PS Sequence Stratigraphy, Climate, and Organic-Richness: Green River Formation, Lake Uinta, Colorado*

Kati Tänavsuu-Milkeviciene[1], J. Frederick Sarg[1], Jufang Feng[1], Suriamin Huang[2], and Yuval Bartov[3]

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Editor's note: Please view a companion article by Jufang Feng, J. Frederick Sarg, Kati Tänavsuu-Milkeviciene, and Suriamin Huang, entitled "Climate History, and Lake Evolution Controls on Oil Shale Organic Richness-Green River Formation, Piceance Creek Basin," Search and Discovery Article #50688 (2012).

[1]Colorado School of Mines, Golden, Colorado, U.S.A. (ktanavas@mines.edu; jsarg@mines.edu; jfeng@mines.edu)
[2]ExxonMobil, Jakarta, Indonesia
[3]Israel Energy Initiatives, Jerusalem, Israel

Abstract

The Green River Formation in the Piceance Creek basin is comprised of kerogen-rich and kerogen-poor mudstones i.e. oil shales, siliciclastics, and carbonates, formed in a deep (10's of meters), stratified lake environment. Small-scale (meters thick) and large-scale (10's meters thick) depositional cycles are composed of deepening-upward depositional sequences that mark abrupt changes in lithofacies and oil shale richness. Cyclicity is controlled by variations in runoff and vegetation that influence the inflow of siliciclastics and nutrients, and therefore also the distribution of facies and formation of organic-rich deposits. Cycles are bounded by sequence boundaries and correlative conformities, and are divided into units that represent low, rising, and high lake levels. During times of low runoff, lake level was low, vegetation decreased, fewer nutrients were brought into the lake, and lean oil shales formed. Thin marginal deposits formed during low lake level, and at times, evaporite deposition occurred in the deeper part of the basin. During the change to a wetter period, runoff increased and nutrient input increased. The rising lake level is, in many places, marked by delta front sandstones on the lake margin. Microbial and shoaling grainstones occur above and adjacent to the sand input areas. In the profundal area, rich oil shale breccias, as gravity flow deposits, formed. Subsequent wet periods increased vegetation and runoff, bringing high lake levels, and increased nutrients, resulting in rich oil shales. Profundal units are composed of gravity flow and laminated oil shale deposits. Correlating cycles to published age dates, the large-scale cycles are interpreted to represent 400ky eccentricity cycles. Published early Eocene hypothermals correlate with five of these sequence boundaries. The small-scale cycles may be a combination of the 100ky eccentricity and 25ky precession cycles.

Depositional cycles are grouped into lake evolution stages that reflect longer-term changes in the basin, controlled by both climate and tectonics. Stage 1, Fresh Lake, was deposited during decreasing tectonic activity and increasing climate control. Climate dominated Lake Stages 2 and 3,

Transitional and Rapidly Fluctuating Lakes. These stages are characterized by high frequency cyclicity. Stages 4, 5, and 6, Rising, High, and Closing Lakes record the change to a wet climate and tectonic activity, resulting in increasing siliciclastic input and closing of the lake.

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ABSTRACT

The Green River Formation in the Lake Uinta (Colorado) is comprised of kerogen-rich and kerogen-poor mudstones i.e. oil shales, siliciclastics, and carbonates, formed in a deep (10's m), stratified lake environment. Small-scale (meters) and large-scale (10's meters) depositional cycles are composed of deepening-upward depositional sequences that mark abrupt changes in lithofacies and oil shale richness. Cyclicity is controlled by variations in runoff and vegetation that influence the inflow of siliciclastics and nutrients, and therefore also the distribution of facies associations and formation of organic-rich deposits. Cycles are bounded by sequence boundaries and correlative conformities, and are divided into units that represent low, rising, and high lake levels. During times of low runoff, lake level was low, vegetation decreased, fewer nutrients were brought into the lake, and lean oil shales formed. Thin marginal deposits formed during low lake level, at times, evaporite deposition occurred in the deeper part of the basin. During the change to a wetter period, runoff increased and nutrient input increased. The rising lake level is, in many places, marked by delta front sandstones on the lake margin. Microbial and shoaling grainstones occur above and adjacent to the clastic input areas. In the profundal area, rich oil shale breccias, as gravity flow deposits formed. Subsequent wet periods increased vegetation and runoff, bringing high lake levels, and increased nutrients, resulting in rich oil shales. Profundal units are composed of gravity flow and laminated oil shale deposits. Correlating cycles to published age dates, we interpret the large-scale cycles to represent 400 ky eccentricity cycles. Published early Eocene hyperthermals correlate with five of these sequence boundaries. The small-scale cycles may be a combination of the 100 ky eccentricity and 25 ky precession cycles.

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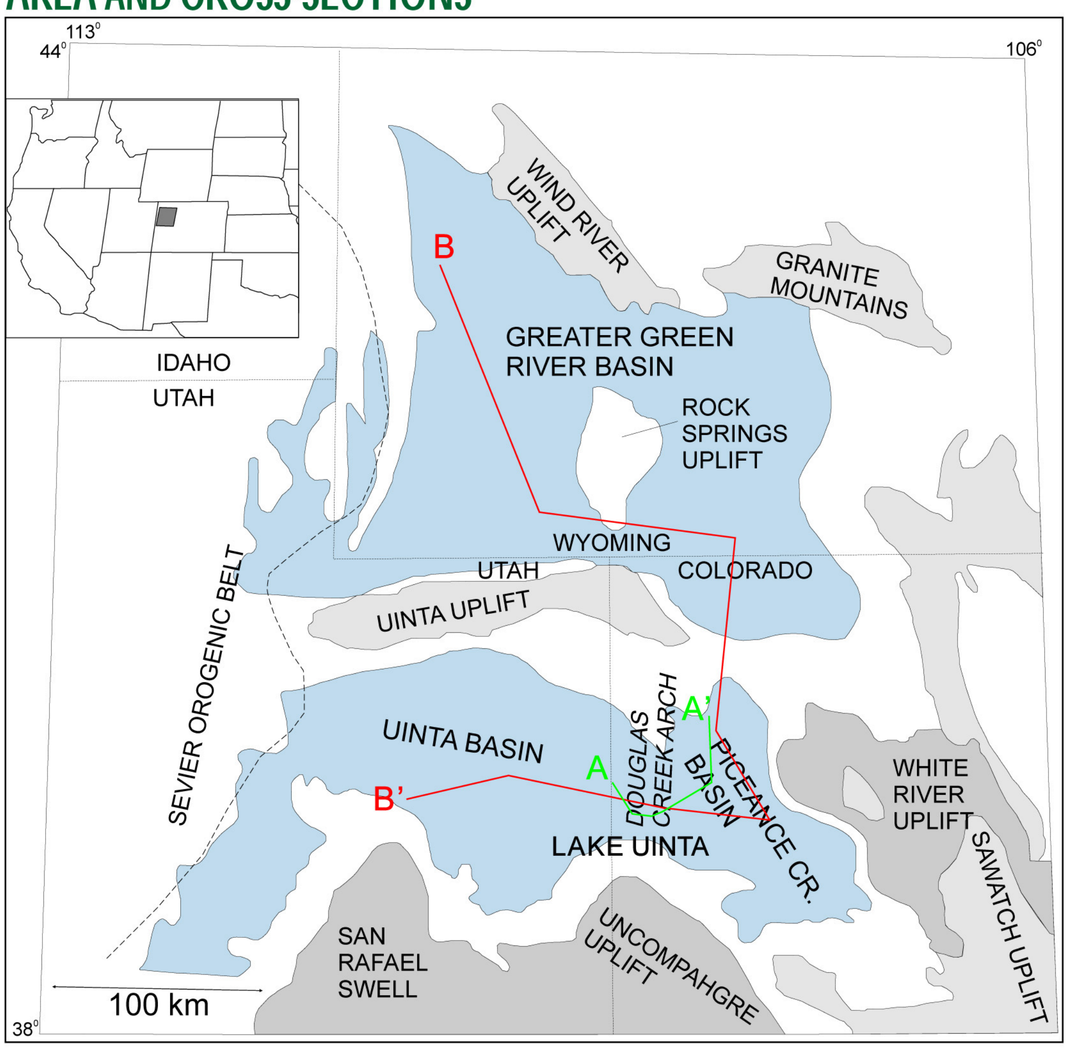
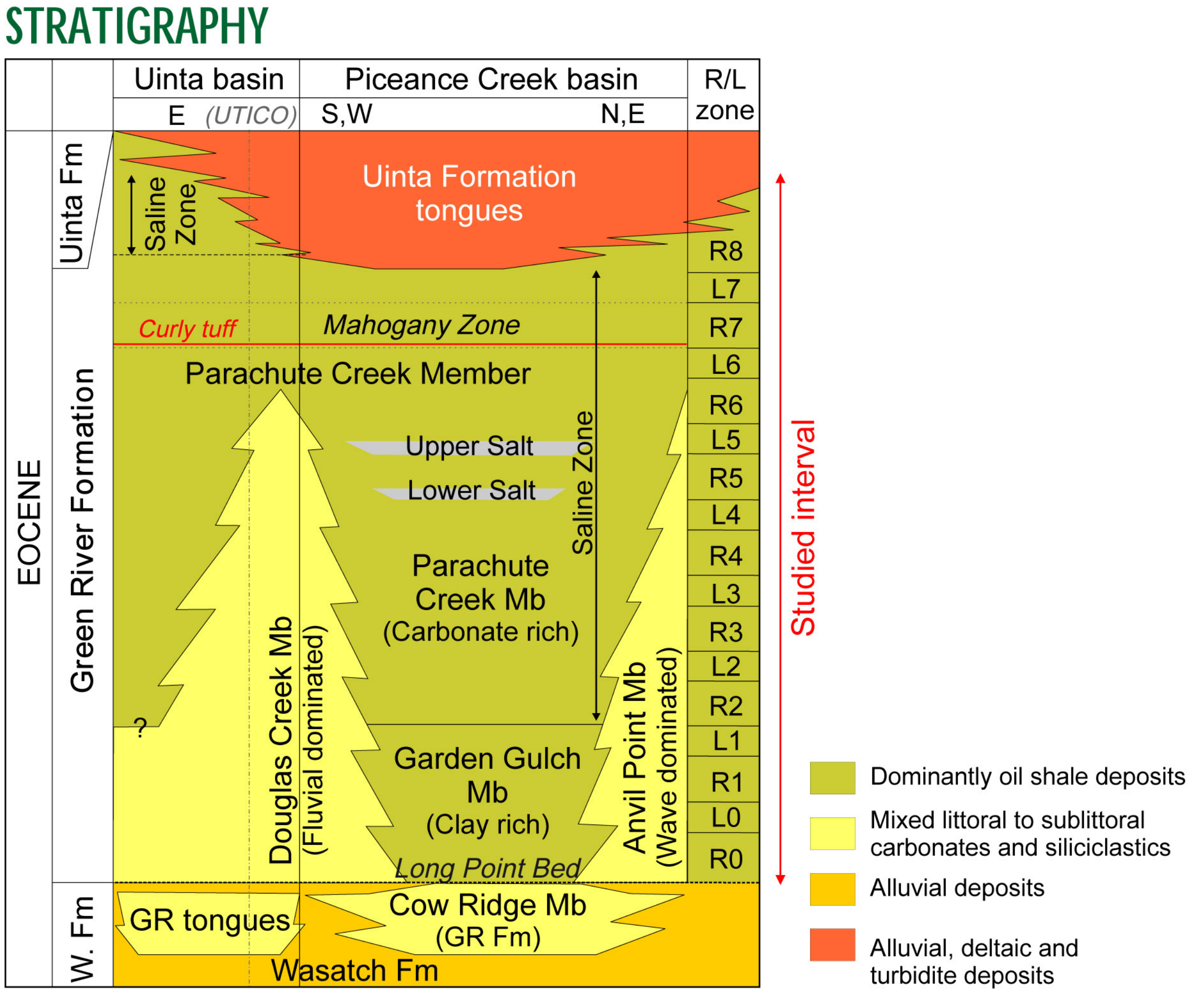
AREA AND CROSS-SECTIONS



STRATIGRAPHY



After Johnson 1984; Vanden Berg 2008; Self et al. 2010a; Tänavasuu-Milkeviciene & Sarg *in press*

Background

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

Deposition of the Green River Formation occurred during the early to middle Eocene (53 to 44 Ma) (Smith et al. 2010).

Lakes formed in the mid-latitude warm to temperate climate (Sewall & Sloan 2006).

The Piceance Creek and Uinta basins form a larger lake, the Lake Uinta.

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%)

COSTAR

MINES

Sequence Stratigraphy, Climate, and Organic-Richness: Green River Formation, Lake Uinta, Colorado

Kati Tänavsuu-Milkeviciene*[1], J. Frederick Sarg[1], Jufang Feng[1], Suriamin Huang[2], and Yuval Bartov[3]

[1]Department of Geology & Geological Engineering,
Colorado School of Mines, Golden, Colorado, U.S.A.*(ktanavas@mines.edu)
[2]ExxonMobil, Jakarta, Indonesia; [3]Israel Energy Initiatives, Jerusalem, Israel

MAIN QUESTIONS

1. Forming of rich and lean oil shale deposits. How and why?

2. Lateral and vertical variation of rich and lean oil shale deposits, margin versus deeper part of the basin. Climate influence.

3. Build sequence stratigaphical model for the organic-rich lake deposits.

Depositional units

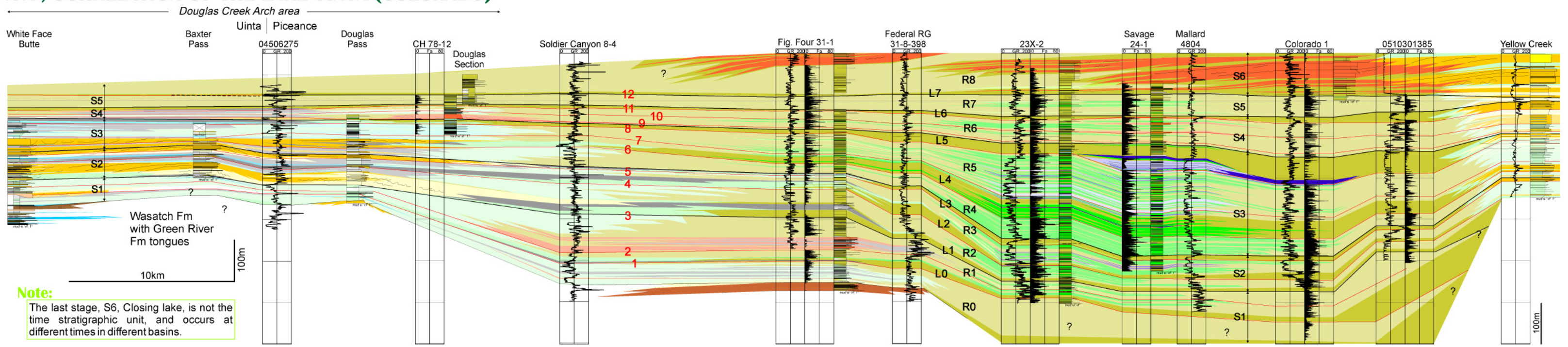
Deposition is characterized by complex upward-deepening cycles in which individual facies associations prograde or aggrade (see sections and photos).

Most prominent depositional units form as 400ky eccentricity cycles, marked with sequence boundaries (SB1 to 12 on cross-section and lake model). These sequence boundaries are correlated over whole study area.

Small-scale and large-scale depositional units form in similar way (see sequence stratigraphy model), and represent changes in inflow and nutrient input i.e. fluctuation between dry and humid climate periods.

During the basin evolution, two types of depositional units formed.
During Stages 1, 4 to 6, homogeneous, laterally continuous depositional units dominated.
During Stages 2 and 3, heterogeneous, laterally discontinuous depositional units dominated.

A-A', CORRELATION OF THE LAKE UINTA (COLORADO)



Note: The last stage, S6, Closing lake, is not the time stratigraphic unit, and occurs at different times in different basins.

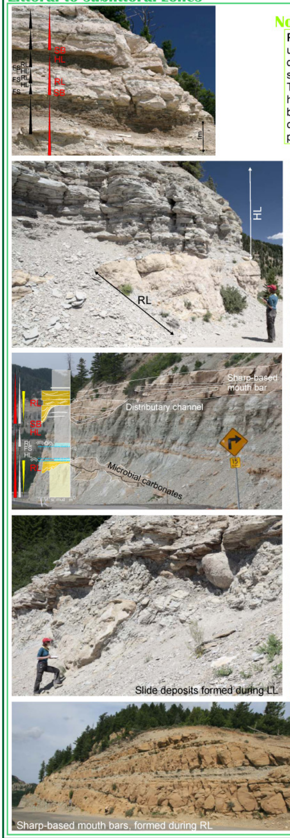
Depositional trends along the basin margin

Note:
Rich zones thin towards the basin margin and interfinger with the leaner zones (see cross-section).

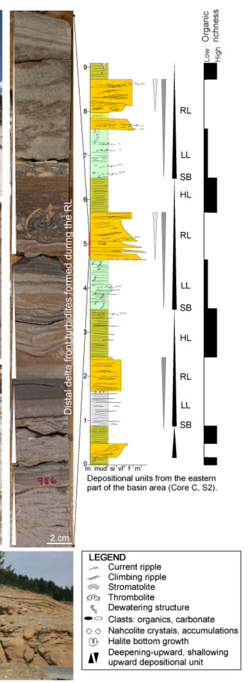
Upper portion of the rich zone forms correlative unit that can be traced into lean oil shale unit or siliciclastic/carbonate mudstone units along the basin margin sections.

In places, correlative rich unit is marked only with the thin siliciclastic mudstones that formed on the upper part of the deepening-upward depositional unit.

Littoral to sublittoral zones



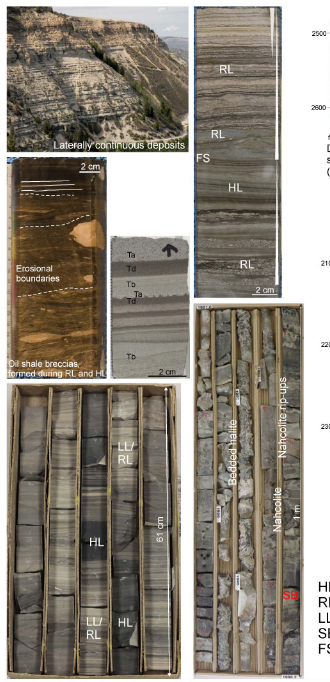
Note: PHOTOS: Different scale deepening-upward and shallowing-upward depositional units are marked with separate colors. The color of letters for low, rising, and high lake levels, sequence boundaries, and flooding surfaces corresponds to the color of the particular depositional unit.

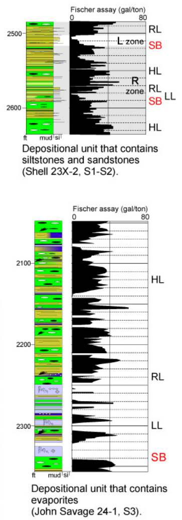


Profundal zone

Differences within the depositional units in the profundal zone

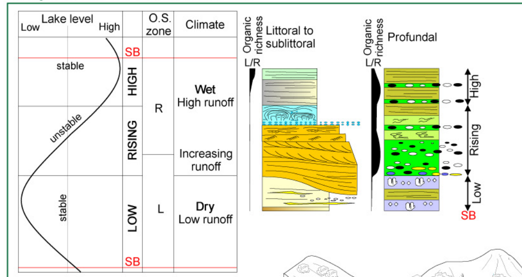
Two types of profundal depositional units formed.
1. Contains thin layers and/or beds of siltstones and sandstones, formed during LL and RL as turbidites or fall-out deposits.
(Stages 1, 4 to 6 in the Piceance portion of the basin.)
2. Contains evaporite crystals or beds, formed during LL.
(Stages 2 and 3 in the Piceance portion of the basin.)





HL - High lake
RL - Rising lake
LL - Low lake
SB - Sequence boundary
FS - Flooding surface

SEQUENCE STRATIGRAPHY



HL - High lake level occurs during humid climate period and coincides with high runoff and high nutrient input.

RL - Beginning of climate change from dry to humid is marked with the rapid increase in runoff and inflow of nutrients and sediments. Beginning of rising lake is characterized with extensive erosion along the lake margins. In the deeper part of the basin, rising lake is marked with the rapid increase of oil shale richness.

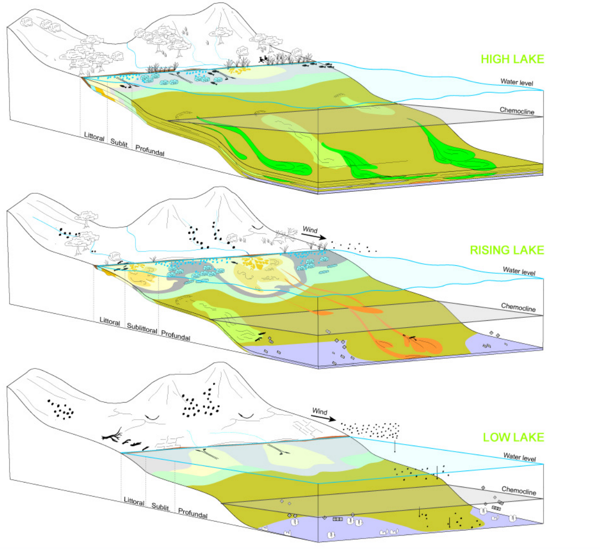
LL - During dry climate period runoff is low. Due the low runoff, nutrient and sediment input into the lake decreases, resulting in low productivity and lean oil shale deposits.

Littoral and sublittoral FAs
Shoreline mudstones
Shoreline sandstones
Carbonate shoal
Delta deposits
Microbial carbonates/carbonate buildups
Littoral to sublittoral siltstones to sandstones
Littoral to sublittoral mudstones
Littoral to sublittoral oil shale

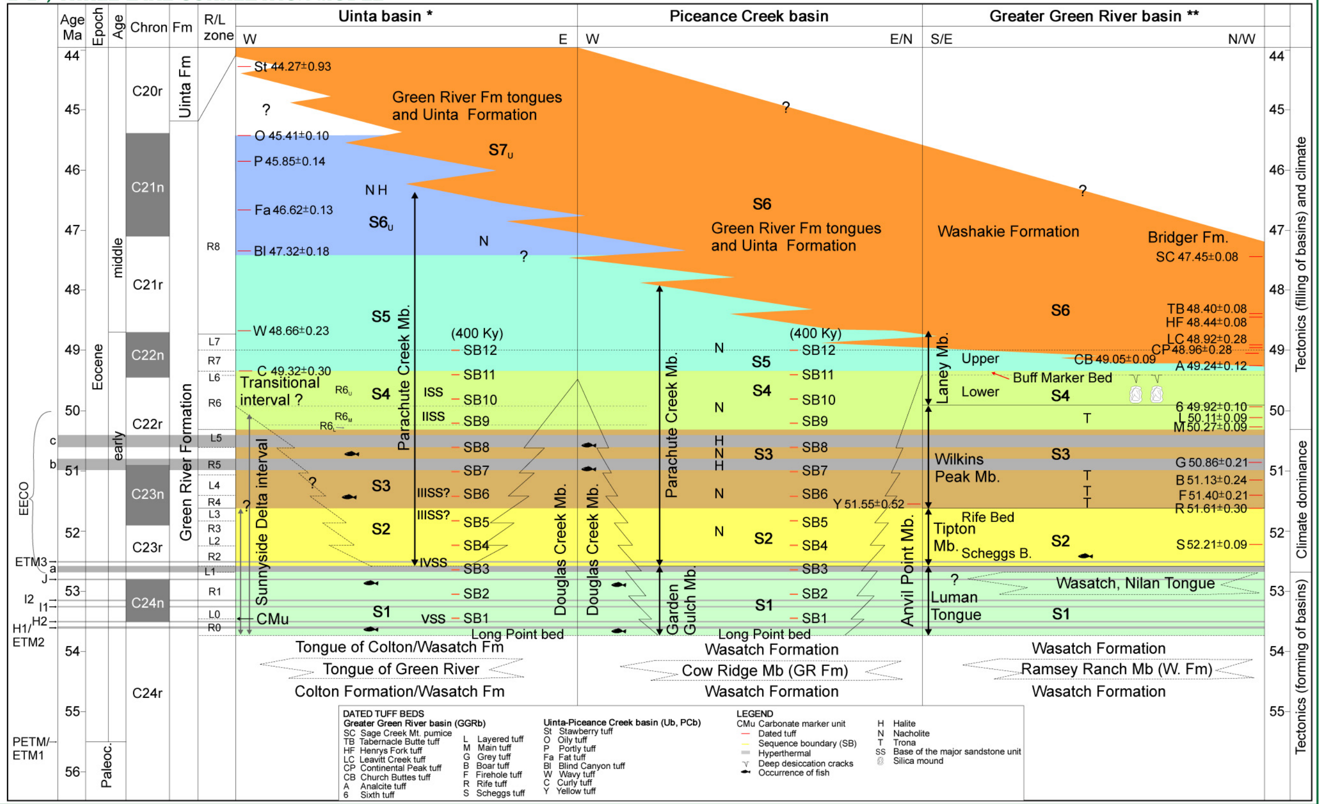
Profundal FAs
Laminated oil shale
Gravitational oil shale
Soft-sediment-deformed oil shale
Oil shale breccias
Siliciclastic turbidites
Subaqueous evaporites
Nahcolite dominated
Halite dominated
Stage boundary (S)
Flattened on Mahogany bed
GR Gamma ray
Fa Fischer assay (gal/ton)

Stages (S)
S1: Fresh lake
S2: Transitional lake
S3: Highly fluctuating lake
S4: Rising lake
S5: High lake
S6: Closing lake

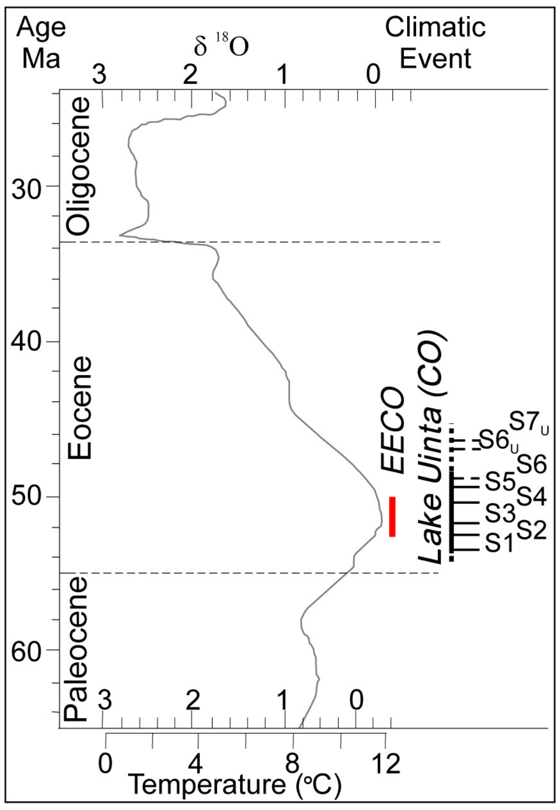
L0-L7 Oil-lean zones
R0-R8 Oil-rich zones
1-12 Sequence boundaries



B-B', THREE LAKE CORRELATION MODEL



EOCENE CLIMATE CURVE AND LAKE STAGES



After Zachos et al. 2001

Lake Stages (S)	R/L zones	Description
$S7_U$. Closing lake (Ub)	R8	Progradation of siliciclastics and closing of the basin.
S6. Closing lake	R8 L7	Progradation of siliciclastics from north to south, and closing of the basin.
$S6_U$. Restricted lake (Ub)	R8	Restricted deep basin with evaporite deposition. Richness decreases upwards.
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 and characterize depositional trends that occured troughout the lake evolution.

THREE LAKE CORRELATION MODEL

Three lake correlation model indicates connection between the Uinta (U), Piceance Creek (PC), and Greater Green River (GGR) basins.

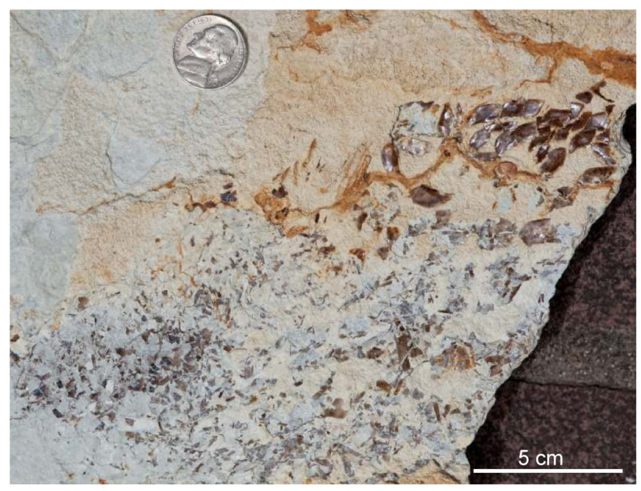
Lake stages are process-based, and were separated based on depositional trends, facies association distribution, richness of oil shale, water chemistry, degrees of lake restriction and salinity, and siliciclastic sediment input. Lake stages characterize large-scale changes in sedimentological pattern and depositional trends that are controlled by combination of climate and tectonics. Originally lake stages were separated for the PCb (Tänavsuu-Milkeviciene & Sarg *in press*). However, similar depositional trends and overall basin behaviour occur also in the Uinta and Greater Green River basins.

Closing of lakes during Stages 6 and 7_U, is not a time-stratigraphic unit and occurs at different times in different basins. Closing lake stage characterizes the final stage of the lake evolution, and marks the intertonguing of mudstones/oil shale deposits with prograding siliciclastic deposits.

Lake stages: PCb (Tänavsuu-Milkeviciene & Sarg *in press*), Ub (*after Vanden Berg & Birgenheier 2011 personal communication), and GGRb (**after Smith et al. 2008, 2010; Carroll 2010 personal communication). Age data and related correlation (after Smith et al. 2008, 2010). Rich and lean zones (Cashion & Donnell 1972, 1974; Vanden Berg 2008; Mercier et al. 2009). The R6 subdivision in Ub (after Birgenheier & Vanden Berg 2010). Geomagnetic polarity timescale, Eocene boundaries, negative carbon isotope excursions, and hyperthermals (Zachos et al. 2001, 2008, 2010; Sexton et al. 2006; Dutton et al. 2005; Lourens et al. 2005; Nicolo et al. 2007; Bijl et al. 2009; Stap et al. 2010). Sequence boundaries (Tänavsuu-Milkeviciene & Sarg 2011). Stratigraphy: Ub (after Remy 1992; Schomacker et al. 2010; Self et al. 2010a), PCb (after Pitman, 1996; Self et al. 2010b; Johnson et al. 2010; Tänavsuu-Milkeviciene & Sarg *in press*), GGRb (after Roehler 1993; Smith et al. 2008, 2010). Buff Marker bed (after Chetel & Carroll 2010).

Microbial carbonate, formed on carbonate shoal.

Middle Eocene insect (unkown species), found from the upper section of the Green River Fm.



Fish remnants, found from HL deposits during the S3.

CONCLUSIONS

Forming of rich or lean oil shale deposits is connected with the climate fluctuation from humid to dry. Climate controls variation in runoff, vegetation, nutrient, and siliciclastic input into the lake that in turn affects lake-level fluctuation and changes in production, destruction, and dilution.

Richest oil shale deposits form in the beginning of the rising lake or in the later part of the high lake level.

Deposits formed during the later part of the high lake level, form a good correlative unit, and can be traced from the margin to the deeper part of the lake. This correlative unit changes from mudstone and siltstone dominated deposits to lean oil shales, and finally to rich oil shales in the deeper part of the basin.

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