



# **Mass-Movement Deposits in the Lacustrine Eocene Green River Formation, Piceance Basin, Western Colorado**

By Ronald C. Johnson, Justin E. Birdwell, Michael E. Brownfield, and Tracey J. Mercier

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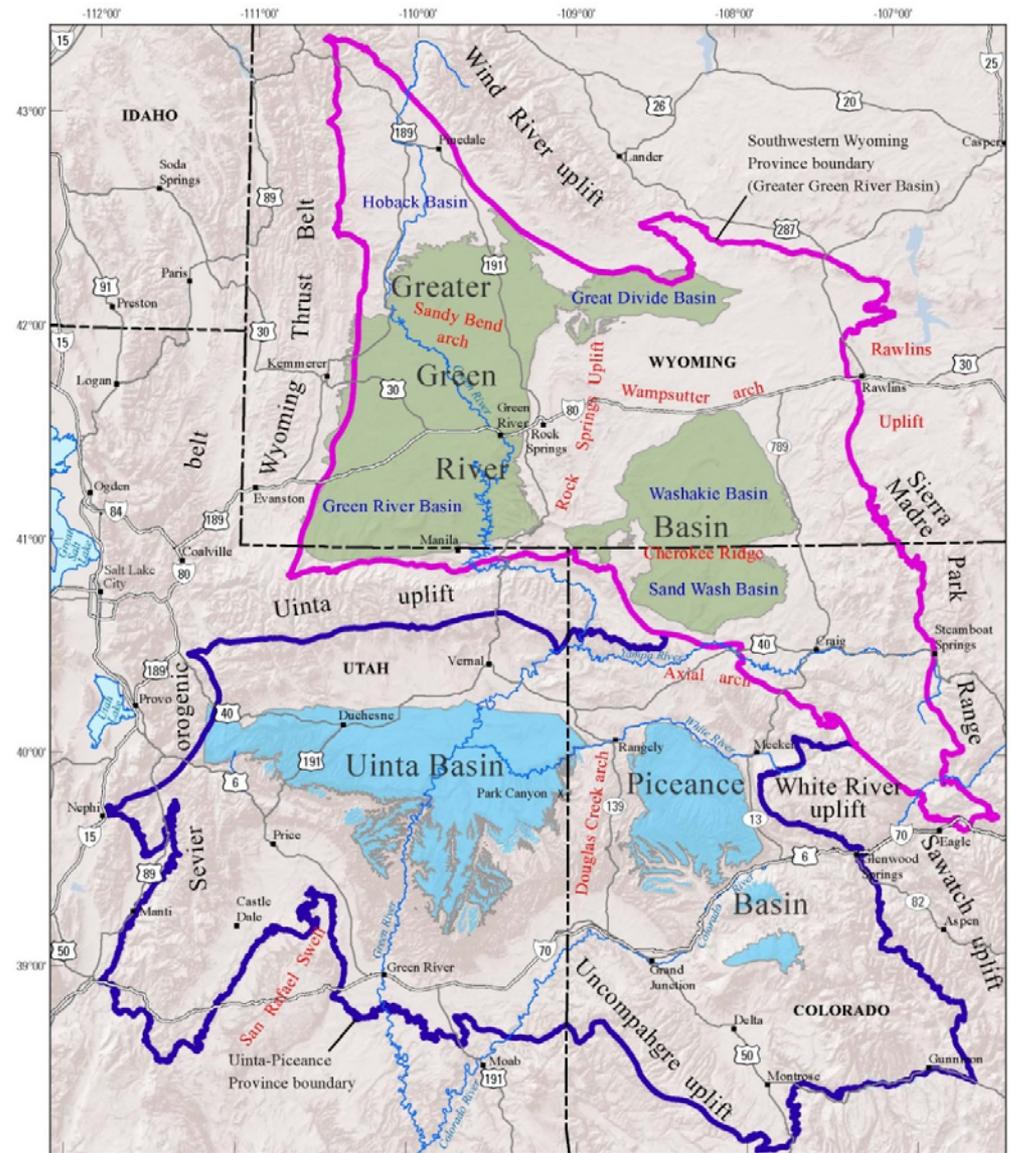


# Mass-Movement Deposits in the Lacustrine Eocene Green River Formation, Piceance Basin, Western Colorado

Ronald C. Johnson, Justin E. Birdwell,  
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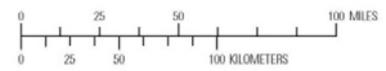
The Eocene Green River Formation was deposited in two large Eocene saline lakes, Lake Uinta in the Uinta and Piceance Basins and Lake Gosiute in the Greater Green River Basin.

Here we will discuss mass-movement deposits in just the Piceance Basin part of Lake Uinta.



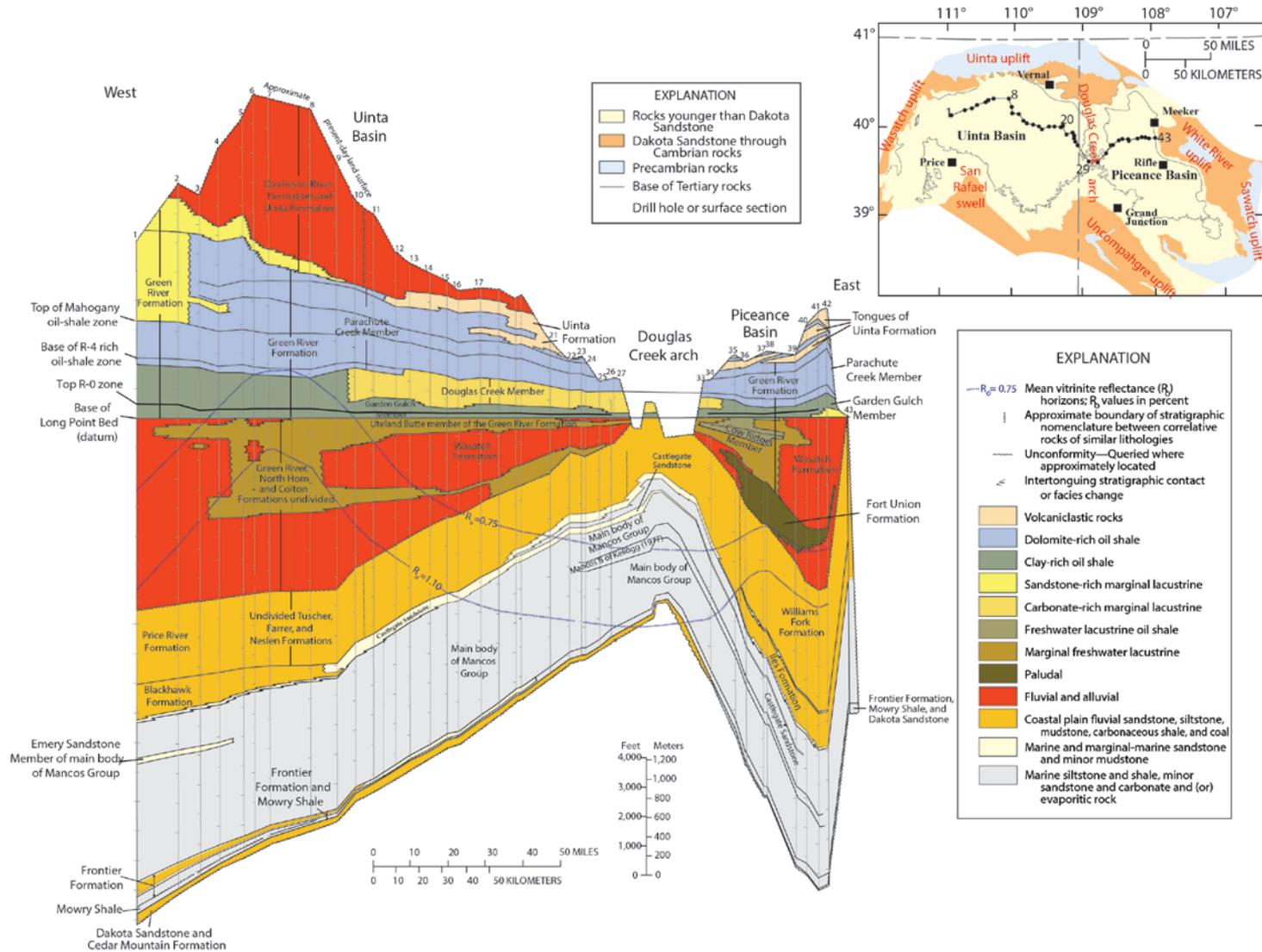
**EXPLANATION**

- Oil shale-bearing rocks deposited in Eocene Lake Gosiute
- Oil shale-bearing rocks deposited in Eocene Lake Uinta
- U.S. Geological Survey Uinta-Piceance Province boundary
- U.S. Geological Survey Southwest Wyoming Province boundary



Modified from Johnson (2012)





West-east cross section across the Uinta and Piceance Basins and the Douglas Creek arch. The arch acted as a hinge-line between the two subsiding basins. Little sediment was deposited on the crest of the arch prior to the development of saline Lake Uinta.

# In a depositional sense, there are generally two types of oil shale in the Piceance Basin



Most people associate the Green River Formation with well-laminated oil shale shown here, largely because it is the dominant type of oil shale where the Green River Formation crops out around the basin margins.

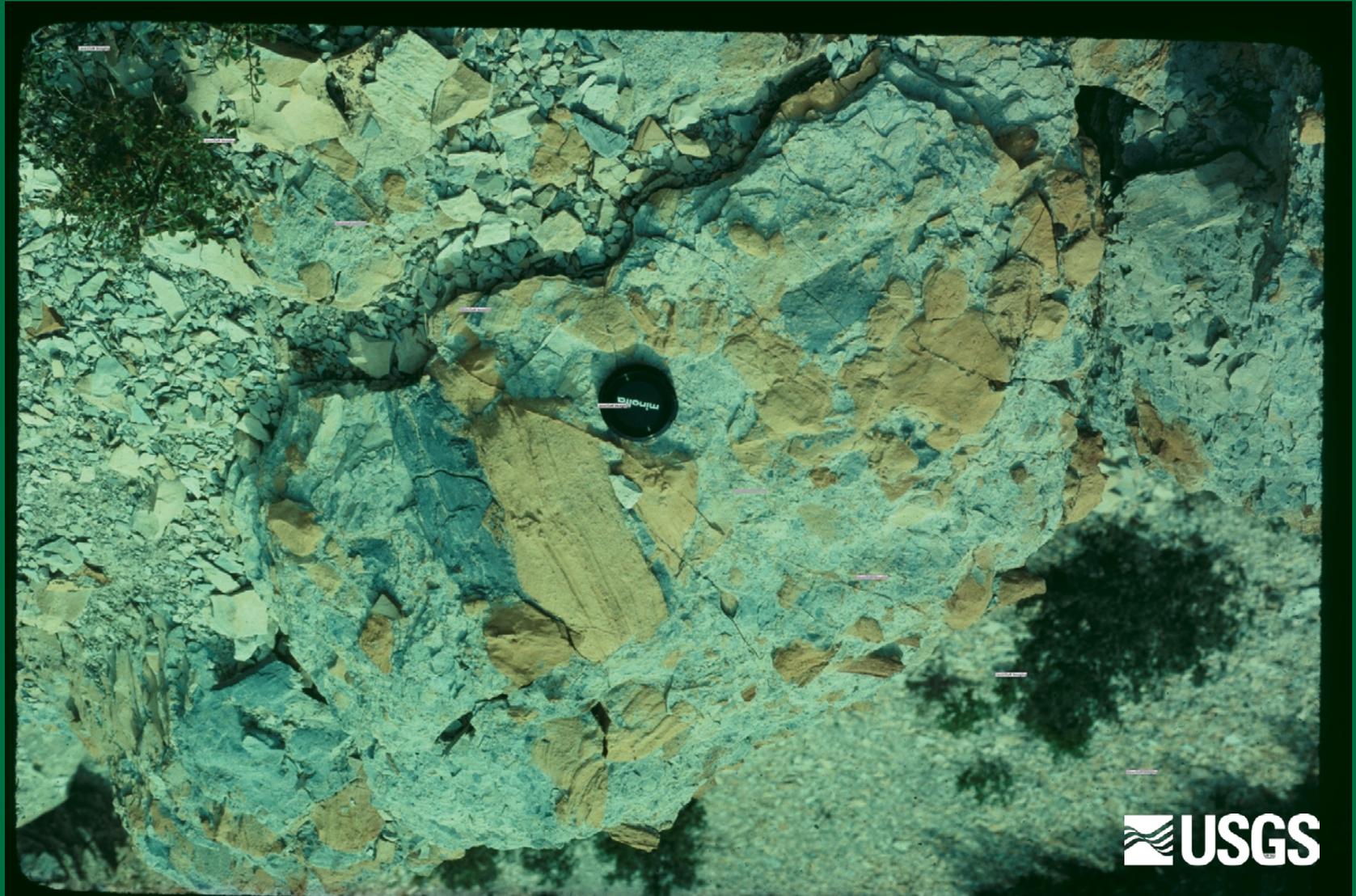
80-112, sec. 16, T. 5 S., R. 98 W., Desert Gulch quadrangle, elevation approx. 6,970 feet (ft), elevation top of Mahogany zone about 7,190. Photo is from 220 ft below top Mahogany zone, near middle of R-6 zone.

But another type of oil shale, generally referred to as “blebby oil shale,” appears to have been deposited by mass-movement processes.





Bradley (1931, p. 28) noted the occurrence of “shale breccias” or oil shales that “contain as inclusions many comparatively large angular fragments or flakes of more or less similar rock, which are clearly derived from the breaking up of a bed elsewhere.”

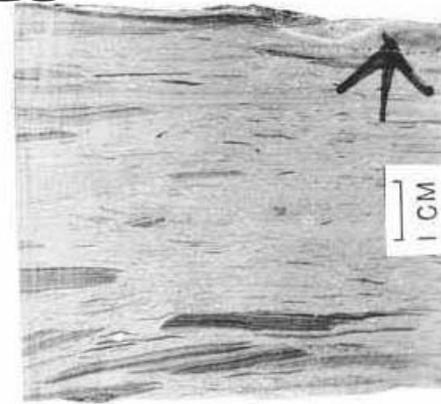


Bradley (1931) also noted that the boundaries of the fragments, some laminated, were commonly sharply defined indicating that they were lithified prior to being exhumed and incorporated into the breccias.

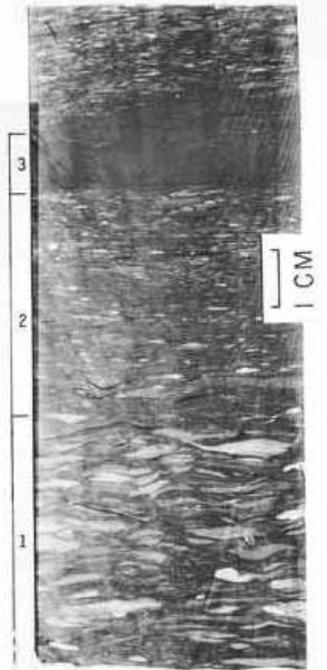
Dyni (1981) and Dyni and Hawkins (1981) studied these mass-movement deposits in core from the central part of the basin and attributed some of them to deep-water turbidity currents.

Dyni (1981) and Dyni and Hawkins (1981) estimated 40–50 percent of the lower part of the Parachute Creek Member in the central part of the basin consisted of “blebby oil shale.”

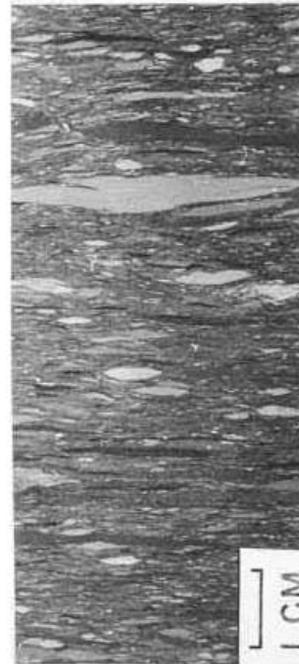
Note the grading in the blebby oil shale bed in the upper right, from abundant large marlstone fragments at the base to kerogen in a very fine-grained matrix at the top.



A



B



C



D

Examples of “blebby oil shale” from the central part of Lake Uinta Piceance Basin (from Dyni, 1981)





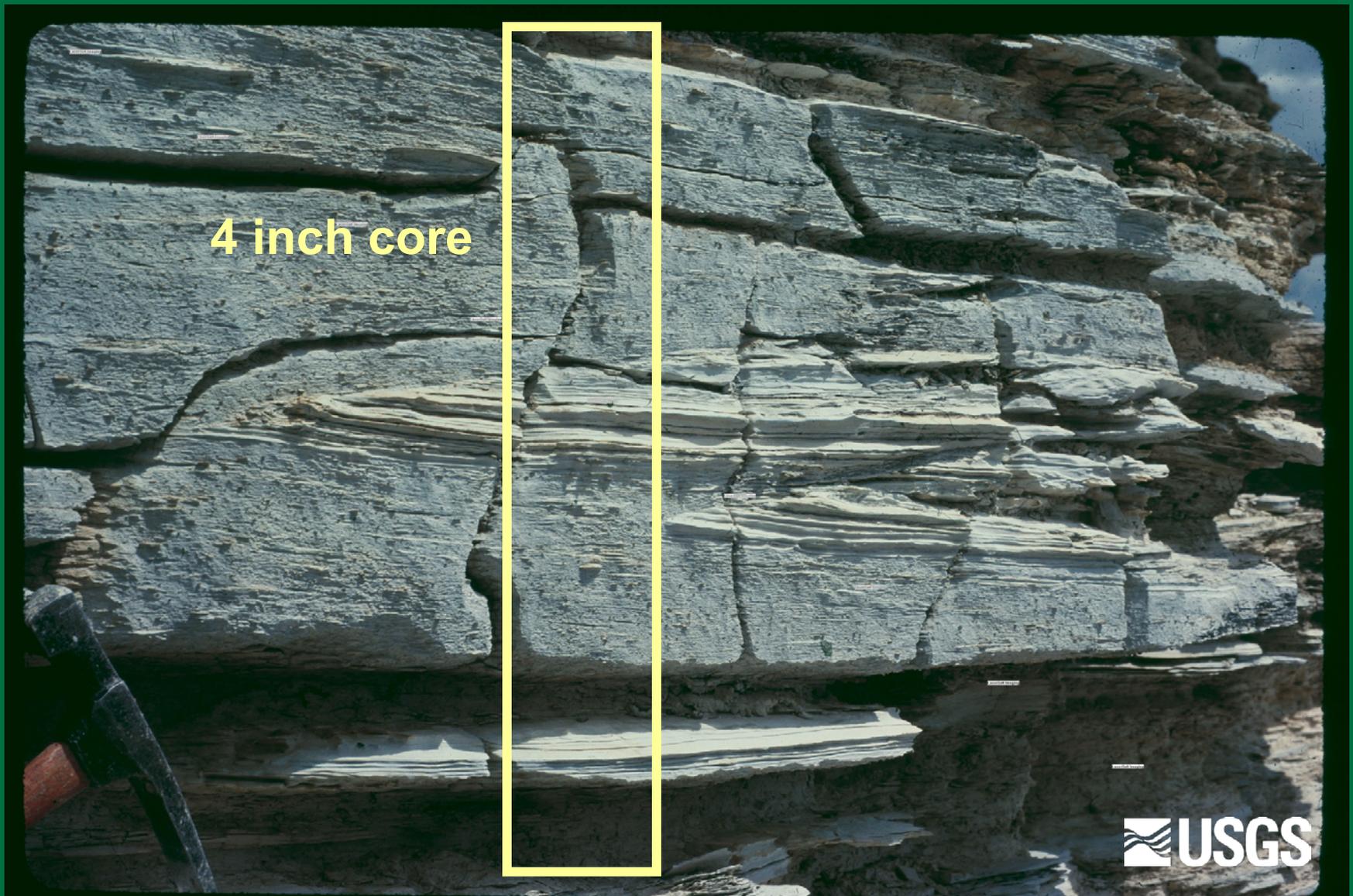
**Tanavsuu-Milkeviciene and Sarg (2012) studied the distribution of lacustrine facies in the Piceance Basin, and like Dyni (1981) and Dyni and Hawkins (1981), they found an increase in oil shale that was affected by mass-movement processes toward the central part of the basin.**



**Here we attempt to build on the excellent work of these previous authors by placing mass-movement deposits into a detailed spatial and temporal framework**

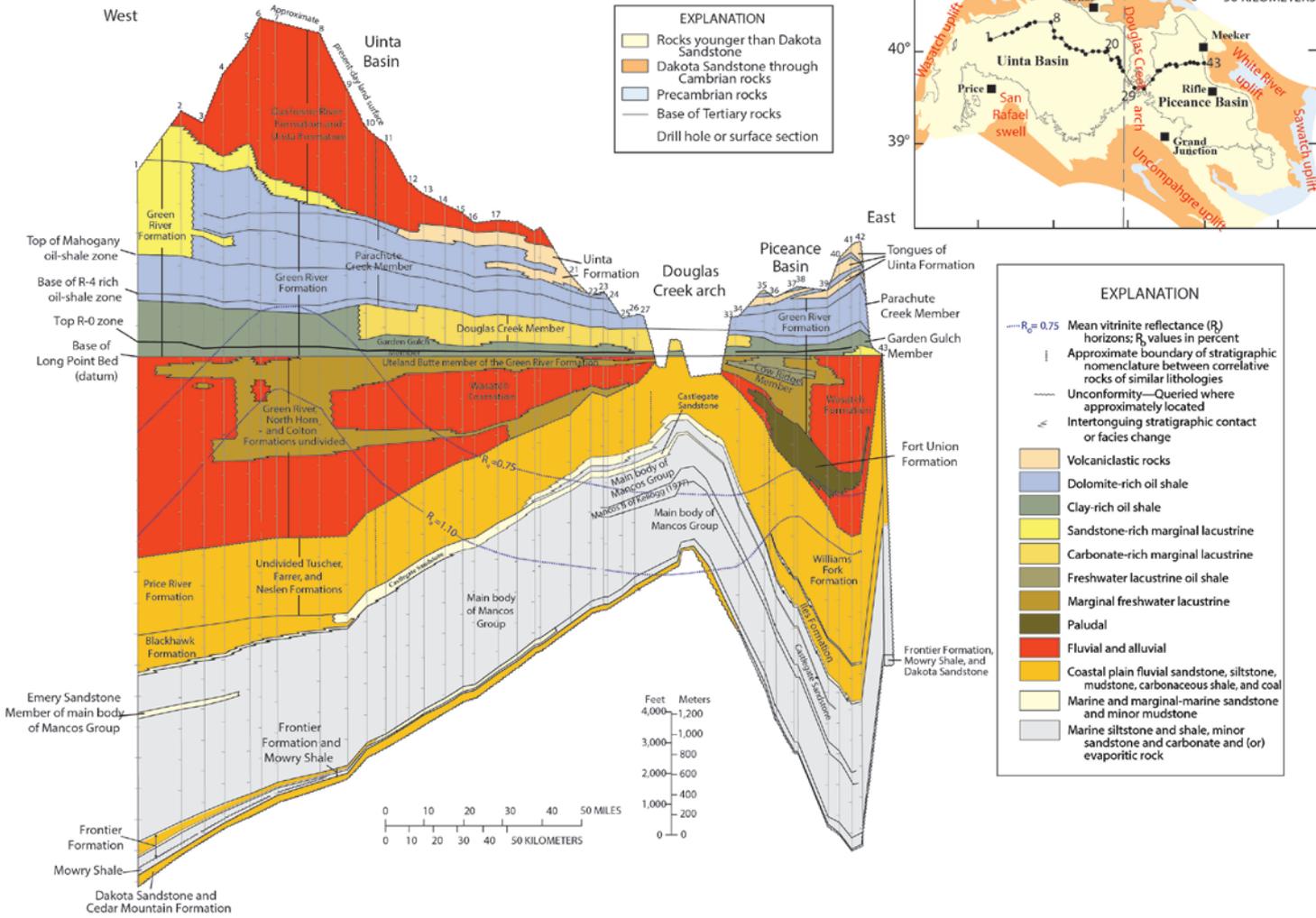
# Data sources

- Photos from nine coreholes that are housed at the U.S. Geological Survey Core Research Facility in Lakewood, Colorado, were examined for bedding features. The photos are available online at the Core Facility's Web Site.
- Outcrop sections were measured and described by the authors. All of the sections have been published, but thickness of individual beds were not reported. Thickness values were obtained from the original descriptions in field notebooks.



4 inch core

Mass-movement deposits commonly incorporated large blocks of laminated oil shale that appear to have been largely lithified prior to re-deposition. These blocks can look like laminated intervals in core.



West-east cross section across the Uinta and Piceance Basins and the Douglas Creek arch.

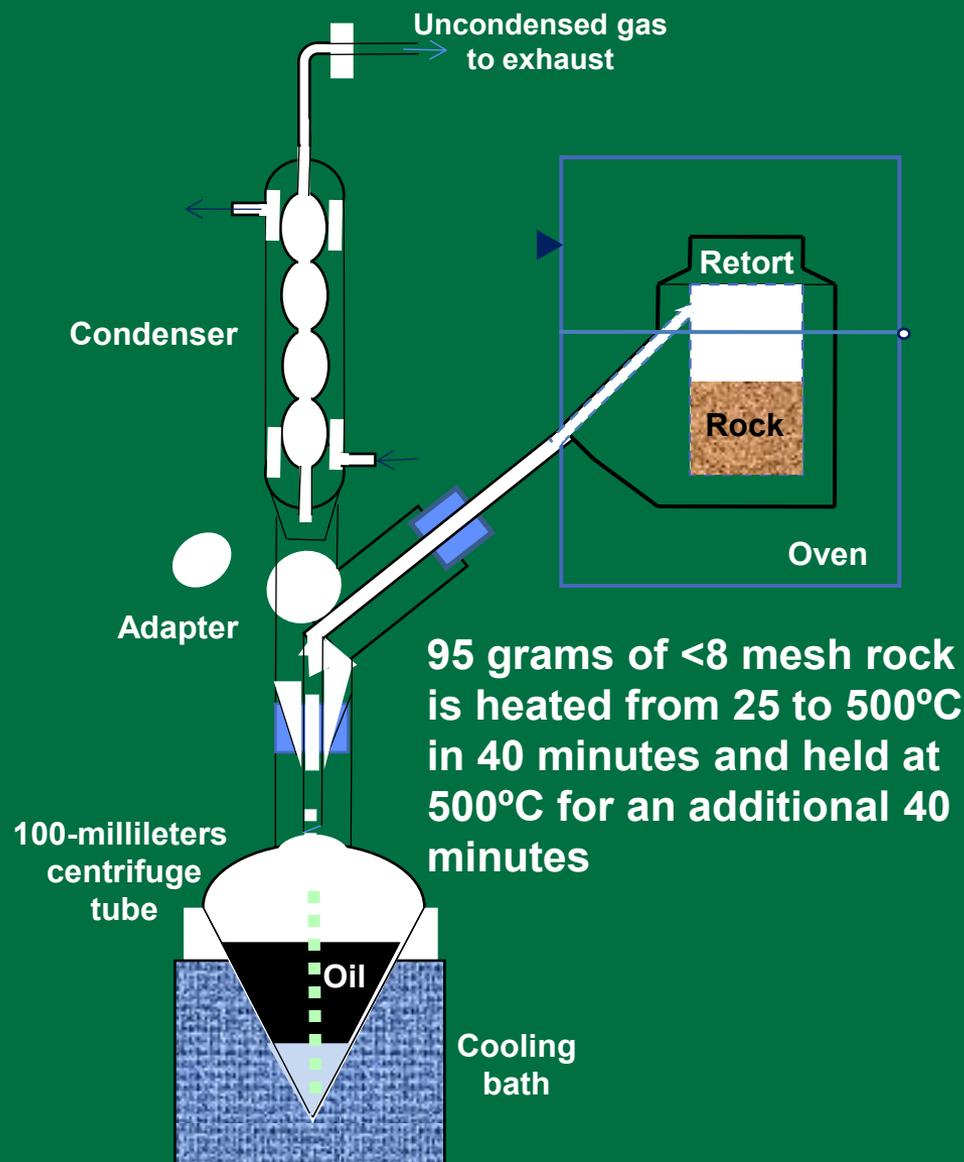


Oil yields using the Fischer assay method are shown on the subsequent slides. Pictured is a Fischer assay retort.

Products collected:  
condensed oil  
condensed water  
spent rock

Reported values:  
weight percent (wt%) oil  
wt% water  
wt% loss (gases)  
oil density  
coking tendency

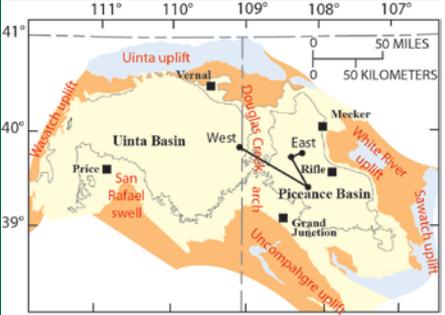
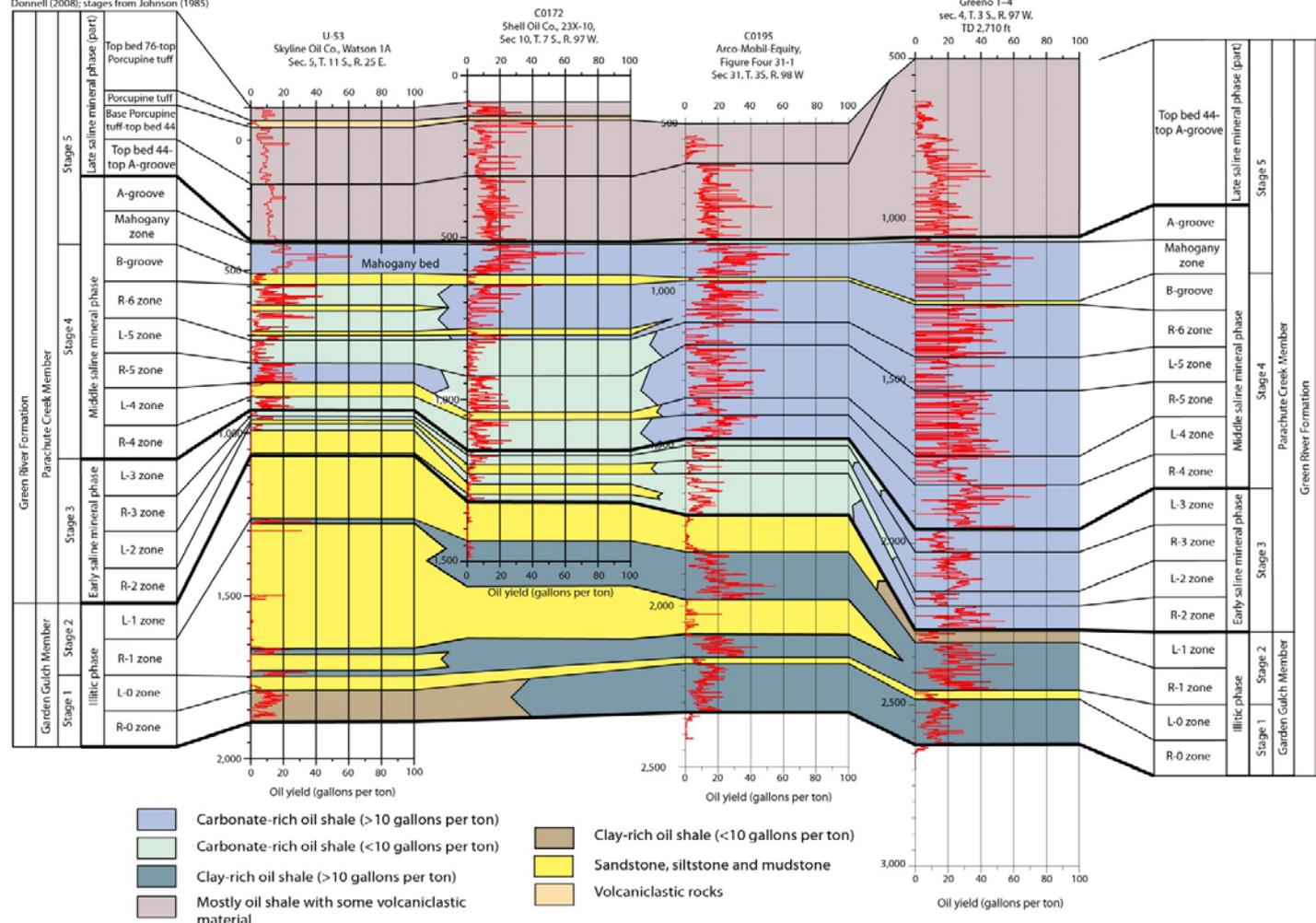
Wt% oil is converted to gallons per ton oil here.



Stratigraphic nomenclature for oil shale zones from Donnell and Blair (1970), Cashion and Donnell (1972), Donnell (2008); stages from Johnson (1985)

A  
West

A'  
East

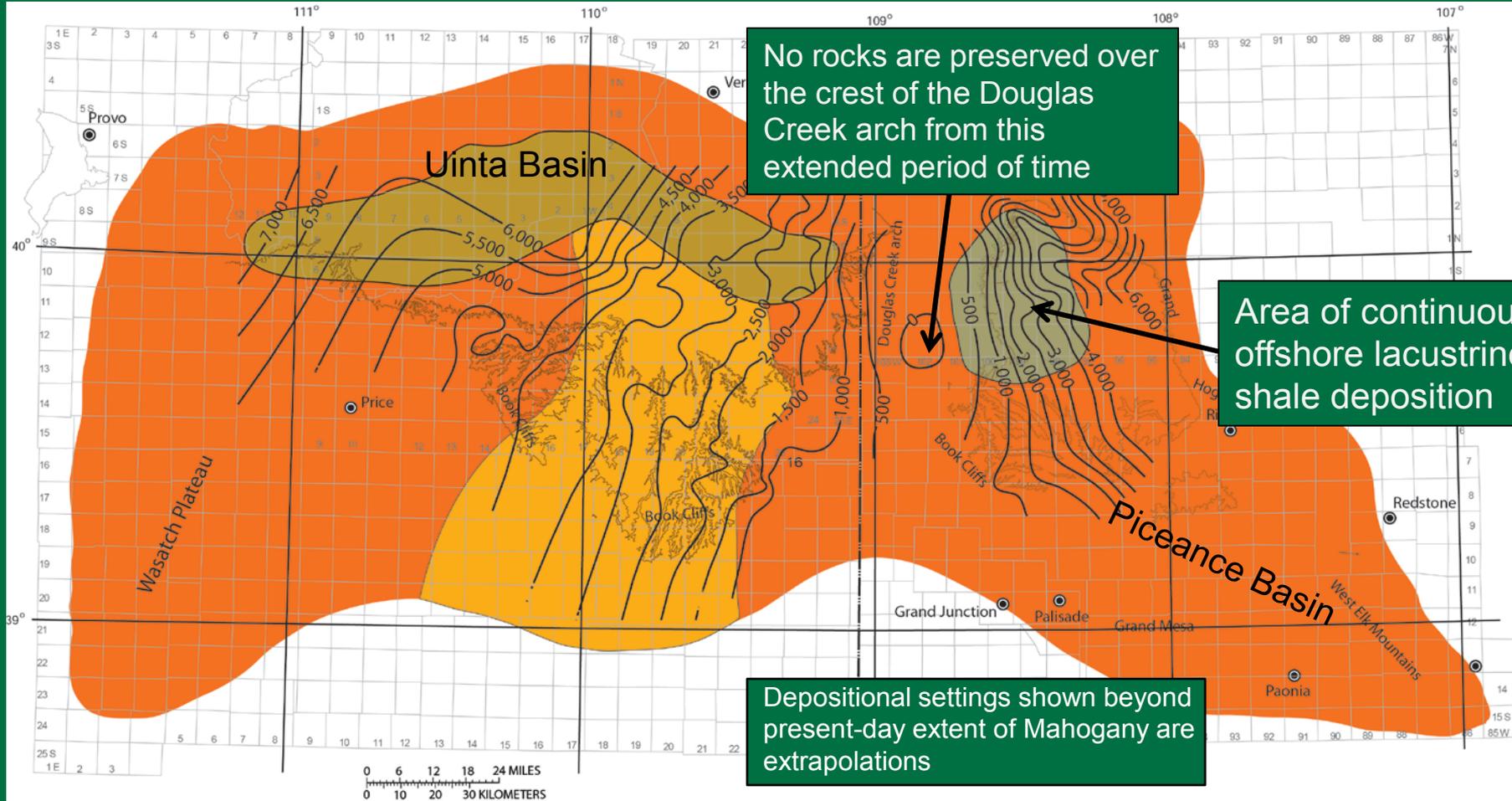


Index map

Modified from Mercier and Johnson (2012)



The Garden Gulch and Parachute Creek Members are subdivided into 16 recognized rich (R) and lean (L) oil-shale zones. Red graphs are gallons per ton oil using Fischer Assay. Maps showing percent of mass-movement deposits in each zone were constructed. The next slide is a paleogeographic map for the end of the preceding freshwater phase.



No rocks are preserved over the crest of the Douglas Creek arch from this extended period of time

Area of continuous offshore lacustrine shale deposition

Depositional settings shown beyond present-day extent of Mahogany are extrapolations

EXPLANATION

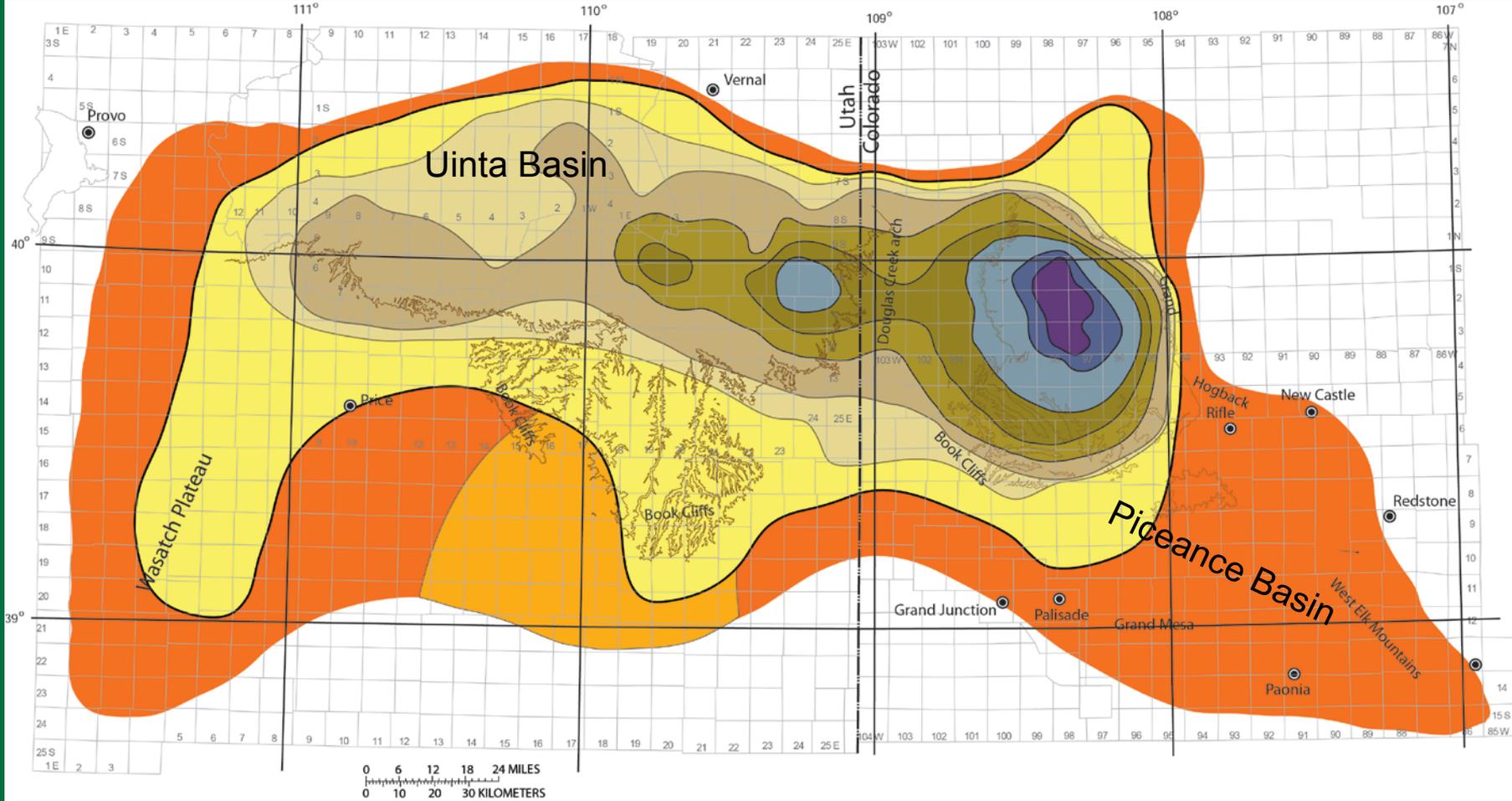
DEPOSITIONAL SETTING AND LITHOLOGY

- Freshwater lacustrine, interbedded fossiliferous limestone, organic-rich dark shale, and sandstone
- Offshore freshwater lacustrine, dark-gray low-grade oil shale
- Fluvial and alluvial, variegated mudstone and sandstone, may contain minor freshwater lacustrine lithologies
- Sandy fluvial and alluvial, variegated mudstone with abundant sandstone, may contain minor freshwater lacustrine lithologies

- 1,000 Thickness in feet from top of Upper Cretaceous Mesaverde Formation/Group to Long Point Bed.
- Top of Mahogany bed (Uinta Basin), Top of Mahogany zone (Piceance Basin)



Extent of freshwater lakes just prior to the development of Lake Uinta. Isopach map is from the top of the Cretaceous to the top of the freshwater phase.



DEPOSITIONAL SETTING AND LITHOLOGY

- Marginal brackish-to saline lacustrine lithologies including sandstone, oolitic, ostracodal, and algal limestone, mudstone, and minor oil shale
- Fluvial and alluvial, variegated mudstone and sandstone, may contain minor brackish-to saline lacustrine lithologies
- Sandy fluvial and alluvial, variegated mudstone with abundant sandstone, may contain minor freshwater lacustrine lithologies

EXPLANATION

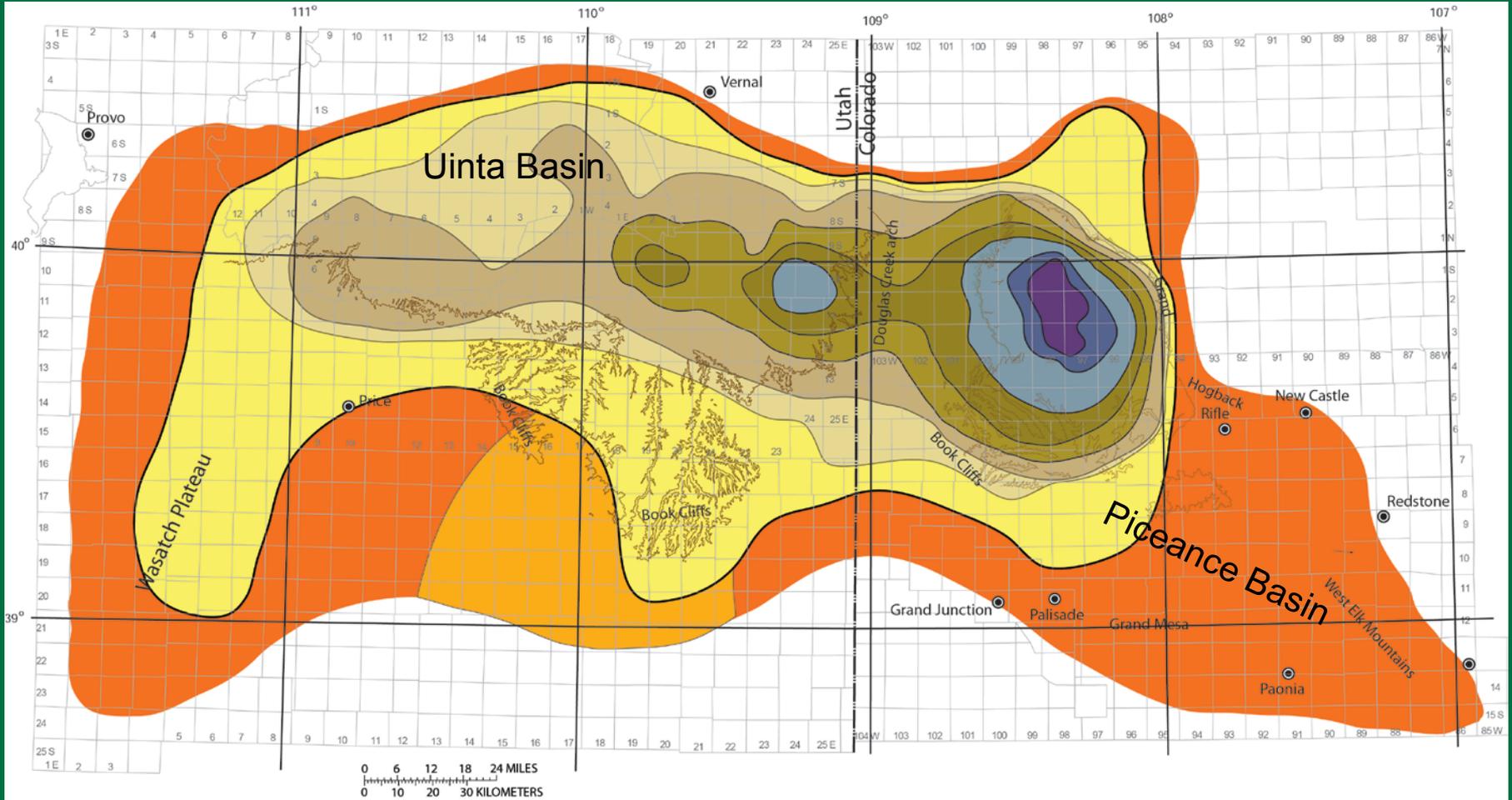
Offshore brackish-to-saline lacustrine oil shale  
Gallons per ton from Fischer assay

	1-2		>14
	2-4		12-14
	4-6		10-12
	6-8		8-10

— Top of Mahogany bed (Uinta Basin),  
— Top of Mahogany zone (Piceance Basin)



Lake Uinta formed as a result of a major transgression—the Long Point transgression. This map shows Lake Uinta during maximum transgression when low-grade oil shale was deposited over large parts of the Uinta and Piceance Basins. Oil yield in gallons per ton Fischer Assay is shown.



**EXPLANATION**

**DEPOSITIONAL SETTING AND LITHOLOGY**

- Marginal brackish-to saline lacustrine lithologies including sandstone, oolitic, ostracodal, and algal limestone, mudstone, and minor oil shale
- Fluvial and alluvial, variegated mudstone and sandstone, may contain minor brackish-to saline lacustrine lithologies
- Sandy fluvial and alluvial, variegated mudstone with abundant sandstone, may contain minor freshwater lacustrine lithologies

**Offshore brackish-to-saline lacustrine oil shale**

Gallons per ton from Fischer assay

	1-2		>14
	2-4		12-14
	4-6		10-12
	6-8		8-10

— Top of Mahogany bed (Uinta Basin),  
— Top of Mahogany zone (Piceance Basin)

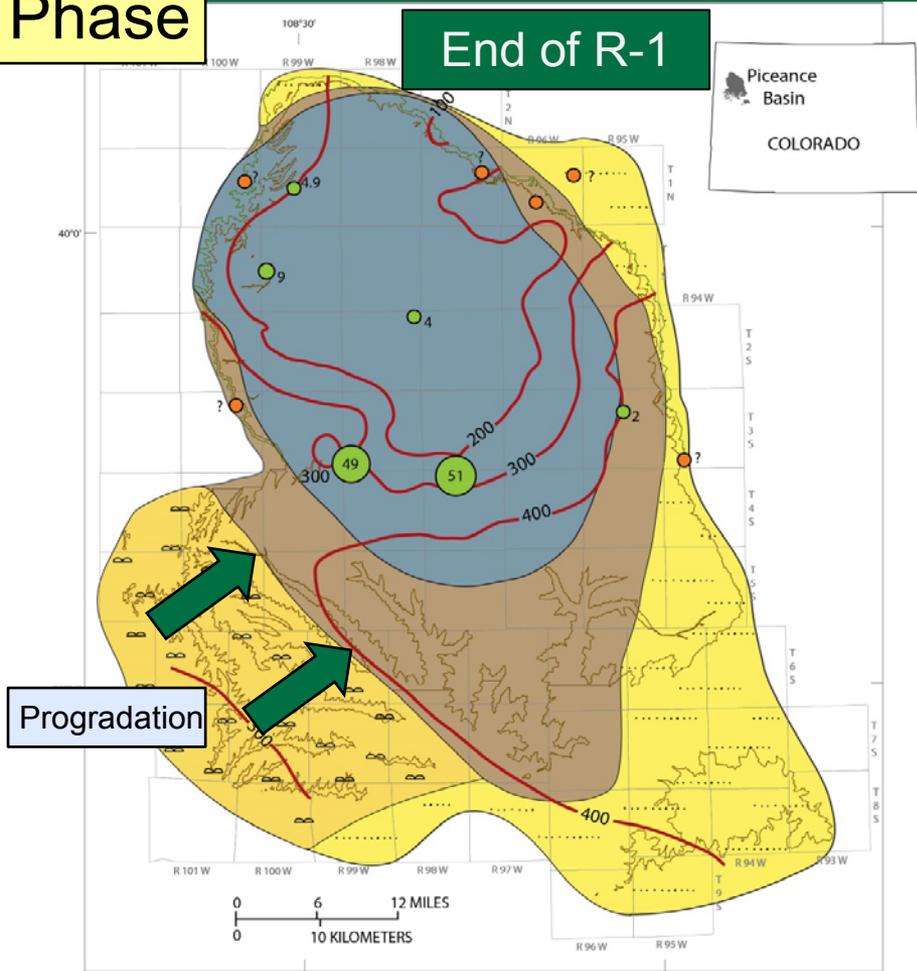
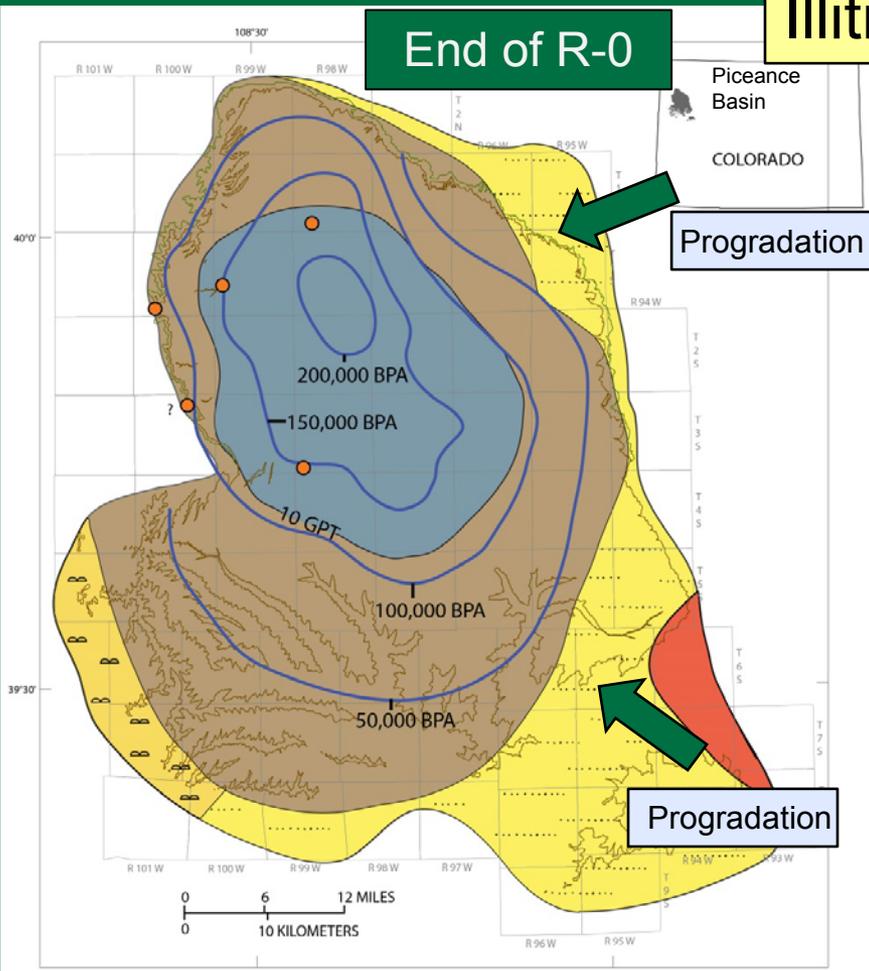


Subsequent slides progress through the development of the rich (R) and lean (L) oil shale zones in the Piceance Basin showing the distribution of mass-movement deposits.

# Illitic Phase

## End of R-0

## End of R-1



- EXPLANATION**
- Carbonate-rich marginal lacustrine
  - Sandstone-rich marginal lacustrine
  - Illitic oil shale > 10 gallons per ton
  - Illitic oil shale < 10 gallons per ton
  - Variegated mudstone, sandstone, and siltstone
  - All laminated
  - Top of Mahogany bed outcrop
  - Base of Parachute Creek Member
- USGS**
- 50,000 BPA  
In-place oil shale resources in barrels per acre (BPA)

- EXPLANATION**
- Carbonate-rich marginal lacustrine
  - Sandstone-rich marginal lacustrine
  - Illitic oil shale > 10 gallons per ton
  - Illitic oil shale < 10 gallons per ton
  - Top of Mahogany bed outcrop
  - Base of Parachute Creek Member
  - 30-35% transported oil shale
  - 0-5% transported oil shale
  - 5-10% transported oil shale
  - 10-15% transported oil shale
  - 15-20% transported oil shale
  - 20-25% transported oil shale
  - 25-30% transported oil shale
  - 35-40% transported oil shale
  - 40-45% transported oil shale
  - 45-50% transported oil shale
  - 50-55% transported oil shale
- 300  
Thickness of R-1 zone in feet

R-0

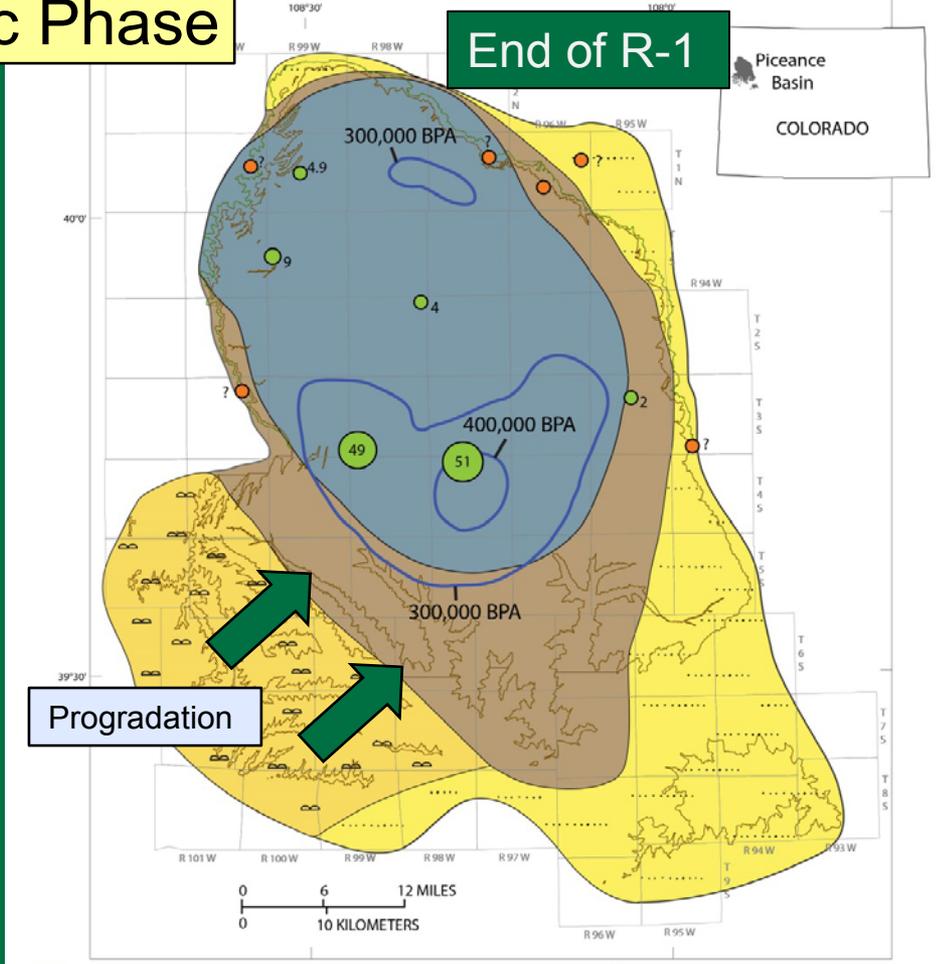
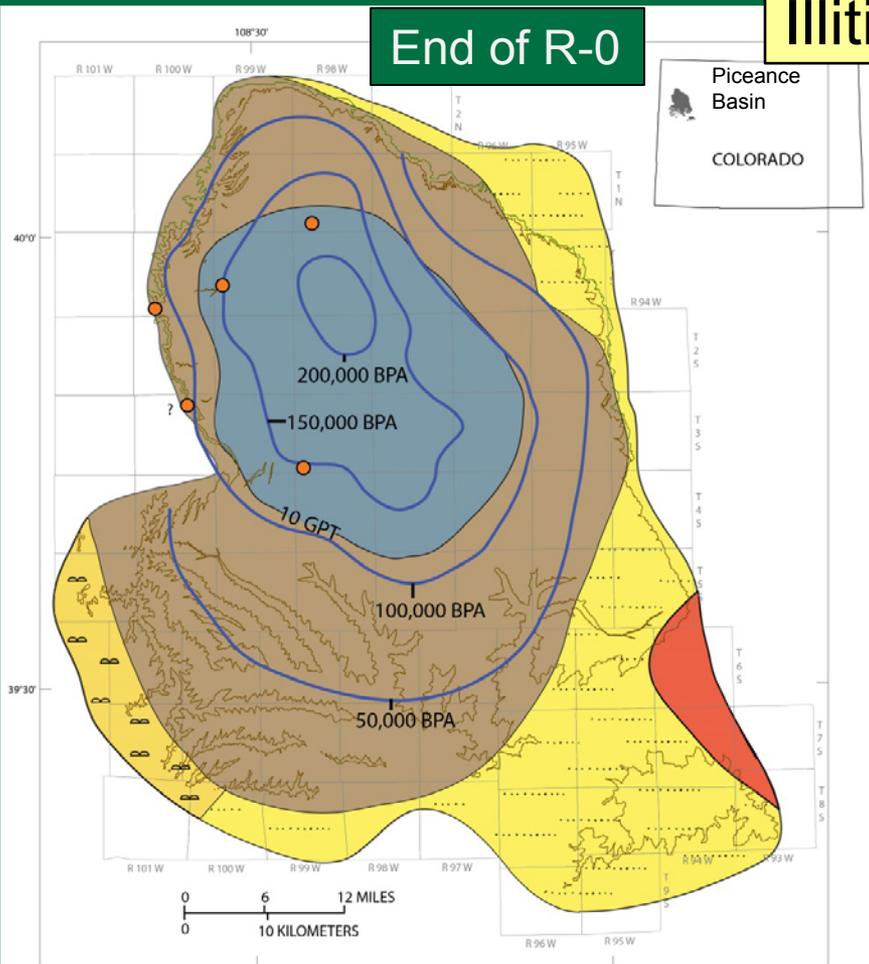
R-1

Marginal shelves prograded (green arrows) from the southeast and northeast during R-0 time and from the southwest during R-1 time. No mass-movement deposits were identified in the R-0 zone, whereas mass-movement deposits accumulated at the base of the expanding shelf during R-1 time.

# Illitic Phase

## End of R-0

## End of R-1



**EXPLANATION**

- All laminated
- Top of Mahogany bed outcrop
- Base of Parachute Creek Member

50,000 BPA

In-place oil shale resources in barrels per acre (BPA)

**EXPLANATION**

- Carbonate-rich marginal lacustrine
- Sandstone-rich marginal lacustrine
- Illitic oil shale > 10 gallons per ton
- Illitic oil shale < 10 gallons per ton
- Top of Mahogany bed outcrop
- Base of Parachute Creek Member

In-place oil in barrels per acre

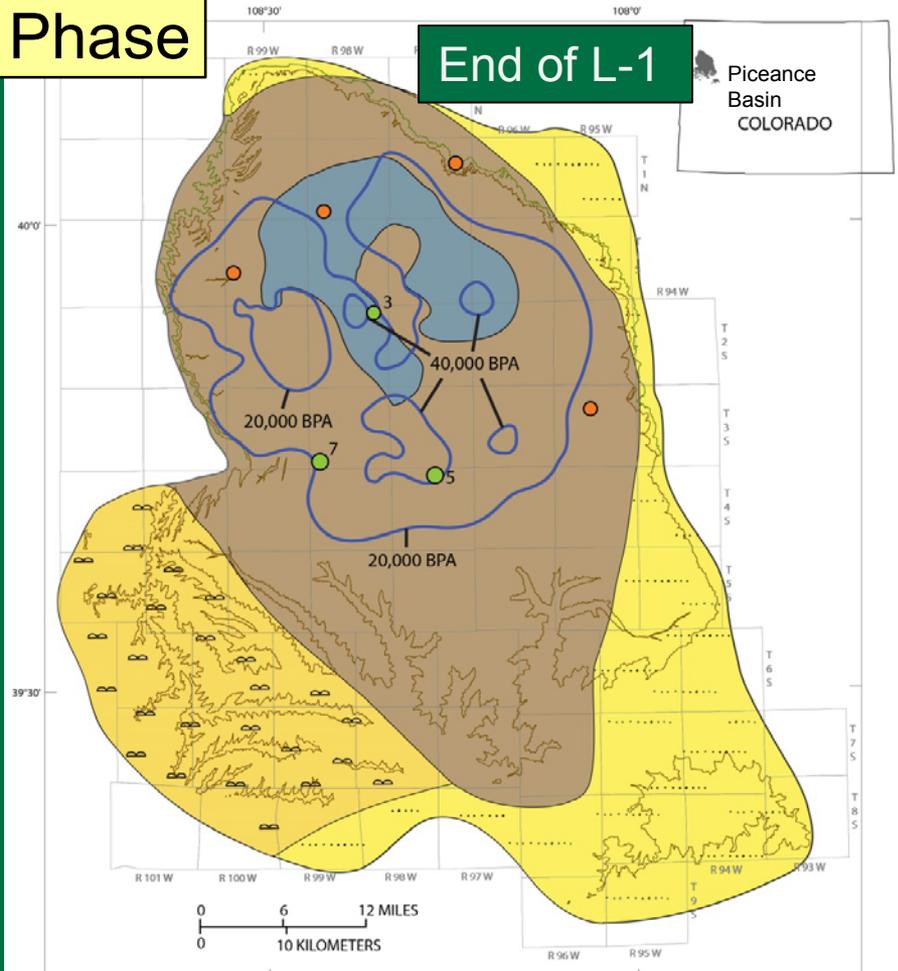
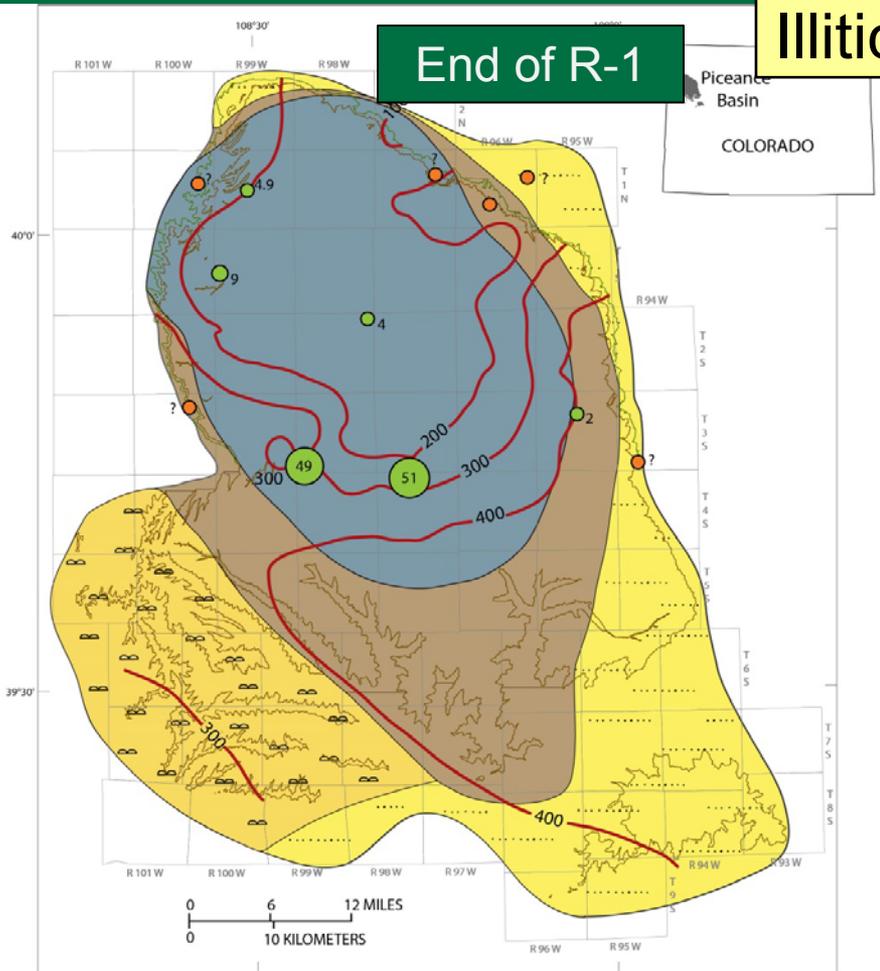
- All laminated
- 0-5% transported oil shale
- 5-10% transported oil shale
- 10-15% transported oil shale
- 15-20% transported oil shale
- 20-25% transported oil shale
- 25-30% transported oil shale
- 30-35% transported oil shale
- 35-40% transported oil shale
- 40-45% transported oil shale
- 45-50% transported oil shale
- 50-55% transported oil shale

Total organic matter, measured by barrels of oil per acre (BPA), increases toward the center of the basin in the R-0 zone, which contains no mass-movement deposits, whereas total organic matter is greatest where mass-movement deposits are greatest in the R-1 zone.

# Illitic Phase

## End of R-1

## End of L-1



<ul style="list-style-type: none"> <li> Carbonate-rich marginal lacustrine</li> <li> Sandstone-rich marginal lacustrine</li> <li> Illitic oil shale &gt; 10 gallons per ton</li> <li> Illitic oil shale &lt; 10 gallons per ton</li> <li> Top of Mahogany bed outcrop</li> <li> Base of Parachute Creek Member</li> </ul>	<p><b>EXPLANATION</b></p> <ul style="list-style-type: none"> <li> All laminated</li> <li> 0-5% transported oil shale</li> <li> 5-10% transported oil shale</li> <li> 10-15% transported oil shale</li> <li> 15-20% transported oil shale</li> <li> 20-25% transported oil shale</li> <li> 25-30% transported oil shale</li> <li> 30-35% transported oil shale</li> <li> 35-40% transported oil shale</li> <li> 40-45% transported oil shale</li> <li> 45-50% transported oil shale</li> <li> 50-55% transported oil shale</li> </ul>
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300  
Thickness of R-1 zone in feet

<ul style="list-style-type: none"> <li> Carbonate-rich marginal lacustrine</li> <li> Sandstone-rich marginal lacustrine</li> <li> Illitic oil shale &gt; 10 gallons per ton</li> <li> Illitic oil shale &lt; 10 gallons per ton</li> </ul>	<p><b>EXPLANATION</b></p> <ul style="list-style-type: none"> <li> All laminated</li> <li> 0-5% transported</li> <li> 5-10% transported</li> </ul> <p>Numbers indicate exact percentages of laterally transported oil shale</p>	<ul style="list-style-type: none"> <li> Top of Mahogany bed outcrop</li> <li> Base of Parachute Creek Member</li> <li> 20,000 BPA</li> <li> In-place oil in barrels per acre</li> </ul>
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R-1

L-1

Mass-movement deposits are much less common in the L-1 lean zone than the underlying richer R-1 zone.



## Illitic Phase

R.C. Johnson field locality 8/75, measured section  
North Dry Fork, The Saddle quad. Sec. 26, T. 7. S.  
R. 99W. Upper part of R-1

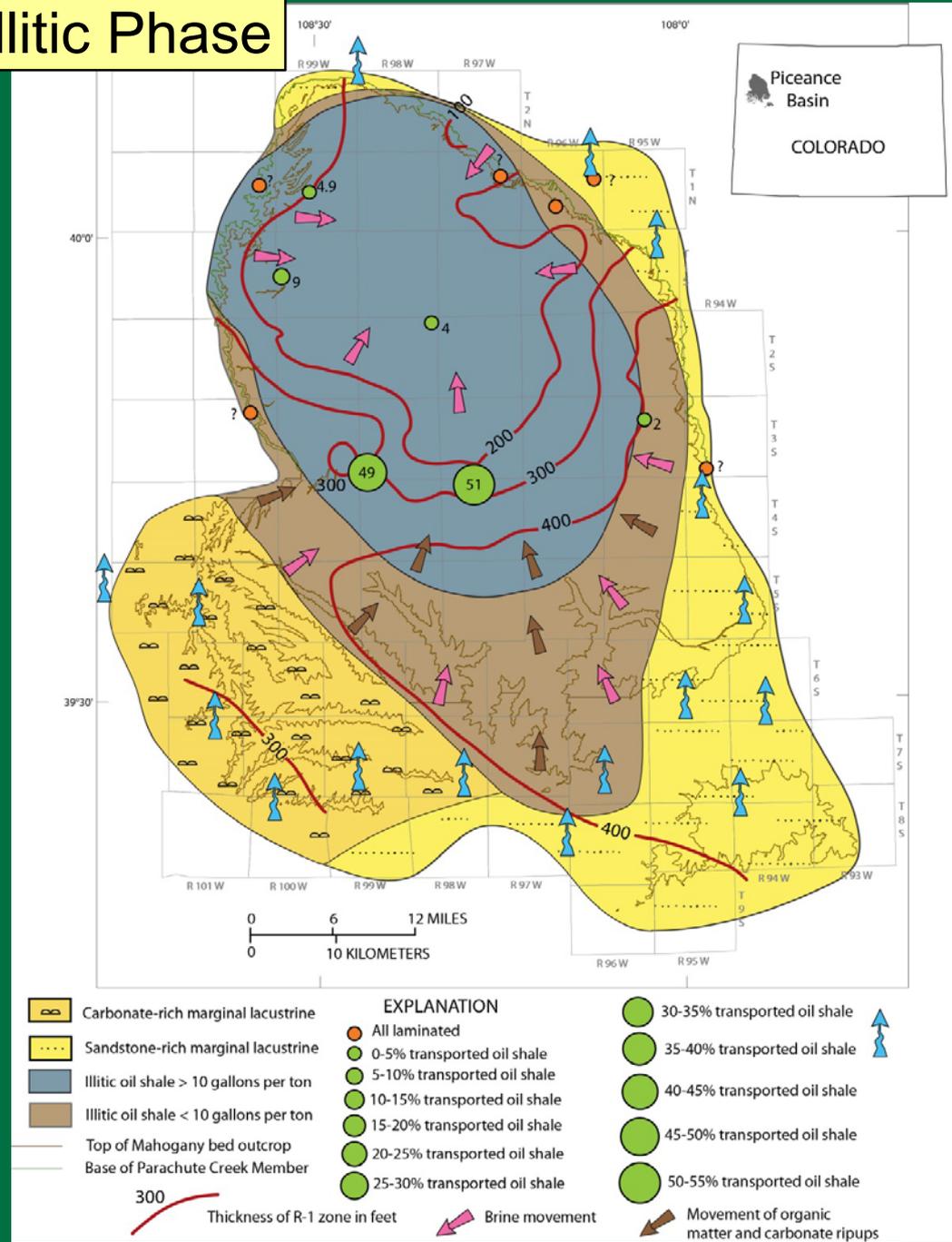


Oil-shale beds are preserved in marginal lacustrine environments, indicating that significant organic matter was accumulating there. Many of these beds occur above the bulbous structures on stromatolites that may have offered protection from lateral transport. This bed is in the R-1 zone.

## Interpretation for R-1 zone

- Mass-movement deposits accumulated at the slope between marginal shelves and the deep lake area.
- The mineral matter and organic matter that made up the mass-movement deposits originated on the marginal shelves and slope on the southeast and southwest parts of the lake.
- Brines that formed on the marginal shelves may have been incorporated into the mass-movement deposits.
- Brines may also have formed on the northeast and north margins of the lake, but mass-movement deposits were rare there.

## Illitic Phase



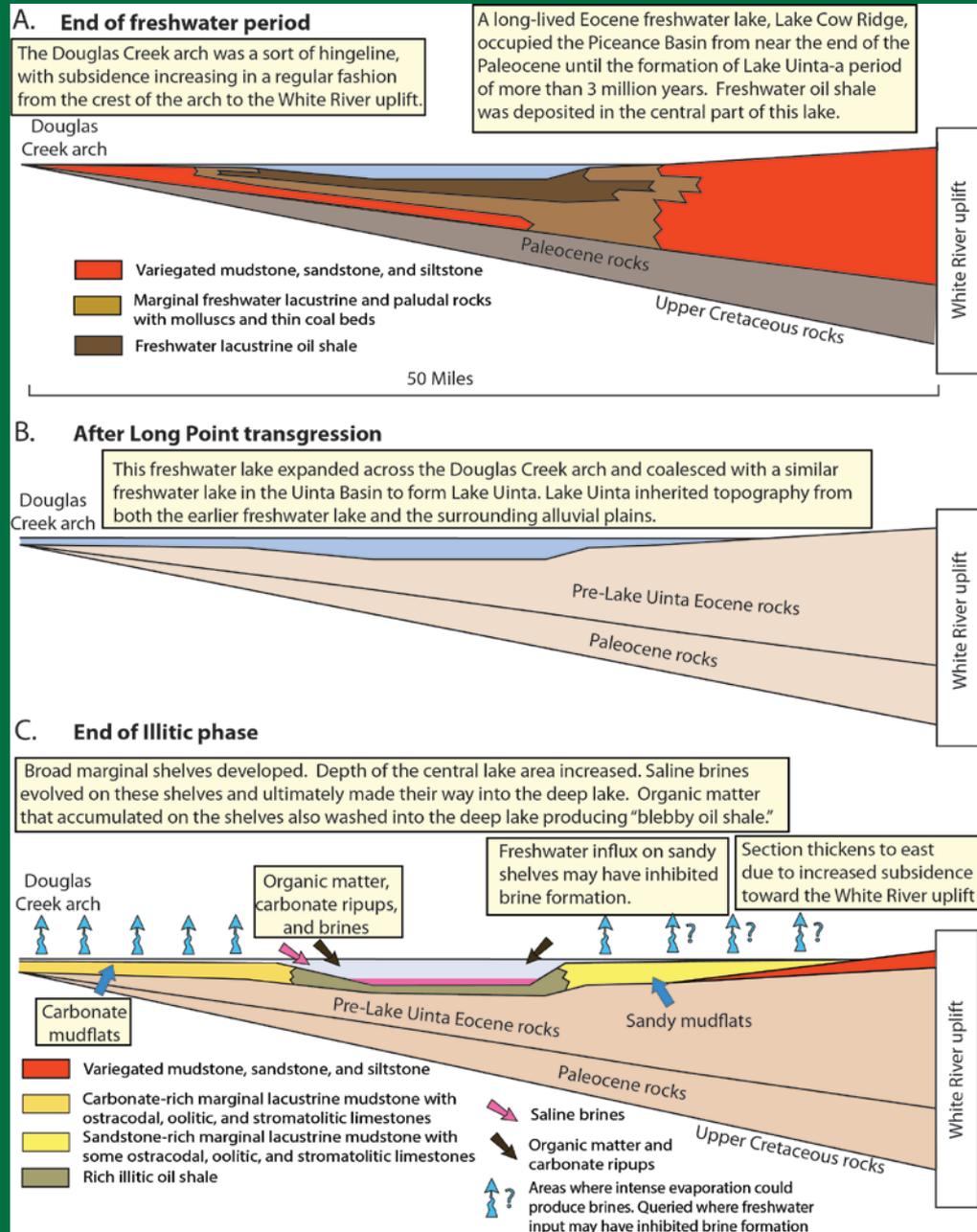
# Illitic Phase Summary

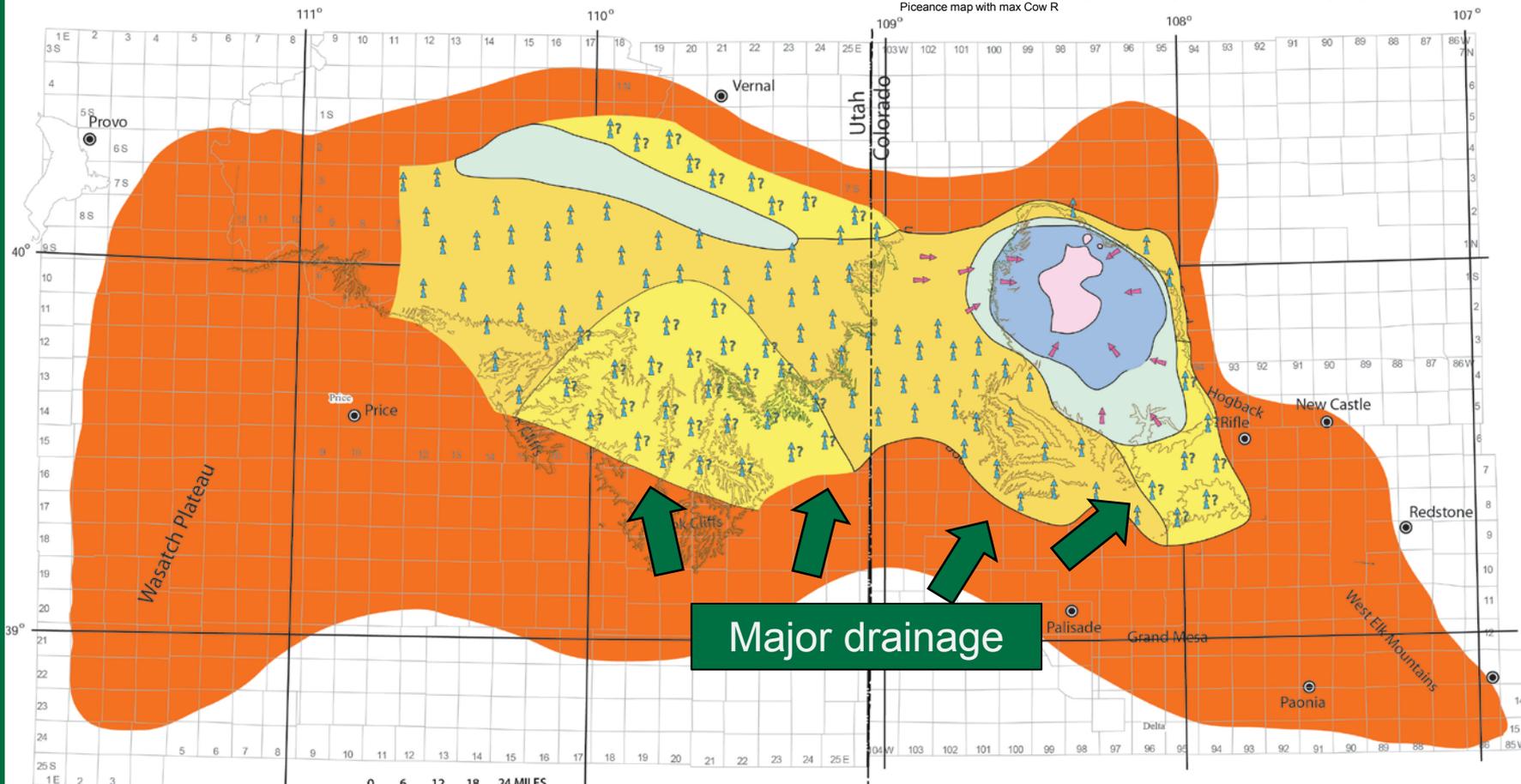
At the time of the Long Point transgression, a freshwater lake had occupied the central part of the Piceance Basin for more than 3 million years. There is no evidence that this lake ever filled in, and it is likely that it was relatively deep.

Lake Uinta transgressed across the marginal shelves and alluvial plains during the Long Point transgression depositing low-grade oil shale over a wide area.

Infilling began, producing broad marginal shelves that ultimately reached the deep central part of Lake Uinta before halting.

The shelf edge and slope were subject to failure with mass-movement deposits accumulating at the base of the slope.





EXPLANATION

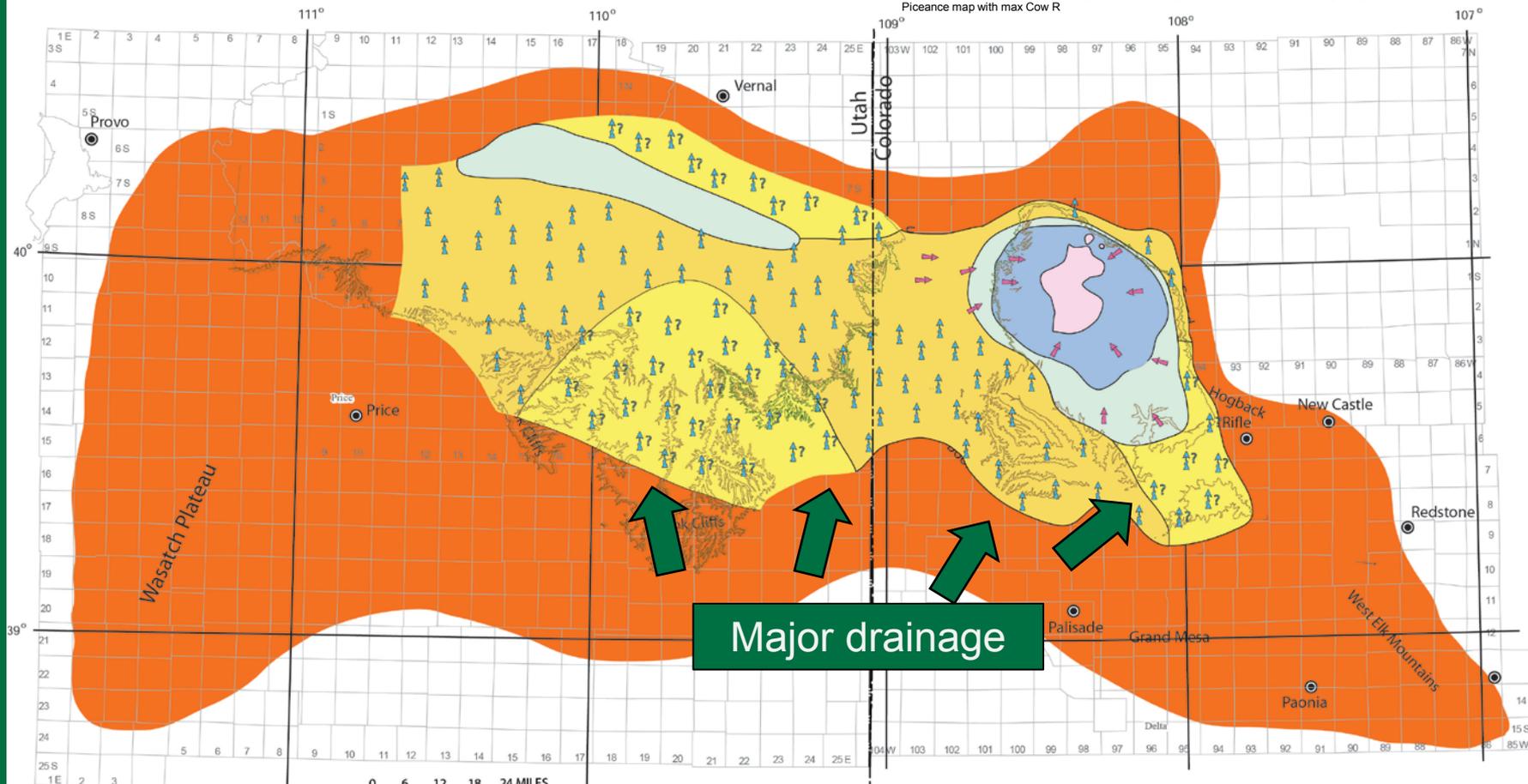


From Johnson and Brownfield (in press)

- Carbonate-rich oil shale > 10 gallons per ton
- Carbonate-rich oil shale < 10 gallons per ton
- Nahcolite < 25,000 short tons/acre
- Areas where intense evaporation could produce brines.
- ? Querred where fresh water input may have inhibited brine formation
- Brine movement
- Carbonate-rich marginal lacustrine
- Sandstone-rich marginal lacustrine
- Fluvial and alluvial variegated mudstone, sandstone, and siltstone
- Top of Mahogany bed (Uinta Basin), Top of Mahogany zone (Piceance Basin)
- Base of Parachute Creek Member

End of illitic phase—beginning of carbonate phase

By the end of the illitic phase, offshore oil-shale deposition had been replaced by shallow-water shelf deposition throughout all but the deep trough of the Uinta Basin. Sediments from the southern Uinta Basin spilled over to create an expanding shelf along the southwest margin of the Piceance Basin.



Major drainage

EXPLANATION



From Johnson and Brownfield (in press)

- Carbonate-rich oil shale > 10 gallons per ton
- Carbonate-rich oil shale < 10 gallons per ton
- Nahcolite < 25,000 short tons/acre
- Carbonate-rich marginal lacustrine
- Sandstone-rich marginal lacustrine
- Fluvial and alluvial variegated mudstone, sandstone, and siltstone
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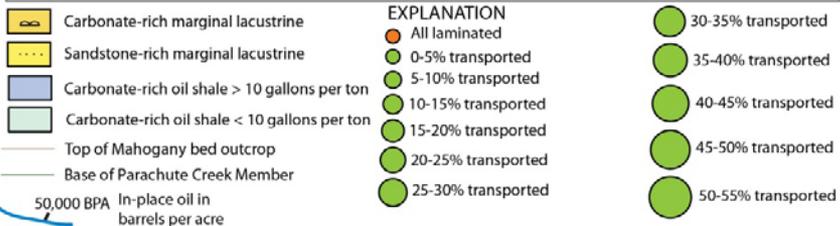
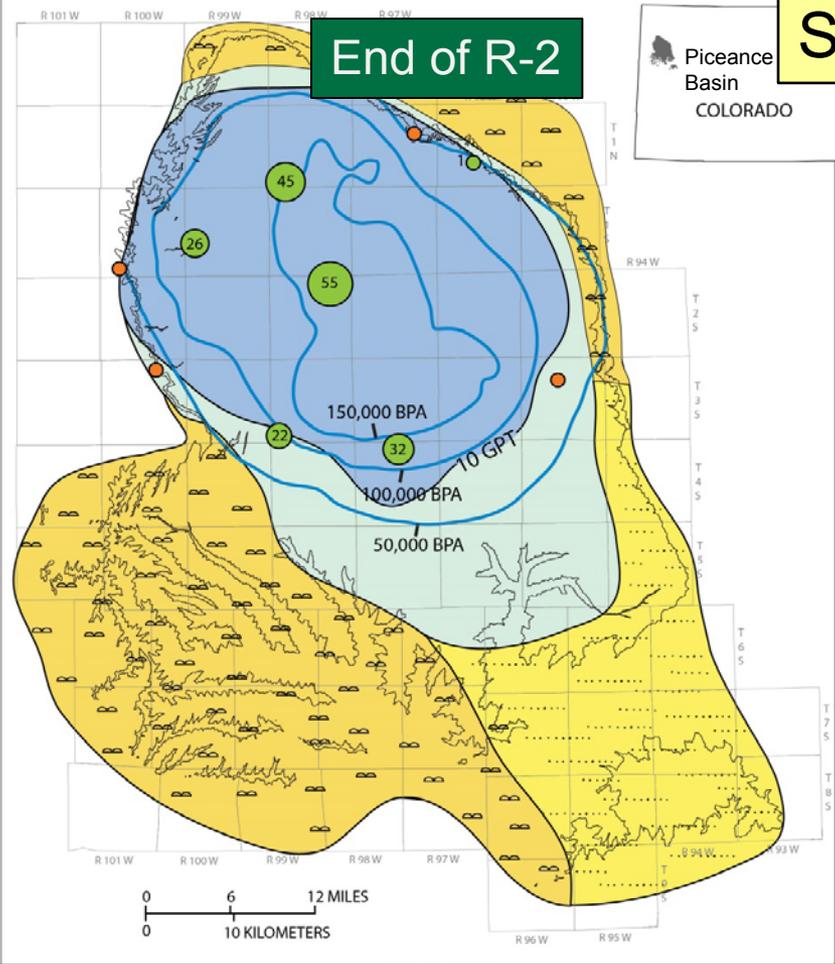
End of illitic phase—beginning of carbonate phase

Many authors have stressed the importance of evaporation on lake-margin mud flats in producing concentrated brines (Smith, 1974, p. 77; Ryder and others, 1976; Eugster and Hardie, 1978; Surdam and Stanley, 1979; Johnson, 1985; Remy and Ferrell, 1989).

# Saline Phase

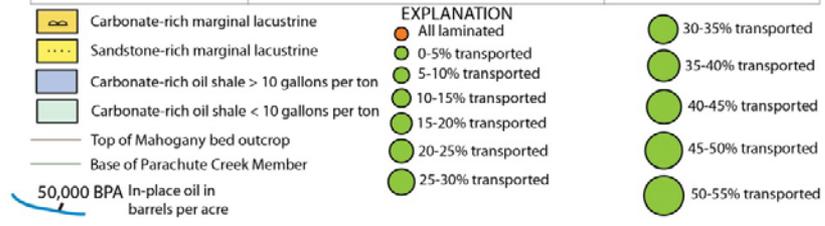
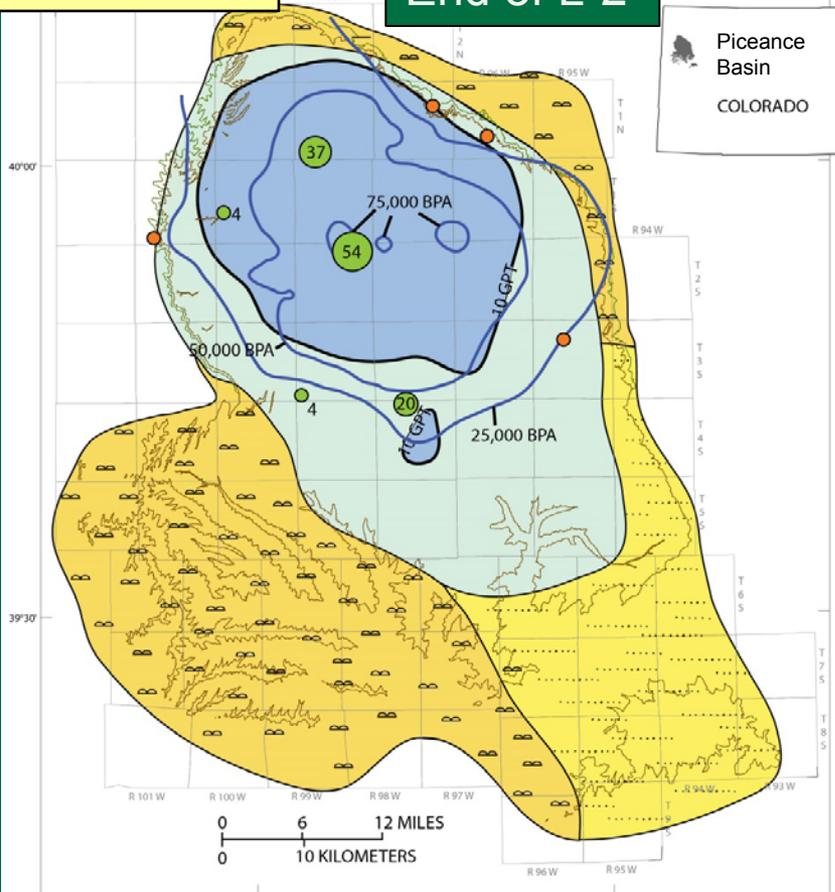
End of R-2

Piceance Basin  
COLORADO



End of L-2

Piceance Basin  
COLORADO

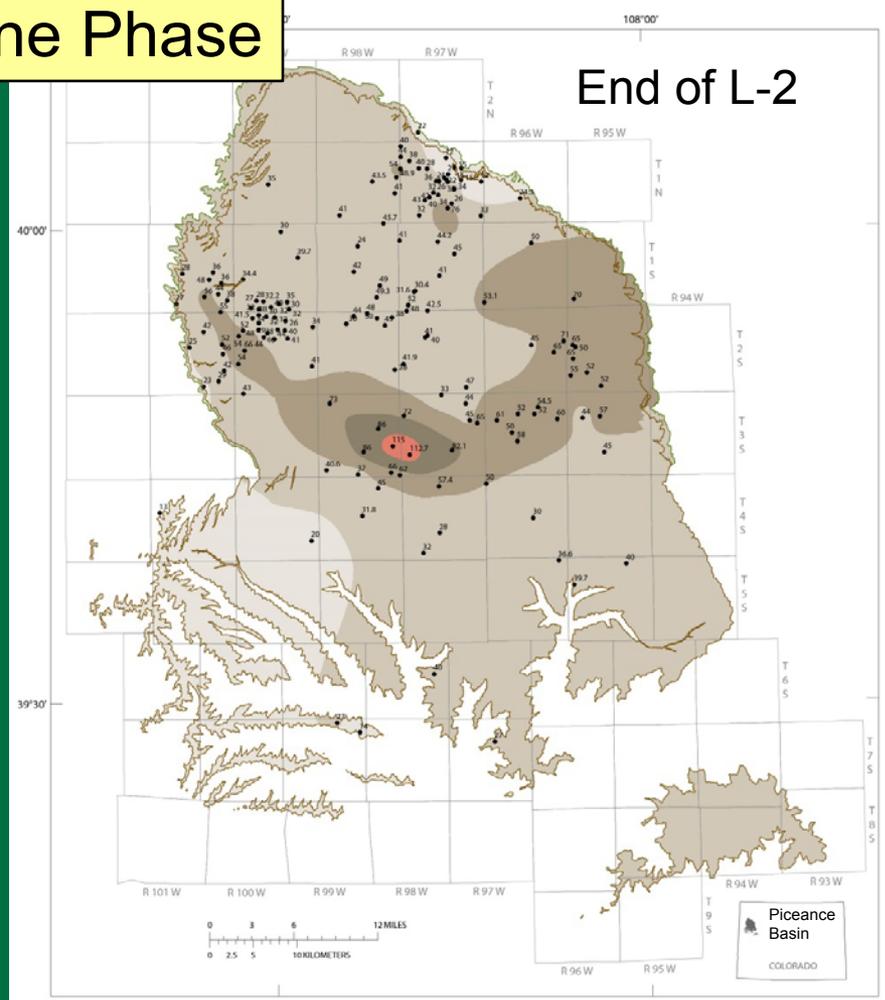
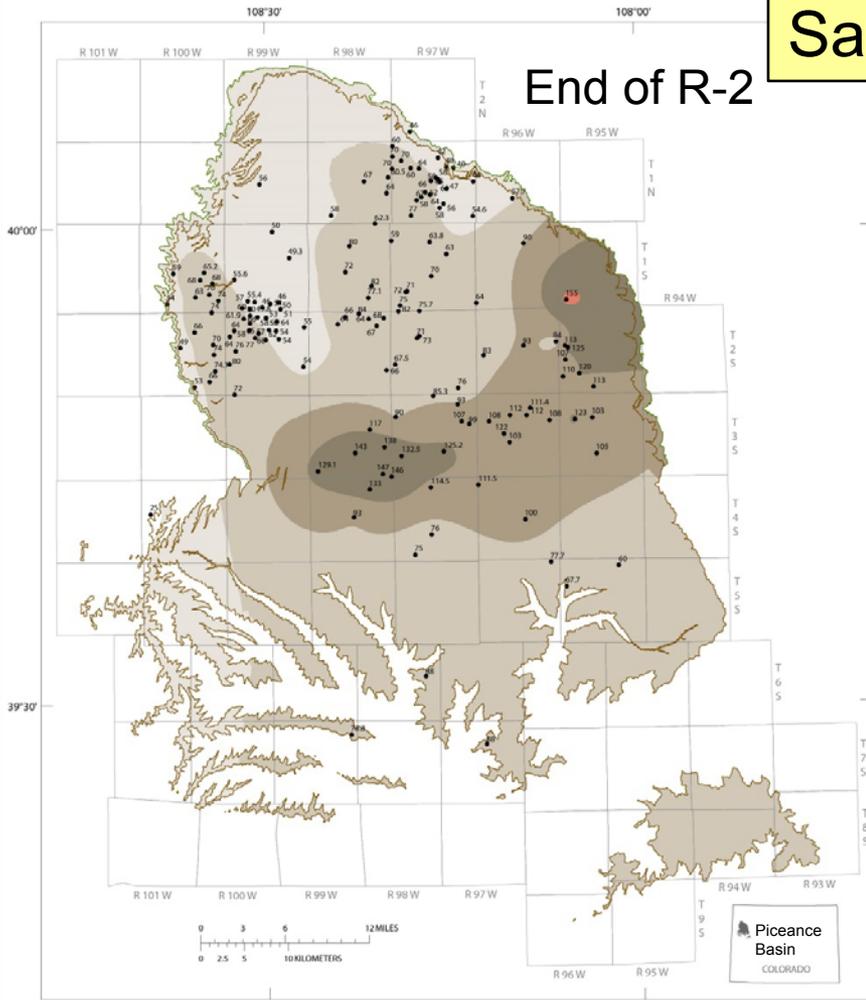


By the beginning of the carbonate and saline mineral phase of the lake (Parachute Creek Member, R-2 oil shale zone), shelf building had slowed. Mass-movement deposits now accumulated mainly in the central part of the lake.

# Saline Phase

## End of R-2

## End of L-2



### EXPLANATION

- Top of Mahogany bed outcrop
- Base of Parachute Creek Member
- Core hole—Thickness of oil shale interval in feet

R-2 interval—Thickness in feet	
White	≤ 30
Light tan	31–60
Medium tan	61–90
Dark brown	91–120
Very dark brown	121–150
Red	151–180

### EXPLANATION

- Top of Mahogany bed outcrop
- Base of Parachute Creek Member
- Core hole—Thickness of oil shale interval in feet

L-2 interval—Thickness in feet	
White	≤ 25
Light tan	26–50
Medium tan	51–75
Dark brown	76–100
Red	101–125

From Johnson and others (2010)



Some shelf building continued during the early carbonate phase. The R-2 and L-2 zones are thickest at the base of the shelf.

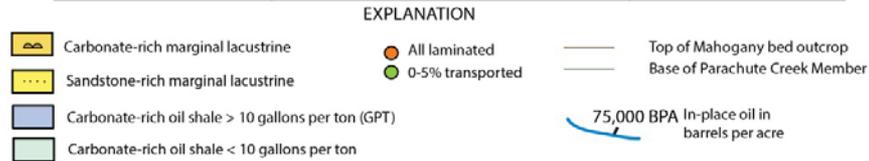
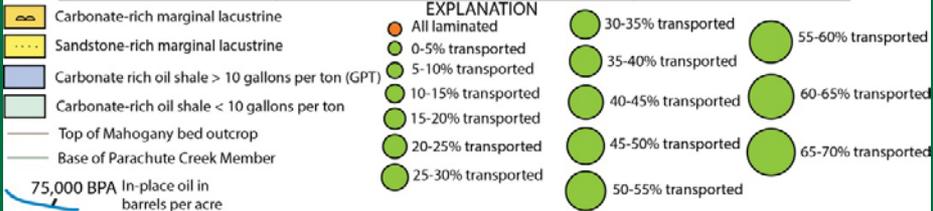
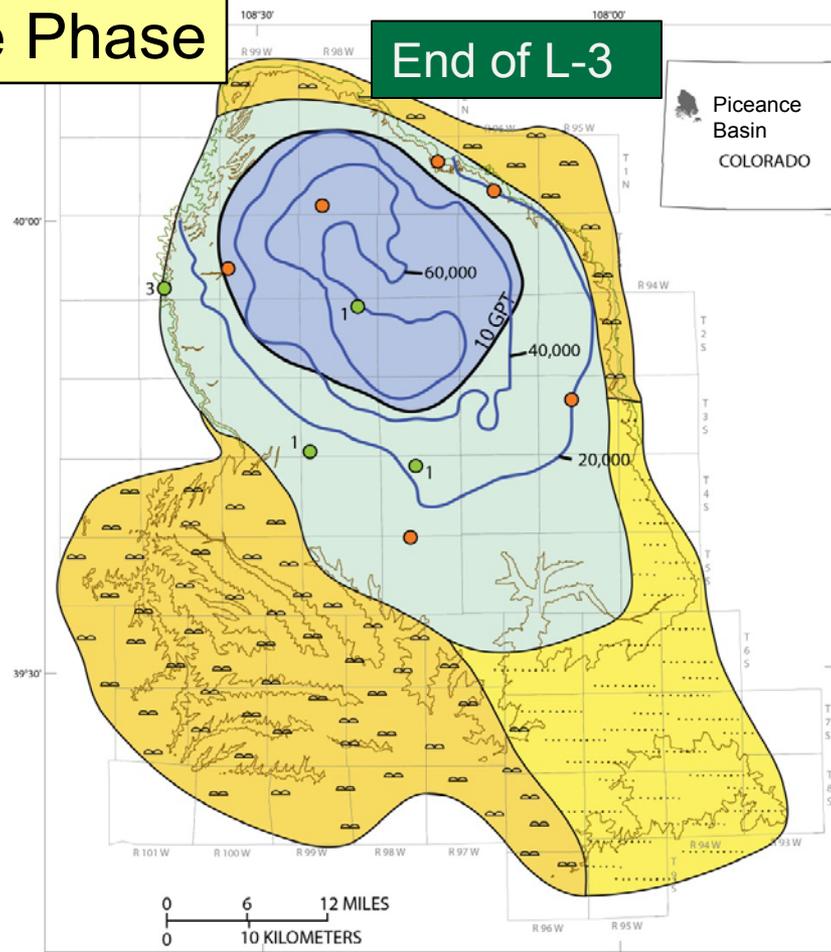
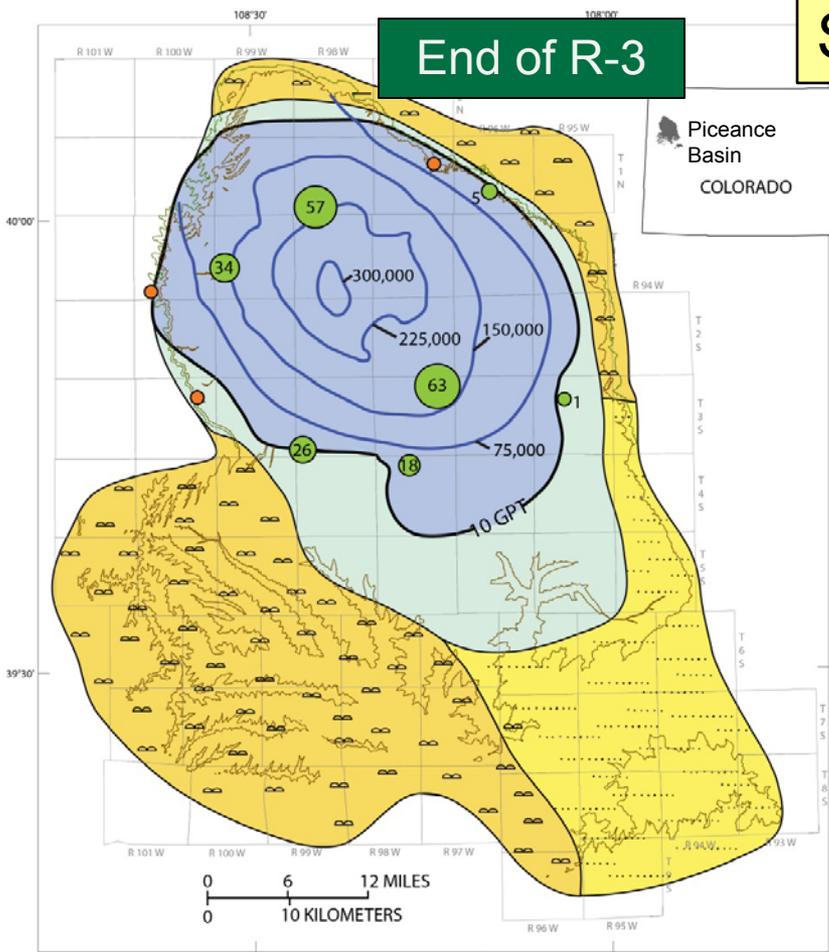
# Saline Phase

## End of R-3

## End of L-3

Piceance Basin  
COLORADO

Piceance Basin  
COLORADO



The R-3 zone is predominantly composed of mass-movement deposits in the center of the lake, whereas the overlying L-3 zone contains almost no mass-movement deposits.

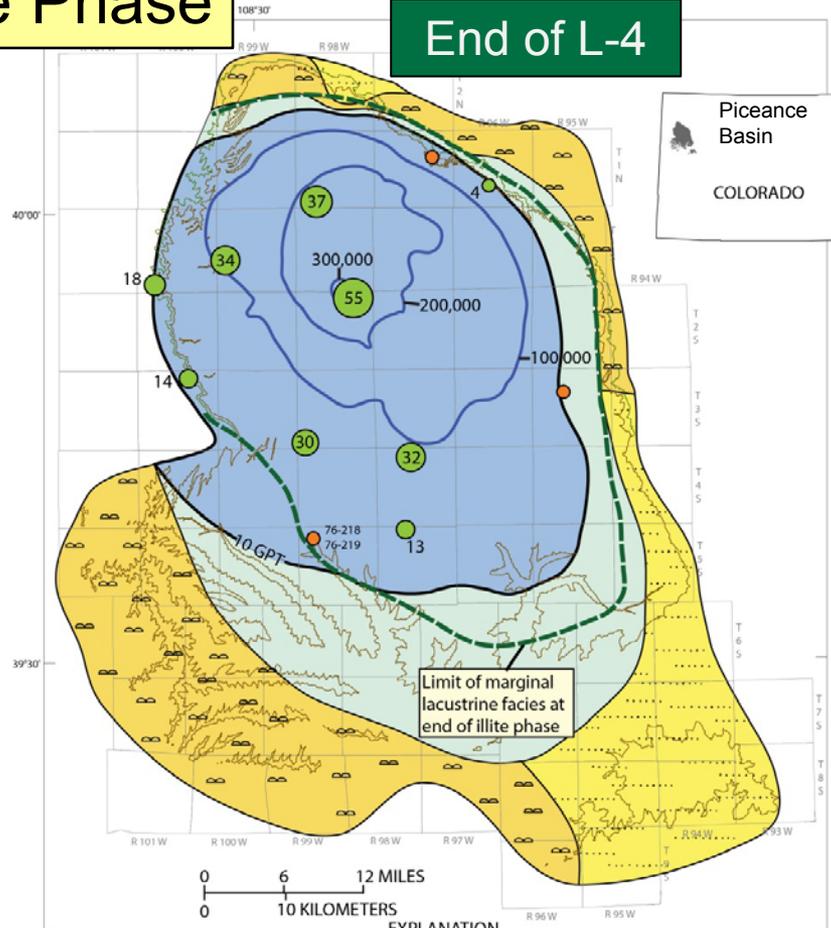
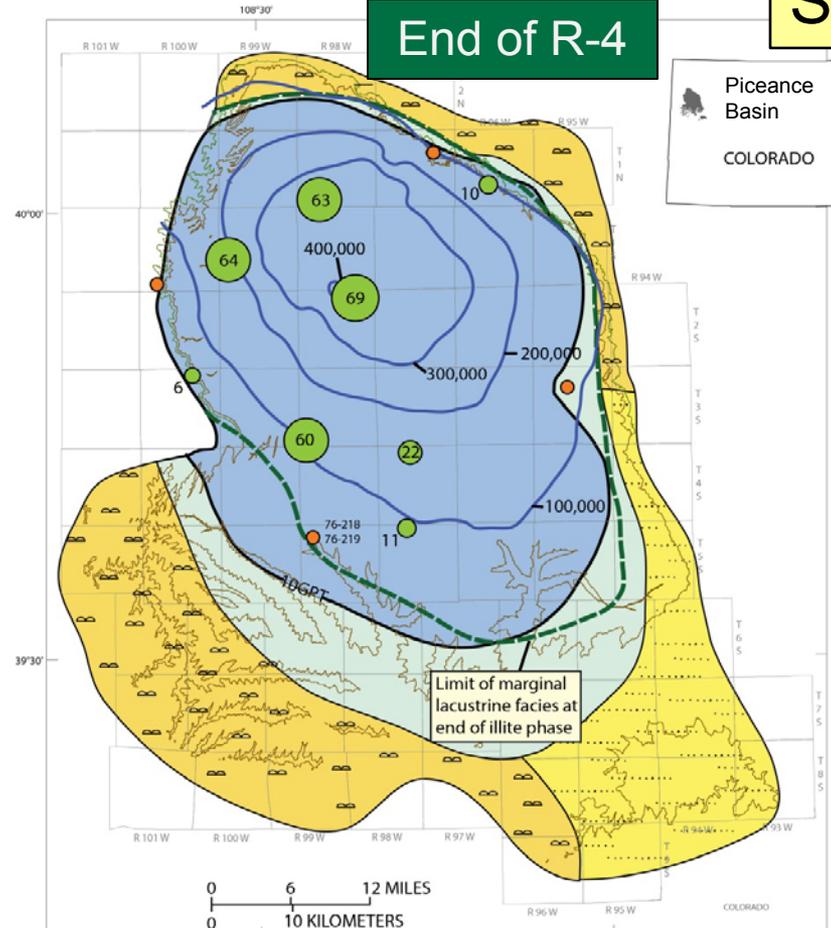
# Saline Phase

## End of R-4

## End of L-4

Piceance Basin  
COLORADO

Piceance Basin  
COLORADO



- |  |                    |                    |                    |
|--|--------------------|--------------------|--------------------|
| Carbonate-rich marginal lacustrine                 | All laminated      | 30-35% transported | 55-60% transported |
| Sandstone-rich marginal lacustrine                 | 0-5% transported   | 35-40% transported | 60-65% transported |
| Carbonate rich oil shale >10 gallons per ton (GPT) | 5-10% transported  | 40-45% transported | 65-70% transported |
| Carbonate-rich oil shale <10 gallons per ton       | 10-15% transported | 45-50% transported | 50-55% transported |
| 100,000 BPA In-place oil in barrels per acre       | 15-20% transported | 50-55% transported |                    |
| Top of Mahogany bed outcrop                        | 20-25% transported |                    |                    |
| Base of Parachute Creek Member                     | 25-30% transported |                    |                    |

- |  |                    |                    |                    |
|--|--------------------|--------------------|--------------------|
| Carbonate-rich marginal lacustrine                 | All laminated      | 30-35% transported | 55-60% transported |
| Sandstone-rich marginal lacustrine                 | 0-5% transported   | 35-40% transported | 60-65% transported |
| Carbonate-rich oil shale >10 gallons per ton (GPT) | 5-10% transported  | 40-45% transported | 65-70% transported |
| Carbonate-rich oil shale <10 gallons per ton       | 10-15% transported | 45-50% transported | 50-55% transported |
| 100,000 BPA In-place oil in barrels per acre       | 15-20% transported | 50-55% transported |                    |
| Top of Mahogany bed outcrop                        | 20-25% transported |                    |                    |
| Base of Parachute Creek Member                     | 25-30% transported |                    |                    |

The lake began to expand over the marginal shelves in R-4 time. The rich R-4 zone is mainly composed of mass-movement deposits in the center of the lake, whereas mass-movement deposits are somewhat less in the overlying leaner L-4 zone.



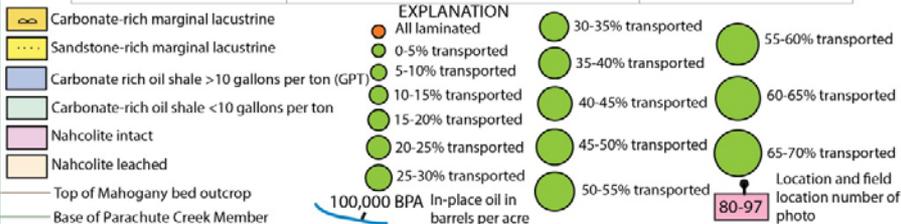
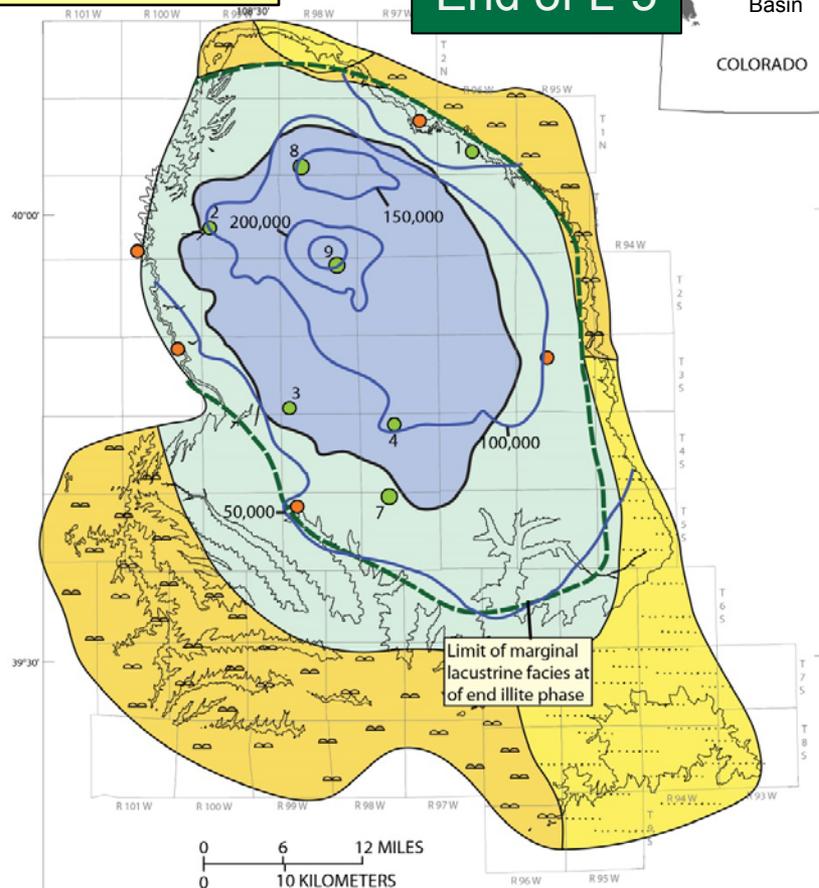
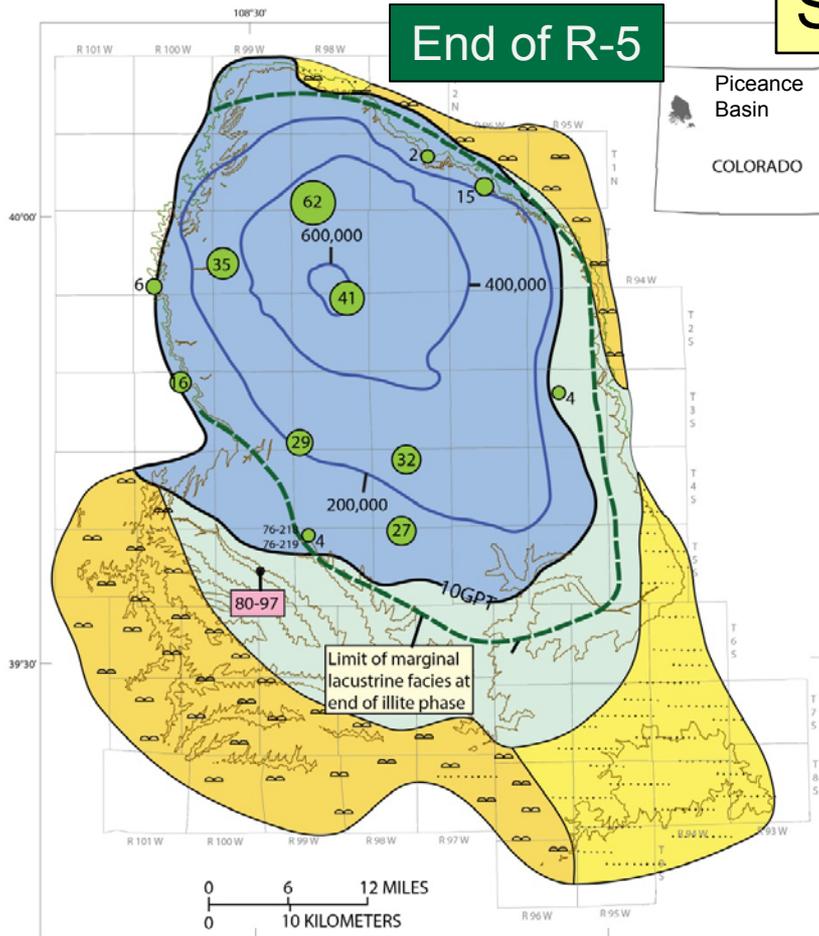
# Saline Phase

## End of R-5

## End of L-5

Piceance Basin  
COLORADO

Piceance Basin  
COLORADO

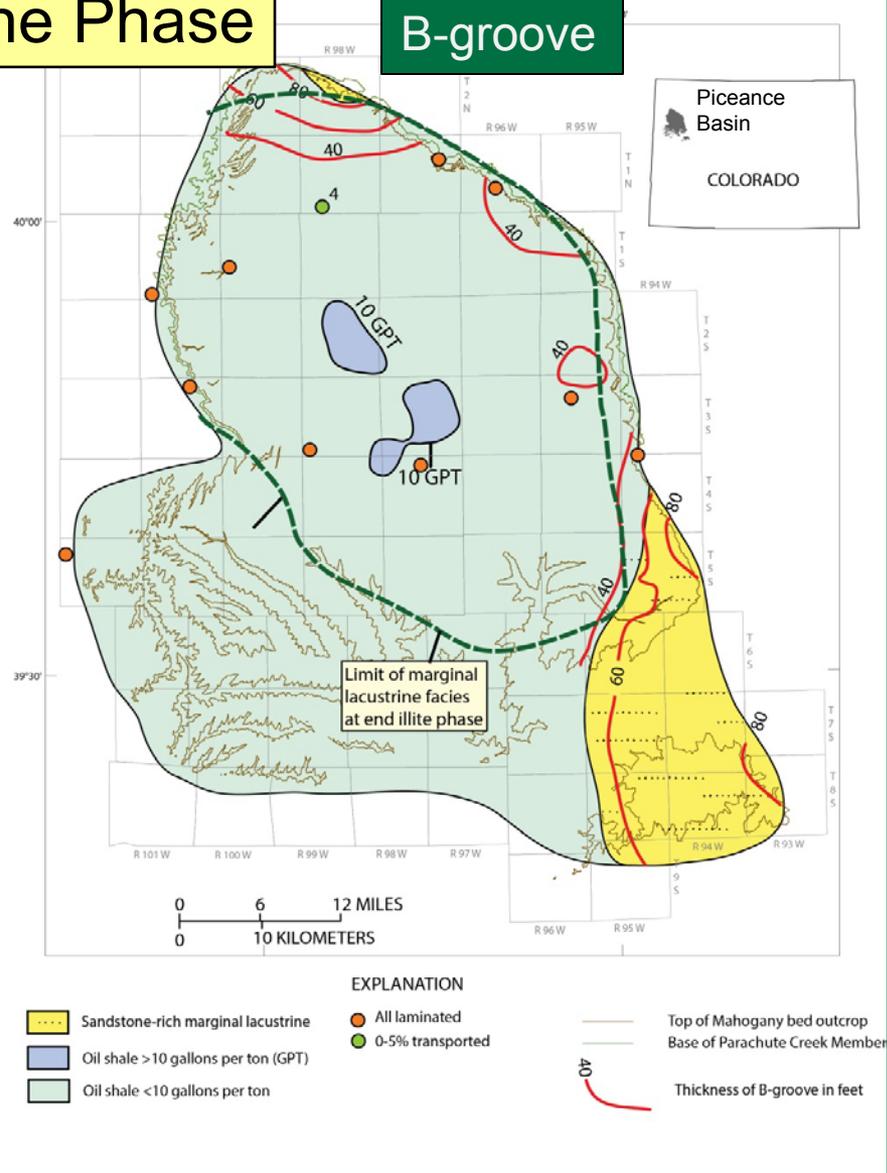
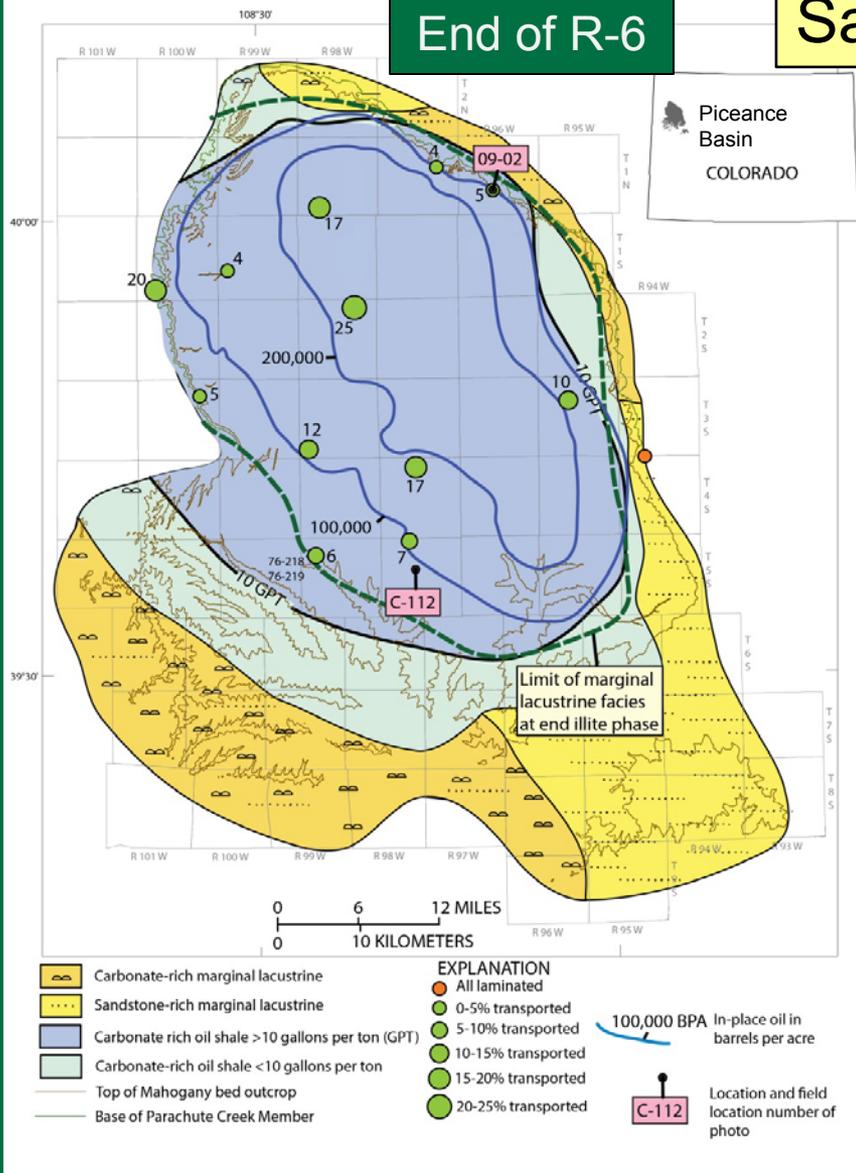


The R-5 zone contains abundant mass-movement deposits, whereas mass-movement deposits are rare in the overlying leaner L-5 zone.

# End of R-6

# Saline Phase

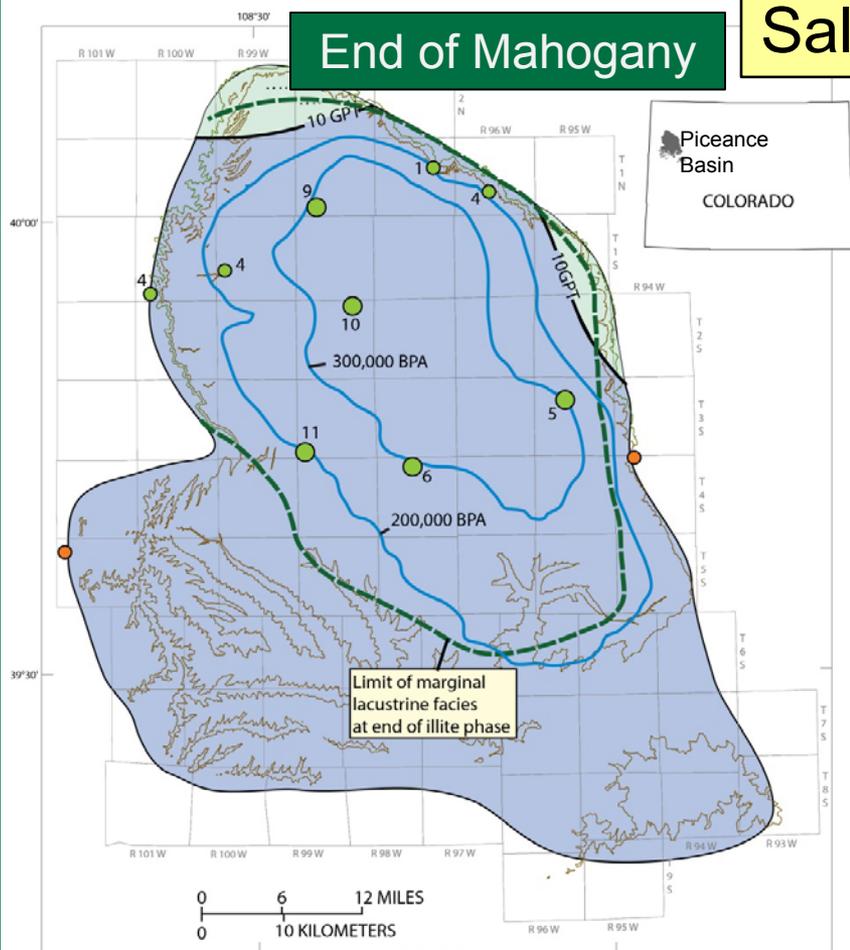
# B-groove



The percentage of mass-movement deposits progressively decreased as deep-water conditions continued to encroach on the marginal shelf during R-6 time. The overlying lean B-groove contains almost no mass-movement deposits.

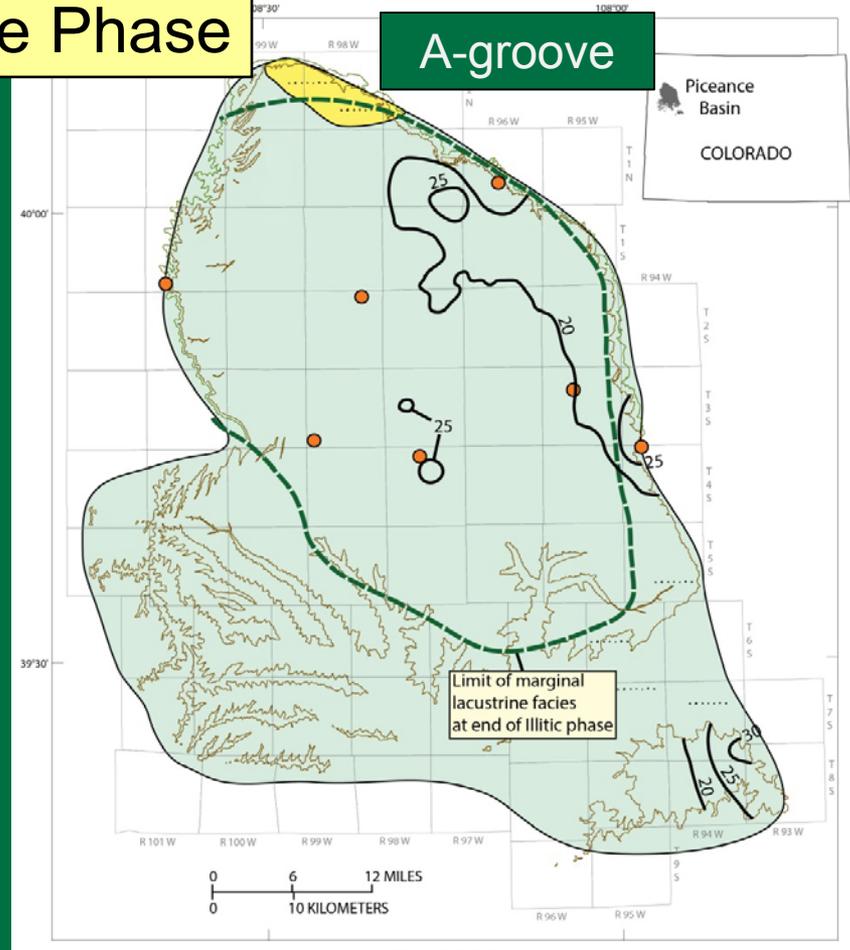
# Saline Phase

## End of Mahogany



# Saline Phase

## A-groove



- EXPLANATION**
- Carbonate-rich oil shale >10 gallons per ton (GPT)
  - Carbonate-rich oil shale <10 gallons per ton
  - Top of Mahogany bed outcrop
  - Base of Parachute Creek Member
  - All laminated
  - 0-5% transported
  - 5-10% transported
  - 10-15% transported
  - 100,000 BPA In-place oil in barrels per acre

- EXPLANATION**
- Sandstone-rich marginal lacustrine
  - Oil shale >10 gallons per ton (GPT)
  - Oil shale <10 gallons per ton
  - All laminated
  - Top of Mahogany bed outcrop
  - Base of Parachute Creek Member
  - Thickness of A-groove in feet.

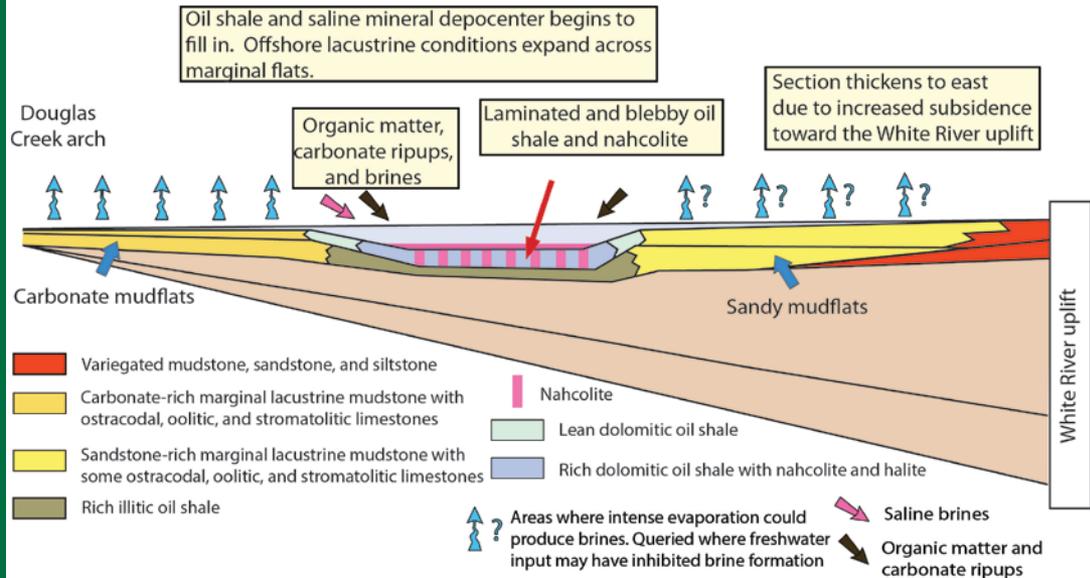
Deep-water conditions were dominant over the former marginal shelves during deposition of the Mahogany zone. Mass-movement deposits are rare in the Mahogany and absent in the overlying lean A-groove.

# Saline Phase Summary

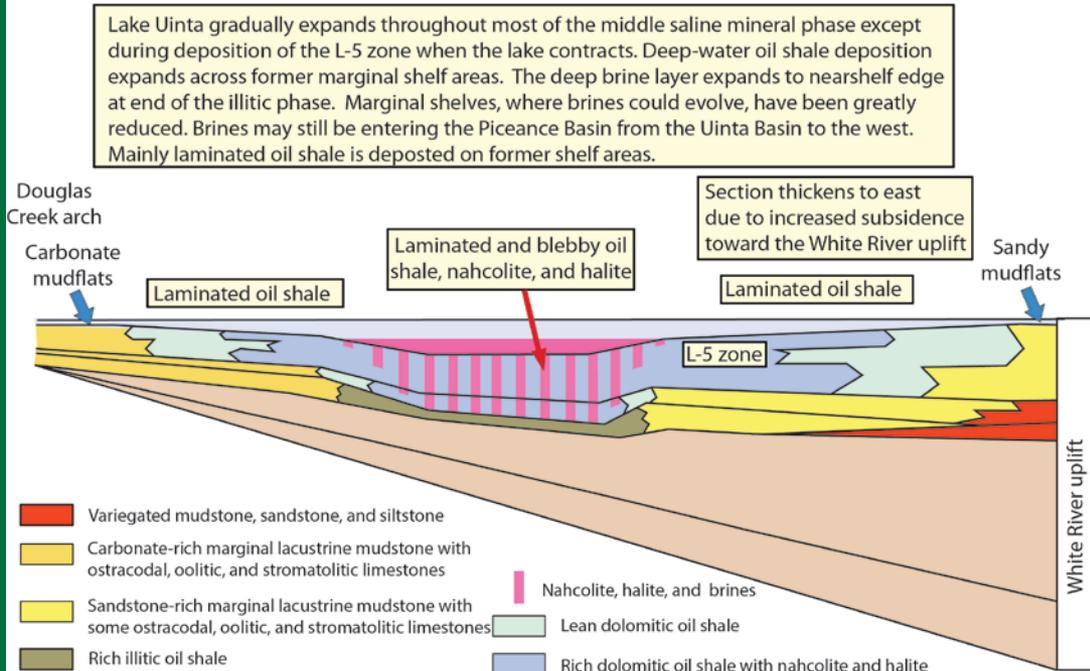
During the early stages of the saline mineral phase (Parachute Creek Member), Lake Uinta repeatedly transgressed and regressed across the marginal shelves, providing opportunities for sediments and organic matter to be exhumed and transported to the central part of the lake.

As Lake Uinta expanded and deepened, mass-movement deposits diminished.

## A. End of early saline mineral phase



## B. Just prior to Mahogany



From Johnson and Brownfield (in press).



## Infilling Phase



Following deposition of the Mahogany zone, Lake Uinta began to fill in from north to south. Slumps during the infilling stage of the lake can be several hundred feet thick, cover several square miles, and can be underlain and overlain by laminated marl and oil shale. This slump extends along a valley wall for 2.1 miles.

# Conclusions

- Mass-movement deposits during the illitic phase of Lake Uinta contain fewer clasts than the carbonate phase of the lake suggesting that the source area was mostly unlithified.
- Mass-movement deposits during the carbonate phase of the lake (Parachute Creek Member) contain abundant clasts indicating early lithification of sediments in marginal areas. These flows are most abundant in the central part of the depocenter.
- Mass-movement deposits accumulated at the base of the prograding shelves until the shelves reached the deep central part of the lake when progradation slowed. Mass-movement deposits then reached the central deep part of the lake.

# Conclusions (continued)

- Large amounts of organic matter were included in mass-movement deposits.
- Highly saline brines that evolved on the marginal shelves may have been incorporated into the mass-movement deposits.
- Lean zones tend to include less mass-movement deposits than adjacent rich zones, possibly because organic-rich sediments were more prone to failure.

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