Climate History, Lake Evolution, and Prediction of Organic Richness, Green River Formation, Piceance Basin, Colorado*

Feng Jufang¹, J. Frederick Sarg¹, Kati Tänavsuu-Milkeviciene¹, and H. Suriamin¹

Search and Discovery Article #50915 (2014)**
Posted January 27, 2014

*Adapted from oral presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013
**AAPG©2013 Serial rights given by author. For all other rights contact author directly.

¹Colorado School of Mines, Golden, CO USA (jsarg@mines.edu)

Abstract

The Green River Fm. lake deposits (E-M Eocene) in the Piceance Creek basin are largely composed of kerogen-rich and kerogen-poor mudstones (clay and carbonate). The organic deposition of the Green River oil shale is related to three factors: production, destruction, and dilution. The pattern of variation suggests a net-productivity-driven organic depositional model modified by variations in dilution related to climate. Inorganic geochemistry proxies (P, Al, V/Cr, C13, O18) suggest net productivity plus dilution by siliciclastics and/or evaporites controls the average organic richness variation on the scale from depositional units to depositional sequences (100 and 400 Ky) over the long term lake history (6 My). On a sequence scale, peaks in organic richness occur during lake level rises and at maximum floods, and vary, related to dilution, during high lake times.

Over long-term lake history, variation occurs between Green River rich-zones (R), expressed in gal/ton average oil yield. Long-term lake evolution is defined by lake stages: S1-Fresh-Mesosaline Lake, S2-Transitional Lake, S3-Highly Fluctuating Lake, S4-Rising Lake, and S5-High Lake. Lake stages correlate to the Eocene climate optimum. S1 formed during the warming phase of the climate optimum and represents change from fresh to mesosaline conditions, suggesting a change from abundant rainfall and high runoff, to more seasonal and dryer climate. Moderately high net productivity and diminishing detrital dilution occurred as the climate dried, resulting in increasing richness (R0-21gal/ton, R1-27gal/ton). Increased seasonality and flashy runoff began during S2, indicating restricted evaporative lake conditions when oil shale changed from clay mudrock to siliceous dolomitic mudstone; and peaked during S3, at the maximum of the climate optimum, when arid conditions prevailed, and nahcolite and halite are abundant. 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 organic content, when increased saline mineral dilution occurred at the maximum warm time (R4-36gal/ton, R5-21gal/ton). The ensuing lake level rise (S4) and high lake (S5) occur during climatic cooling, accompanied by increased precipitation. Net productivity increased with a return to wet conditions. Diminished saline dilution resulted in increasing organic richness (R6-24gal/ton, R7-30gal/ton).
References Cited


Smith, M.E., K.R. Chamberlain, B.S. Singer, and A.R. Carroll, 2010, Eocene clocks agree; coeval\(^{40}\text{Ar}^{39}\text{Ar}, \text{U-Pb}, \text{and astronomical ages} from the Green River Formation: Geology, v. 38/6, p. 527-530.

Climate History, Lake Evolution, and Prediction of Organic Richness, Green River Formation, Piceance Basin, Colorado

Feng Jufang, J. Frederick Sarg, Kati Tänavsuu-Milkeviciene, and H. Suriamin
Colorado School of Mines, USA
Duration ~5Ma

Divided into:
1. Members, based on lithofacies.
2. Rich and lean zones (R/L), based on kerogen content.
3. Kerogen is dominantly Type I.
   Average TOC ~ 15 wt.%

After Johnson 1984; Dyni 2006; Johnson et al. 2010; Self et al. 2010
## Datasets and Methods

### Source Rock Analyzer

**Basin Center Section:**
- John Savage 24-1:
  - (117 samples)
- Shell 23x-2:
  - (46 samples)

**Basin Margin Section:**
- Lower Douglas
  - (50 samples)
- Upper Douglas
  - (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
Depositional Environments

- Lake margin littoral and sublittoral zones. Dominantly sandstones and carbonates.
- Lake center profundal zone. Dominantly mudstones, kerogen-rich mudstones (carbonate and clay) i.e., oil shale deposits, and evaporites.
Profundal Facies Associations

Laminated oil shale

Oil shale breccia

Nahcolite, halite

Slumped oil shale

Laminated oil shale
Profundal Zone and Organic Richness

Well developed rich and lean zones
Littoral, sublittoral facies associations

Gradationally based delta mouth bars

Prograding delta deposits

Sharp based delta mouth bar

Distributary channel

Littoral, sublittoral oil shale

Microbial carbonates

Microbial carbonate

3 cm
Organic Richness Variations (Margin)
Arid climate $\rightarrow$ Low runoff $\rightarrow$ Low lake level $\rightarrow$ Lean oil shale

**Organic Enrichment** = Production - Destruction

Dilution

(after Bohacs, et al., 2005)

**SOURCE POTENTIAL – LOW, ALGAL**
- Production: low runoff, low nutrients, high salinity
- Destruction: low oxygen, high preservation
- Dilution: low detritus, evaporite deposition

- Littoral, sublittoral siliciclastics
- Evaporites (halite, nahcolite)
- Laminated oil shale
Increasing precipitation \(\rightarrow\) Rising lake level \(\rightarrow\) Lean to rich oil shale

**Organic Enrichment = Production - Destruction / Dilution**

**SOURCE POTENTIAL – MODERATE-HIGH, MIXED ALGAL/TERRIGENOUS**

+ Production: increasing runoff & nutrients
- Destruction: higher oxygen, lower preservation
+ Dilution: high detritus
Humid climate $\rightarrow$ High runoff $\rightarrow$ High lake level $\rightarrow$ Rich oil shale

**Organic Enrichment** = \[	ext{Production} - \text{Destruction} \over \text{Dilution}\]

**SOURCE POTENTIAL – MODERATE-HIGH, ALGAL**

+ Production: high runoff & nutrients, high photic zone
+ Destruction: high O2 consumption, high chemocline, high preservation
+ Dilution: low detritus
Eocene climate and evolution of the Piceance Creek basin

After Zachos et al. 2001
Age data after Smith et al. 2008, 2010

EECO – Early Eocene Climatic Optimum

Clastic flood
Deepest, stratified
Increasing runoff
Nahcolite, halite
Nahcolite + clastics
Stratified, fresh to brackish, no evaporites
Presenter’s notes: To further support this idea of net productivity drives organic richness change, I looked at the inorganic geochemistry data of USBM-01A well, trying to use some geochemistry proxies to indicate production, destruction and dilution. Phosphorus is usually used to indicate the nutrient level in water. The nutrient level shows moderate to high production in stage 1 and highly fluctuate in stage 2 and 3, as it decrease to a minimum value in late Stage 3 and it starts to increase from Stage 4 and is very high in stage 5. I also use Al/K ratio to indicate the intensity of chemical weathering. I use this proxy here because the nutrient level in the lake is positively related to the intensity of chemical weathering. Larger ratio means more chemical weathering and vise versa. The trends show that rich zone usually correspond to more chemical weathering but here are also some exceptions, and the overall trend is similar to this trend here. V/Cr is used to indicate the redox condition. The majority of Green river oil shale samples fall in the range of dysoxic condition. However, just one proxy here is not reliable enough to indicate the redox condition, literature usually use it combined with biomarkers. So more data is required to make further interpretation here. However, the salinity change is helpful in figuring out the destruction factor in the basin center. Evaporite sedimentation is most intense in Stage 2 and 3, which indicates that the highest salinity and density stratification is most likely to develop during these stages. Oxygen solubility and oxygen renewal rate would be low during these stages. So preservation condition should be especially high during in Stage 2 and 3. This explains the high net productivity in Stage 2 and early stage 3, when production is not very high.
Climate Effects on Productivity & Dilution

<table>
<thead>
<tr>
<th>Stage (Climate)</th>
<th>Lake Condition</th>
<th>Net Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 5 (cooling climate)</td>
<td>Significant runoff &amp; high lake level</td>
<td>High Net Productivity (high prod. &amp; low destr.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>30 gal/ton</strong></td>
</tr>
<tr>
<td>Stage 4 (beginning of cooling climate)</td>
<td>Runoff increases &amp; increased nutrient influx</td>
<td>Moderate Net Productivity (mod. Prod. &amp; mod. destr.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>24 gal/ton</strong></td>
</tr>
<tr>
<td>Stage 3 (peak of climate optimum)</td>
<td>Increasing salinity. Nutrient supply is restricted and mostly from periodic increases in runoff</td>
<td>High Net Productivity, but incr. dilution by evaporites</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R5 - 21 gal/ton</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R4 – 36 gal/ton</strong></td>
</tr>
<tr>
<td>Stage 2 (beginning of climate optimum)</td>
<td>Increasing lake restriction, brackish to saline water</td>
<td>High Net Productivity (mod. prod. &amp; low destr.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R3 - 25 gal/ton</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R2 - 39 gal/ton</strong></td>
</tr>
<tr>
<td>Stage 1 (warm up to climate optimum)</td>
<td>High runoff and nutrient input into fresh lake</td>
<td>High Net Productivity (high prod. &amp; mod. destr.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R1 - 27 gal/ton</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>R0 – 21 gal/ton</strong></td>
</tr>
</tbody>
</table>
Conclusions

• GR kerogen dominantly Type I, average TOC ~ 15 wt.%.

• Organic richness variation suggests net productivity-driven deposition modified by variations in dilution related to climate.

• Inorganic proxies (P, Al, V/Cr, C\textsuperscript{13}, O\textsuperscript{18}) suggest net productivity + dilution by clastics and evaporites controls richness.

• Organic richness varies within Eccentricity cycles (100 & 400K yrs.).

• Richness also varies over long-term lake history –
  1. Stage 1, Fresh Lake – high net productivity, diminishing dilution, increasing richness (R0 – 21 gal/ton, R1 – 27 gal/ton)