PS Climate History, and Lake Evolution Controls on Oil Shale Organic Richness - Green River Formation, Piceance Creek Basin*

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Editor's note: Please view a companion article by Kati Tänavsuu-Milkeviciene, J. Frederick Sarg, Jufang Feng, Suriamin Huang, and Yuval Bartov entitled "Sequence Stratigraphy, Climate, and Organic-Richness: Green River Formation, Lake Uinta, Colorado," Search and Discovery Article #50695 (2012).

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Abstract

The Green River Fm. lake deposits (early-middle Eocene) in the Piceance Creek basin are largely composed of kerogen-rich and kerogen-poor mudstones (clay and carbonate). Lake evolution is defined by lake stages: S1-Fresh Lake, S2-Transitional Lake, S3-Rapidly Fluctuating Lake, S4-Rising Lake, S5-High Lake, and S6-Closing Lake. Lake stages correlate to the early to middle Eocene optimum. S1 appears to have formed during the warming phase of the climate optimum and represent the basin evolution from fresh to saline conditions. The lake changed during S1 from an open lake to a closed lake basin suggesting a change from abundant rainfall and high runoff, to more seasonal and dryer climate. Increased seasonality and flashy runoff began during S2, indicating restricted lake conditions, and peaked during S3, at the maximum of the climate optimum, when arid conditions prevailed, and nahcolite and halite are abundant. The ensuing lake level rise (S4) and high lake (S5) occur during climatic cooling, accompanied by increased precipitation.

The organic deposition of the Green River oil shale is related to three factors: production, destruction, and dilution. The pattern of organic richness variation within 400k year sequences suggests a net-productivity-driven organic depositional model modified by variations in dilution related to climate. Inorganic geochemistry proxies (P, Al, V/Cr, C13, and O18) suggest net productivity and dilution by siliciclastics and/or evaporites also controls the average organic richness variation over the long-term lake history. This is evident in the variation between Green River rich-zones (R), expressed here as changes in average oil yield in gal/ton. During S1, stratified conditions first developed, and moderately high net productivity and diminishing detrital dilution occurred as the climate dried, resulting in increasing richness (R0-21gal/ton, R1-27gal/ton). High productivity and low dilution peaked in early S2, resulting in very high richness (R2-39gal/ton). Richness then declined as evaporate precipitation increased (R3-25gal/ton). S3 shows decreasing average organic richness from an early high to a minimum at the end of

S3, when increased saline mineral dilution occurred at the peak of the climate optimum (R4-36gal/ton, R5-21gal/ton). Net productivity increased during subsequent climate cooling, with a return to wet conditions (S4, S5). Diminished saline dilution resulted in increasing organic richness (R6-24gal/ton, R7-30gal/ton).

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ABSTRACT

The Green River Fm. lake deposits (early-middle Eocene) in the Piceance Creek basin are largely composed of kerogen-rich and kerogen-poor mudstones (clay and carbonate). Lake evolution is defined by lake stages: S1-Fresh Lake, S2-Transitional Lake, S3-Highly Fluctuating Lake, S4-Rising Lake, S5-High Lake, and S6-Closing Lake. Lake stages correlate to the early to middle Eocene climate optimum. S1 appears to have formed during the warming phase of the climate optimum and represents the basin evolution from fresh to saline conditions. The lake changed during S1 from an open lake to a closed lake basin suggesting a change from abundant rainfall and high runoff, to more seasonal and dryer climate. Increased seasonality, and flashy runoff began during S2, indicating restricted lake conditions, and peaked during S3, at the maximum of the climate optimum, when arid conditions prevailed, and nahcolite and halite are abundant. The ensuing lake level rise (S4) and high lake (S5) occur during climatic cooling, accompanied by increased precipitation.

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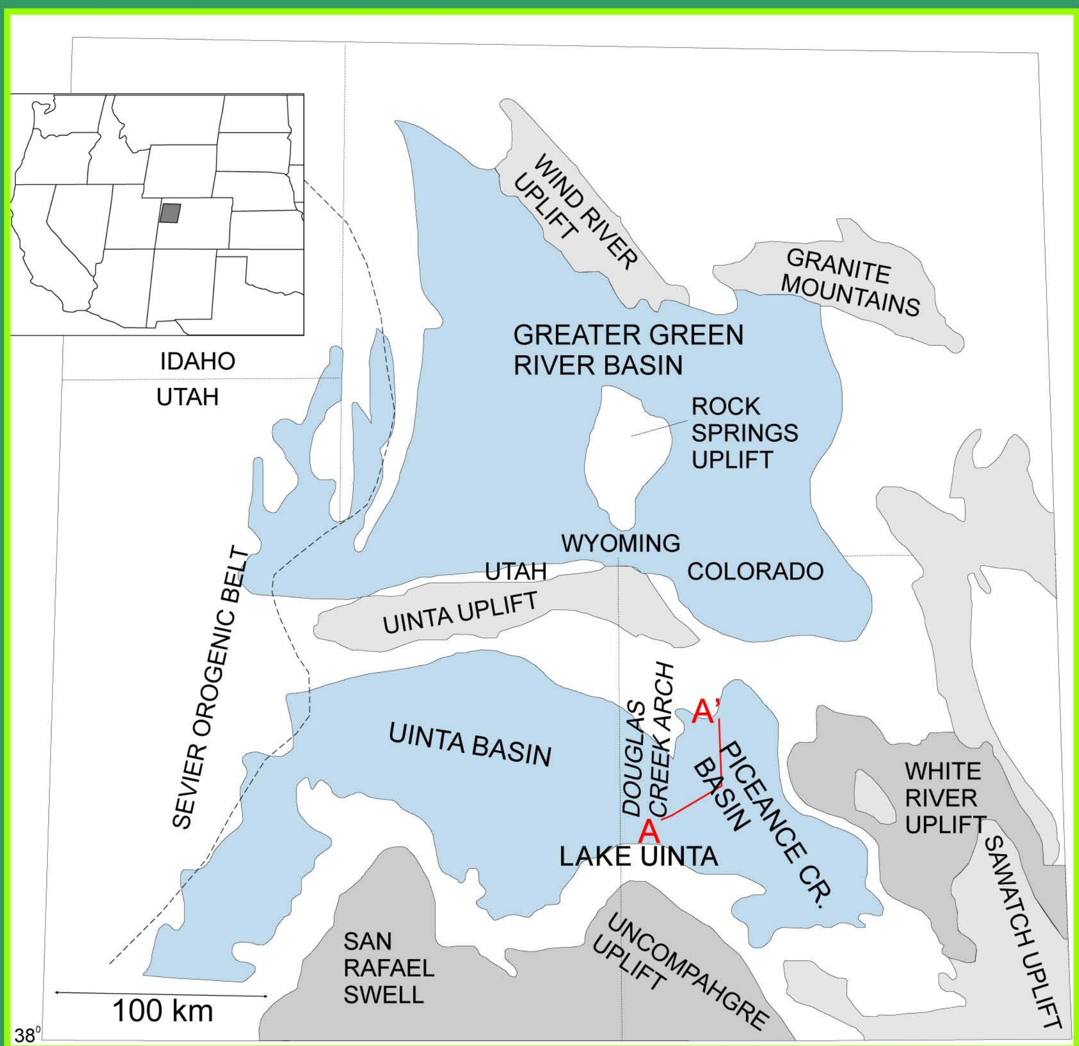
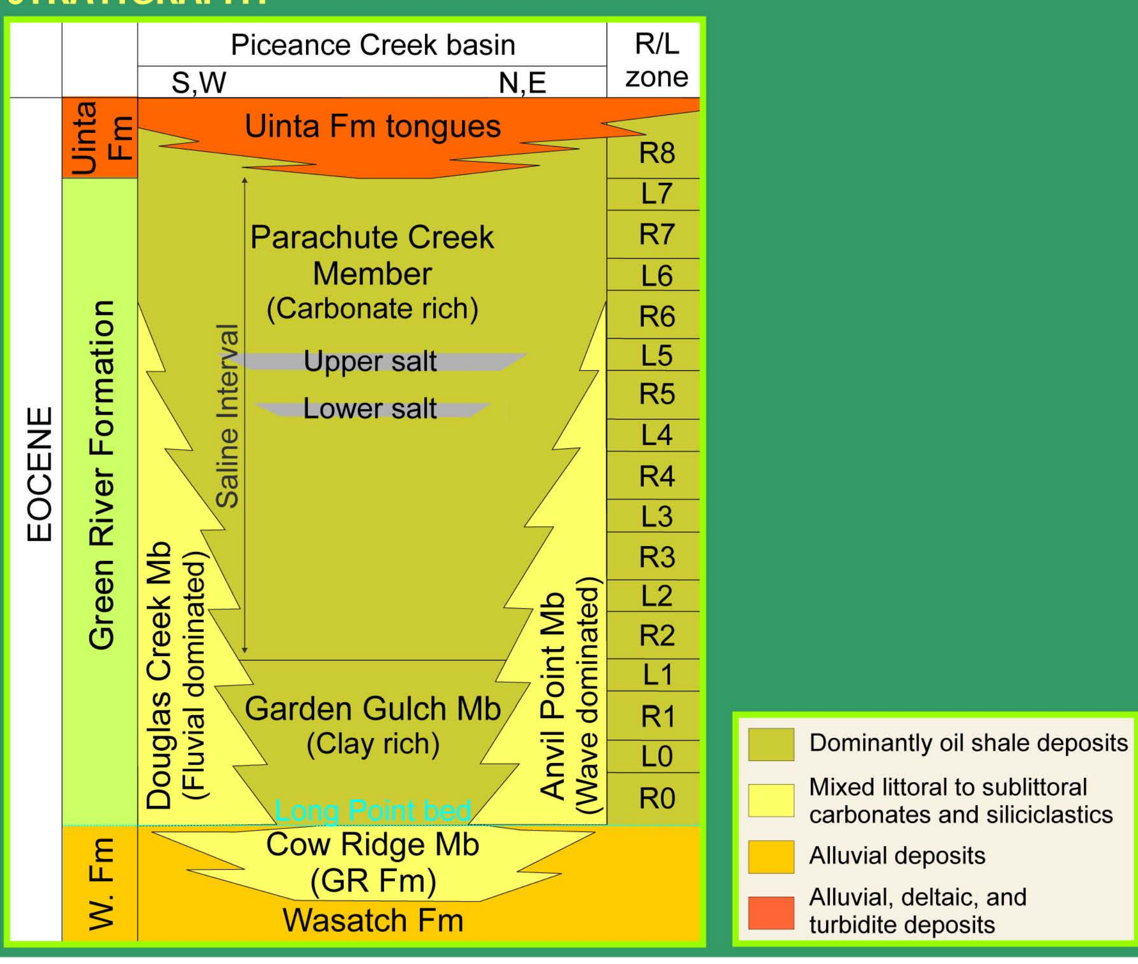
AREA and CROSS-SECTION



STRATIGRAPHY



Background

Green River Formation lake basins formed as intermountain basins during the Laramide Orogeny.

Deposition of the Green River Formation in the Piceance Creek basin occurred during the early to middle Eocene (53 to 48 Ma) (Smith et al. 2010).

Piceance Creek lake basin formed in the mid-latitude warm to temperate climate (Sewall & Sloan 2006).

Deposits are divided into:
1. Members, based on lithofacies.
2. Rich and lean zones (R/L), based on the kerogen content.

Kerogen content is measured by,
Fischer Assay (gal/ton)
TOC (Total organic carbon) (Weight%)

After Johnson 1984; Self et al. 2010; Tänavsuu-Milkeviciene & Sarg *in press*

COSTAR

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ORGANIC CARBON DEPOSITIONAL MODEL

$$\text{Organic Enrichment} = \frac{\text{Production - Destruction}}{\text{Dilution}}$$

Bohacs et al. 2005

DATASET and METHODS

Source Rock Analyzer

Basin Center Section:
- John Savage 24-1: 117 samples
- Shell 23X-2: 46 samples

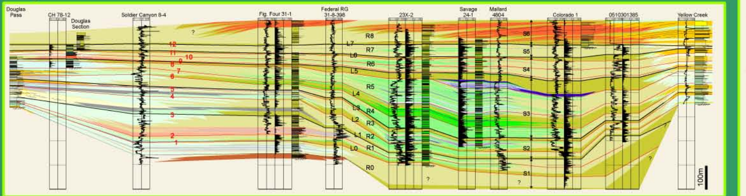
Basin margin Section:
- Douglas Pass Section: 50 samples
- Douglas Section: 11 samples

USGS Data Re-evaluation

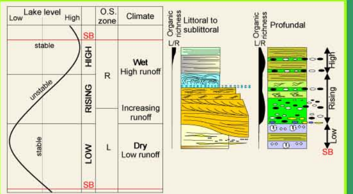
Fischer Assay Database:
- 782 sets of borehole for mapping in Petra
- Central Well USBM01-A:

Major-oxide concentrations analyzed by WDXRF.
Major-, minor-, and trace-element concentrations analyzed by ICP-AES

A-A', CORRELATION OF THE PICEANCE CREEK BASIN

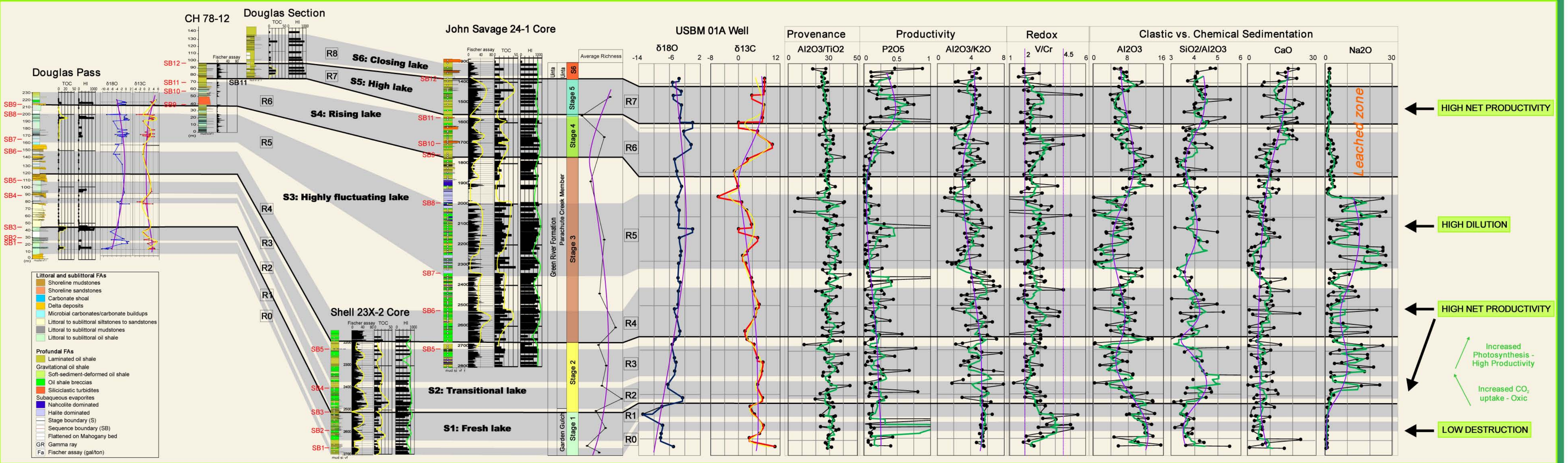


SEQUENCE STRATIGRAPHY MODEL

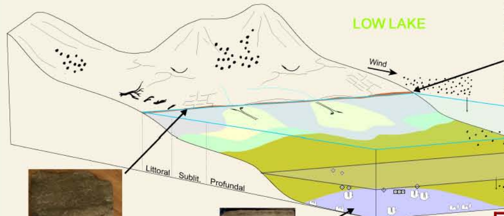


HL - High lake
RL - Rising lake
LL - Low lake
SB - Sequence boundary
TOC - Total Organic Carbon
OMT - Organic Matter Type

GEOCHEMISTRY AND ISOTOPE DATA OF THE PICEANCE CREEK BASIN



Arid climate → Low runoff → Low lake level → Lean oil shale



Halite

Intraclastic mudstone

Halite and nahcolite couplets and halite bottom growth

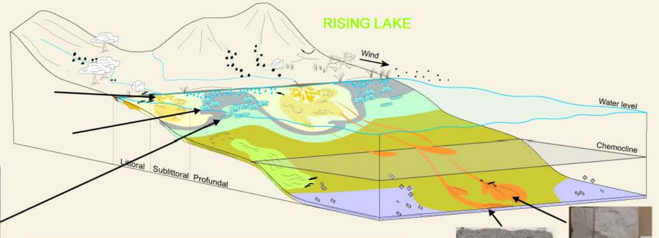
System tract		Production		Destruction		Dilution	Source Potential
Low lake	-	Few runoffs and thus less nutrient input	+	Few runoffs which restrict renewed oxygen supply	+	Detrital material trapped in the basin margin area	TOC: Low, average, with some thin layers of high quality source rock intervals. OMT: Algal (Type I)
	-	Extreme concentration of solutes kills organisms	+	Higher salinity enhances density stratification, prohibits oxygen circulation	-	Significant deposition of evaporites	
	-	Higher salinity enhance density stratification and prohibit nutrient circulation					

Increasing precipitation → Increasing runoff → Rising lake level → Lean to rich oil shale

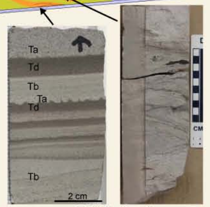
Sharp-based delta mouth bars

Microbial carbonate that grow on carbonate shoal

Parallel-laminated, thin sublittoral microbial carbonate



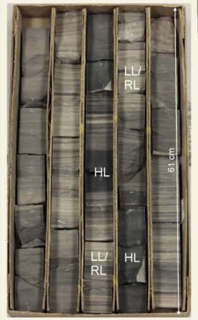
System tract		Production		Destruction		Dilution	Source Potential
Rising lake	+	Increasing runoff thus higher nutrient input	-	Fresh water input introduces oxygen, consumers	+	Abudant clastic detritus	TOC: Moderate to high, oil/gas prone, increasing trend towards maximum flooding surface. OMT: Mixed algal/terrigenous
			-	Increased turbulence			



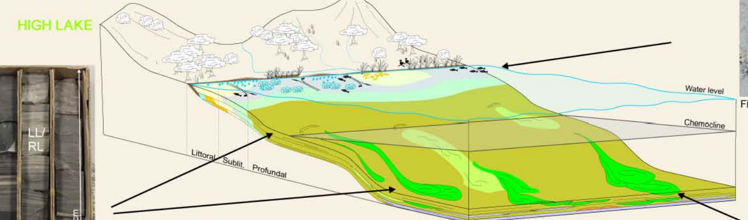
Turbidite deposits

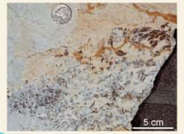
Laminated and disturbed oil shale

Humid climate → High runoff → High lake level → Rich oil shale



Laminated oil shale



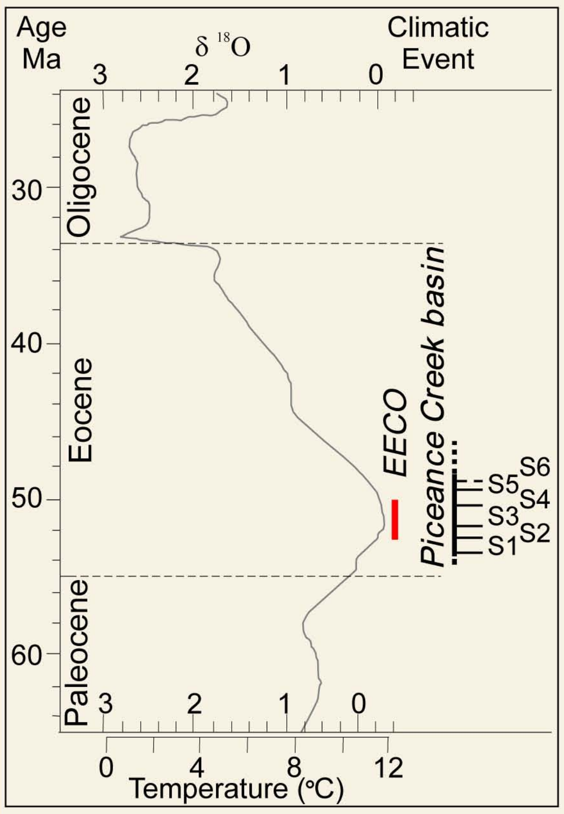


Fish remnants

Oil shale breccia

System tract		Production		Destruction		Dilution	Source Potential
High lake	+	Appreciable runoffs bring in nutrients	+	Larger amount of production consumes oxygen at bottom	+	Varying, but relatively minor clastic detritus	TOC: Moderate to high, excellent oil. OMT: Mostly algal
	+	Larger percent of lake volume in photic zone	+	Higher level chemocline			

EOCENE CLIMATE CURVE and LAKE STAGES



After Zachos et al. 2001

Lake Stages (S)	R/L zones	Description
S6. Closing lake	R8 L7	Progradation of siliciclastics from north to south.
S5. High lake	R7	Profundal, laterally continuous FAs dominate. Very rich oil shale.
S4. Rising lake	R6, L6	Increase of profundal FAs and laterally continuous depositional units. Richness increases upwards.
S3. Highly fluctuating lake	R5, L5 R4, L4	Highly cyclic units, laterally discontinuous depositional units. Clastic input decreases upwards within the Stage. Fluctuating richness, in places occur very rich oil shale intervals.
S2. Transitional lake	R3, L3 R2, L2 L1	High siliciclastic input, increasing cyclicity, laterally discontinuous depositional units. Changes in mineralogy. Fluctuating richness, in places occur very rich oil shale intervals.
S1. Fresh lake	R1 R0, L0	Beginning of large lake systems. Laterally continuous depositional units. Richness increases upwards.

Lake stages correlate well with the early to middle Eocene climate curve.

CLIMATE EFFECTS ON PRODUCTIVITY and DILUTION

Stage and Climate	Lake Condition	Net Productivity
S5 High lake *Cooling of the climate*	Significant runoff and high lake level. High chemocline.	High to moderate productivity, low destruction and dilution. R7 - 30 gal/ton
S4 Rising lake *Beginning of the cooling of the climate*	Increasing runoff and nutrient influx.	High to moderate productivity, moderate to high destruction. R6 - 24 gal/ton
S3 Highly fluctuating lake *Climate optimum*	Saline lake, halite deposition. Nutrient supply from periodic runoffs.	Moderate to high productivity, increasing dilution by evaporites. R5 - 21 gal/ton R4 - 36 gal/ton
S2 Transitional lake *Beginning of the climate optimum*	Increasing lake restriction and salinity. Beginning of stage is marked with increased siliciclastic input.	Moderate to high productivity and low destruction. Increasing evaporite dilution. R3 - 25 gal/ton R2 - 39 gal/ton
S1 Fresh lake *Warm up to the climate optimum*	Increasing lake restriction, fresh to brackish water. High runoff and nutrient input.	High productivity, moderate destruction. R1 - 27 gal/ton R0 - 21 gal/ton

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