

**PS Formation of Rich and Lean Oil Shale Deposits in the Eocene Green River Lake Basin - Link to Climate Changes: Piceance Creek Basin, Colorado, U.S.A.\***

**Kati Tänavsuu-Milkeviciene<sup>1</sup> and J. Frederick Sarg<sup>1</sup>**

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<sup>1</sup>Department of Geology & Geological Engineering, Colorado School of Mines, Golden, CO 80401, USA ([jsarg@mines.edu](mailto:jsarg@mines.edu))

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**Abstract**

Lake deposits formed in the Green River Formation in the Piceance Creek Basin (PCB) during the early to middle Eocene, comprise the Green River Formation, and are largely composed of kerogen-rich and kerogen-poor carbonates (rich and lean oil shale). Deltas, shoreline sandstones, carbonate shoals, and microbial carbonates formed in the littoral and sub-littoral areas, whereas fine-laminated, soft sediment disturbed, and brecciated oil shale deposits were deposited in deeper parts of the lake, perhaps in water depths on the order of 70-150 m. Six evolutionary lake stages and at least two levels of cyclicity occur in the PCB, and are bounded by sequence boundaries or correlative conformities. Formation of rich and lean oil shale zones is correlative with PCB stratigraphic cycles. The larger-scale lake stages characterize changes in vertical depositional trends, and are interpreted to have been controlled by a combination of climate and tectonics, whereas the smaller-scale, higher frequency cyclicity, and occurrence of rich and lean oil shale appear controlled by the climatically variations in runoff and vegetation.

Lake stages are defined as: S1-Fresh to Brackish Lake, S2-Stable Restricted Lake, S3-Rapidly Fluctuating Lake, S4-Rising Lake, S5-High Lake, and S6-Closing Lake. Lake stages indicate an overall lake evolution and correlate well with the long-term climate curve during the early to middle Eocene. We suggest that the Stage 1 formed during the warming phase of the climate optimum and represents the basin evolution from fresh to brackish lake conditions. PCB changed during the Stage 1 from an open lake to a closed lake basin that indicates a change from abundant rainfall and high runoff, to somewhat more seasonal and dryer climate. Increased seasonality and flashy runoff began during Stage 2, indicating restricted lake conditions, and peaked during Stage 3, at the maximum of the climate optimum when more arid conditions prevailed. This is well illustrated by a rapidly fluctuating lake (S3) that contains thick evaporite intervals deposited in high frequency cycles, and containing

thin, very rich oil shale beds. The ensuing lake level rise (Stage 4) and high lake (Stage 5) indicate cooling of climate that was likely accompanied by more humid conditions, and an increase in the precipitation. Stages 4 and 5 correlate well with cooling part of the Eocene climate curve and contain thick, widespread profundal deposits, and thick, rich oil shale beds. The closing of the lake (Stage 6) was marked by the continued occurrence of a deep, stratified lake system. Relatively continuous sandstone inflow into the lake eventually filled the lake and suggests increased humidity and runoff that coincides with overall middle Eocene cooling climate curve as well as increased tectonic activity in provenance areas.

Higher frequency cyclic deposition is marked, in many places, by abrupt changes in lithofacies and oil shale richness. Sequence boundaries and their correlative conformities separate rich oil shale zones from lean oil shale zones, and are marked by rapid changes in runoff and vegetation. Sequence boundaries are followed by fine-grained, kerogen-poor oil shale zones that suggest low vegetation and low runoff. Finely-laminated oil shale and evaporite deposits dominate in deeper lake areas. Increased runoff during the rising lake level is marked by progradation of shoreline sandstones and deltaic deposits. Microbial and shoaling oolitic and intraclastic lime grainstones occur above and adjacent to clastic input areas. Subsequent high runoff and high vegetation is marked by rich oil shale zones formed during the high lake levels. These profundal units are composed of gravity flow brecciated, and laminated oil shale deposits.

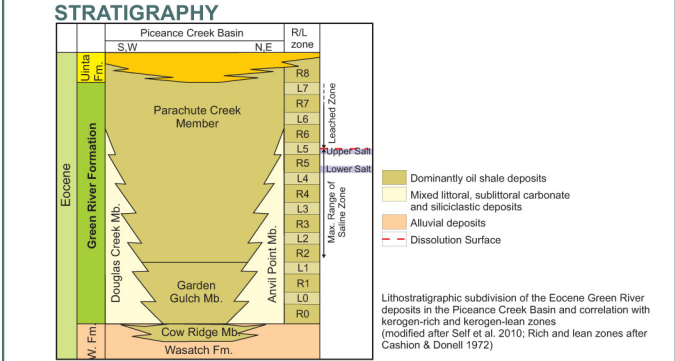
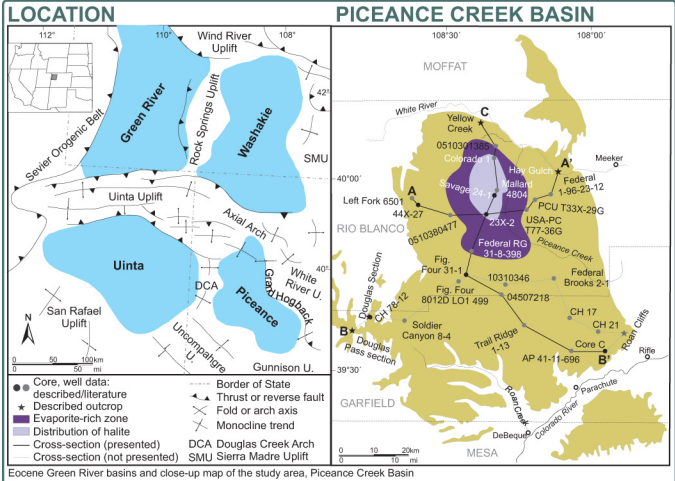


**ABSTRACT**

Lake deposits formed in the Green River Formation in the Piceance Creek Basin (PCB) during the early to middle Eocene, comprise the Green River Formation, and are largely composed of kerogen-rich and kerogen-poor carbonates (rich and lean oil shale). Deltas, shoreline sandstones, carbonate shoals, and microbial carbonates formed in the littoral and sublittoral areas, whereas fine-laminated, soft sediment disturbed, and brecciated oil shale deposits were deposited in deeper parts of the lake, perhaps in water depths on the order of 70-150 m. Six evolutionary lake stages and at least two levels of cyclicity occur in the PCB. Formation of rich and lean oil shale zones is correlative with PCB stratigraphic cycles. The larger-scale lake stages characterize changes in vertical depositional trends, and are interpreted to have been controlled by a combination of climate and tectonics, whereas the smaller-scale, higher frequency cyclicity, and occurrence of rich and lean oil shales appear to be controlled by the climatically variations in runoff and vegetation.

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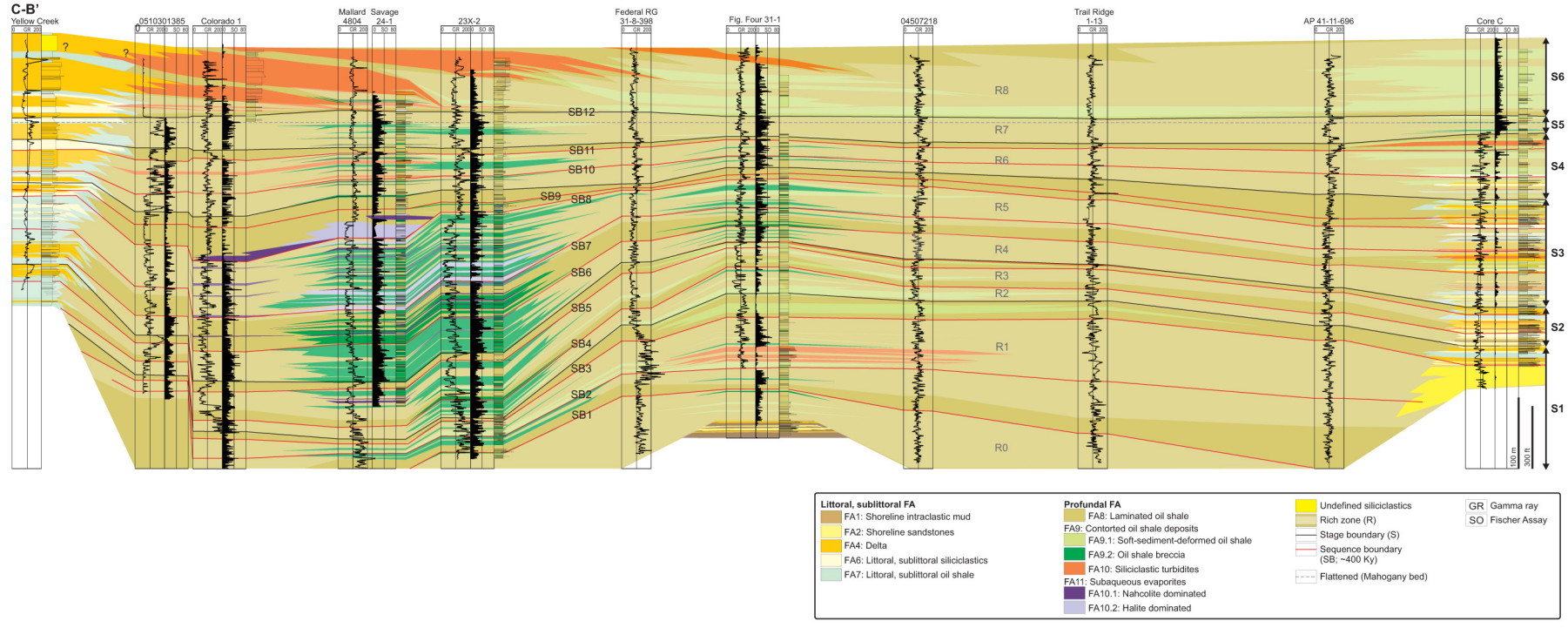
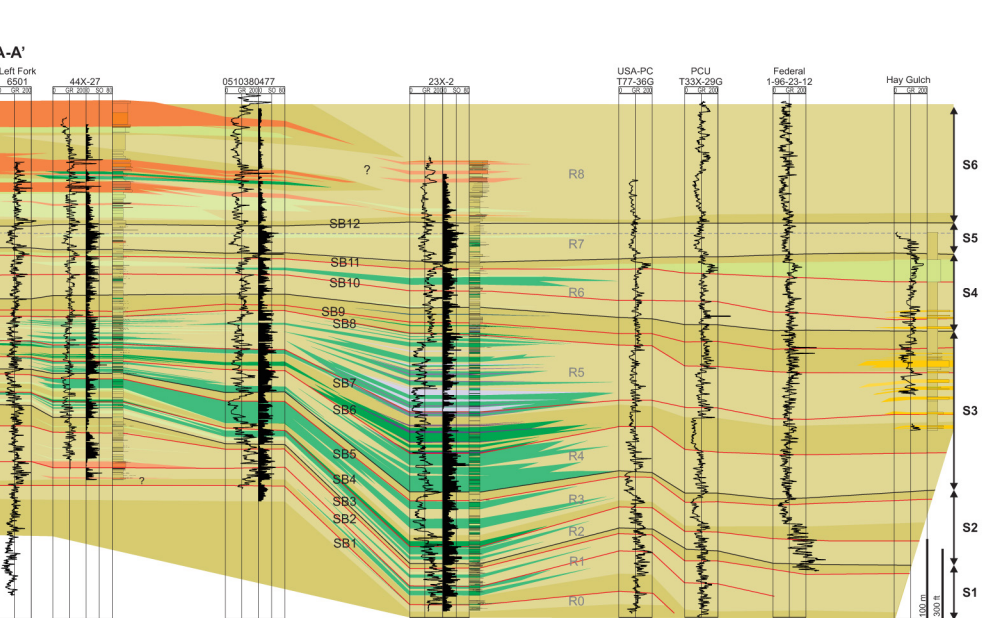
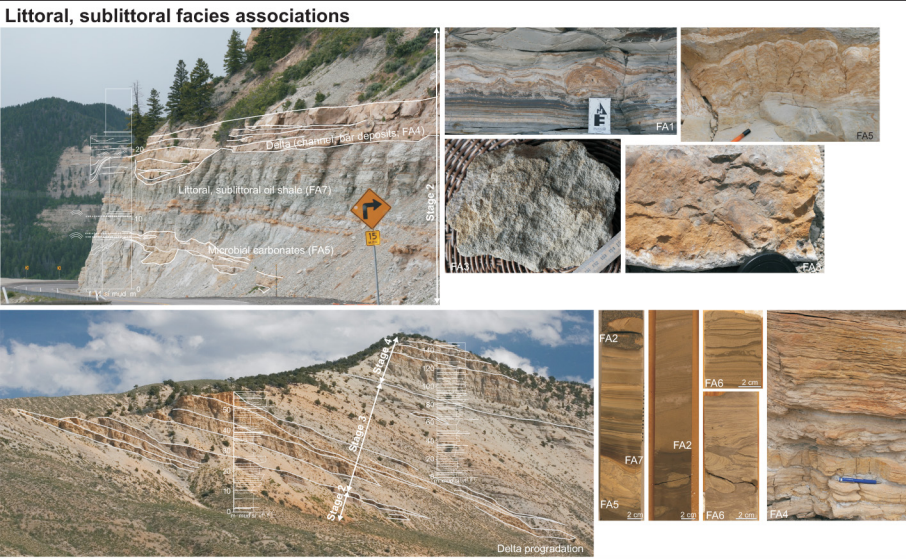
Higher frequency cyclic deposition is marked, in many places, by abrupt changes in lithofacies and oil shale richness. Sequence boundaries and their correlative conformities separate rich oil shale zones from lean oil shale zones, and are marked by rapid changes in runoff and vegetation. Sequence boundaries are followed by fine-grained, kerogen-poor oil shale zones that suggest low vegetation and low runoff. Finely-laminated oil shale, and evaporite deposits dominate in deeper lake areas. Increased runoff during the rising lake level is marked by progradation of shoreline sandstones and deltaic deposits. Microbial and shoaling oolitic and intraclastic lime grainstones occur above and adjacent to clastic input areas. Subsequent high runoff and high vegetation is marked by rich oil shale zones formed during the high lake levels. These profundal units are composed of gravity flow brecciated, and laminated oil shale deposits.



**RESULTS**

**FACIES ASSOCIATIONS**

Lake Zone	Facies Association (FA)	Description
Littoral, sublittoral	FA1: Shoreline intraclastic mud	Intraclastic mudstones, microbial carbonates, and laminated, homogeneous mudstones and siltstones. In places, crumbly structured mudstones
	FA2: Shoreline sandstones	Low-angle cross-stratified, hummocky and swaley cross-bedded, normally graded or amalgamated fine- to coarse-grained sandstones. In places, wave-ripple laminated fine-grained sandstones. Occur carbonate clasts organic rip-ups, shell and plant fragments
	FA3: Carbonate shoal	Massive, plane-parallel, or cross-stratified, coated carbonate grainstones and coquina deposits. Carbonate grainstones consists of well to very well sorted ooids with ostracode cores, pisoids, and peloids. Conquina beds are composed of bivalve and gastropod shells
	FA4: Delta	Wave, climbing, and current-ripple laminated, plane-parallel, and trough cross-stratified very fine- to fine-grained sandstones. Laterally discontinuous, in places with erosional lower boundary. Occur mudstone clasts, dewatering structures, soft sediment deformations
	FA5: Microbial carbonates	Thinly laminated (mm to cm in scale) limestones interbedded with boundstones with shrub-like features, and massive limestones displaying clotted fabric. Occur as laterally continuous horizontal layers, and beds, or laterally discontinuous columns, with well developed domal heads. Deposits are porous due the fenestral porosity, vuggy deposits, and interparticle porosity
Profundal	FA6: Littoral, sublittoral siliclastics	Parallel-laminated, wave ripple-laminated, and current ripple-laminated mudstones and siltstones, interbedded with very fine- to fine-grained sandstones. Occur small- and large-scale soft sediment deformations, dewatering structures, and syneresis cracks
	FA7: Littoral, sublittoral oil shale	Finely laminated silt rich oil shales, in places disrupted, wavy-lamination. Occur, mm thick siltstone to very fine-grained sandstone layers and lenses, ooids, fish scales, and plant fragments
	FA8: Laminated oil shale	Rhythmically laminated light brown, black or gray mm-thick lamina of oil shale. In places, bedding is sharply constricted, giving a morphology of loops or links of a chain, i.e. loop bedding
	FA9.1: Soft-sediment-disturbed oil shale	Composed of soft sediment folds and overturned strata. The scale of deformed deposits varies between several mm to a meter
	FA9.2: Oil shale breccia	Matrix supported oil shale deposits contain angular, subangular, and subrounded carbonate and siliclastic clasts, and organic clasts. The clasts preserve primary lamination. Occur evaporite rip-ups and normal grading. The boundary with underlying and overlying deposits can be sharp or gradational
	FA10: Siliclastic turbidites	Dominantly structureless, in places, cross-stratified siltstones up to medium-grained sandstones. Occur soft sediment deformations, load casts, flame structures, oil shale and organic material rip-ups. Very well sorted
	FA11.1: Nahcolite dominated subaqueous evaporites	Laminated tan to light brown crystal accumulations, in-sediment growths, and black, diagenetic nodules of nahcolite
	FA11.2: Halite dominated subaqueous evaporites	Clear to gray crystal cubes, hopper crystals, and bottom growth of halite. Form couplets with nahcolite



- Littoral, sublittoral FA**
- FA1: Shoreline intraclastic mud
  - FA2: Shoreline sandstones
  - FA4: Delta
  - FA6: Littoral, sublittoral siliclastics
  - FA7: Littoral, sublittoral oil shale
- Profundal FA**
- FA8: Laminated oil shale
  - FA9: Contorted oil shale deposits
  - FA9.1: Soft-sediment-deformed oil shale
  - FA9.2: Oil shale breccia
  - FA10: Siliclastic turbidites
  - FA11: Subaqueous evaporites
  - FA11.1: Nahcolite dominated
  - FA11.2: Halite dominated
- Legend**
- Undefined siliclastics
  - Rich zone (R)
  - Stage boundary (S)
  - Sequence boundary (SB; ~400 Ky)
  - Flattened (Mahogany bed)
  - GR Gamma ray
  - SO Fischer Assay

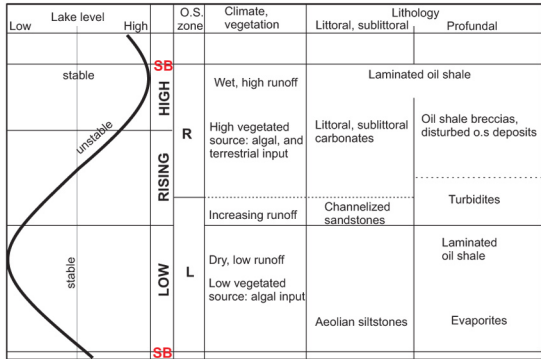
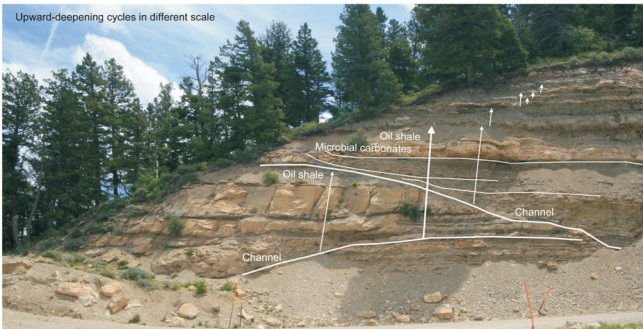


RESULTS  
LAKE STAGES

Lake Stage	Description	Zone w/mean, max (gal/ton)		Lake Types (for comparison)
Stage 6: Closing Lake	Siliciclastic deposits from the Uinta Fm. are interbedded with laminated and disturbed oil shale deposits. Nahcolite nodules in the southern part of the basin. Siliciclastic deposition prograde from north to south. This suggests the progradation of the Uinta Fm. sandstones and closing of the lake basin	Upper oil shale beds, R8, L7: Mean 18, Avg. Max 31.2	Tectonically influenced: high vulcanoclastic material input.	Overfilled
Stage 5: High Lake	Profundal facies associations dominate in lake section. This suggests overall widening of the lake area and possible high lake level. Thick, continues, and rich oil shale units formed in the lake. Nahcolite nodules occur. This suggests stratified lake conditions	R7/Mahogany: Mean 29.2, Avg. Max 56		Balanced-filled
Stage 4: Rising Lake	Increase of profundal facies associations in the whole basin area. Thickness of depositional units increase and they form laterally continues units	L6: Mean 6.2, Avg. Max 11.1 R6: Mean 24.7, Avg. Max 56	Dominantly climate influence	Underfilled
Stage 3: Rapidly Fluctuating Lake	Highly cyclic depositional units formed from relatively thin beds compared with other lake stages. Abundant oil shale breccia beds that form laterally discontinues oil shale breccia units due to the deposition as slump and slide deposits. Highly cyclic depositional units indicate unstable lake conditions caused by rapid changes in background climate system. Formed very rich oil shale beds that are separated with very lean beds and bedded evaporites. Richest oil shale beds formed as oil shale breccia beds	L5: Mean 14.9, Avg. Max 37.5 R5: Mean 20.9, Avg. Max 55.7 L4: Mean 17.7, Avg. Max 39.4 R4: Mean 31, Avg. Max 66.9		Balanced-filled
Stage 2: Restricted lake	First occurrence of evaporites, nahcolite crystal accumulations and diagenetic nodules. High siliciclastic input to the marginal areas that possibly affected the forming of oil shale deposits in the deeper part of the basin and resulted in somewhat leaner oil shale deposits	L3: Mean 14.9, Avg. Max 27.3 R3: Mean 19.6, Avg. Max 38 L2: Mean 13.4, Avg. Max 27.9 R2: Mean 23.5, Avg. max 40.8		
Stage 1: Fresh to Brackish Lake	Forming of one single lake. Intensive river inflow and siliciclastic turbidites with organic rip-ups	L1: Mean 10.2, Avg. Max 23.9 R1: Mean 22.9, Avg. Max 53.7 L0: Mean 8.6, Avg. Max 19.1 R0: Mean 16.4, Avg. Max 27.4		

Lake Stages characterize large-scale changes in sedimentological pattern and depositional trend that are controlled by a combination of climate and tectonics and indicate the overall evolutionary trend in the Piceance Creek Basin.  
Lake Types after Bohacs et al. 2000

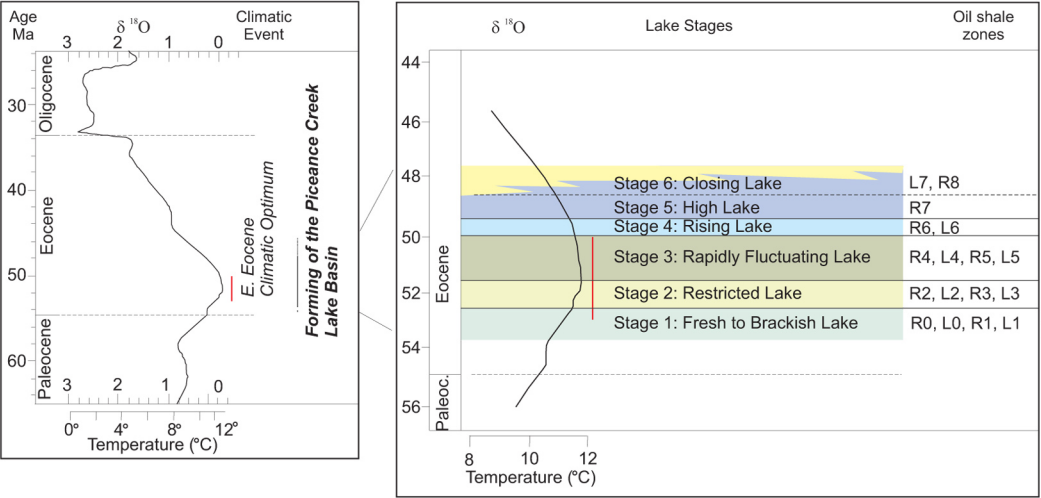
Climate has similar affect to both, smaller-scale and larger-scale cycles



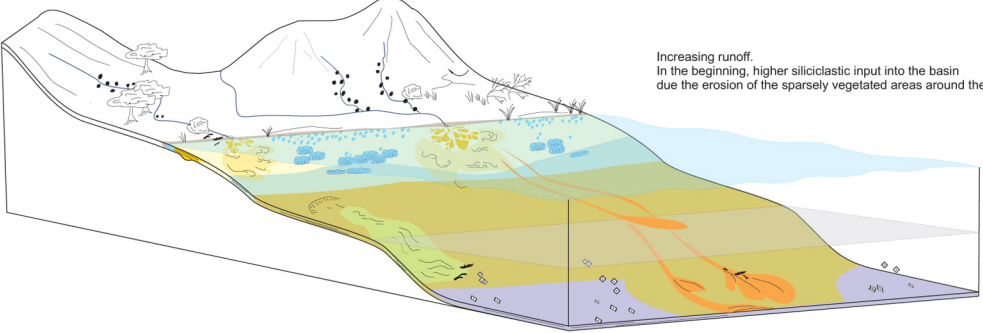
Stage	R/L zone		
	I Order	II Order	
S6	U/R8	U/R8	L
		400 ky L7/A-Groove SB12	R
S5	7	R	R
			L
			L
			R
S4	6	L6/B-Groove SB11	L
		R	R
		SB10	L
			R
S3	5	L	L
		SB9	L
		SB8	L
		R	R
S2	4	SB7	L
		L	R
		SB6	L
		R	R
S1	3	L	L
		SB5	R
		R	R
		L	L
S1	2	L	L
		SB4	R
		R	R
		L	L
S1	1	L	L
		SB3	R
		R	R
		L	L
S1	0	L	L
		SB2	R
S1		L	L
		SB1	R

Numbers for rich and lean oil shale zones after Cashion & Donnell 1972. Smaller-scale rich and lean zones are based on changes of the fischer assay logs

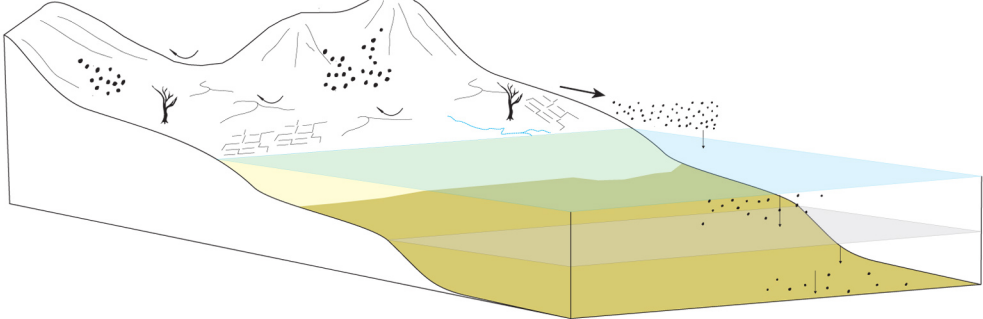
EOCENE CLIMATE AND LAKE STAGES



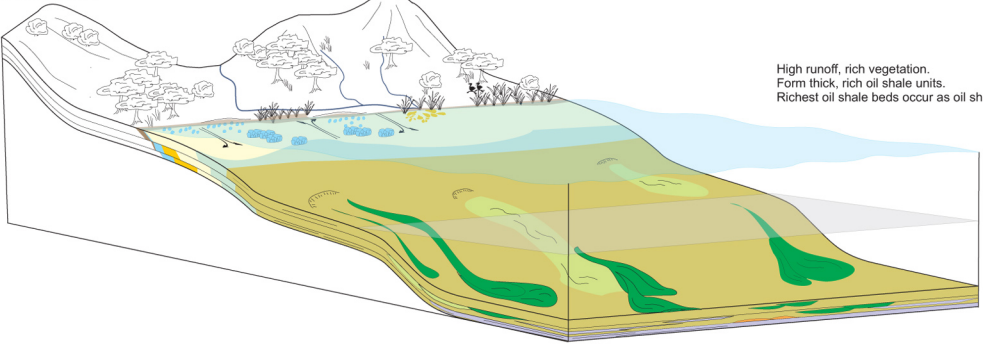
RISING LAKE



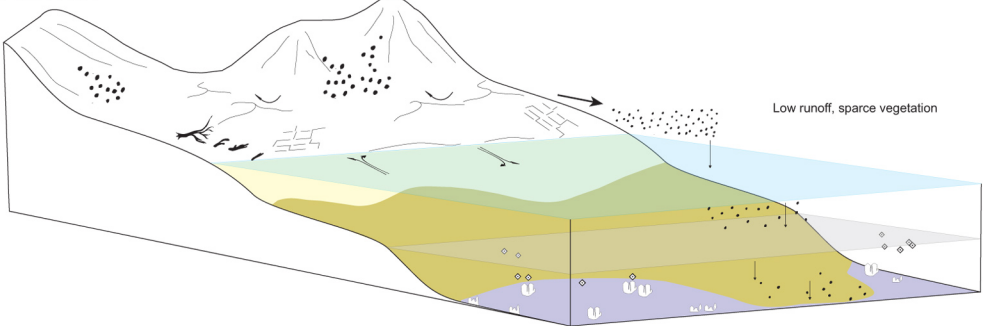
LAKE DURING SEQUENCE BOUNDARY



HIGH LAKE



LOW LAKE



CONCLUSIONS

Large-scale changes in the basin, Lake Stages, are controlled by both, climate and tectonics changes.

Smaller-scale cyclicity and occurrence of rich and lean zones are controlled by climate changes.

Tectonics affected the provenance, and the changes of siliciclastic input areas during the lake evolution.

Eocene climate changes affected the depositional trends, runoff, and transport of nutrients and siliciclastic material into the basin.

REFERENCES

Bohacs, K.M., Carroll, A.R., Neal, J.E. and Markiewicz, P.J. 2000. Lake-basin type, source potential, and hydrocarbon character: an integrated sequence-stratigraphic-geochemical framework. In: Lake basins through space and time (Eds E.H. Gierlowski-Kordesch and K.R. Kelts). AAPG Studies in Geol., 46, 3-34.  
Cashion, W.B. and Donnell, J.R. 1972. Chart showing correlation of selected key units in the organic-rich sequence of the Green River Formation, Piceance Creek Basin, Colorado, and Uinta Basin, Utah, US Geol. Surv. Oil and Gas Investigations, Chart OC-65.  
Self, J.G., Johnson, R.C., Brownfield, M.E. and Mercier, T.J. 2010. Stratigraphic Cross Sections of the Eocene Green River Formation in the Piceance Creek Basin, Northwestern Colorado. US. Geol. Surv. Digital Data Series, DDS-69-Y, Chp. 5, 7 pp.  
Smith, M.E., Carroll, A.R. and Singer, B.S. 2008. Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States. Geol. Soc. Am. Bull., 120, 54-84.  
Smith, M.E., Chamberlain, K.R., Singer, B.S. and Carroll, A.R. 2010. Eocene clocks agree: Coeval 40Ar/39Ar, U-Pb, and astronomical ages from the Green River Formation. Geology, 38, 527-530.

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