including 5 fields with > 1 BBO
- Conventional petroleum reservoirs at every stratigraphic level (including Pennsylvanian); numerous prolific HC source rocks
- Vast unconventional reserves, primarily in Late Penn and early Permian (Wolfcampian, Leonardian) shales

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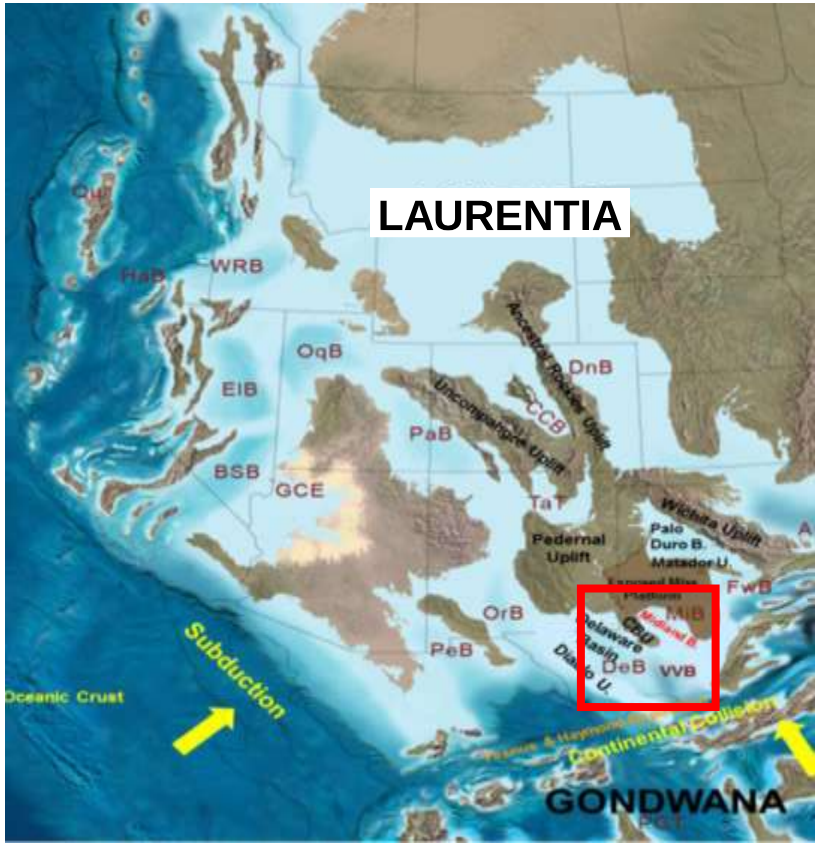
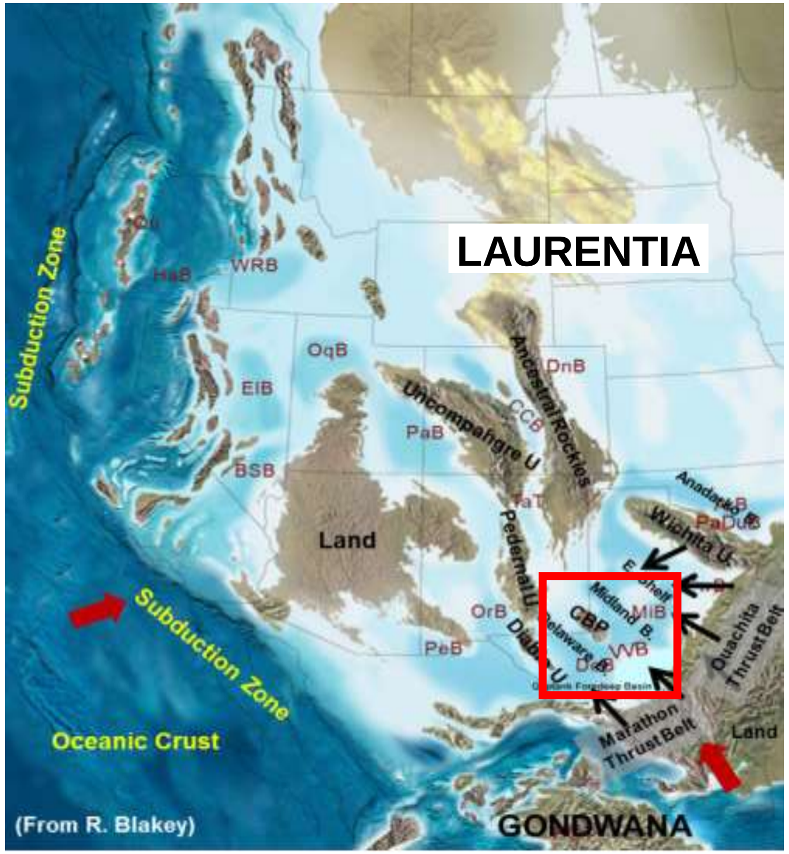
# Pennsylvanian – Early Permian Themes

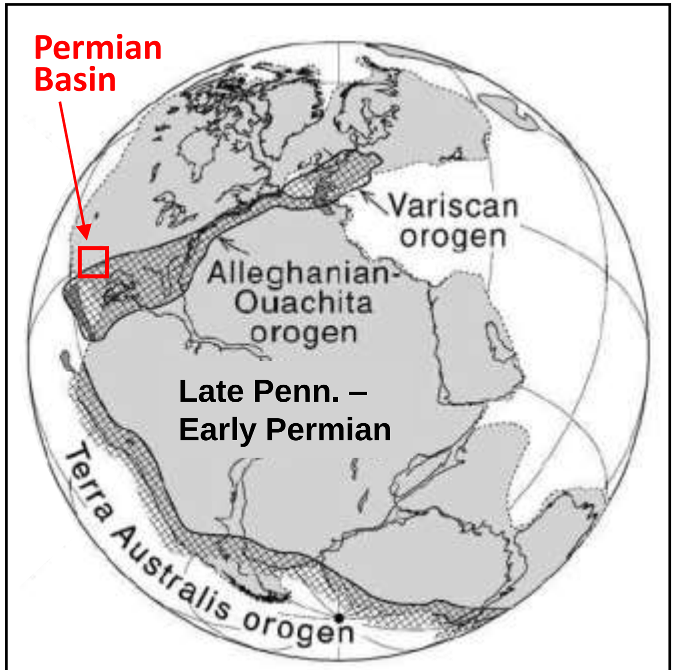
- SW Laurentian margin: active margin phase (Tobosa Basin becomes Permian Basin) Hercynian/Variscan orogeny & rise of Ancestral Rockies
- Climate: Icehouse phase throughout Penn. – Early Permian, transitioning to greenhouse; Permian Basin in low-latitudes (tropics); humid w/ monsoonal precipitation
- Sea level: long-term rise and expansion of Penn. seaway; short-term: high frequency, high amplitude glacioeustatic cycles **(Penn cyclothems)**
- Rise and dominance of phylloid algae as main reef builders

**Early Penn. (Atokan)**




**Late Penn. (Missourian)**

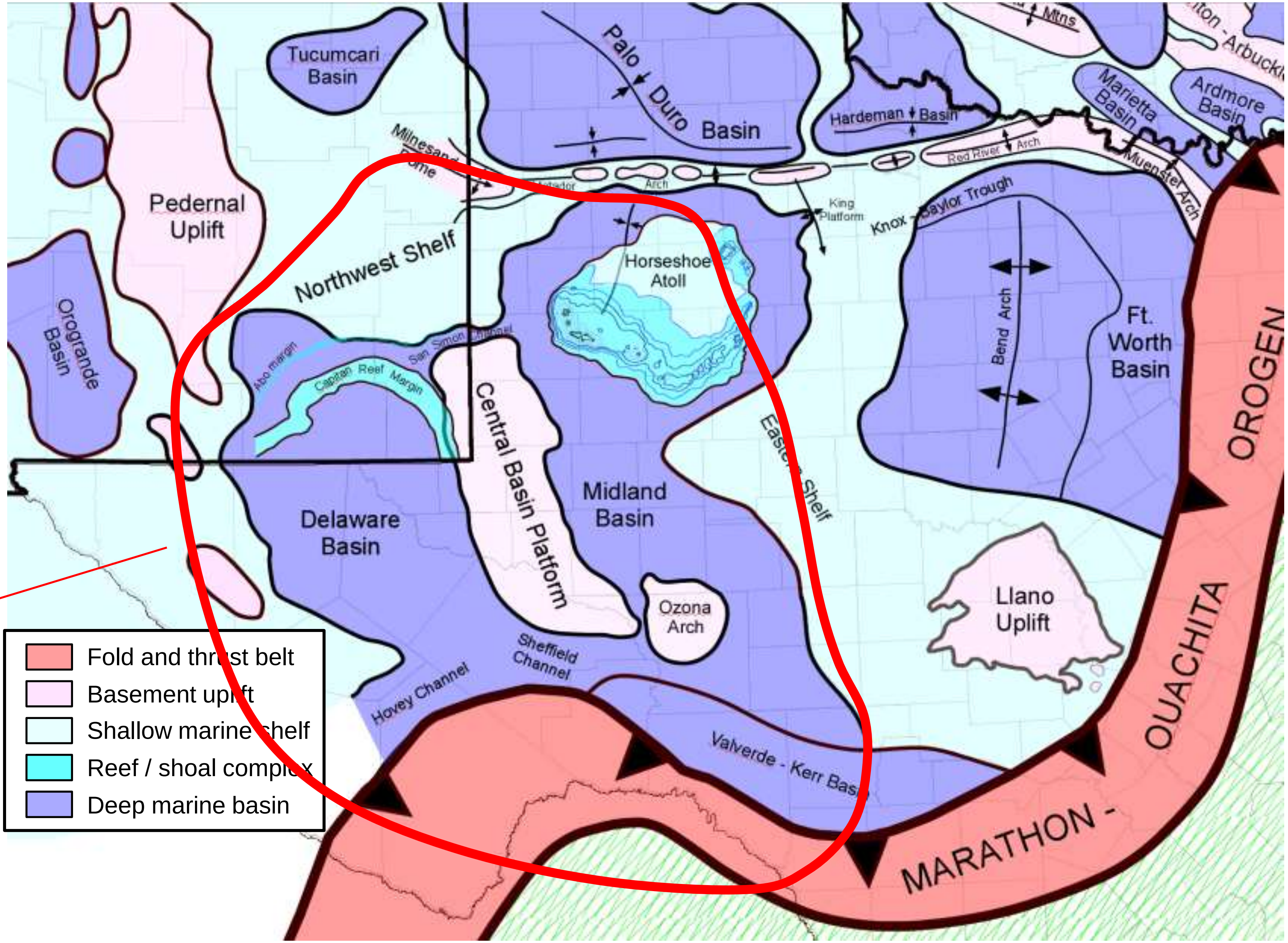


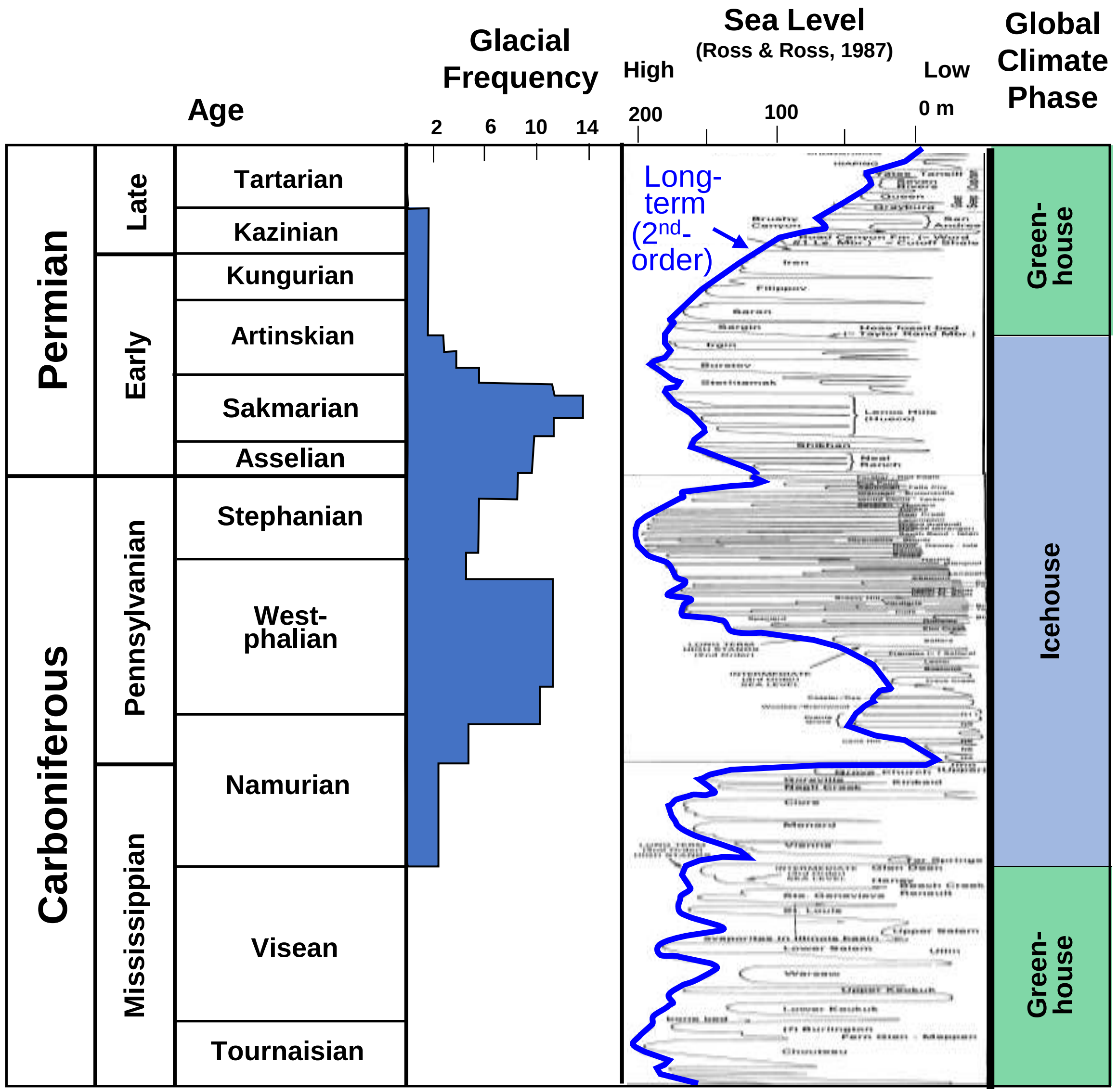

(Murphy et al., 2009)

# Greater Permian Basin Region of west Texas and SE New Mexico

- Includes deep Delaware Basin (west) and shallower Midland Basin (east) separated by high-standing CBP; carbonate-clastic shelves to west, north, and east
- Located at intersection of two interregional tectonic systems
  - Marathon-Ouachita (Hercynian) fold and thrust belt
  - Ancestral Rockies (basement-involved, fault-bounded uplifts, including Central Basin Uplift)
- Precursor intracratonic-like basin (Tobosa Basin) and associated passive margin transforms into active margin (Permian Basin) during early Pennsylvanian time

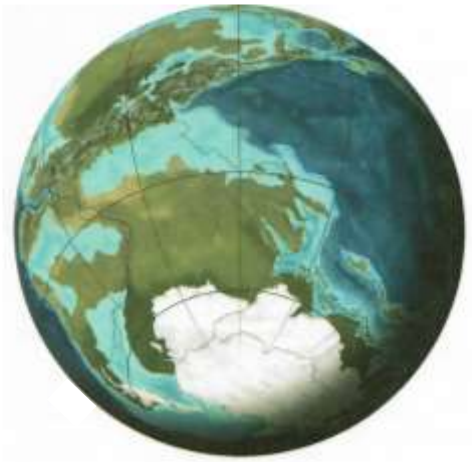


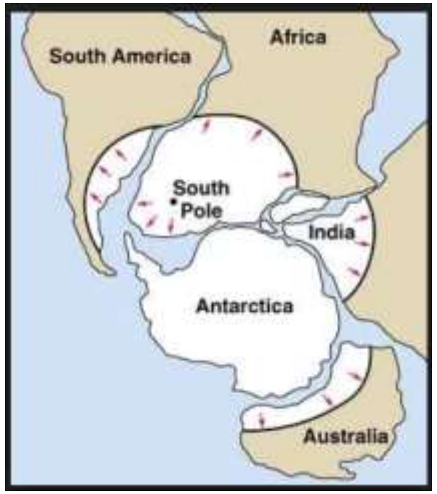
# Themes #2 - 3: Late Paleozoic Climate and Eustacy




(Modified from Frakes, et al., 1992)

- Following Late Miss. lowstand, long-term eustatic sea-level rise in mid Pennsylvanian (expansion of Penn. seaway)
- Global ice age (“icehouse” climate phase) initiates in Late Mississippian time as Gondwana drifts over S. pole
- Peak” icehouse occurs in two pulses
  - mid Pennsylvanian / Westphalian
  - earliest Permian / Asselian - Sakmarian
- Short-term high-amplitude, high frequency glacioeustatic changes exert a fundamental control sediment distribution and early diagenesis of Late Penn-early Permian units (**cyclothems**)





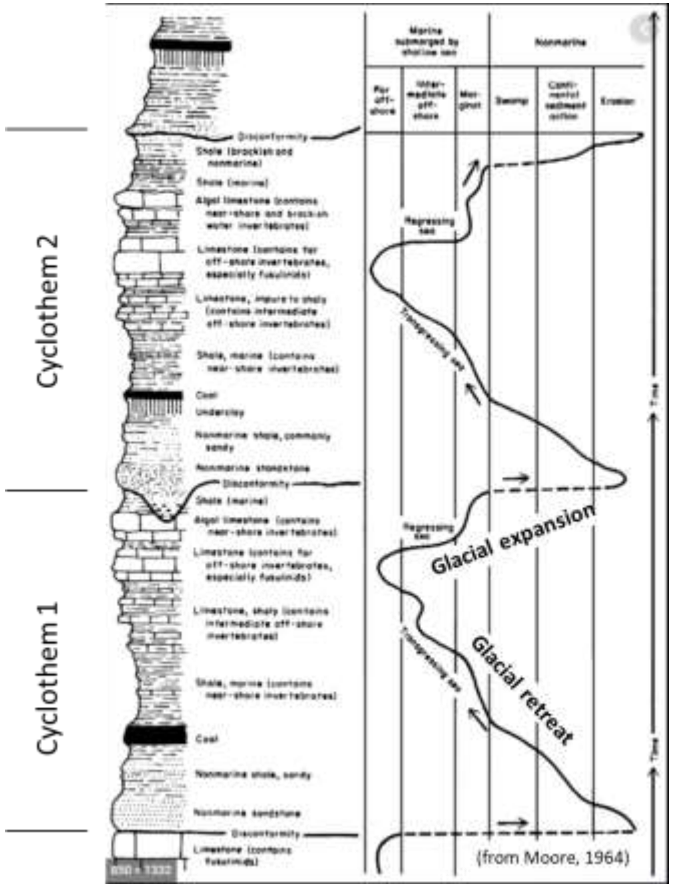
# Cyclothems

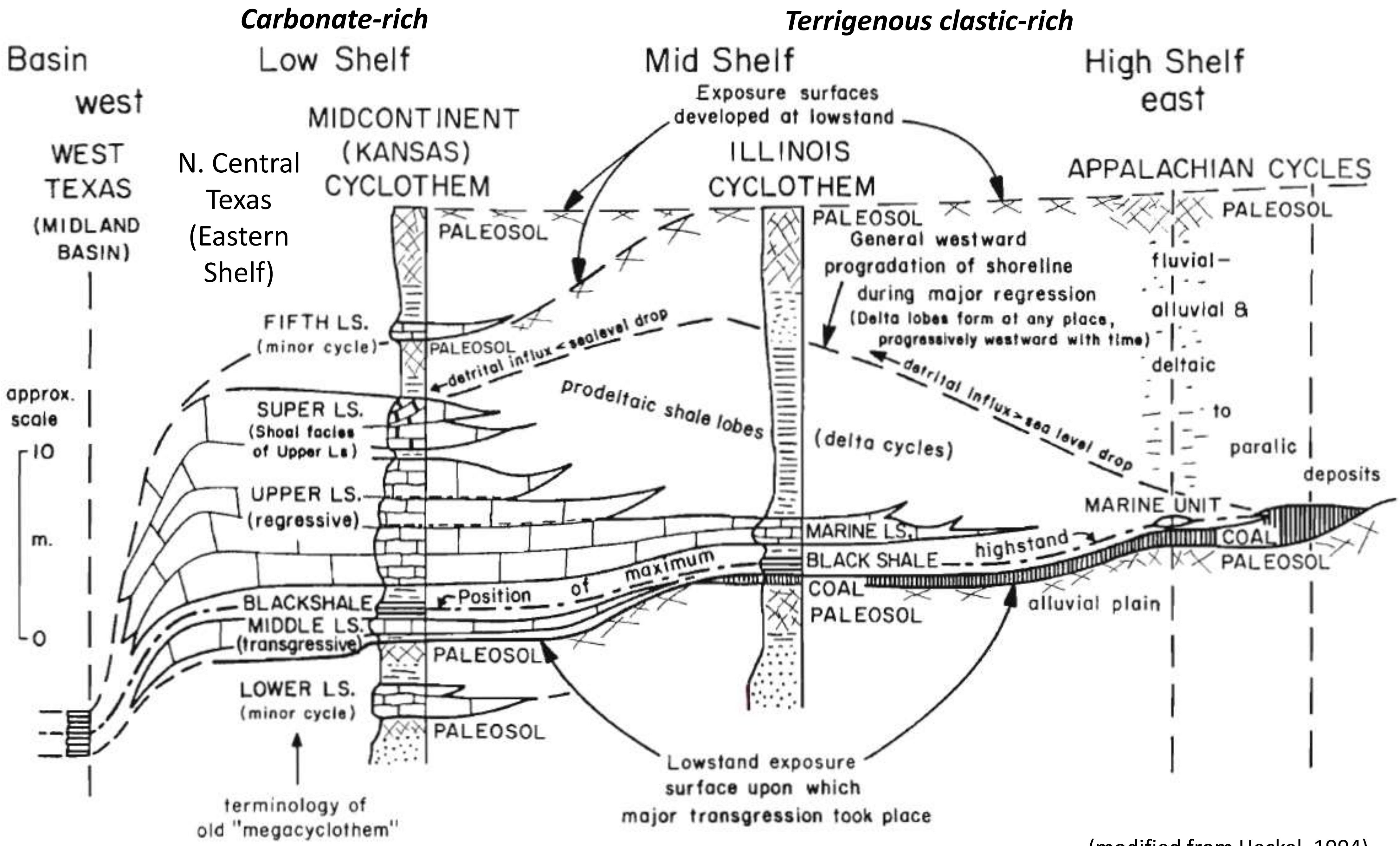
- **Cyclothems** are alternating stratigraphic sequences of non-marine and marine strata, a product of glacially-controlled sea-level changes (the term “cyclothem was first defined by European coal geologists in the 1800’s who were mining coals of Late Carboniferous age)

- Each cyclothem deposit, typically 5 – 15m in thickness, is the product of a short-term (~ 0.5 million-year) transgressive-regressive cycle of sea-level

- Terminating sea-level fall often results in a capping significant exposure surface

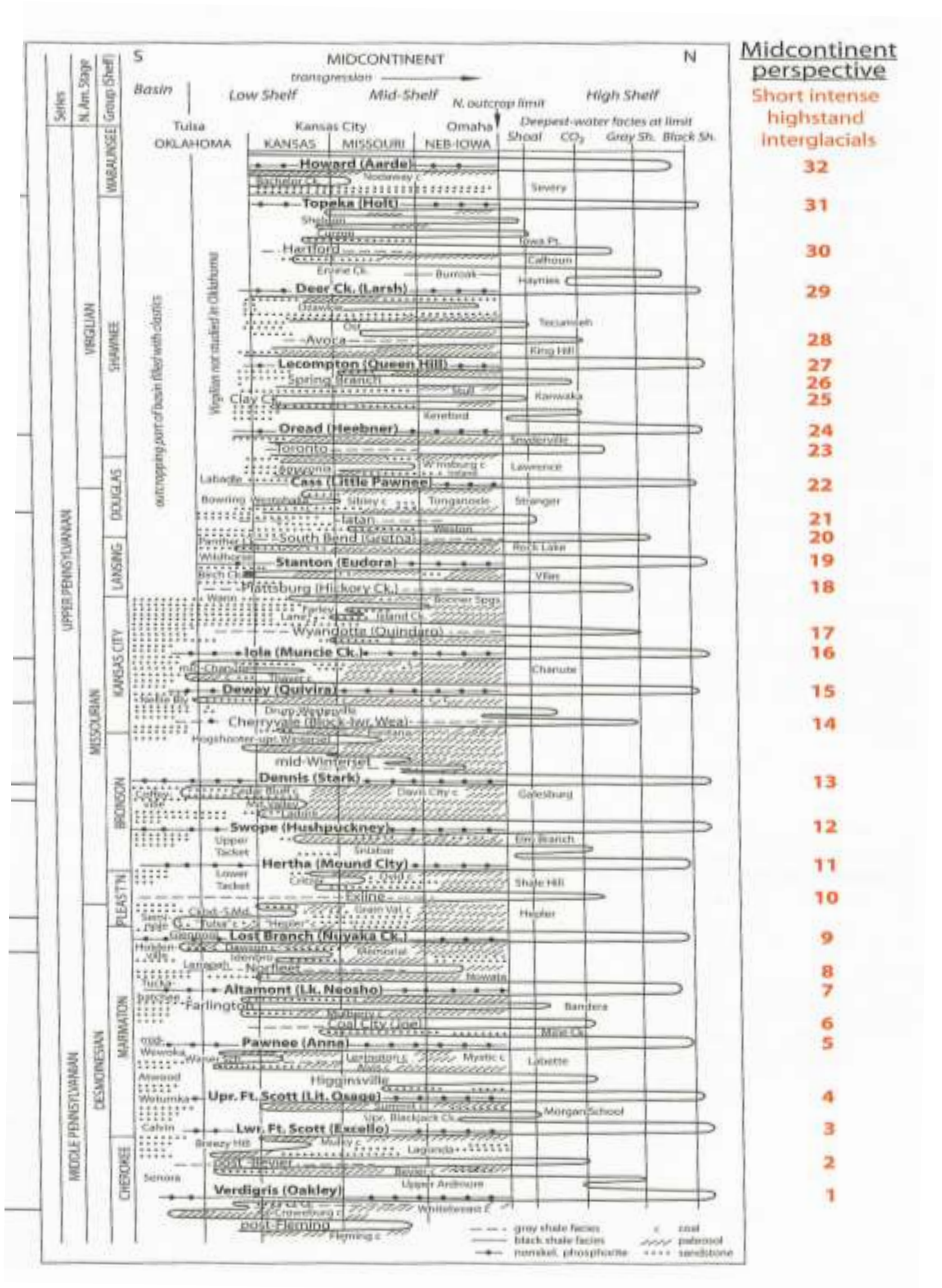
- Cyclothems are characteristic of Upper Carboniferous (Pennsylvanian) – early Permian strata worldwide



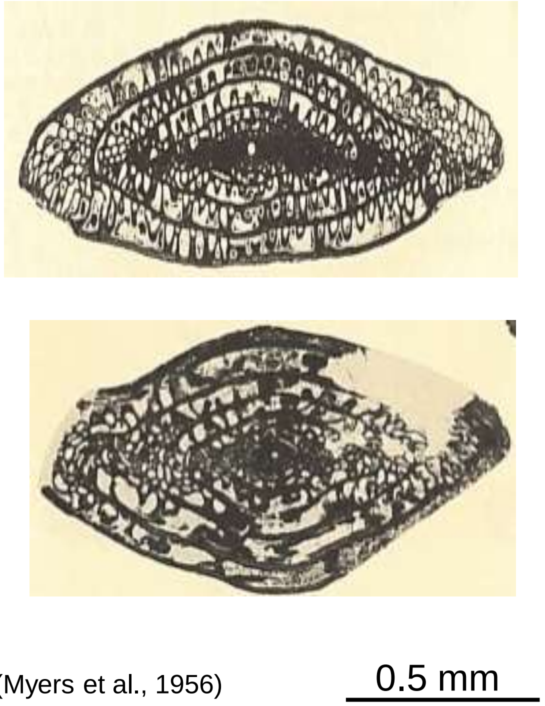



(modified from Heckel, 1994)

Midcontinent cyclothems
(Heckel, 2008)

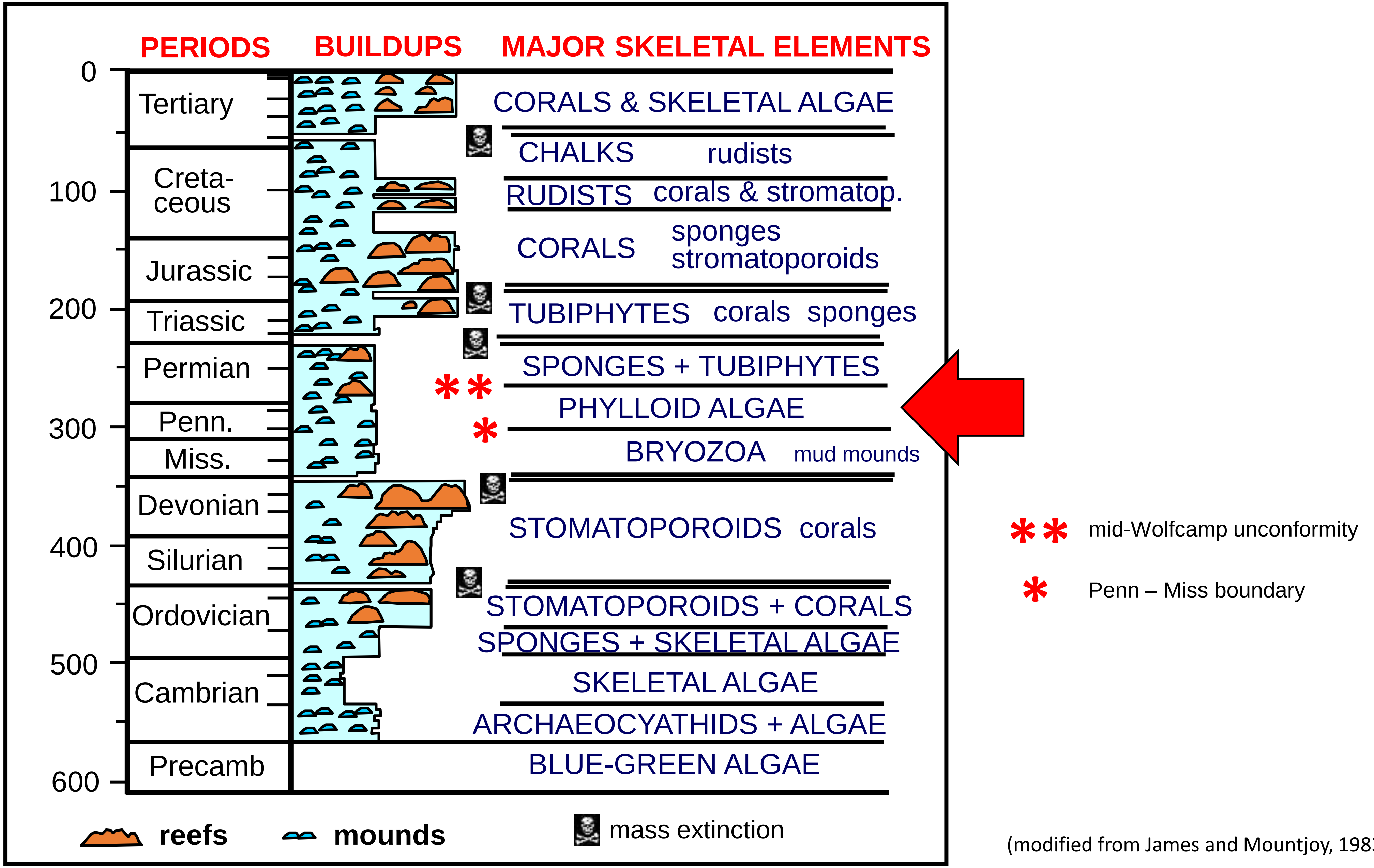



Fusulinid foraminifera provide precise biostratigraphic control to correlate individual cyclothems across midcontinent into north-central TX




(Myers et al., 1956)

# Theme #4: Rise of phylloid algae as major reef builders




(modified from James and Mountjoy, 1983)

# Phylloid Algae

- An extinct group of algae of problematic taxonomy – most likely a red algae
- Age range: Late Carboniferous (Pennsylvanian) to late Permian
- Dominant component of Penn – early Permian reefs and shelf limestones (common in Permian Basin)
- Present in middle – late Permian reefs, but much reduced; replaced by sponges and other algal forms
- Platy, "lettuce-like" morphology; Individual fronds resemble "corn flakes" in hand specimen and thin-section, often showing a dark amber color
- Mostly **aragonitic** forms (secondary porosity important in subsurface)


(N. King, University of Southern Indiana)

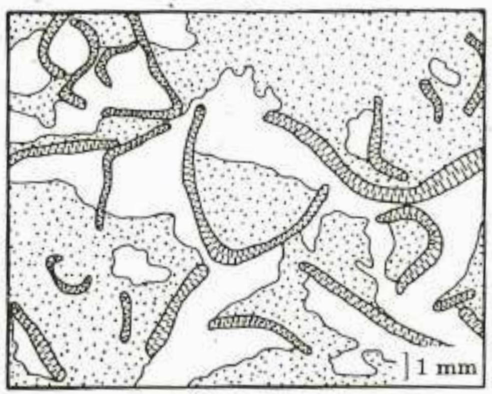



Fig. 3. Typical texture of phylloid algal limestone consisting of algal fragments (*hachured pattern*), carbonate mud matrix (*stippled pattern*), and cavity-filling calcite and/or porosity (*clear areas*). Vertically oriented section, ×3

(Wray, 1968)

**Reconstructions of complex phylloid algae**

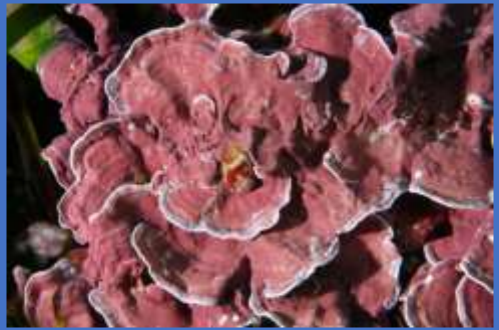
**Left:** Artist's reconstruction of complex, cup-like phylloid algae that formed biohermal buildups in the Lower Permian (Wolfcampian) of New Mexico. Other phylloid algae most likely had simpler, platy or leaf-like morphologies. Courtesy of Robert B. Halley.

**Right:** Reconstruction of a phylloid alga, *Eugonophyllum*. External shape of organism supplied by Cross and Klostermann (1981) based on serial slabbing of neomorphosed thalli. Internal morphology added by Kirkland et al. (1993), based on thin sections of broken, still aragonitic thalli.

(Scholle and Ulmer-Scholle, 2003)

*Calcipatera*, a phylloid algae from the Wolfcamp of Kansas (Sawin and Wood, 2005)

Modern red algae – analog



(www.thefossilforum.com)

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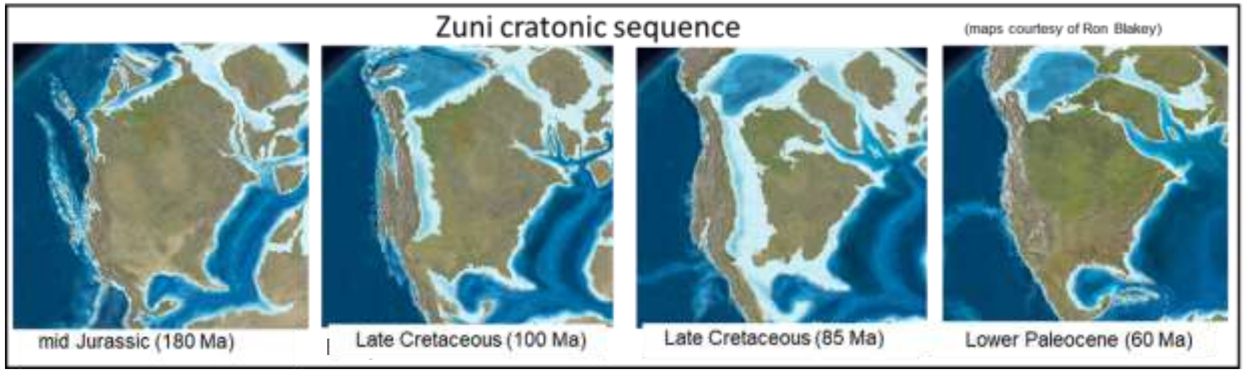
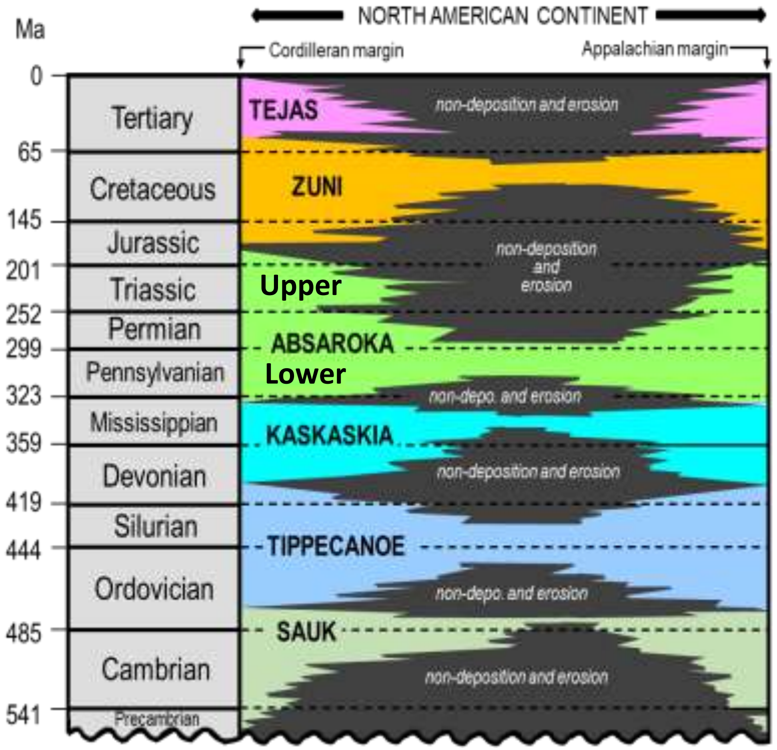
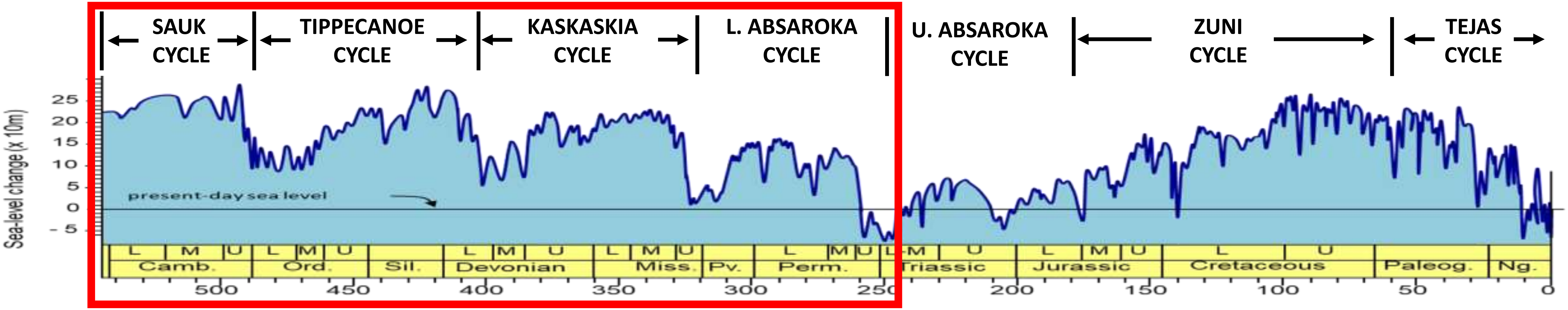
# Megacycles: North American cratonic sequences (modified from Sloss, 1963)

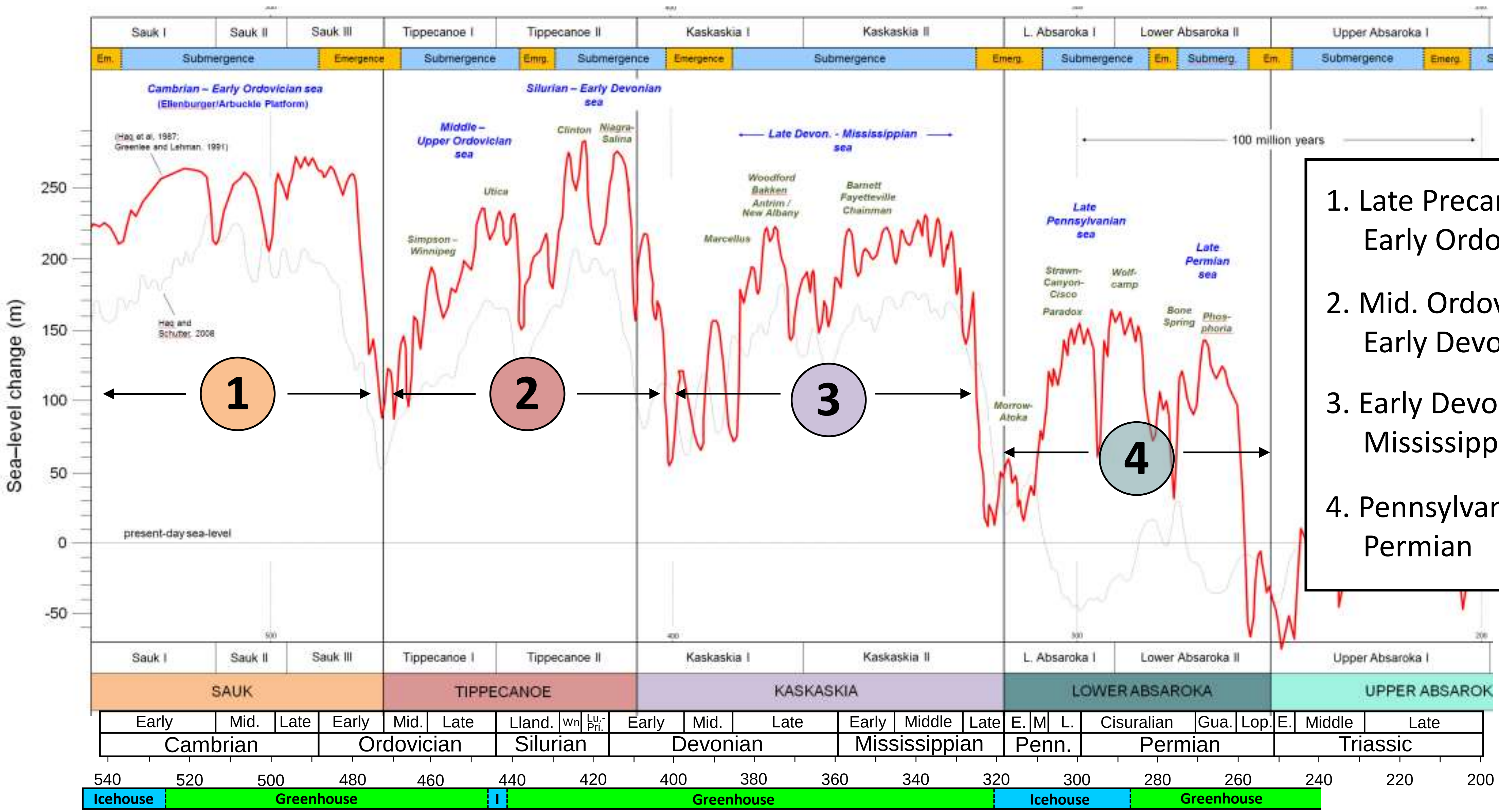
- First documented by L.L. Sloss in 1963, cratonic sequences include multiple formations and groups deposited over 50 million yrs. or more, bounded by interregional unconformities
- Seven Phanerozoic megasequences: named after native North American Indian tribes
- Correlate to phases of tectonism and long-term megacycles of sea-level change (flooding and draining of epicontinental seas)



# Four long-term cycles of sea level during the Paleozoic (4 megacycles)




1. Late Precamb. – Early Ordovician
2. Mid. Ordovician – Early Devonian
3. Early Devonian – Mississippian
4. Pennsylvanian – Permian

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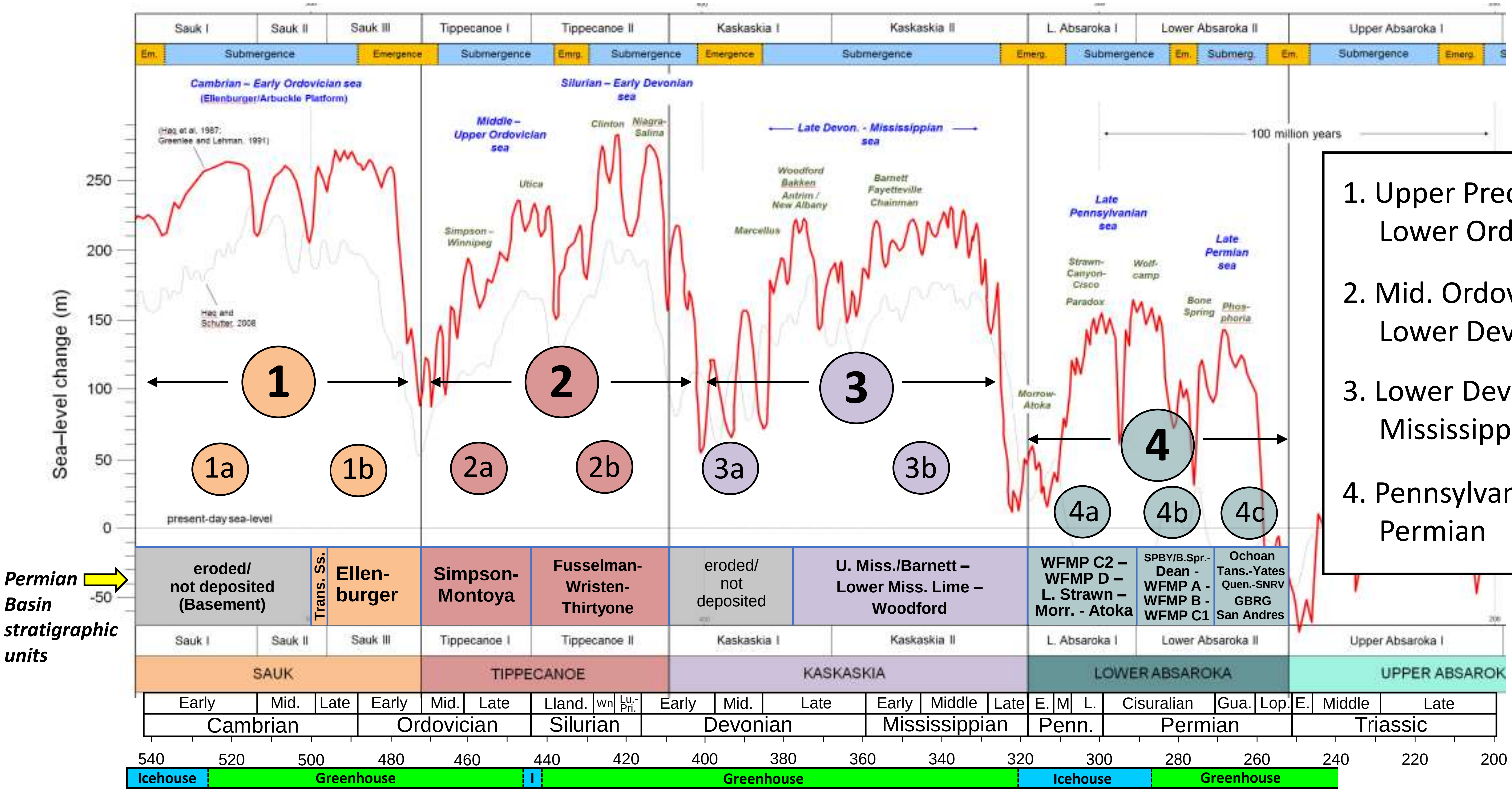


1. Upper Precamb. – Lower Ordovician
2. Mid. Ordovician – Lower Devonian
3. Lower Devonian – Mississippian
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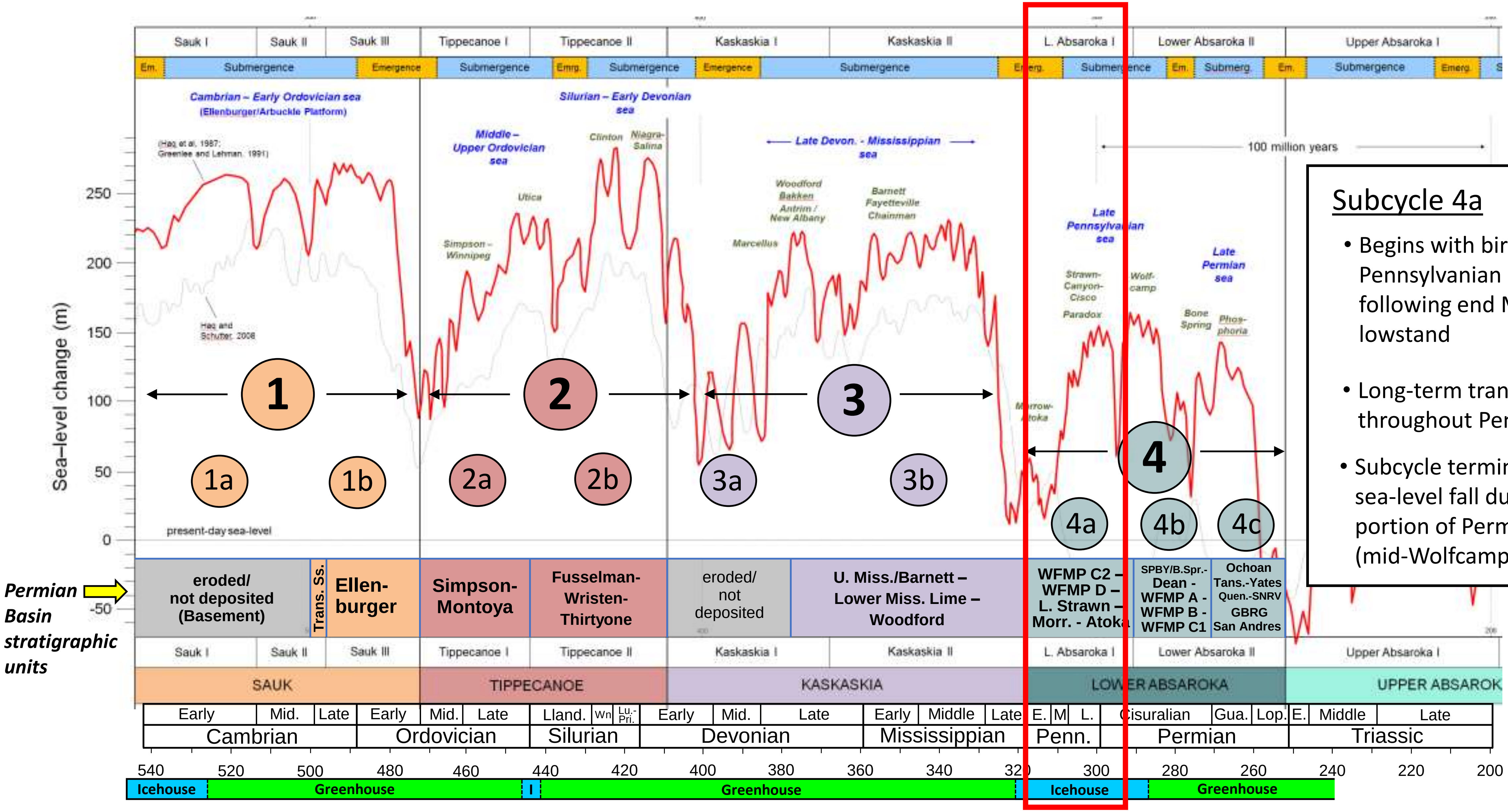


## Subcycle 4a

- Begins with birth of Pennsylvanian seaway following end Miss. lowstand
- Long-term transgression throughout Pennsylvanian
- Subcycle terminates with sea-level fall during earliest portion of Permian time (mid-Wolfcamp unconf.)

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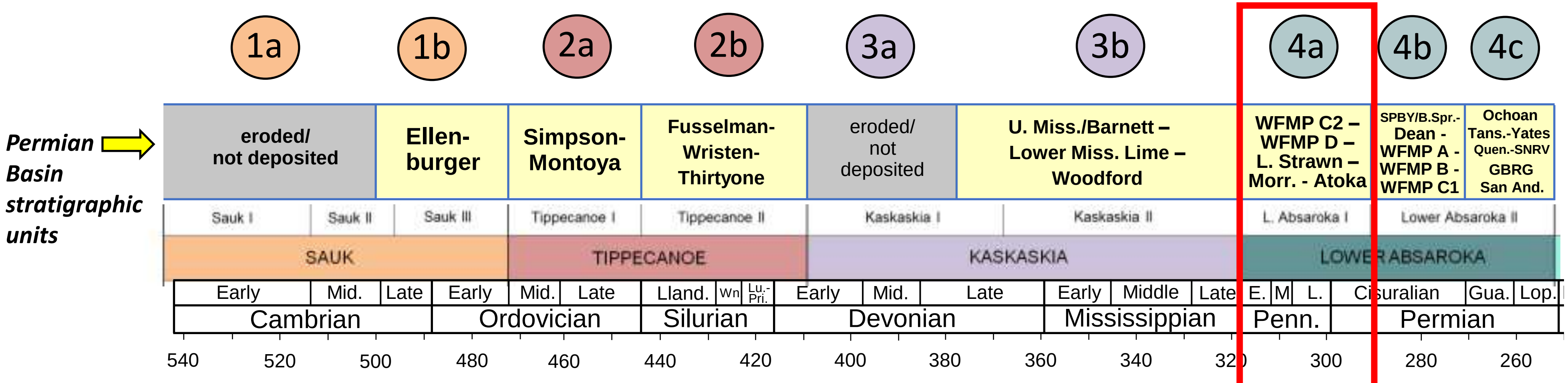
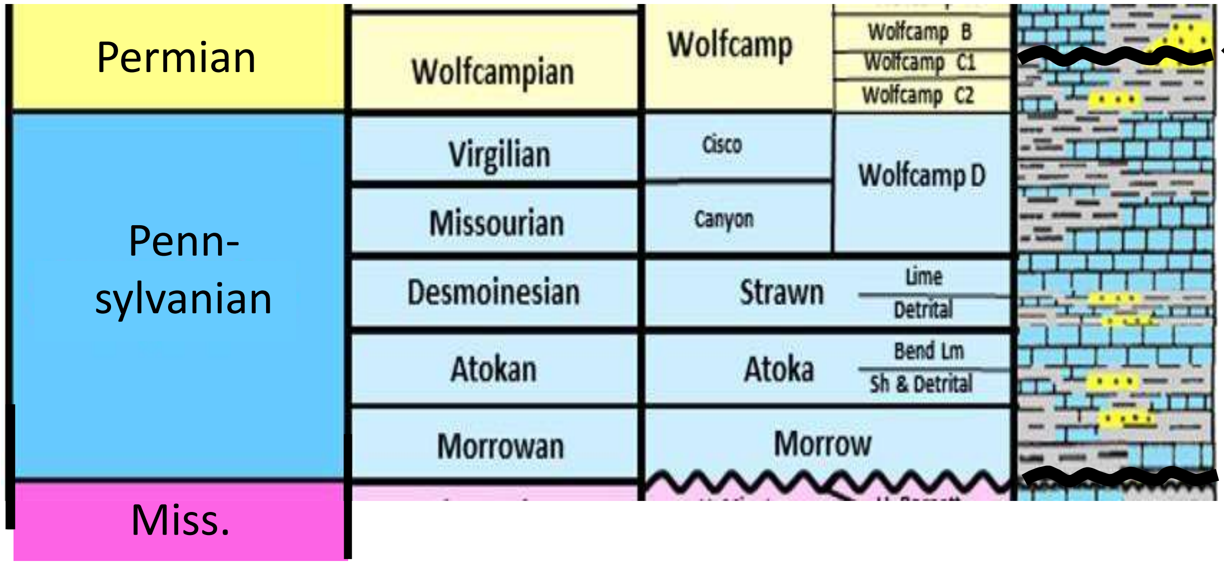
# Genetic Cycle 4a: (Penn. – early Permian)




Permian Basin Cycle 4a strat. units
<u>(from youngest to oldest):</u>

- Lowermost (Wolfcamp C) Permian
- Cisco
- Canyon
- Strawn
- Atoka
- Morrow ?

Cisco, Canyon, Strawn: Wolfcamp D (Cline shale) in basin




Tectonic uplift

**mid Wolfcamp** Regional unconf.

***Four pulses of tectonic uplift***

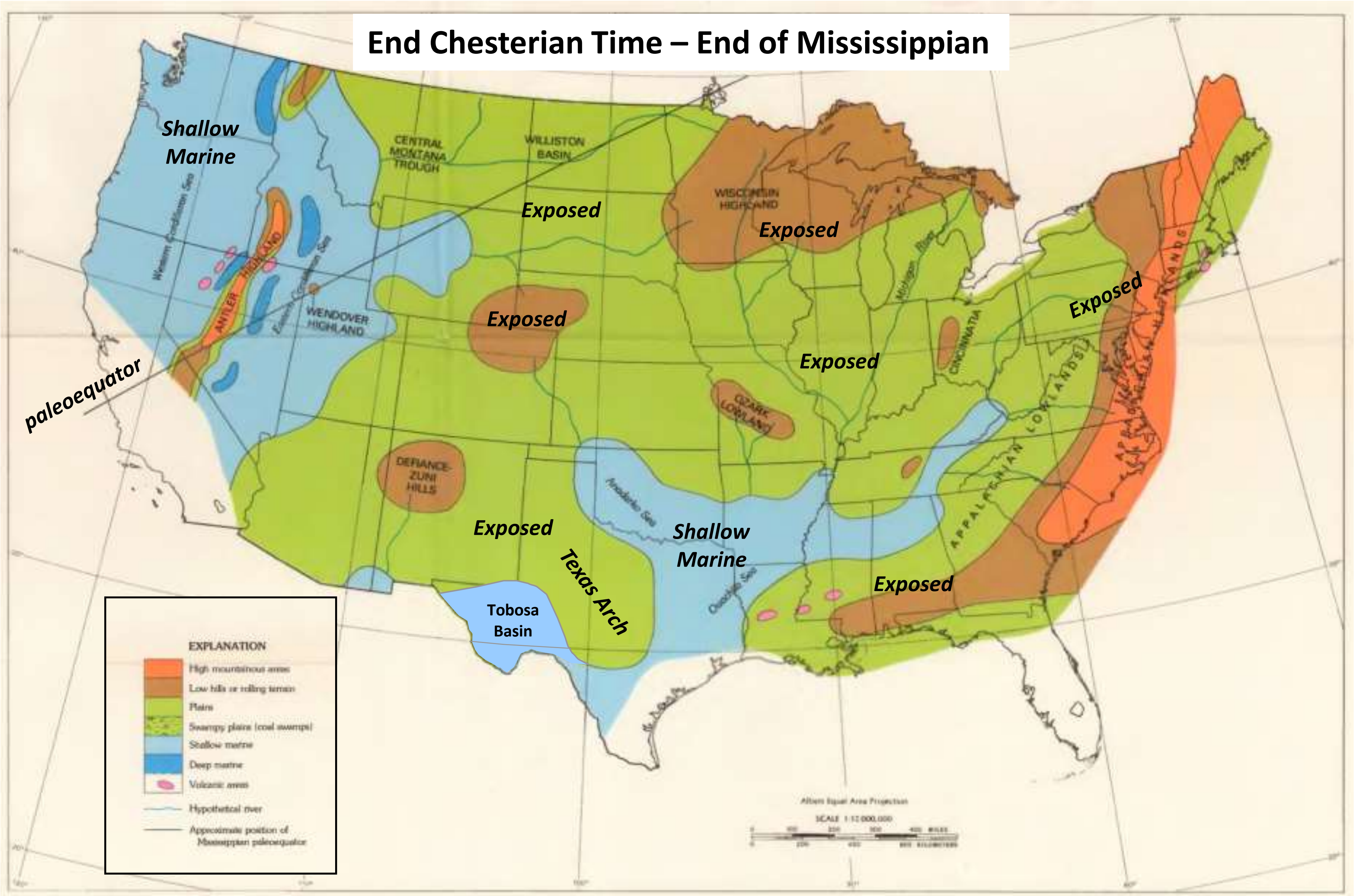
**early Strawn**

**Atoka**

**Morrow**

Interregional unconf.

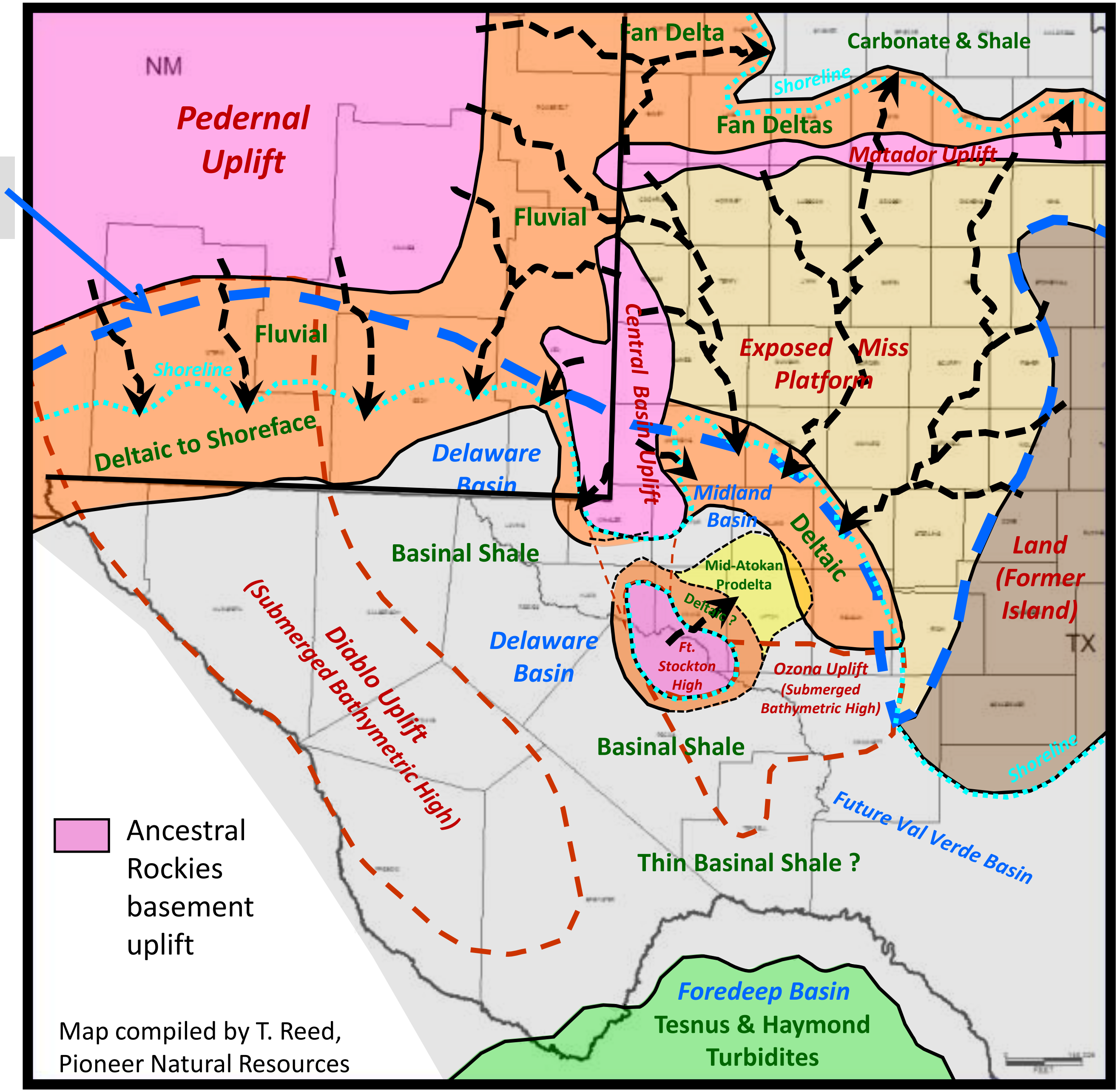
# Paleoenvironmental Reconstruction for the U.S at end of Mississippian time




- Large portions of N Amer. are emergent lowlands, including Texas Arch
- Core from center of Midland Basin shows Late Miss. (Barnett shale) unconformably overlain by Atoka shales (no Morrow/ lowermost Pennsylvanian)

(From USGS Prof Paper 1010, 1979, Part III, Plate 12)

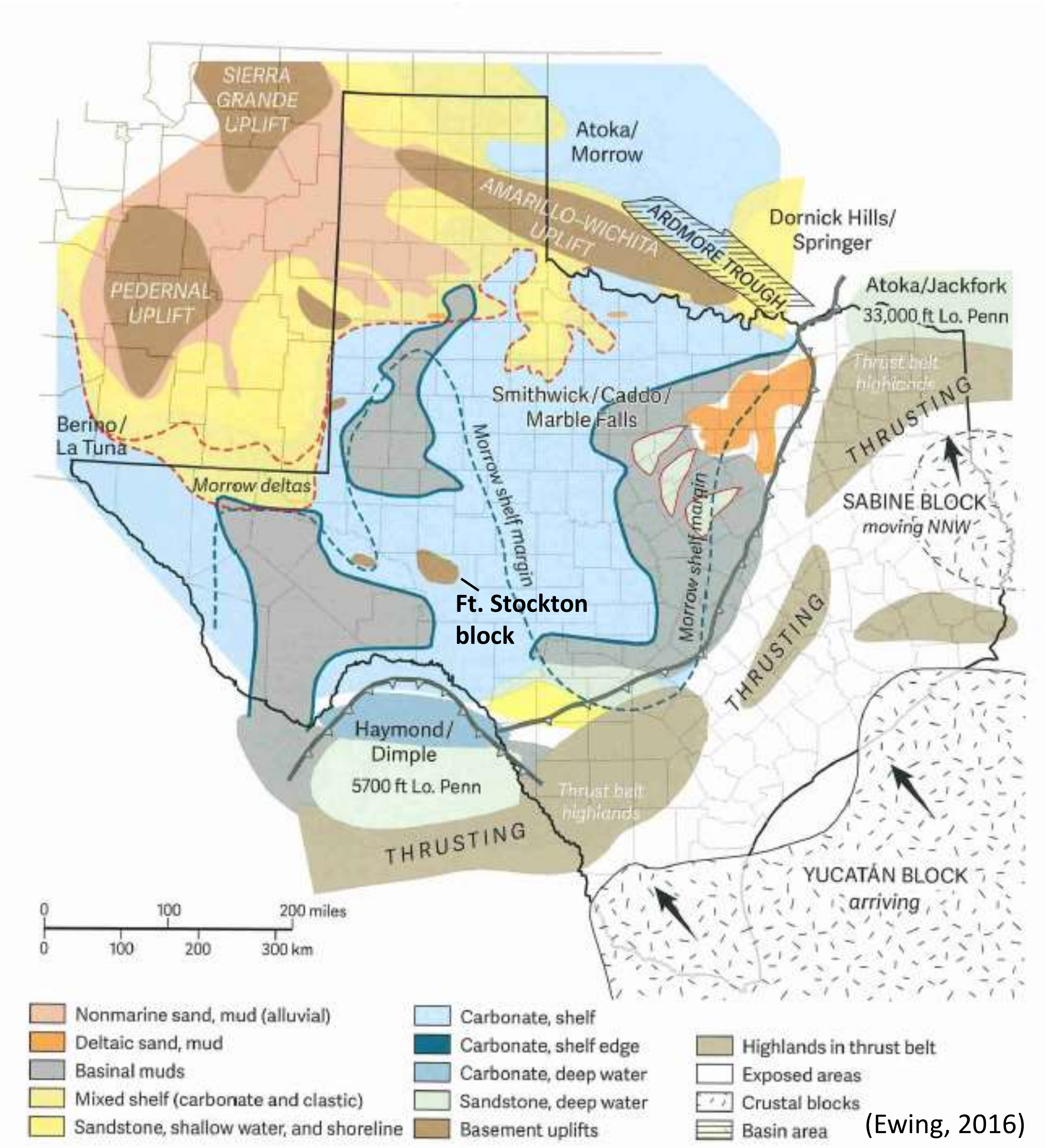
# Early Atoka Facies



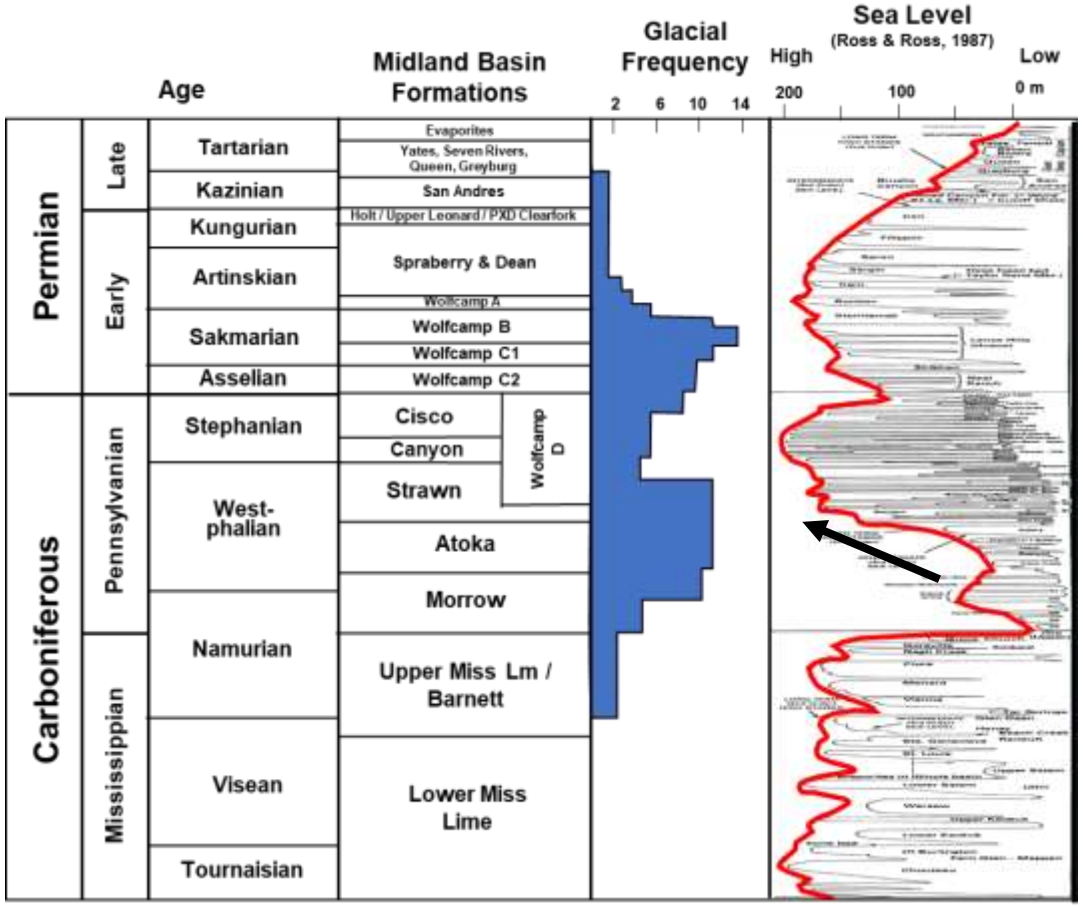

*Edge of underlying Miss Platform*

- Relative low sea level
- Miss carb. platform & Eastern Shelf Exposed
- Ancestral Rockies blocks (Pedernal and Matador Uplifts) rise and shed clastics southward
- Central Basin Uplift rising and shedding clastics (1st major tectonic "pulse" in Morrow, 2nd in Atoka)
- Series of large streams delivering coarse clastics off Pedernal Uplift into Delaware Basin; streams into Midland basin are smaller, muddier; coal-bearing

# Late Atoka

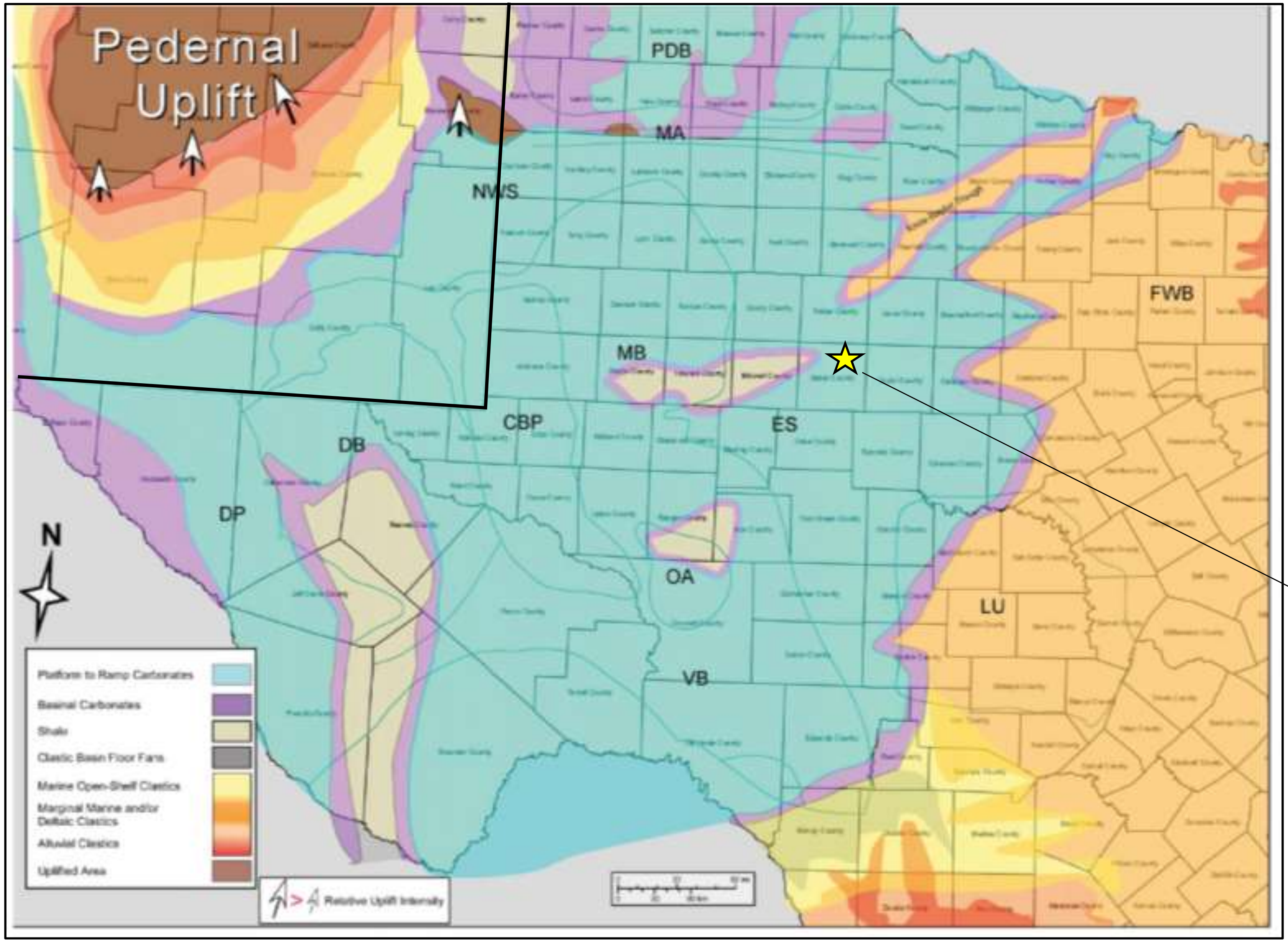



(Ewing, 2016)



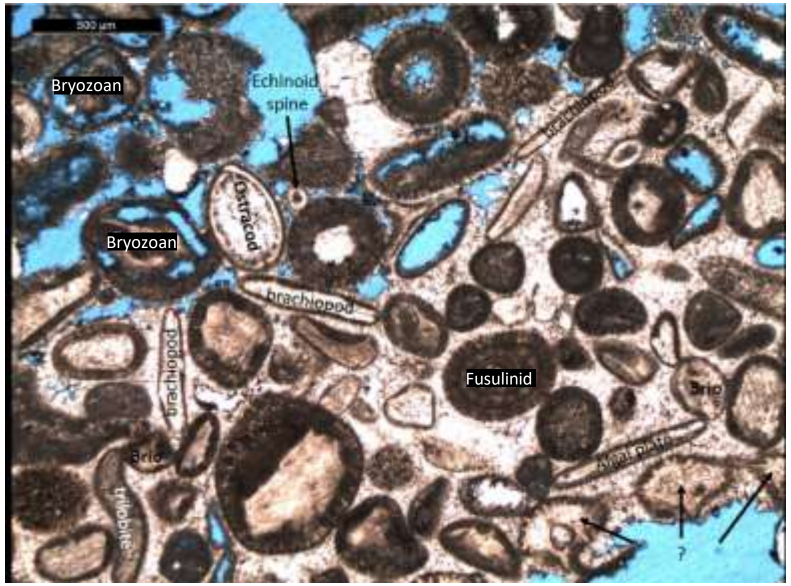

- Long-term rise in sea-level reduces main sources of terrigenous clastics; expansion of carbonate shelves
- Some areas of deep-water shale deposition
- Note small exposed land area in southern Central Basin Uplift (Fort Stockton block)

# Lower Desmoinesian Facies (Lower Strawn Limestone)

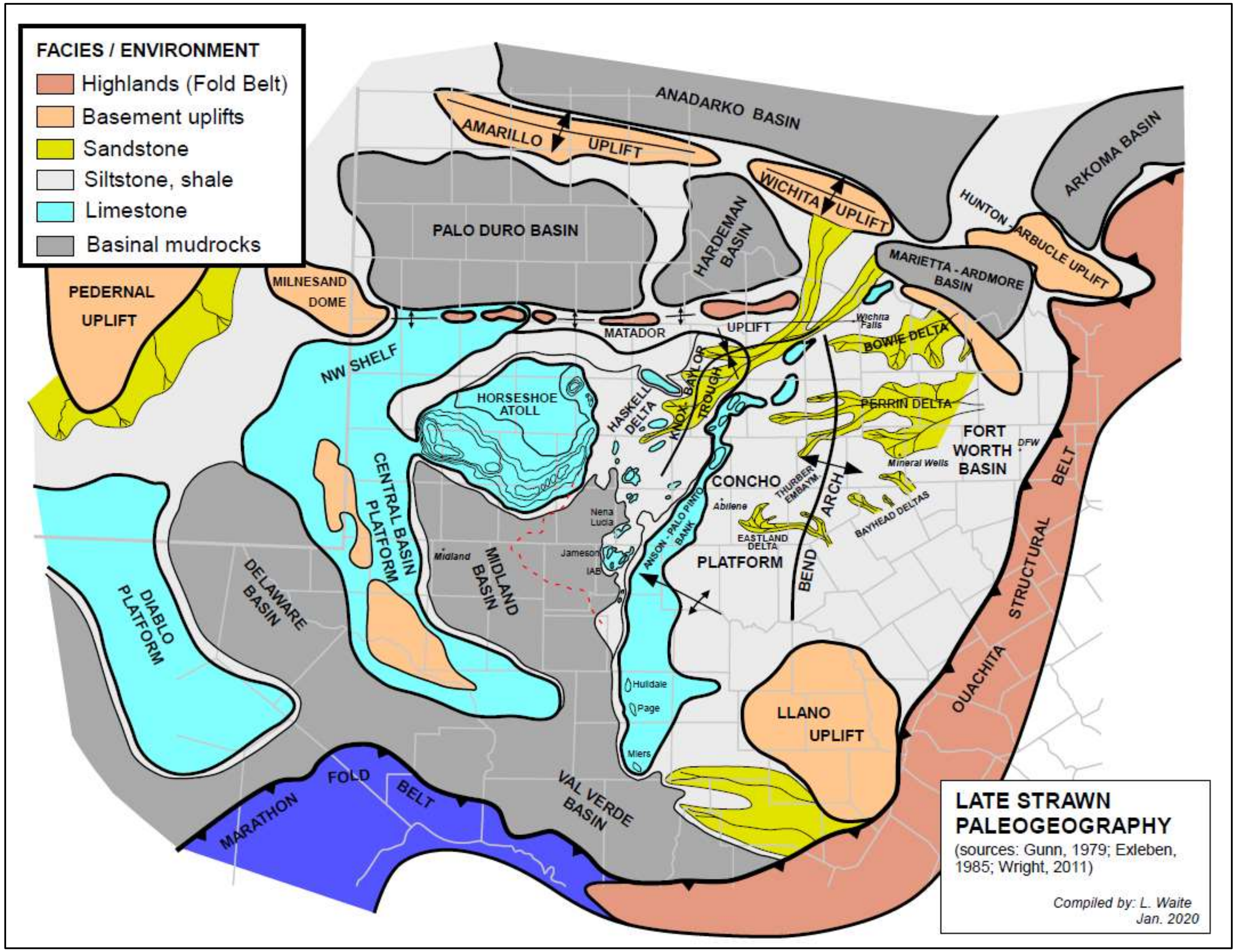


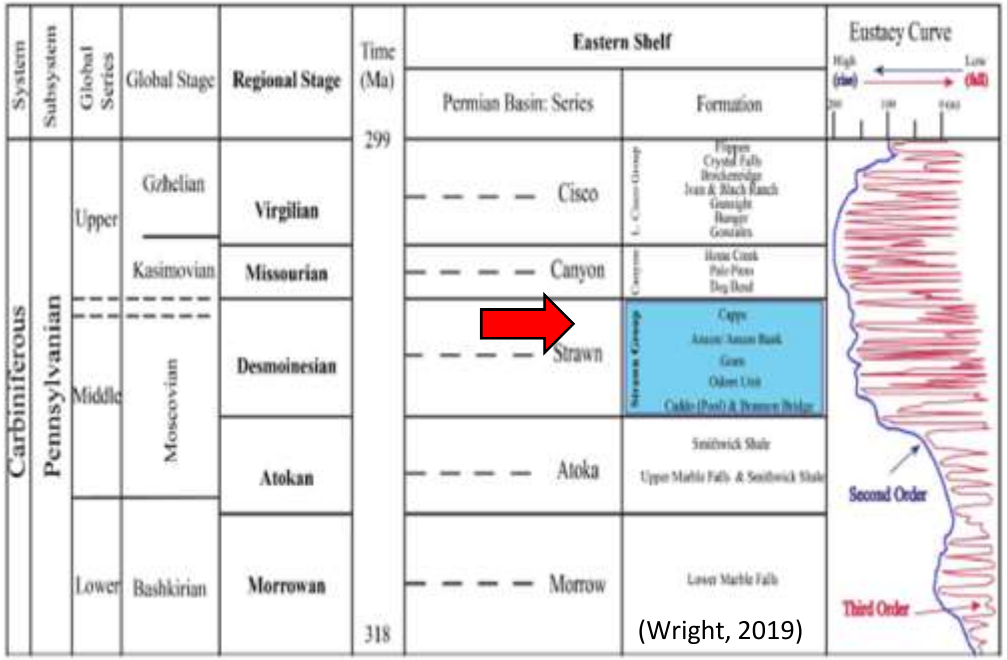

(Wright, 2011)

- Shallow water platform carbonate facies extend across entire Permian Basin
- 3rd-major tectonic pulse; local clastics shed off of CBU blocks (not shown on map)
- Lower Strawn Limestone is generally < 200 ft. thick in Midland Basin; good log / seismic marker
- Core analyses indicate typical Penn shelf cyclothem deposits: burrowed skeletal wackestones grading upward into phylloid algal packstones and skeletal grainstones, capped by exposure surfaces



# Late Desmoinesian (Upper Strawn) Facies



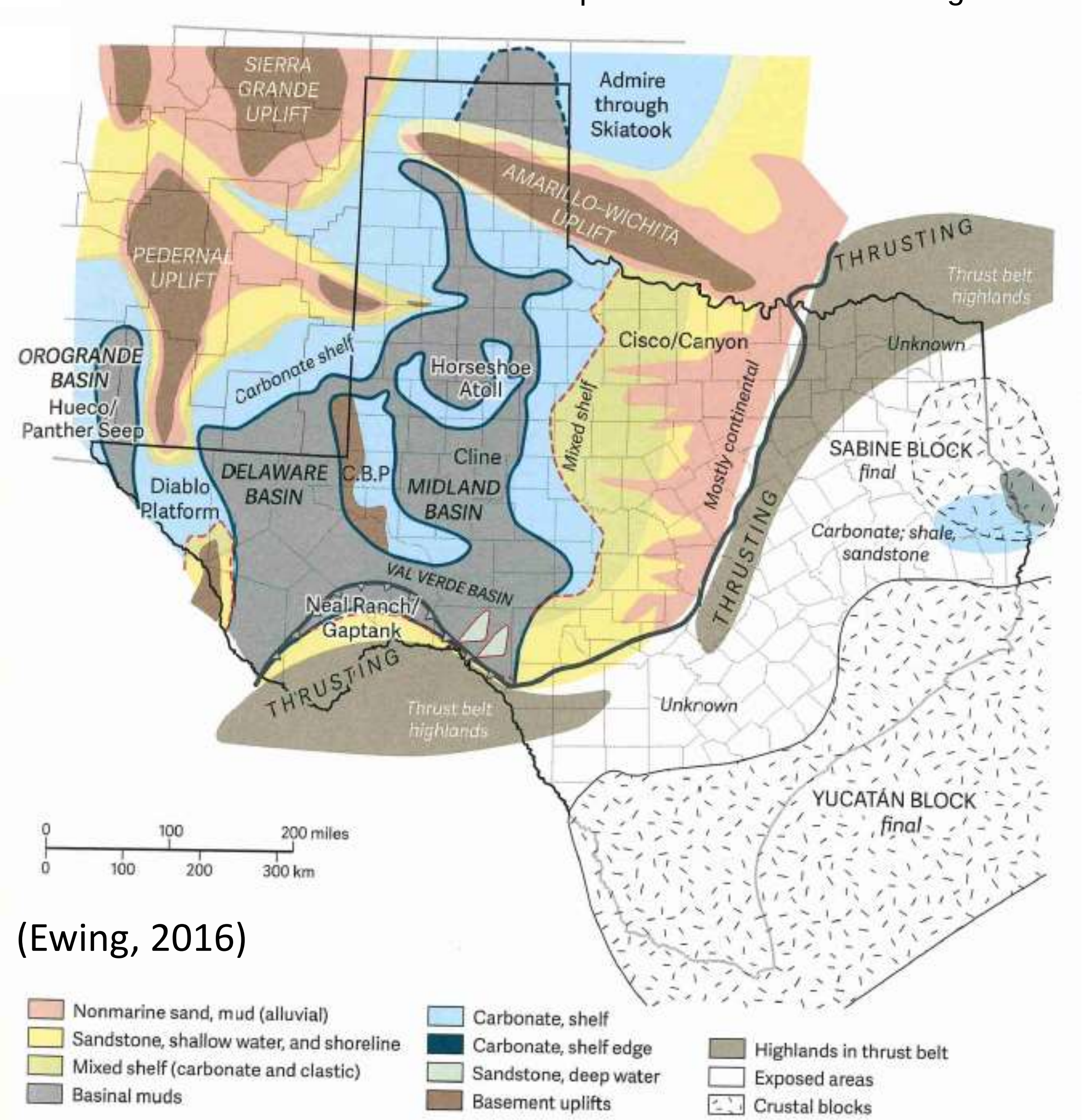




(Wright, 2019)

- Long-term sea-level highstand "drowns" the underlying, basin-wide Lower Strawn carbonate platform
- Tectonically-active Ancestral Rockies uplifts and Ouachita Fold Belt begin shedding voluminous amounts of terrigenous clastics during glacial lowstands
- Shallow-water carbonate deposition now restricted to surrounding shelves during highstand portion of glacial cycles
- Organic-rich black shales deposited in subsiding "starved" basins

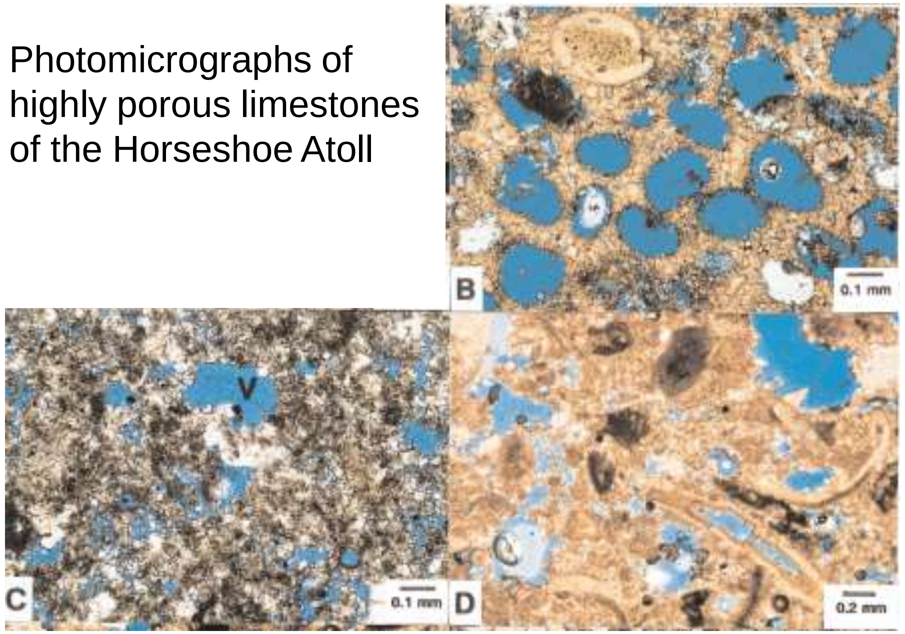
# Missourian – Virgilian (Canyon – Cisco) facies:

- Continuation of Late Desmoinesian pattern w/ further drowning




(Ewing, 2016)

Photomicrographs of highly porous limestones of the Horseshoe Atoll

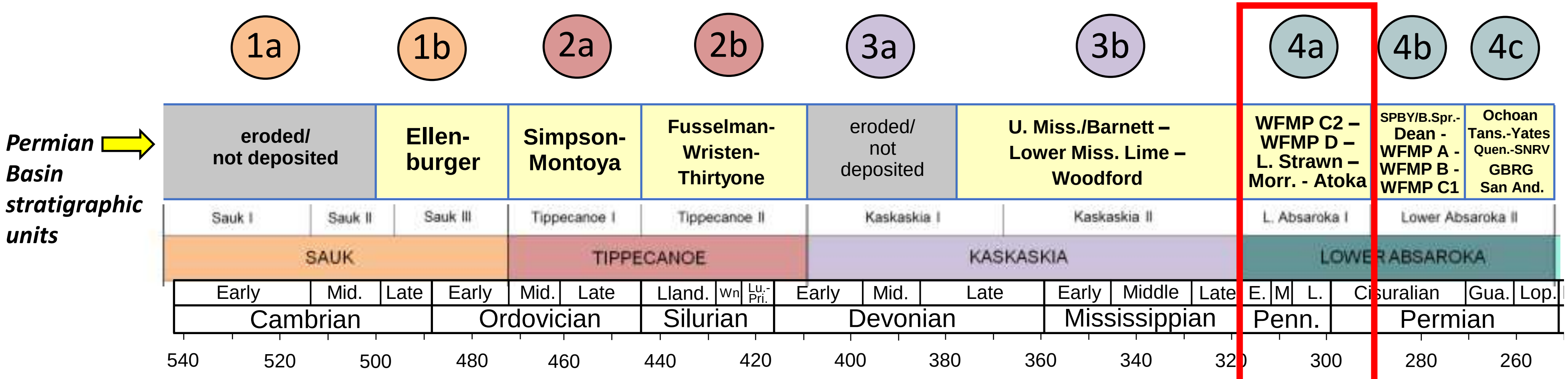



(Saller et al., 1999)

Organic-rich Wolfcamp D (Canyon – Cisco) black shales in core from the center of Midland Basin

# Lowermost Permian (Wolfcamp C)

- Penn-Permian boundary is a paleo event but not a depositional event/seq. boundary




Permian Basin Cycle 4a strat. units (from youngest to oldest):

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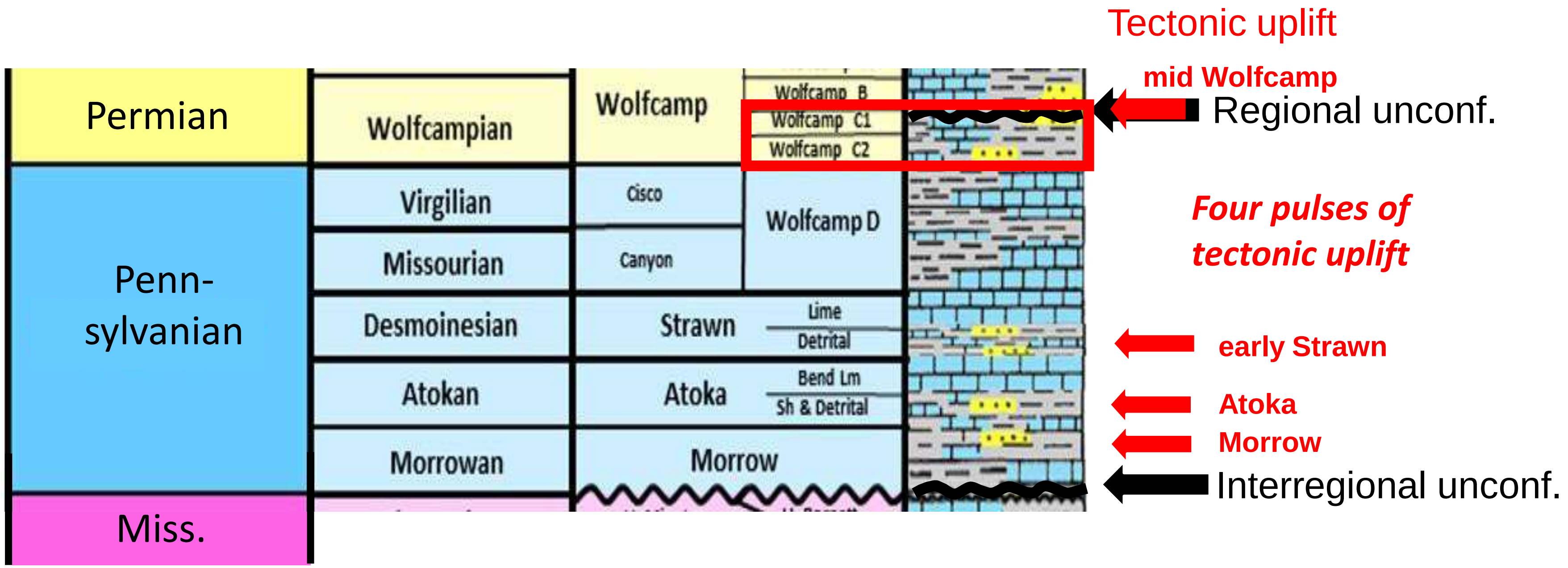
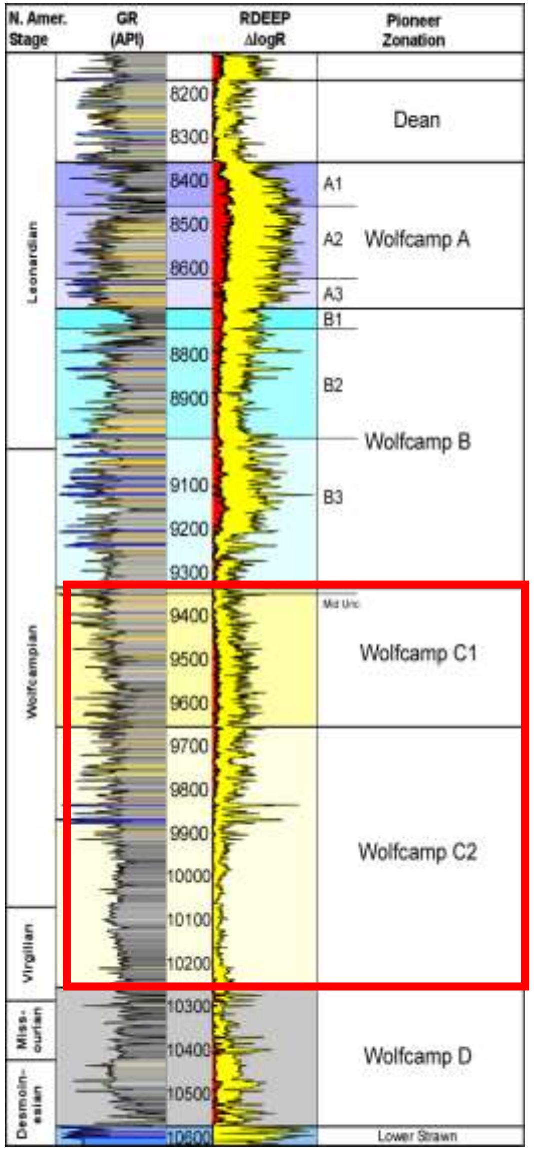
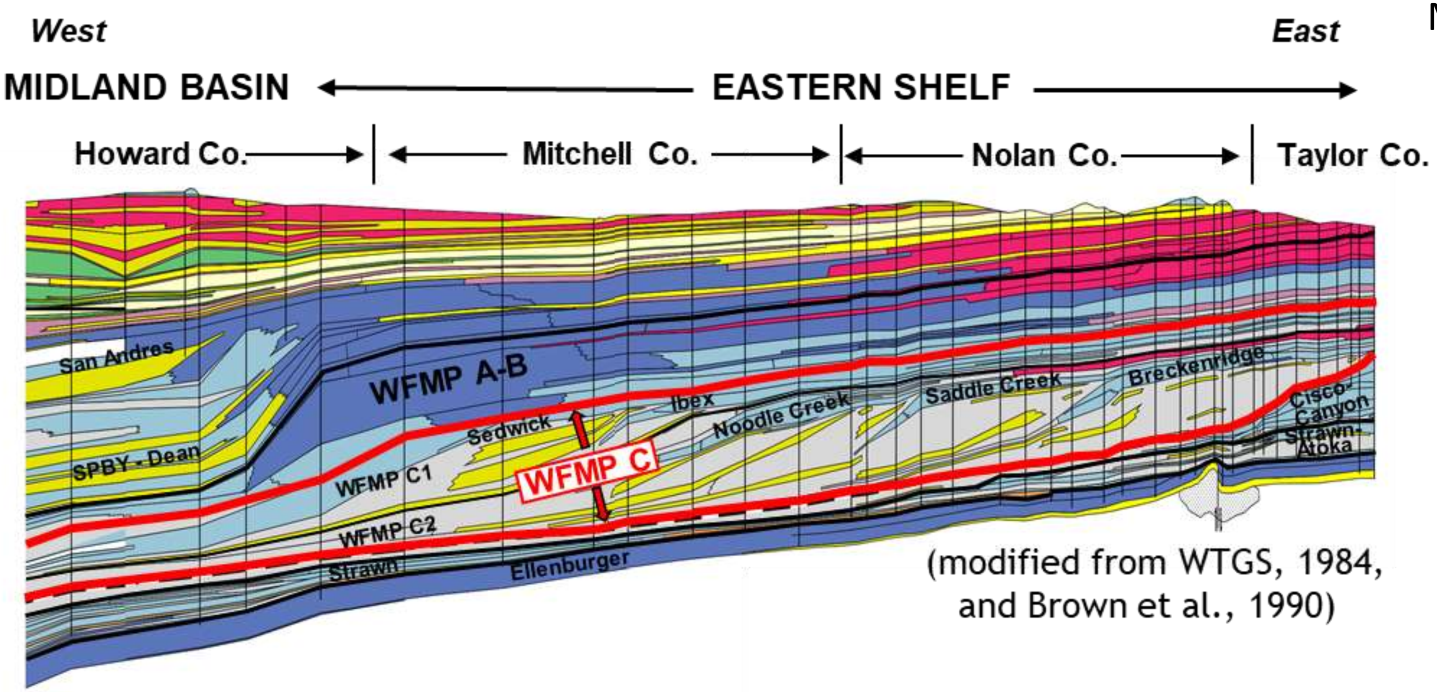


# Lower Wolfcamp (Wolfcamp C2 and C1)

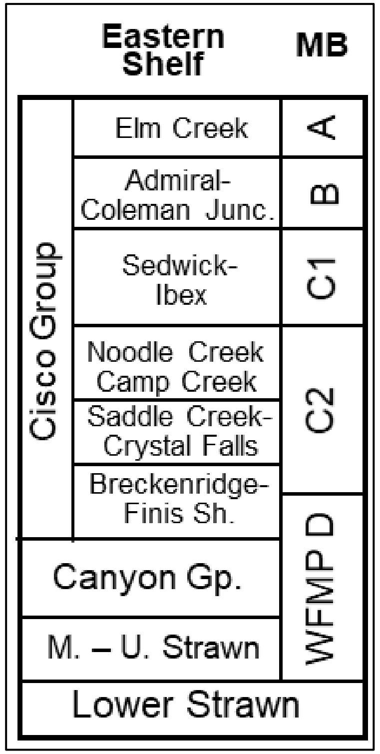



(Sinclair et al., 2018)



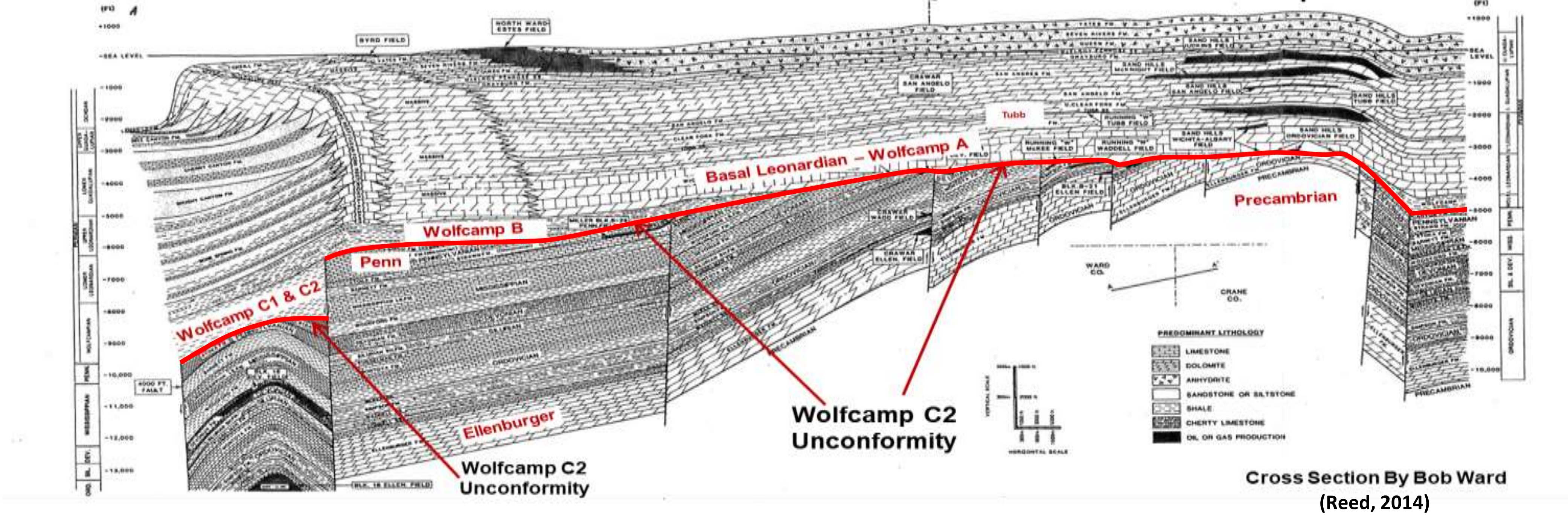

(modified from WTGS, 1984, and Brown et al., 1990)

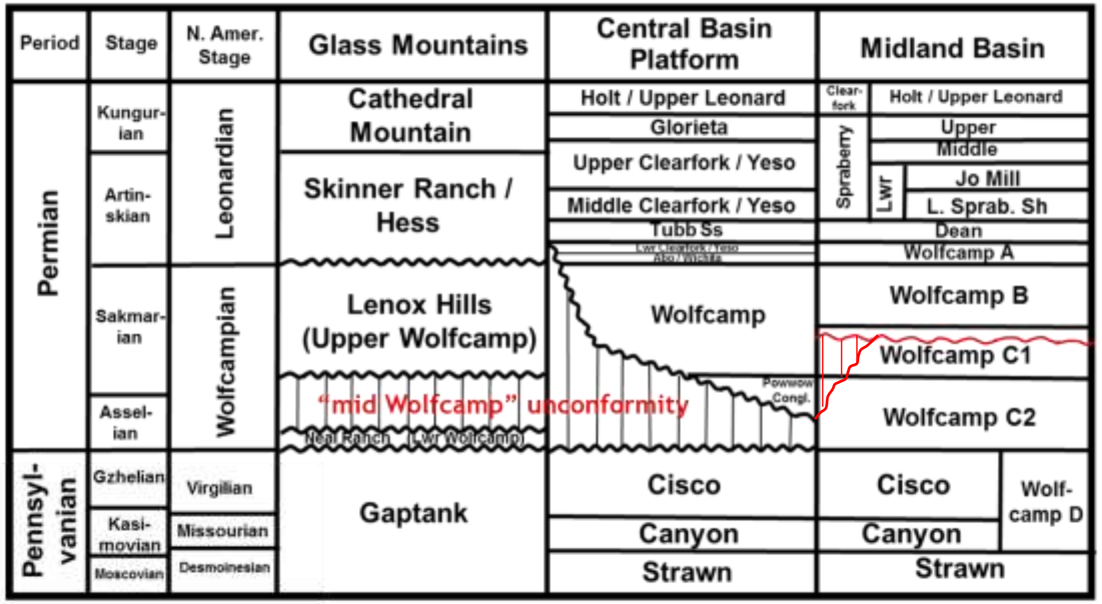
Preliminary correlation of MB tops to Eastern Shelf




- Westward progradation of Eastern Shelf delta systems and platform margins (100 -150 km)
- Thick sequence of clay-rich, organic-poor shales in Midland and Delaware basins
- Uplift of structural blocks on CBP and development of mid-Wolfcamp unconformity

# mid-Wolfcamp unconformity on the CBP




## Early Wolfcamp

- **last major tectonic pulse prior to middle – late Permian subsidence phase**
- note diachronous nature of unconformity across Permian Basin region
- Midland Basin: angular unconf. identified on 3D seismic

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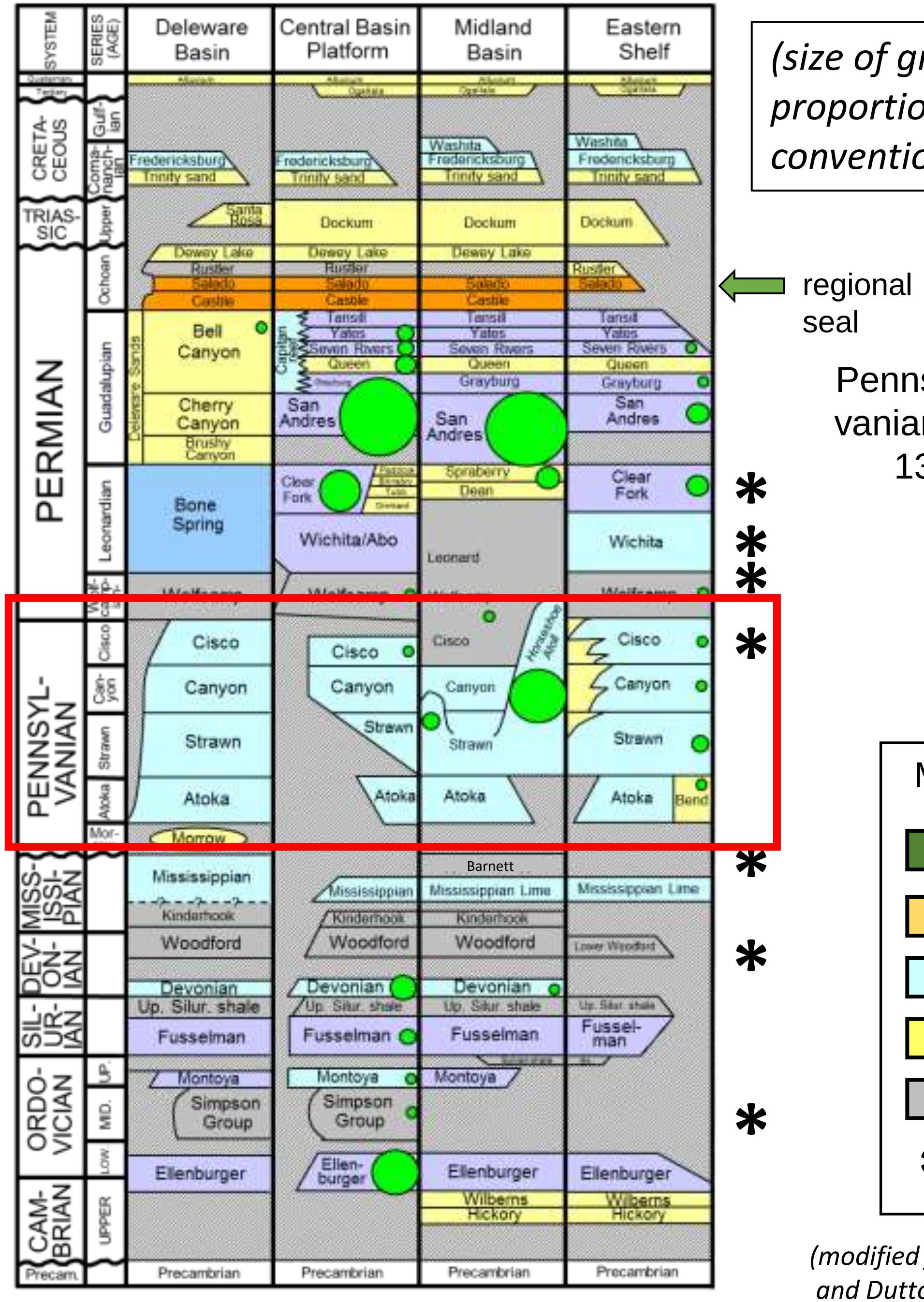
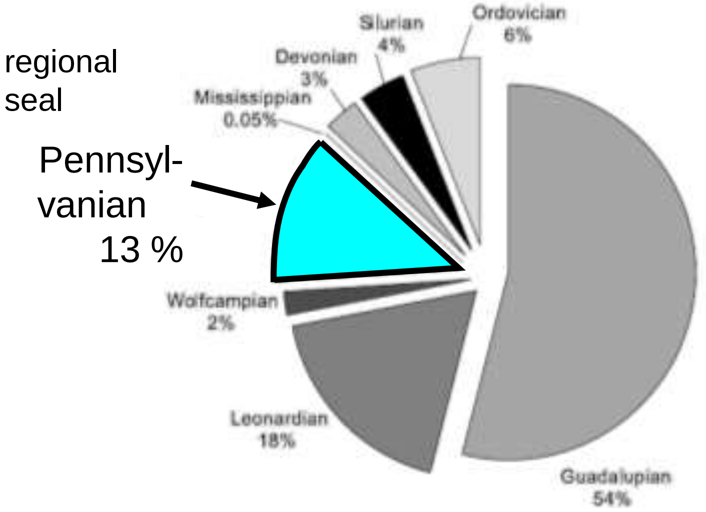
# Permian Basin Reservoir and Source intervals




*(size of green bubbles are proportional to total conventional reserves)*




**Main Lithologies**

- Evaporites
- Dolomite
- Limestone
- Sandstone/siltstone
- Shale
- *** HC source rock interval**

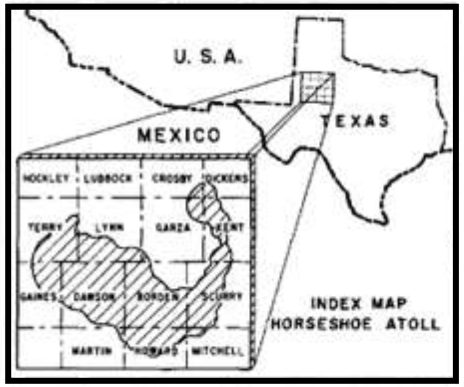
*(modified from BEG, 1983, Atlas of Major Texas Oil Reservoirs, and Dutton et al., 2005)*

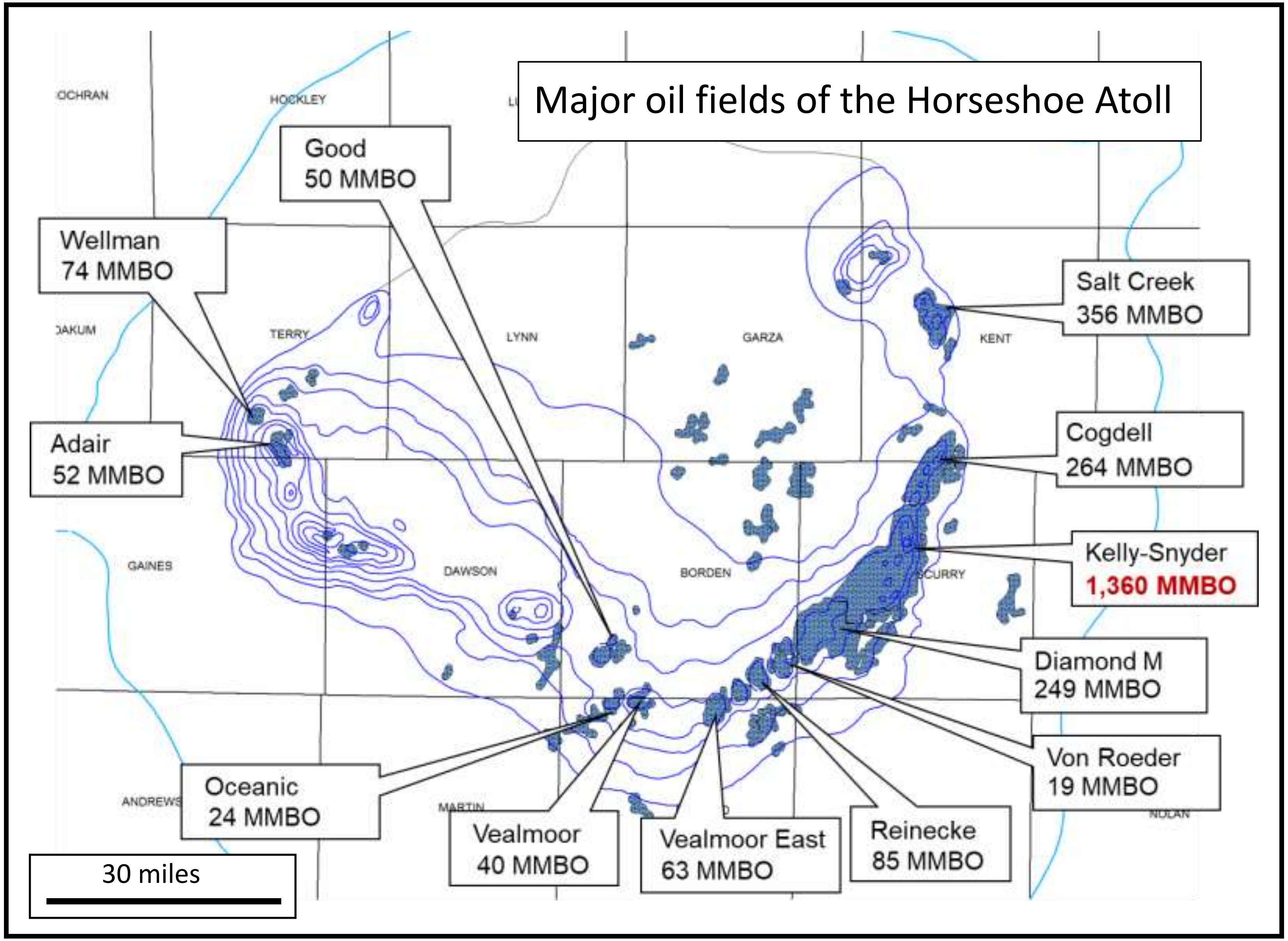
- Conventional reservoirs of Pennsylvanian age (limestones and sandstones) account for 13% of total oil production within the Permian Basin (~5 BBO oil)
- Majority of these conventional reserves are housed in carbonate reefs and shoals of the giant Horseshoe Atoll complex in northern portion of Midland Basin
- Recent (2016) USGS assessment estimates an additional 5 BBO recoverable reserves in Wolfcamp D in Midland Basin

# Horseshoe Atoll of the northern Midland Basin

- An enormous, isolated carbonate platform of Pennsylvanian to early Permian age, including an arcuate chain of phylloid-algal reefs and ooid shoals

- The Atoll contains many large oil fields including the supergiant Kelly-Snyder field



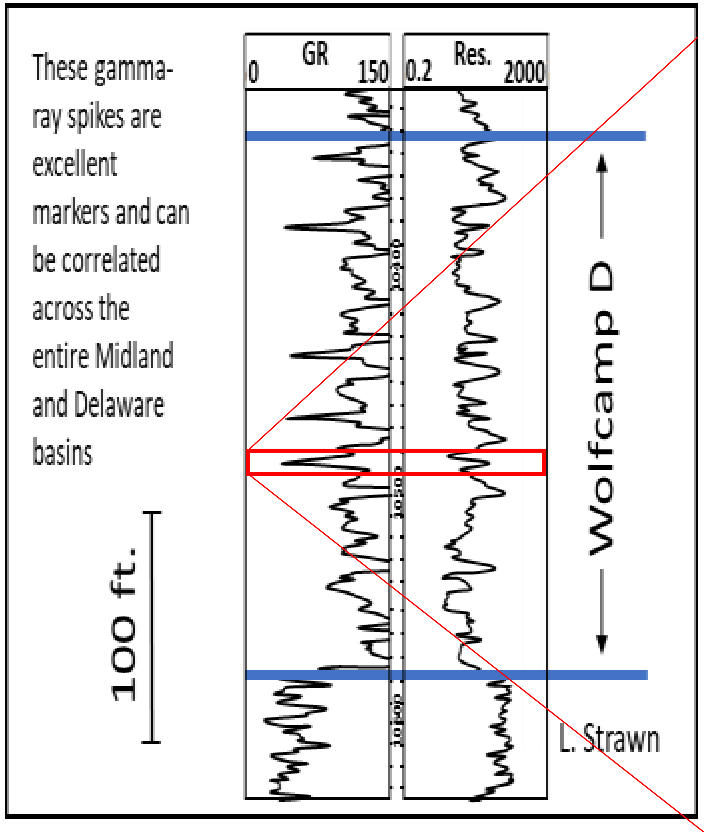
# Horseshoe Atoll Reservoir and hydrocarbon properties

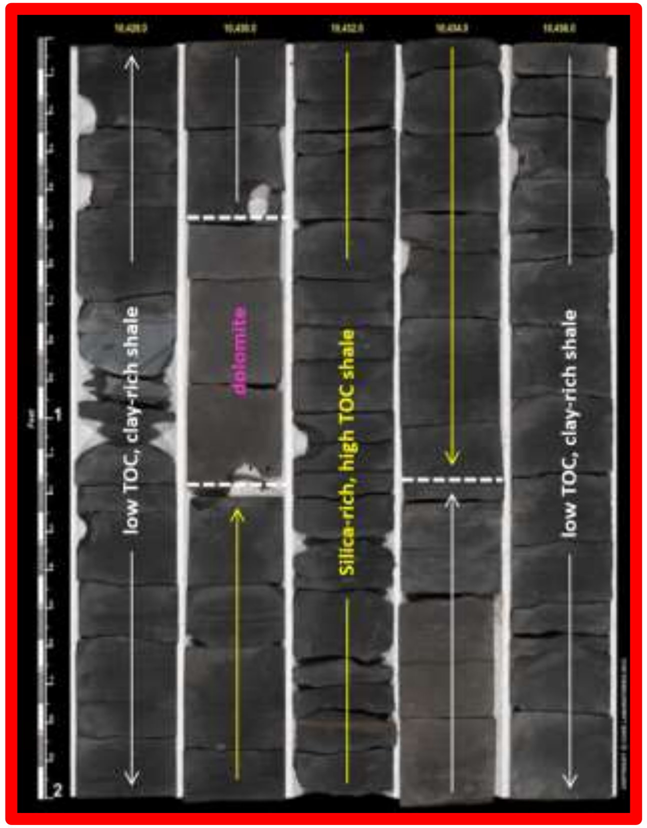
| | |
|---|---|
| **Trap type** | Combination structural - stratigraphic<br>Depth: 4,000 – 6,000 ft TVD ss |
| **Reservoir thickness** | 800 ft. (gross, max); 270 ft. (avg. net) |
| **Reservoir spacing** | 160 ac. (orig.); 20 – 80 ac. (current) |
| **Porosity types** | Moldic, vuggy, intercrystalline |
| **Matrix porosity** | 2.5 – 20+% (avg. 7.6%) |
| **Permeability (air)** | 0.1 – 51mD (avg. 19.4 mD) |
| **Hydrocarbon type** | Light oil (41$^o$ API), low sulphur |
| **Initial GOR** | 1010 SCF/STB |
| **Gas composition** | 28.7% $C_1$; 11.3 % $C_2$; 58.9 % $C_3$+; 0.18% S |
| **Reservoir pressure (orig.)** | 3122 psi @ 4500 ft TVD ss (0.69 psi/ft) |
| **Water saturation (orig.)** | 21.9 % |
| **Production methods** | Primary (1948); Secondary - water injection (1954);<br>Enhanced – $CO_2$ miscible flood (1972) |

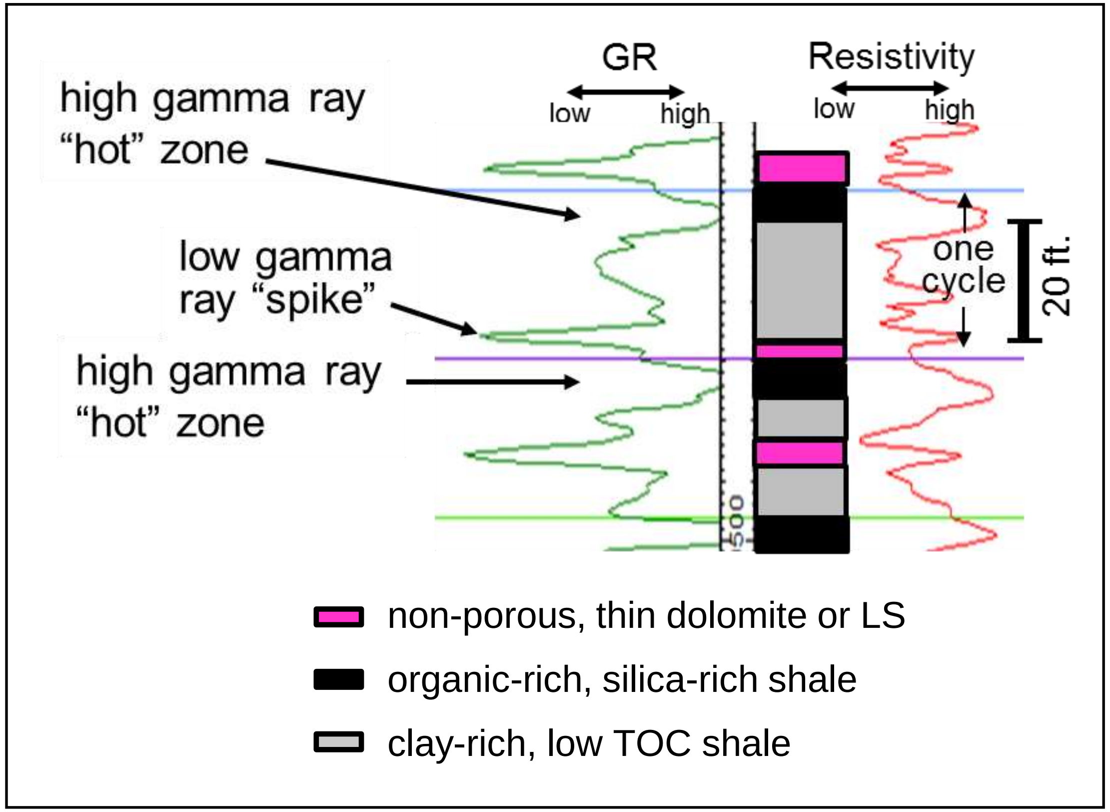
*(C&C Reservoirs, 2013)*

# Wolfcamp D: organic-rich basinal cyclothems

- Equivalent to classic "Penn. cyclothems" on shelves
- Silica – rich shales; relatively high clay content
- Each consists of a clay-rich gray shale and an organic-rich black shale capped by a thin LS/dolomite
- Wet gas zone in Midland Basin; high reservoir pressure



# Geologic framework of Penn – lower Permian of Permian Basin: Summary

- Pennsylvanian – lower Permian units of the Permian Basin consist largely of classic shelf cyclothems (alternating shallow water limestones and sandstones) and time-equivalent starved basinal cyclothems (alternating siliceous clay-rich, organic-poor shales and organic-rich shales)

- These units are the product of a unique combination of tectonic, climatic, eustatic, and biologic factors that existed along the SW margin of Laurentia during the assembly of Pangea

- Pennsylvanian – lower Permian units of the U.S. Permian Basin constitute important economic hydrocarbon reservoirs; potential for future conventional and unconventional reserves is high