Thermal Conductivity of Organic Shales and Coals – How Their Presence and Persistence Effect Thermal Maturity*

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Abstract

Mature source-rock intervals commonly act as thermal insulators to heat flow and can be identified by the first derivative of a wireline temperature log. When displayed in a cross section, the first derivative curve readily identifies intervals where the temperature curve flattens (insulators) and steepens (conductors). The lithologic control of thermal conductivity is so strong that stratigraphy can be easily correlated using only the first derivative curve. The first derivate correlates strongly to the sonic curve in mature source rock intervals; the sonic curve shows slow velocities and the first derivative indicates flattening of the temperature curve. Because thermal gradient increases at capillary seals, they can be readily identified on first derivative curves. While it is important to identify the insulating lithologies, it is equally important to identify their persistence through time as this can profoundly affect the thermal maturity of underlying source rocks. The burial and exhumation history of the Front Range from southeastern Wyoming to the Monument Hill area of Colorado provides an example of how the pre-Oligocene erosion of nearly 2500 to 3000 feet of Paleocene section including the Arapahoe, Denver, and Dawson formations can affect the thermal maturity of source rocks such as the Niobrara or other lower Cretaceous organic shales. While it appears that the Wattenberg geothermal anomaly controls where the Niobrara is highly thermally mature, the areas where the Niobrara is anomalously immature may be a function of the erosion of the Paleocene thermal insulator prior to the Oligocene.

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Denver Basin, *in* J. Woodward, F.F. Meissner, and, J.L. Clayton, (eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, p.339-354.

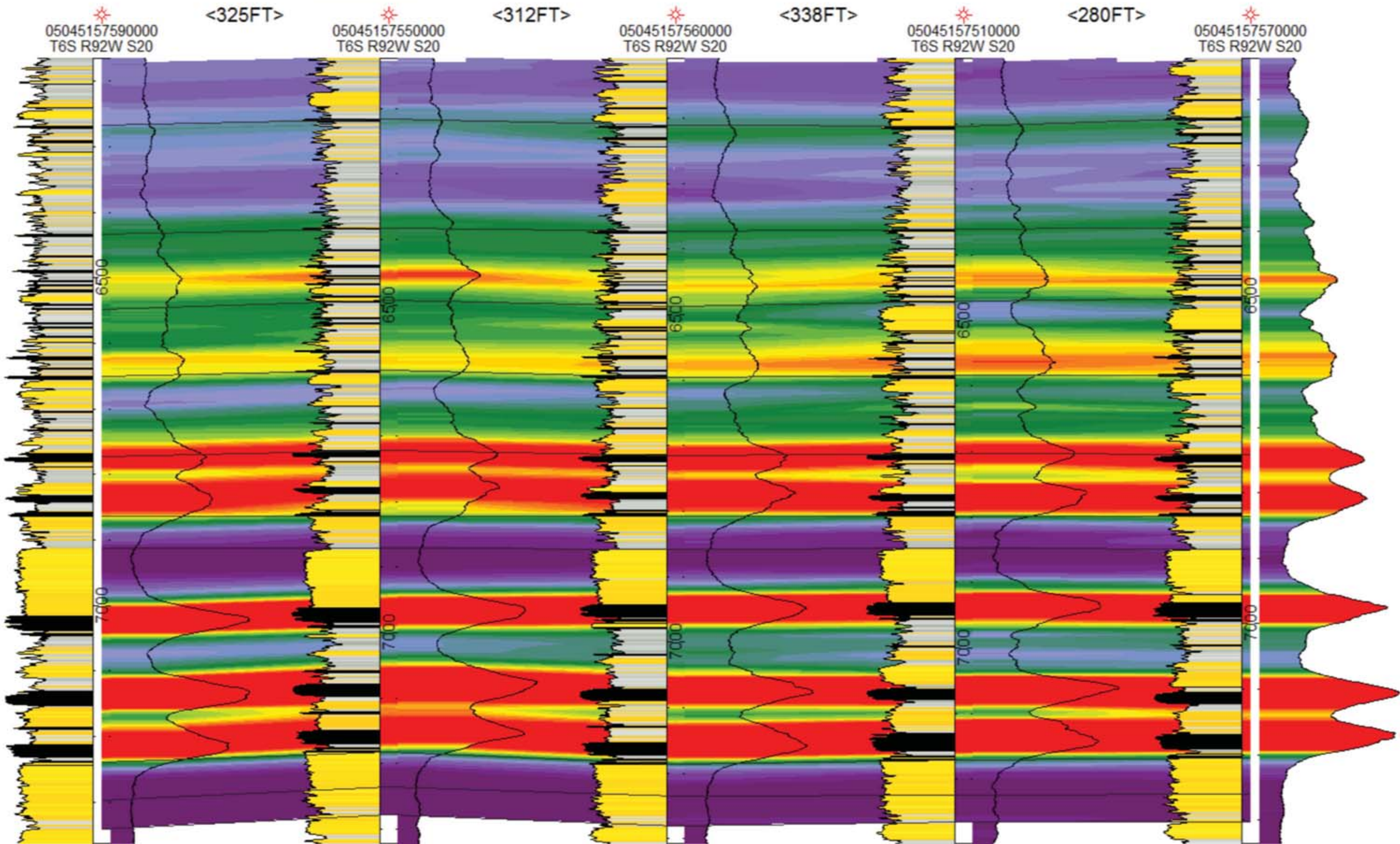
USGS, 1979, Geologic Map of the Greater Denver Area, Front Range Urban Corridor, Colorado: U.S. Geological Survey, IMAP 856-H.

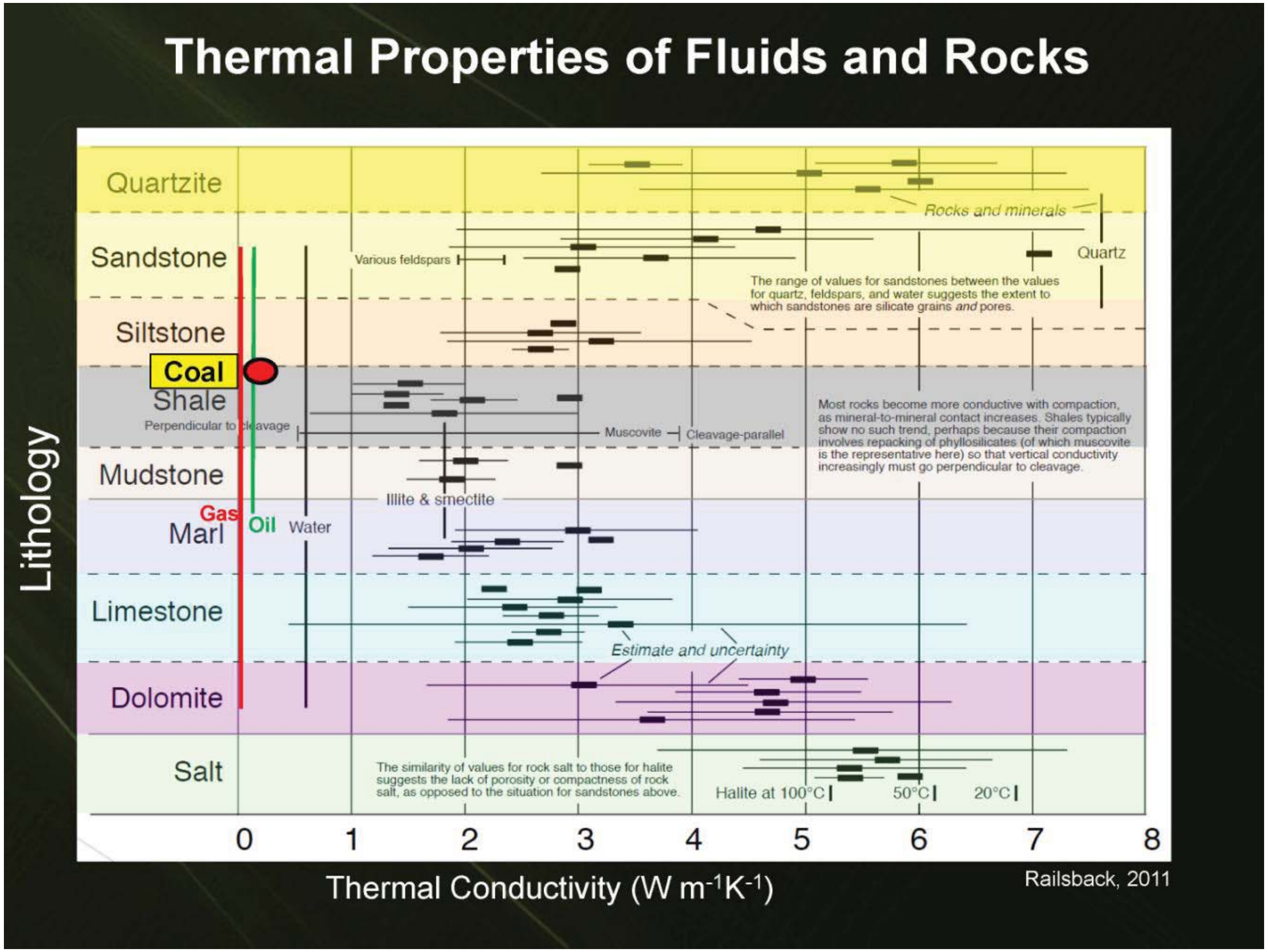
Website Cited

Early Paleocene Paleogeography Map from Blakey http://cpgeosystems.com/namKT65.jpg

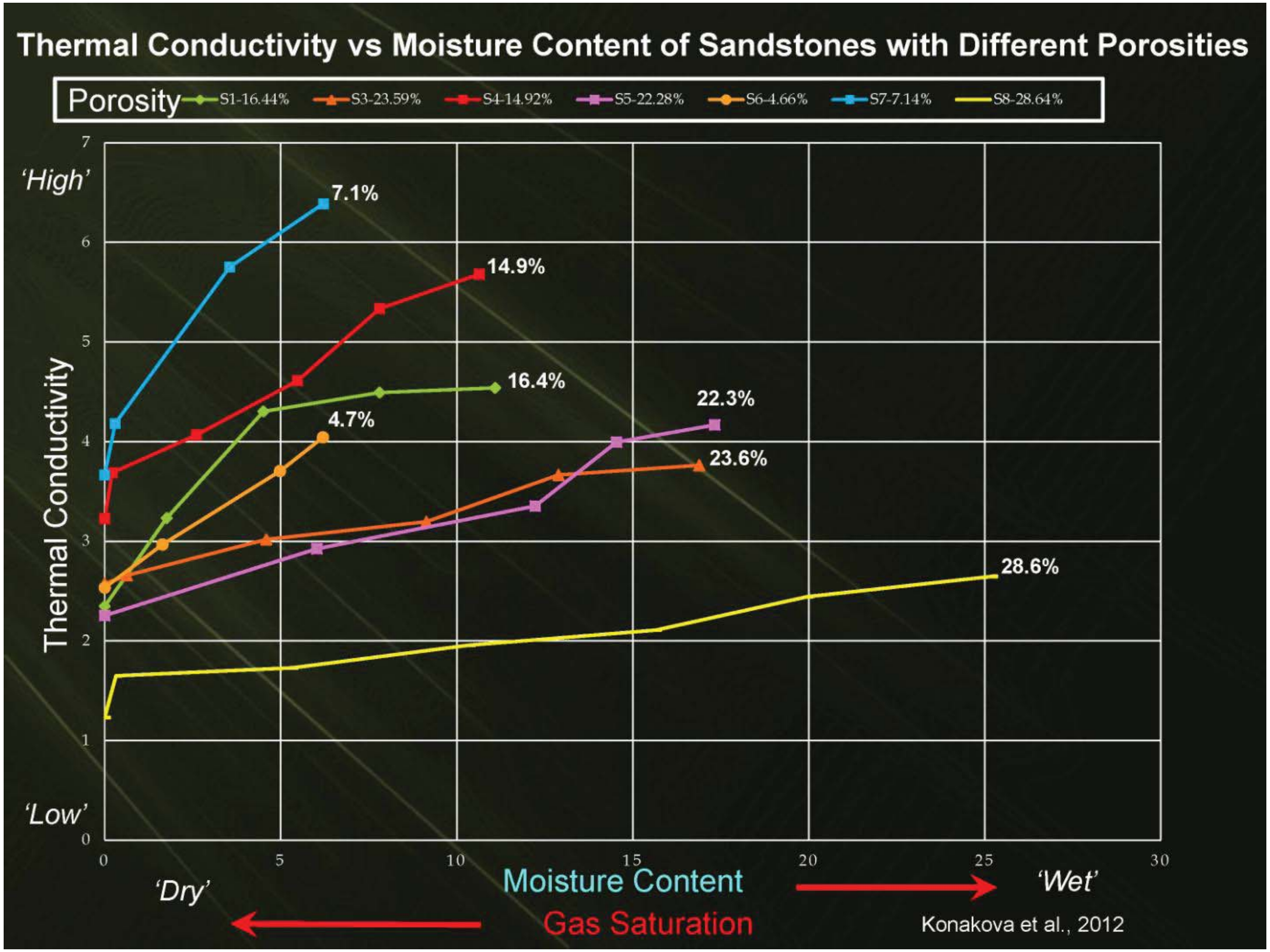
Thermal Conductivity of Organic Shales and Coals: How Their Presence and Persistence Affect Thermal Maturity

Bob Coskey and Steve Cumella

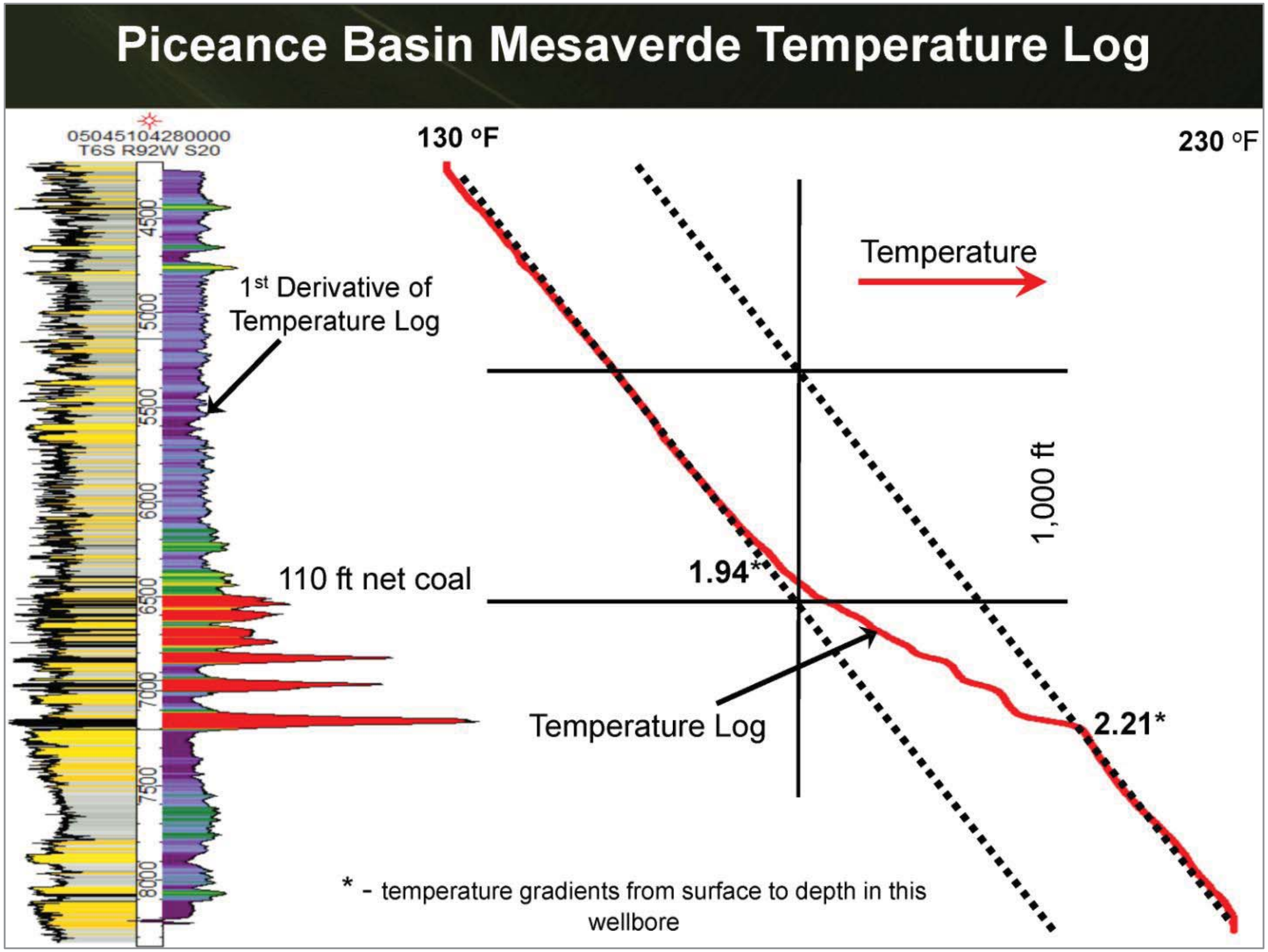




Presenter's notes: This graph shows the thermal conductivity of different rock types and subsurface fluids. Thermal conductivity is shown on the x axis. Better thermal conductors plot farther to the right and better insulators plot farther to the left. The key point on this graph is that all subsurface fluids are better insulators than all rock types and that hydrocarbons are better insulators than water. Therefore, more porous rocks are better insulators than low porosity rocks. Oil is about 4 times better insulator than water and gas has a thermal conductivity near zero, i.e., it is almost a perfect insulator. As a result coal is a very strong insulator because it has high porosity that is commonly gas filled.



Presenter's notes: This slide shows that thermal conductivity of different sandstones decreases with porosity and increases with increased moisture content (water is a better thermal conductor than air). The porosities of different sandstones (S1, S2, etc.) are listed at the top of the slide, as well as next to the graphed data. Data from Konakova, Vejmelkova, and Cerny, 2012, Thermal properties of selected sandstones: Advances in Modern Mechanical Engineering, p. 100-104, ISBN: 978-960-474-307-0.



Presenter's notes: Coals act as insulators to heat flow. This slide shows a temperature log of the Mesaverde in the southern Piceance. The temperature log is shown in red and the scale is 130 to 230 degrees F. The intervals where the temperature curve flattens are insulators (e.g., coals) and are easily identified on the 1st derivative of the temperature curve (warm colors).

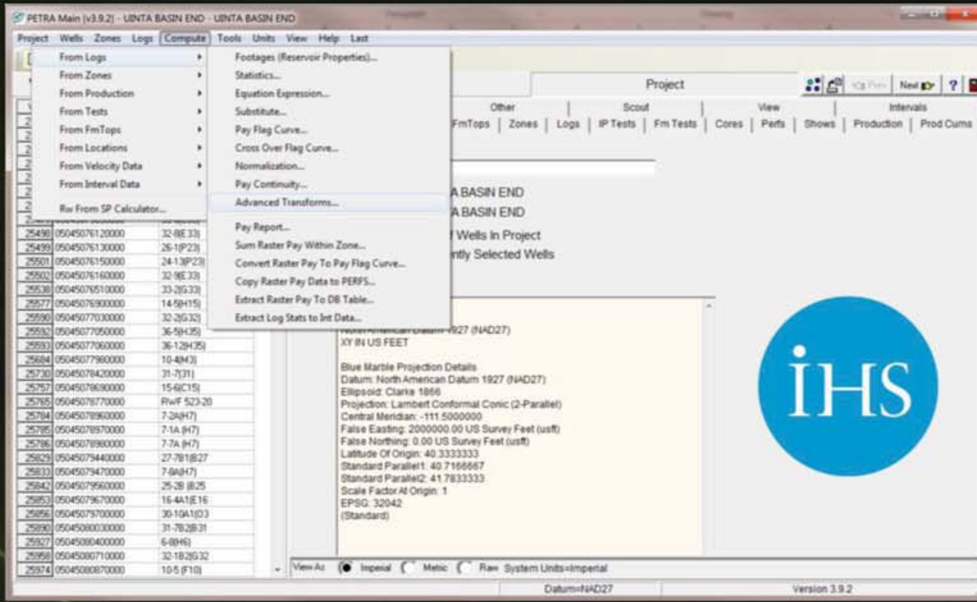
(Presenter's notes continued on next slide)

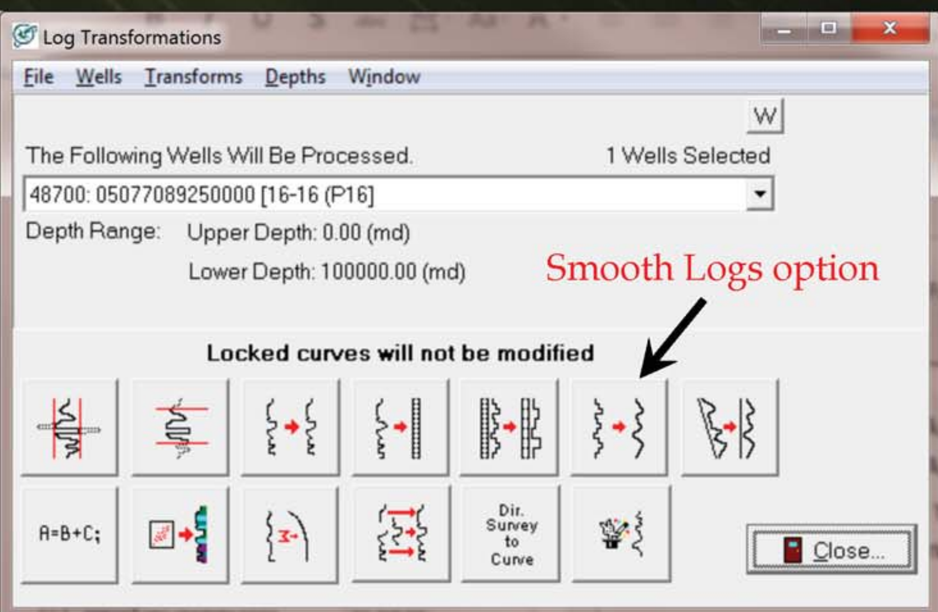
(Presenter's notes continued from previous slide)

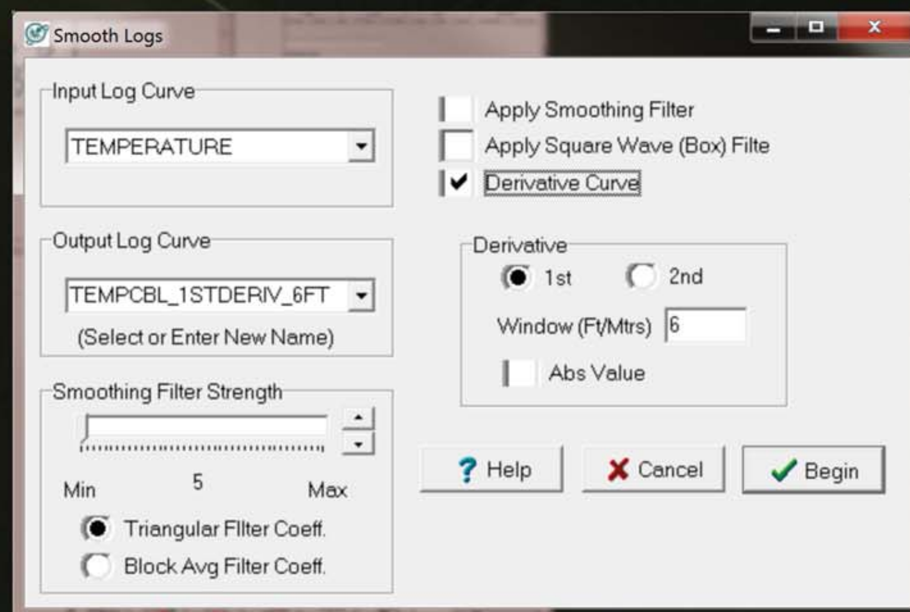
The first derivative of the temperature curve shows insulating lithologies like coals in warm colors and conducting lithologies like sandstone in cool colors. Black dashed trend lines above and below the coal interval are sub-parallel. The offset of those trend lines is equivalent to about 1,000 ft, therefore the insulating effect of the Cameo coals is roughly equivalent to adding an additional 1,000 ft of overburden. Recognition of insulating intervals is important when mapping temperature gradient because the calculated thermal gradient can be very different if the bottom-hole temperature is above versus below the insulating interval. For example, in this well the thermal gradient increases from 1.94 ^{o}F/100 ft above the coal interval to 2.21 ^{o}F/100 ft below.

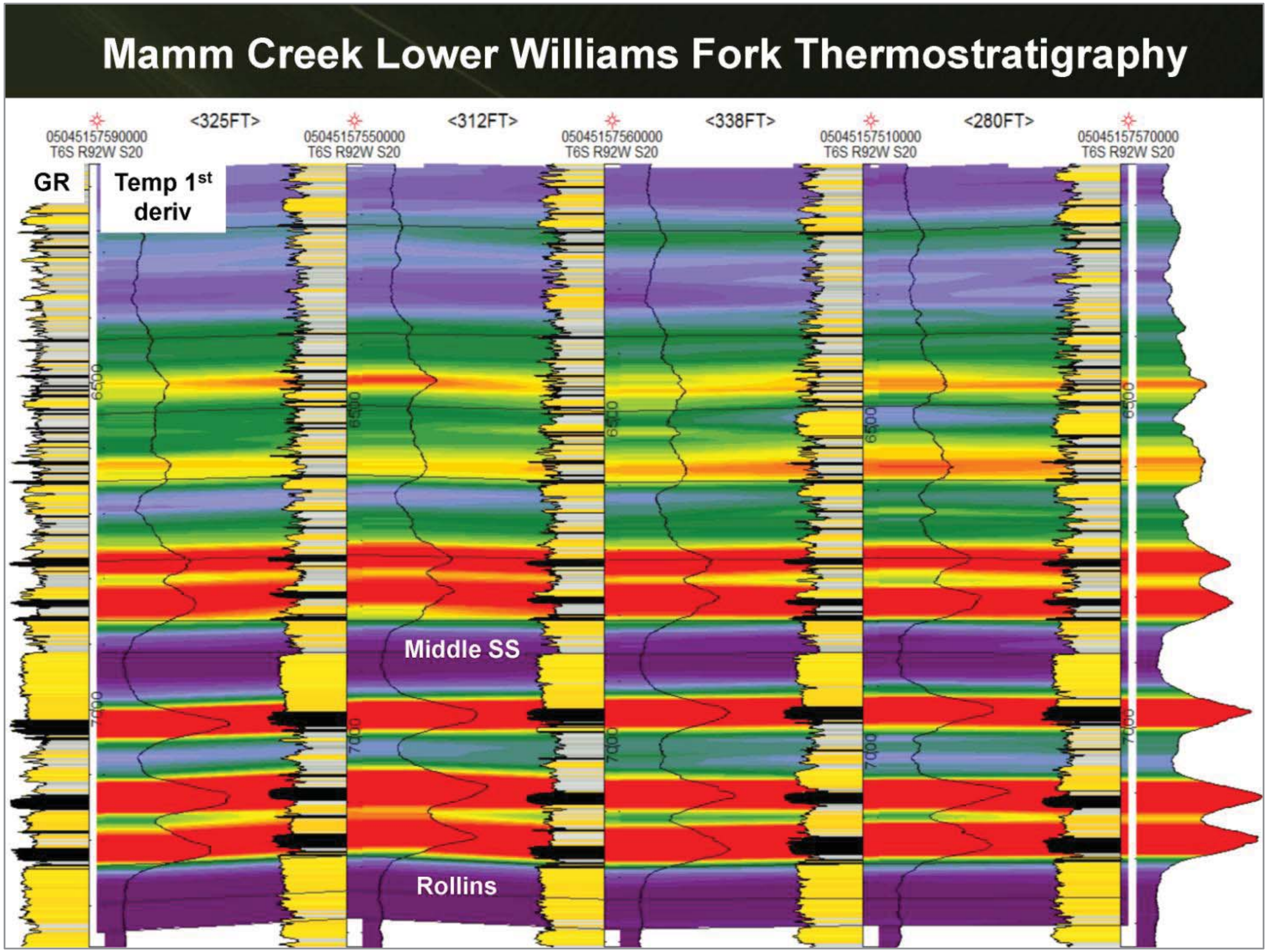
How to Create a 1st Derivative Curve in Petra

1. In main model, select Compute, From Logs, Advanced Transforms.
2. In Log Transformations module, select Smooth Logs option.
3. Select the temperature curve that you want to use, name output log curve, check Derivative curve box, 1st radio button and chose a window (e.g., 6 ft).

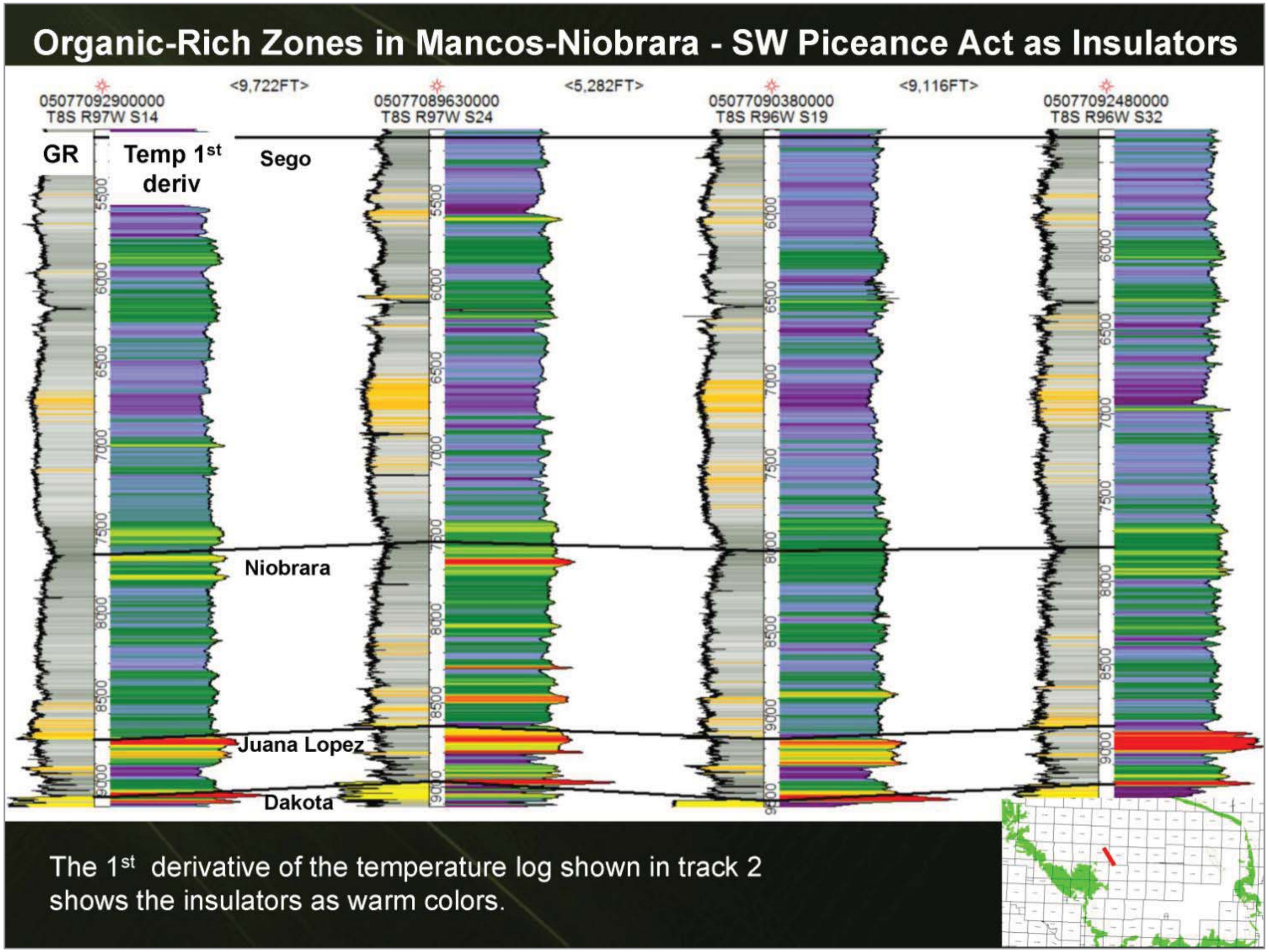








Presenter's notes: This slide shows the correlation of first derivative curves of temperature curves from cement-bond logs in five closely spaced wells in the southern Piceance Basin. Coals are good insulators and the first derivative curve deflects to the right in the intervals that are color filled with warm colors. Sandstones are good conductors and are color filled with cool colors. The good correlation of the first derivative curve from well to well indicates that the data are good static temperatures.

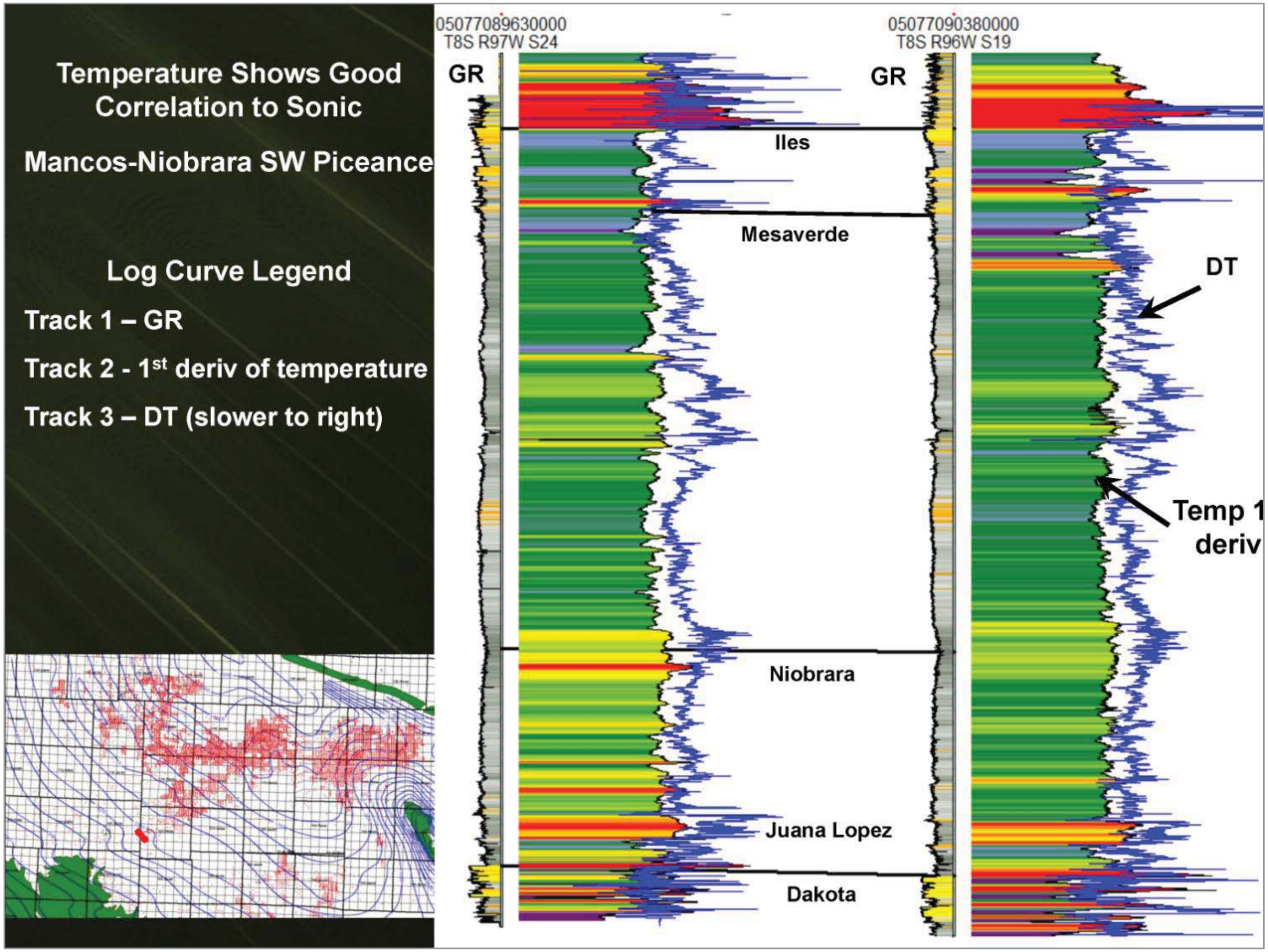


Presenter's notes: This slide shows first derivative curves from temperature logs run with cement-bond logs from wells in the southern Piceance Basin. The Mancos and Niobrara are composed of a thick sequence of marine shale that contain organic-rich intervals. In this area, the Niobrara is in the dry-gas window and gas is produced at high rates from horizontal wells that are landed in

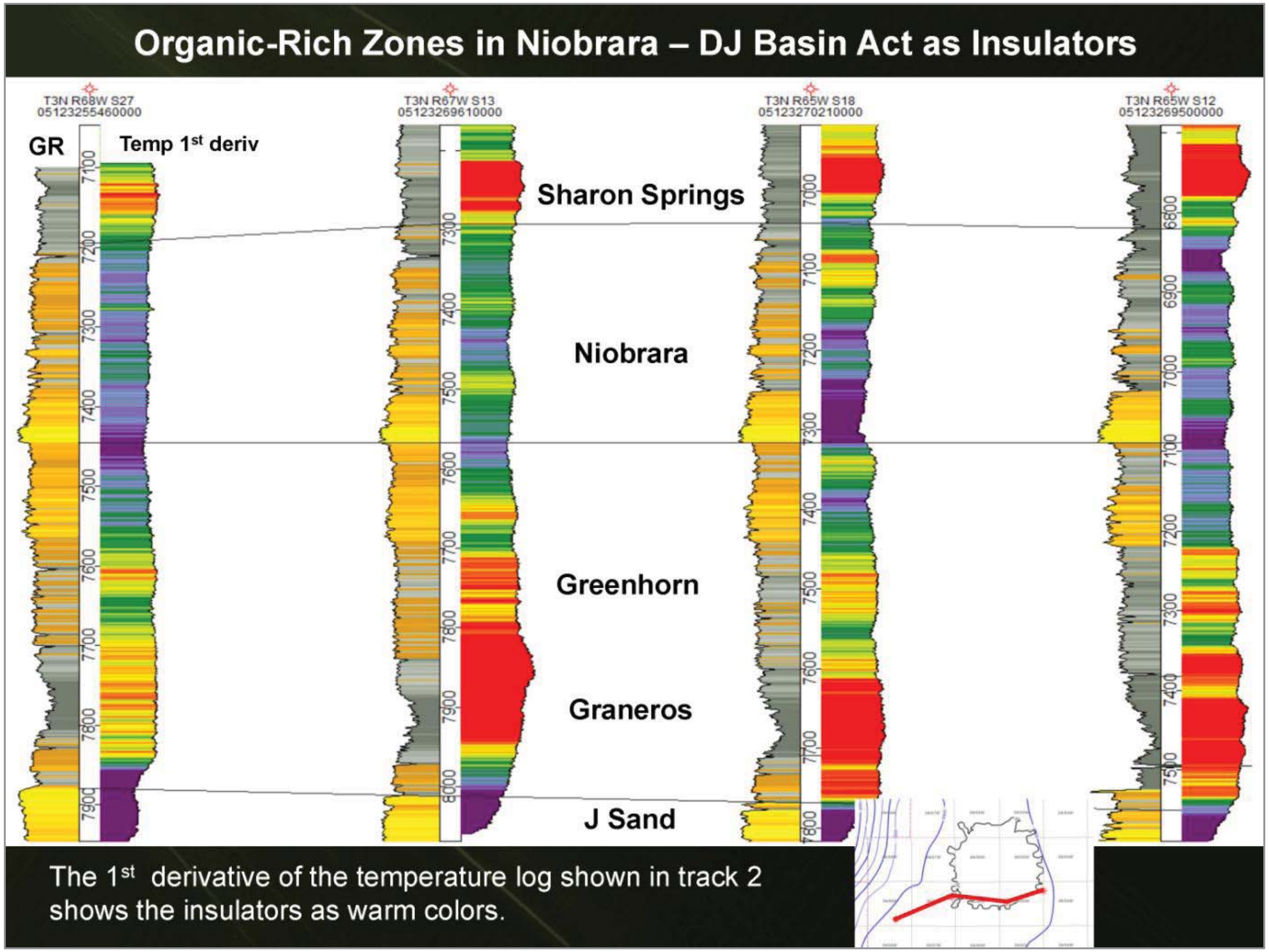
(Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

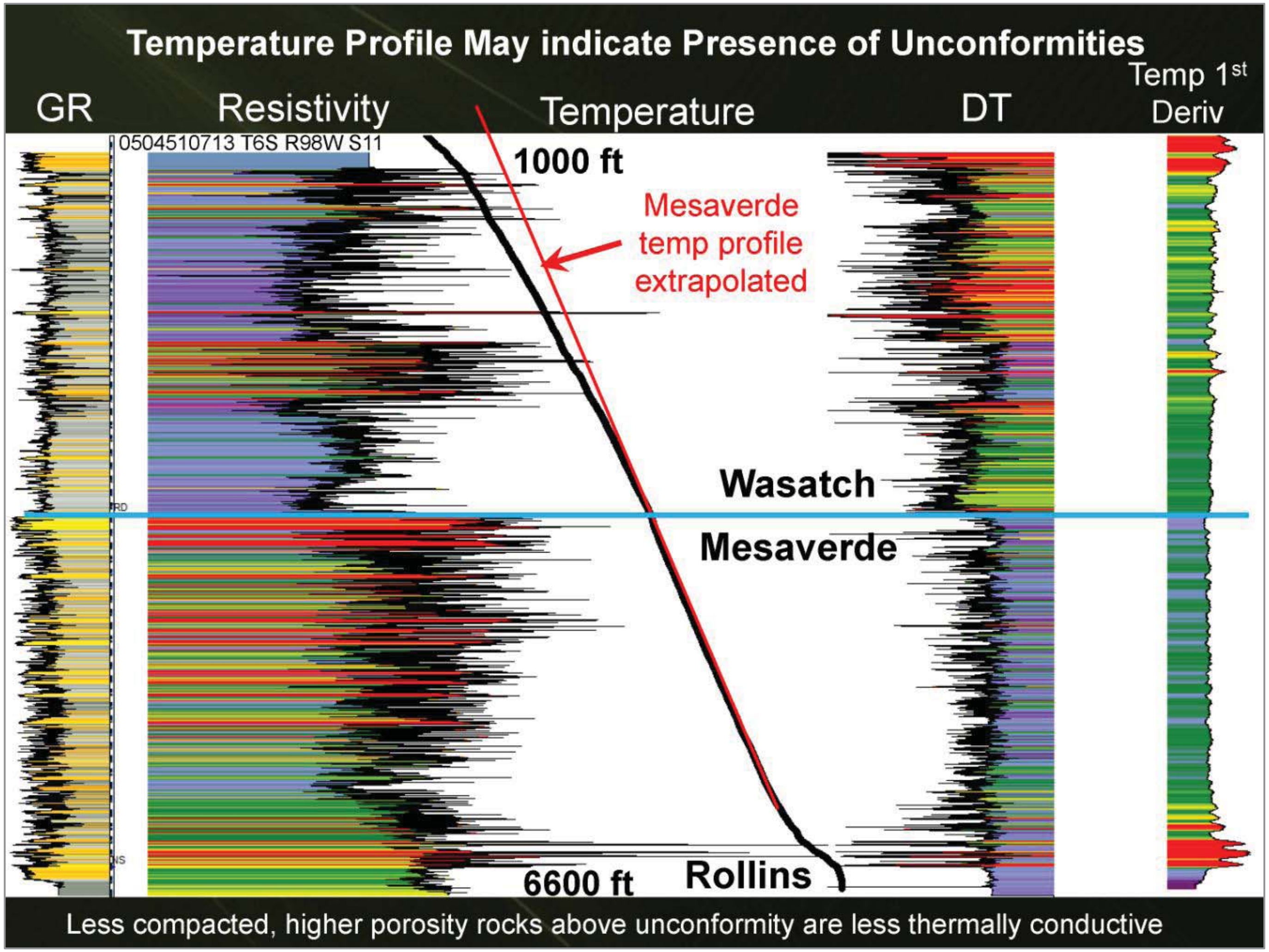
the more calcareous and organic-rich benches. These intervals are good insulators due to their high gas saturation and can be identified by the warm color fill of the first derivative curve. The Juana Lopez has the highest organic content of this entire interval and the first derivative curve indicates it is the best insulator. The interval at the top of the Niobrara has good organic richness as indicated on the gamma-ray curve; the first derivative curve indicates it is a good insulator. Line of cross section indicated by red line on inset map.



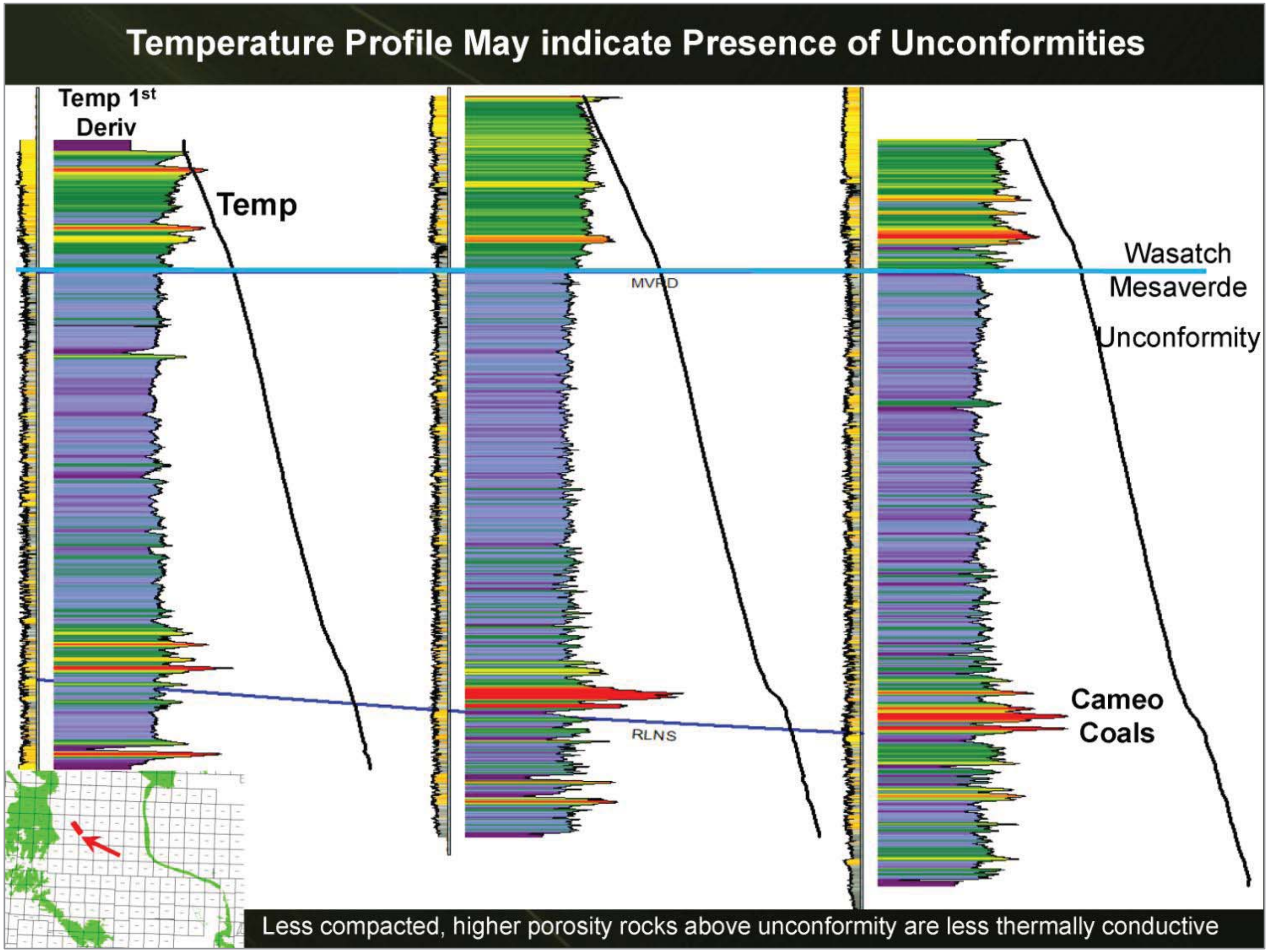
Presenter's notes: The sonic log is displayed adjacent to the first derivative curve in these two wells from the southern Piceance Basin. High gas saturation in the organic-rich intervals results in slower travel times and good insulating properties as indicated by the warm colors of the first derivative curve. Line of cross section indicated by red line on inset map.



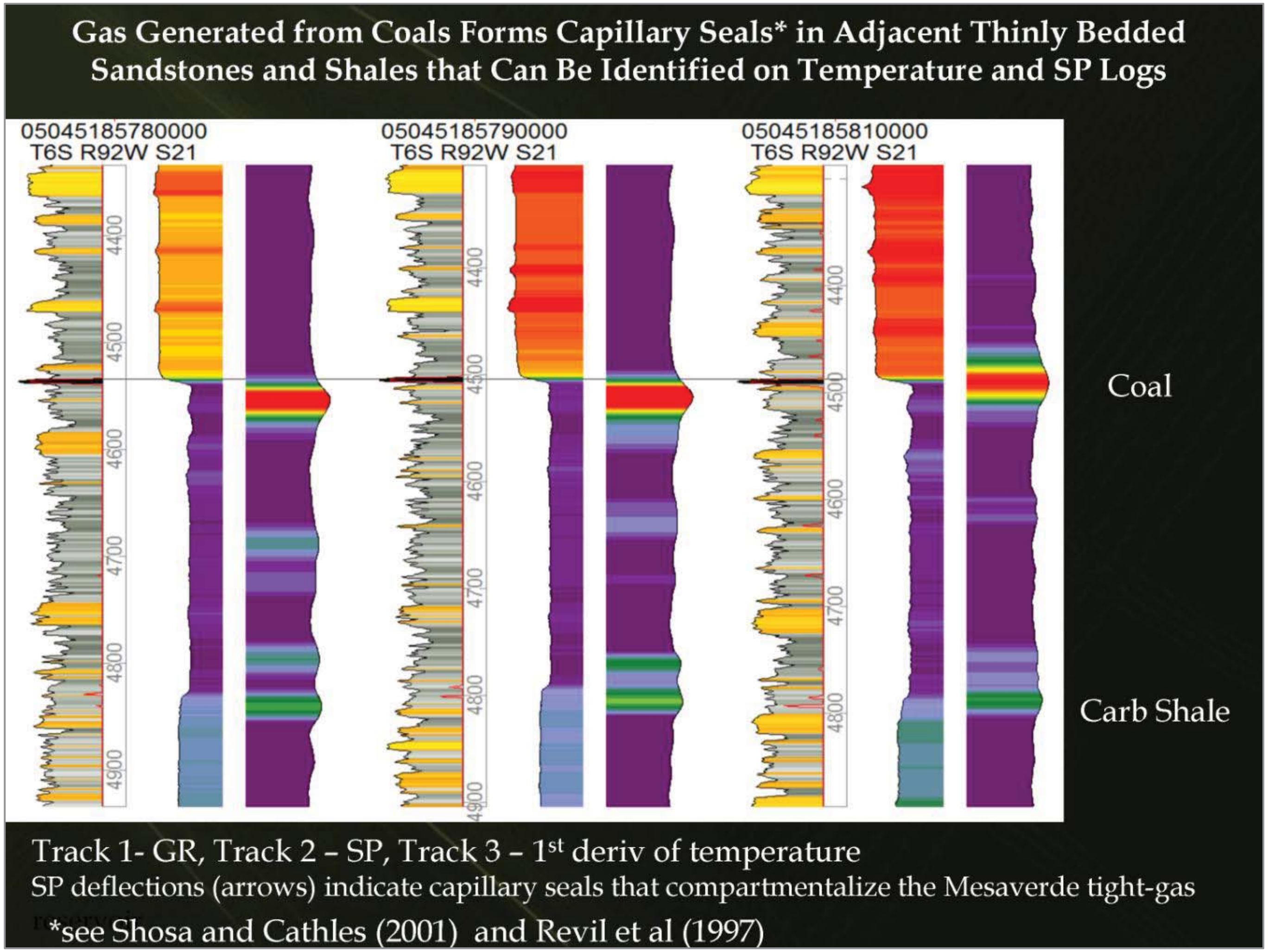
Presenter's notes: This slide shows first derivative curves from temperature logs run with cement-bond logs from wells in the greater Wattenberg area of the Denver Basin. The most organic-rich intervals are the Graneros and Sharon Springs and the warm colors of the first derivative curve show that these intervals are the best insulators. Other intervals within the Greenhorn and Niobrara have warm colors indicating possible organic richness. The inset map shows the line of cross section along with top Niobrara structure contours in blue and the 20,000 GOR contour for Codell-Niobrara wells in black.



Presenter's notes: The temperature log from this southern Piceance Basin well shows the effect of less compacted, higher porosity rocks above the Wasatch/Mesaverde unconformity. In this area of the Piceance Basin the entire interval shown on this log is water saturated, and the less compacted rocks above the unconformity are have lower thermal conductivity. Well depths of 1000 and 6600 ft are shown in the middle of the slide.



Presenter's notes: This slide shows that the decreased thermal conductivity of the less compacted rocks above the Wasatch/Mesaverde unconformity discussed in the previous slide can be correlated to several wells in this area of the western Piceance Basin. Line of cross section indicated by red line on inset map.



Presenter's notes: Gas generated from coals forms capillary seals in adjacent thinly bedded sandstones and shales that can be identified on temperature and SP logs. Cathles (2001) and Revil et al. (1997) describe these types of capillary seals. The increased gas saturation within the capillary seals results in better insulating properties as indicated warm colors on the first derivative curve. The (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

baseline of the SP curve shows sharp deflections at these capillary seals as discussed in a paper by Cumella, Woodruff, and Revil submitted to AAPG Bulletin in June 2015.

Revil et al., 1998, Capillary sealing in sedimentary basins: a clear field example: Geophysical Research Letters, v. 25, p. 389-392.
Shosa, J.D. and L.M. Cathles, Experimental investigation of capillary blockage of two phase flow in layered porous media: *in* P. Weimer and R. H. Fillon, eds. Petroleum systems of deep water basins: Proceedings of the 21st Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists (now Society for Sedimentary Geology) Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 1–26.

Temperature Log Observations

- Temperature logs are more common than most people realize.
- Cement-bond logs commonly have temperature logs.
- CBLs are commonly run some time after the well has been drilled and cased, allowing temperature equilibration of the formation and the borehole.
- Temperature log 1st derivative curves can be used for QC; if the 1st derivative curves show good correlation, you have good temperature data.
- Temperature log 1st derivative curves are effective at showing insulating and conducting lithologies.
- Insulating lithologies are commonly good source rocks.
- Temperature gradients calculated from BHTs can be very different if calculated above versus below source-rock intervals.

How the Presence and Persistence of Coal Effects Thermal Maturity

(an example from the DJ basin, eastern Colorado)

Coskey

- Why did I get started on this? (Michigan basin and Jonah Field)
- Why do coals have such low thermal conductivity?
- Late Cretaceous and Paleocene – where were the coals?
- Present-day coal distribution – Eastern Colorado
- Vitrinite reflectance – maturity indicator – error issues
- Burial history modeling scenarios
- Presence of coal vs thermal maturity indicators

Presenter's notes: Overview

Observations of Cercone, et al, 1989, 1996
Michigan Basin

“Almost all Paleozoic strata in the Michigan basin display elevated levels of organic maturity that cannot be explained by present-day burial depths, geothermal gradients, or heat flow”

“In basins that contain significant thicknesses of coal-bearing or other carbonaceous strata, it seems likely that underlying units can experience temperature increases of 10 K (18 F) or more; due simply to the insulating effect of the carbonaceous overburden.”

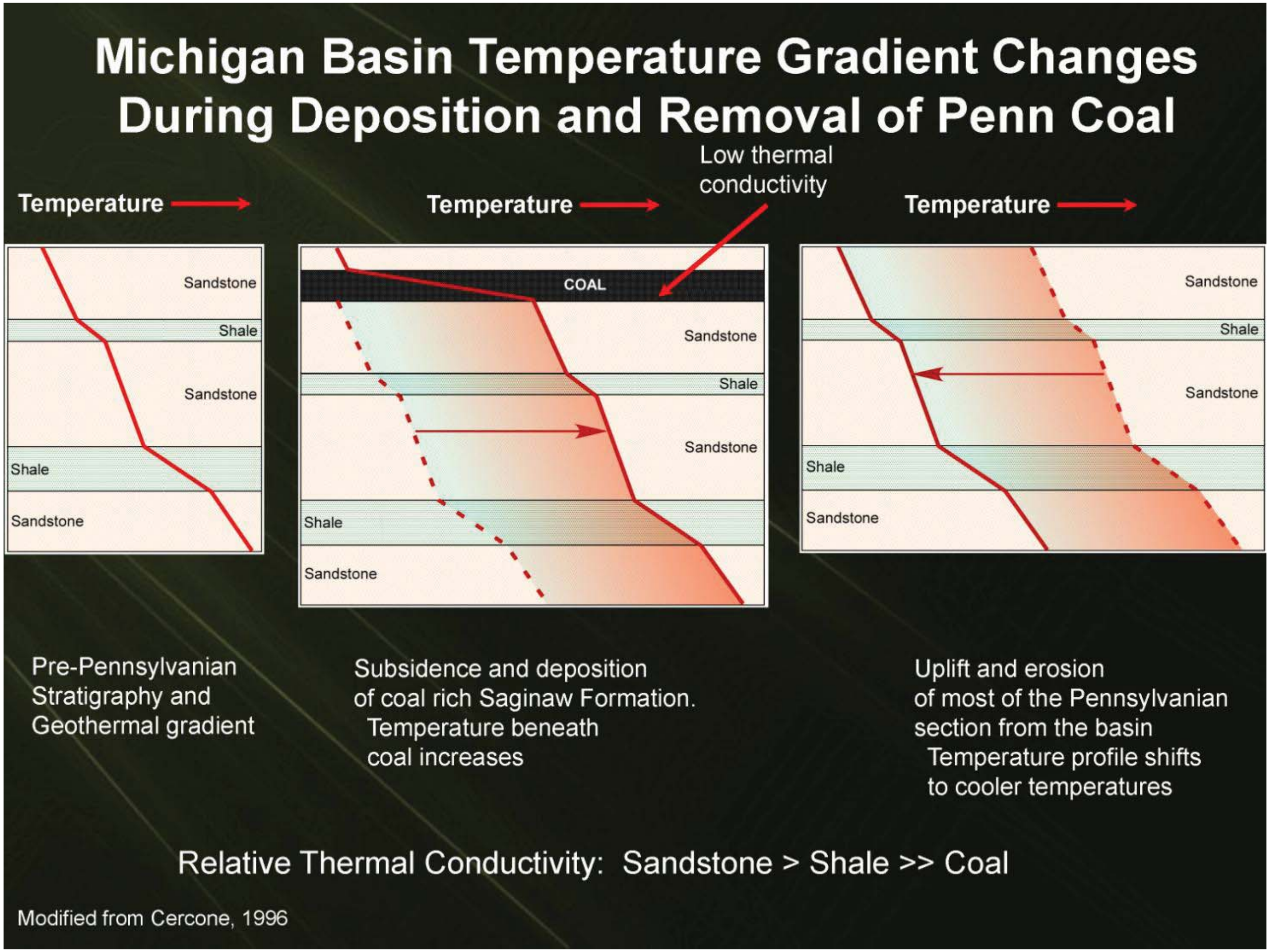
“A 10 K (18 F) increase in temperature roughly doubles organic reaction rates.”

(Cercone, et al, 1989, 1996)

Presenter’s notes:

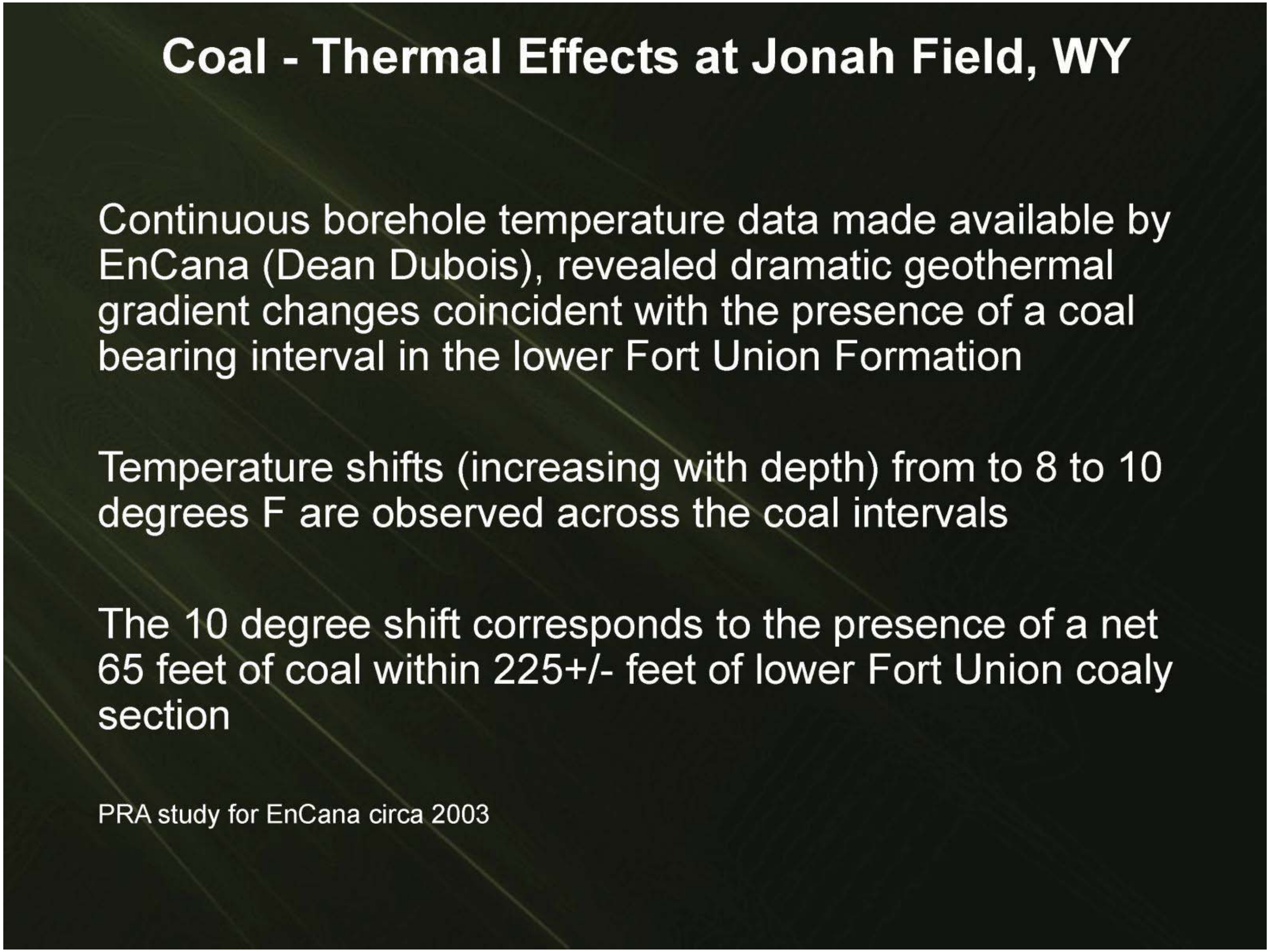
Cercone, K.R., and Pollack, H.N., 1989, Anomalous thermal maturity of Michigan basin: New hypothesis: Meeting abstract AAPG, Vol. 73, No. 3, pp 342.

Cercone, K.R., Deming, D., and Pollack, H.N., 1996, Insulating effect of coals and black shales in the Appalachian basin, western Pennsylvania: Organic Geochemistry, v. 24, no. 2, p. 243-249.

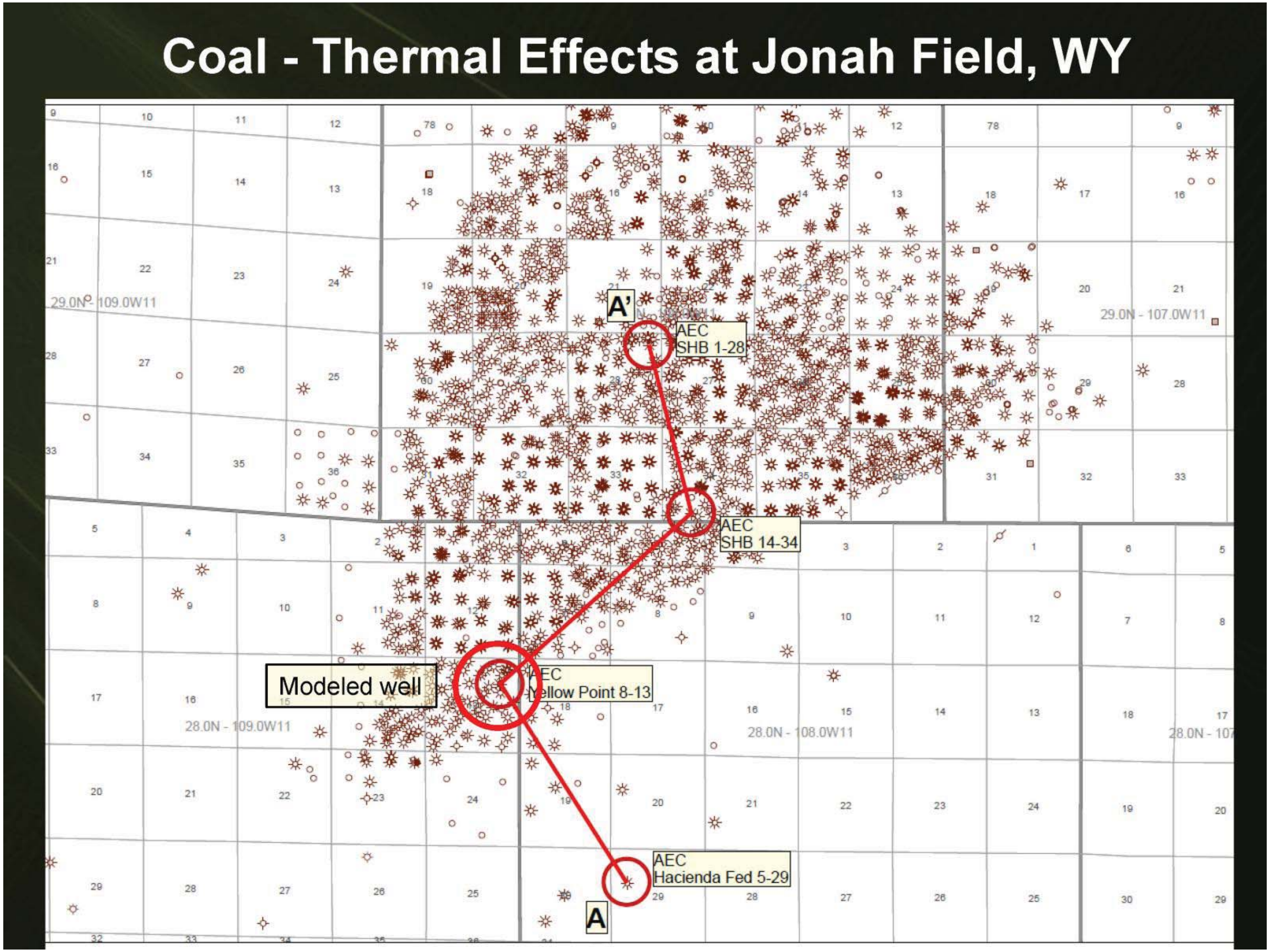


Presenter's notes:

Cercone, K.R., Deming, D., and Pollack, H.N., 1996, Insulating effect of coals and black shales in the Appalachian basin, western Pennsylvania: Organic Geochemistry, v. 24, no. 2, p. 243-249.

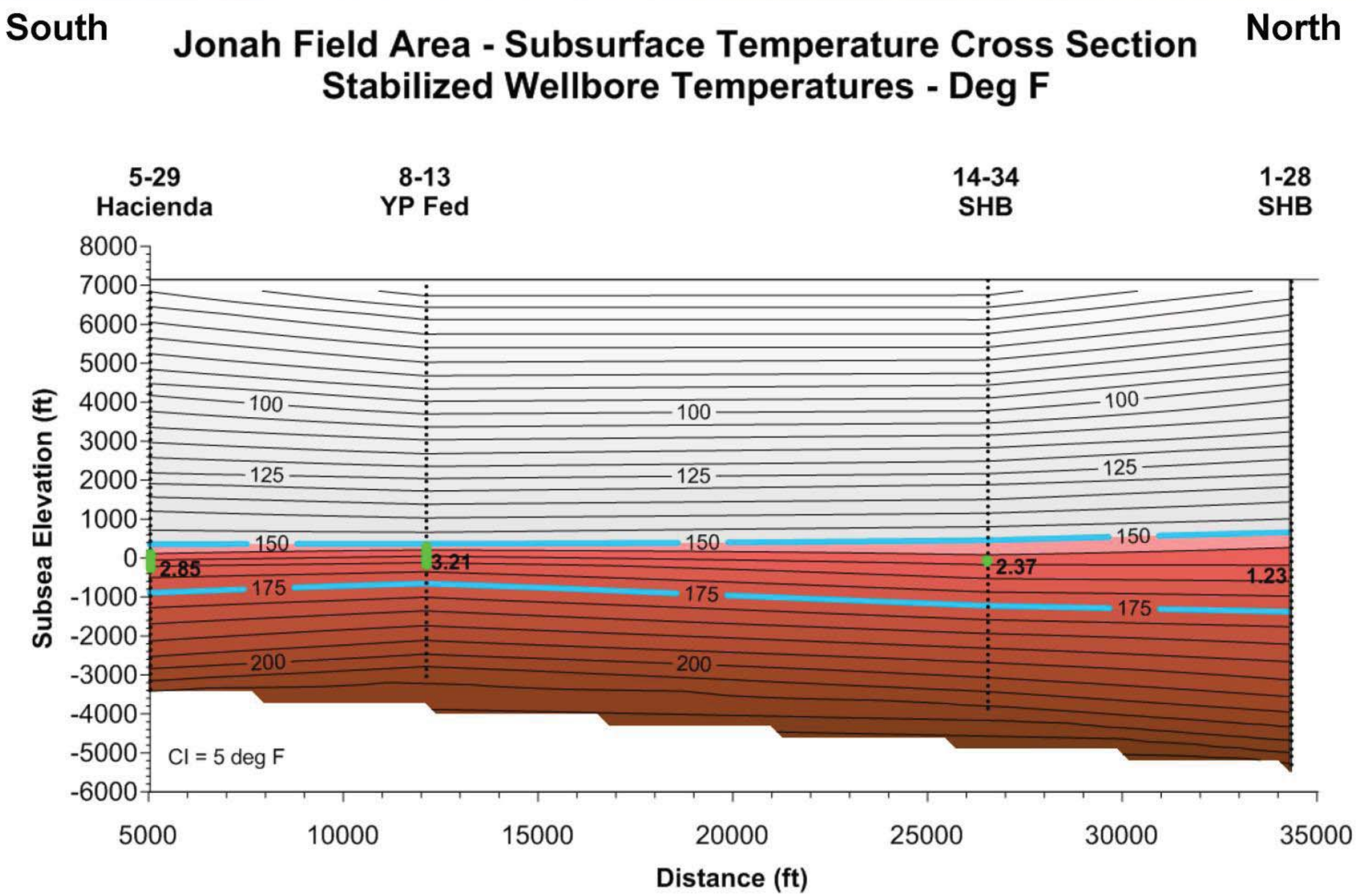


Presenter's notes: Coal – Thermal effects at Jonah Field, Sublette county, WY.

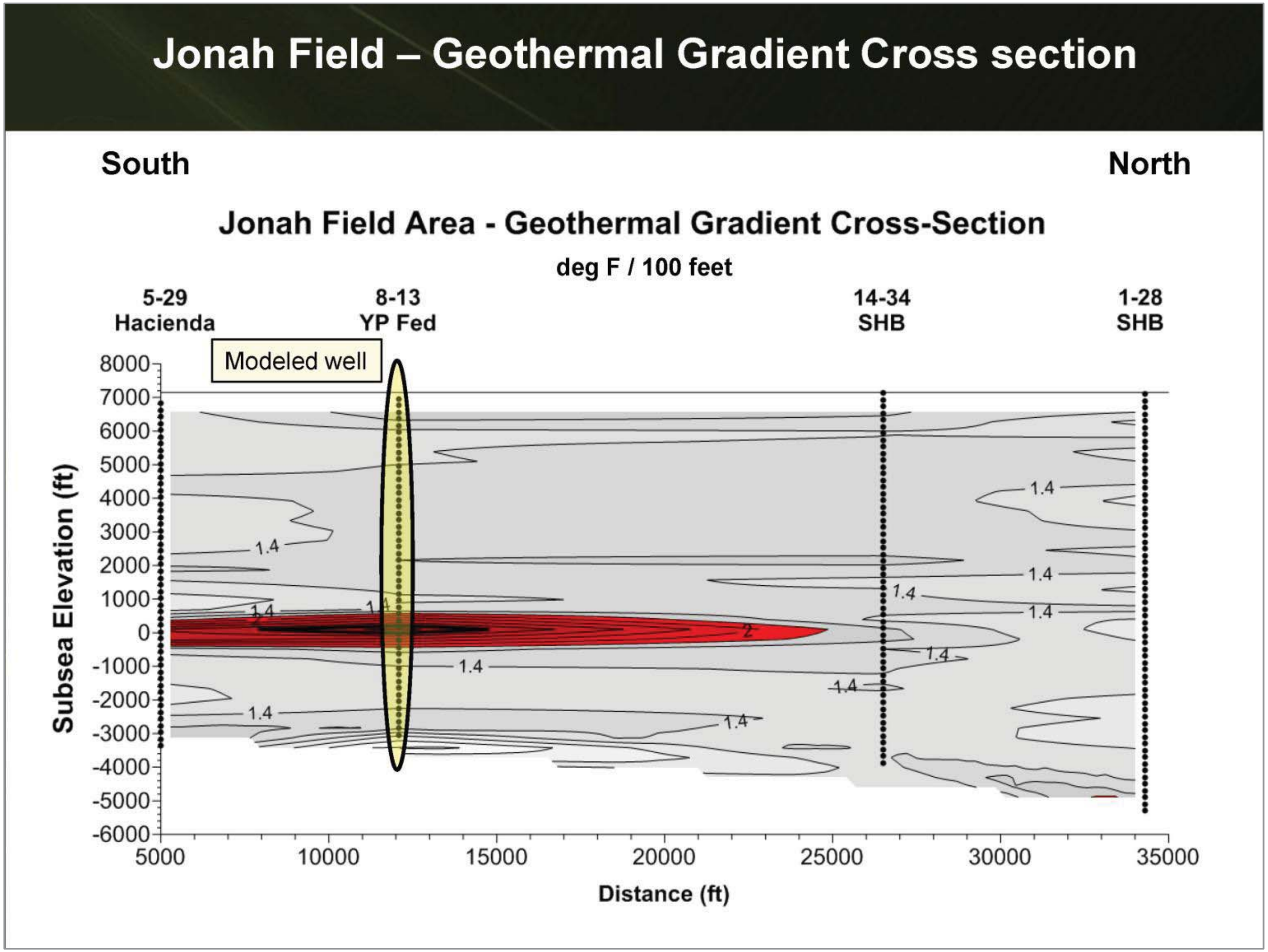


Presenter's notes: Index map showing the temperature log control wells and the line of cross-section presented in following slides.

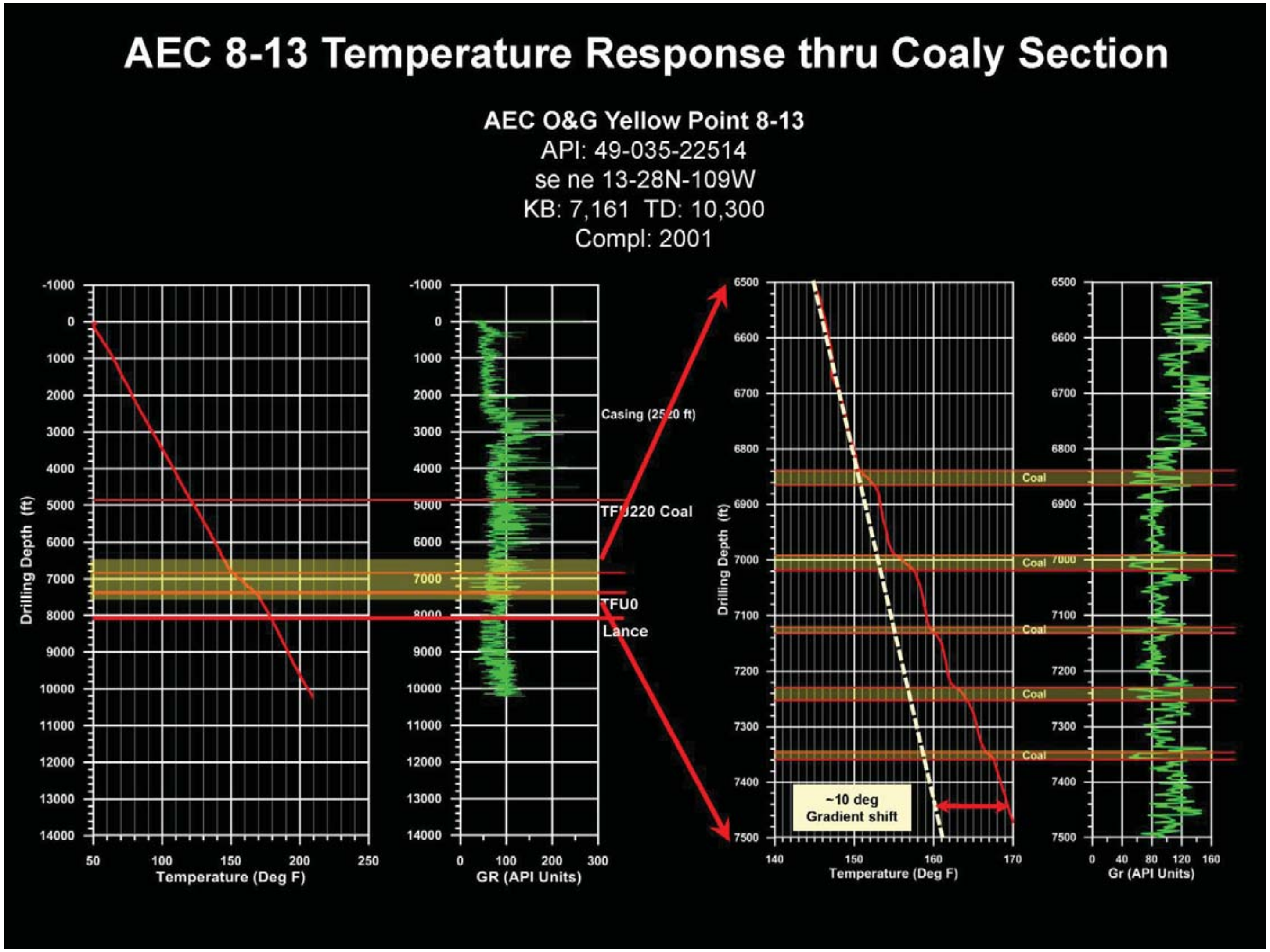
Jonah Field – Subsurface Temperature Cross section



Presenter's notes: Temperature cross-section through the four temperature data control wells. Wells 5-29, 8-13 and 14-34 contain coals in the Fort Union section. The 1-28 well does not have coal present in the Fort Union.

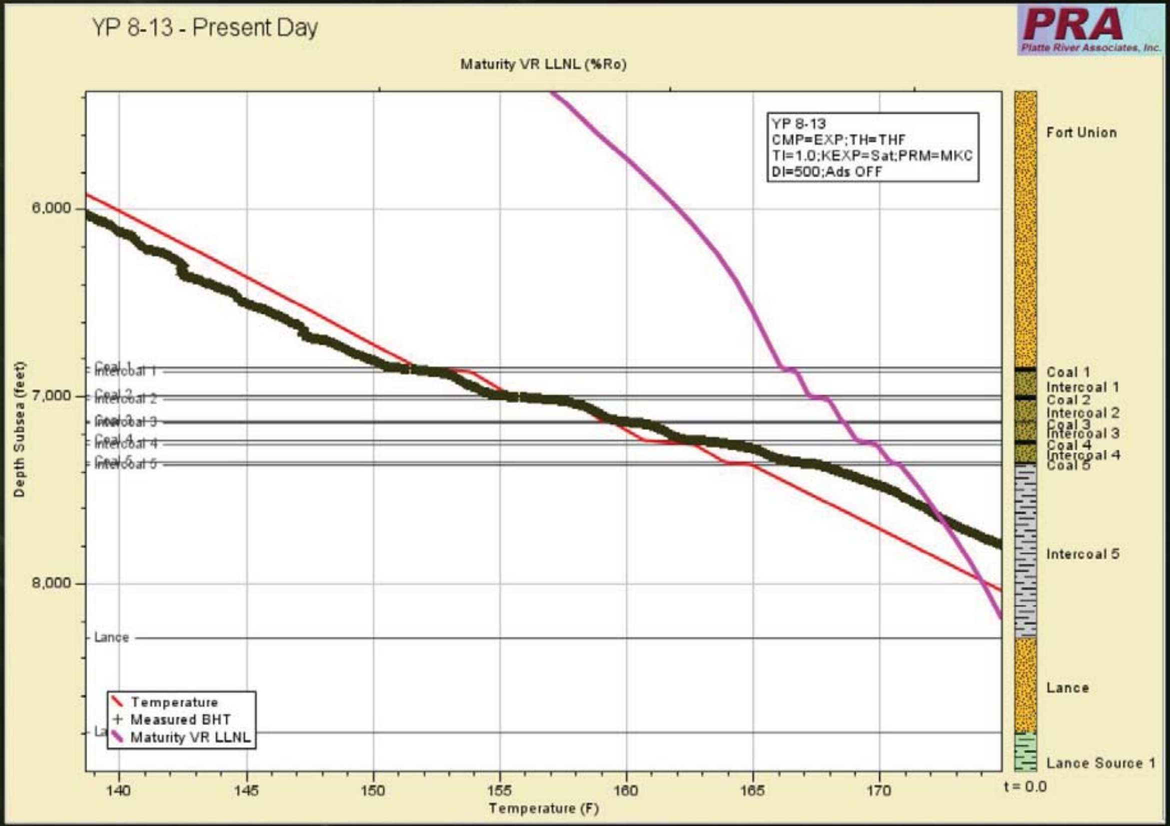


Presenter's notes: Geothermal gradient cross-section through the four temperature data control wells. Wells 5-29, 8-13 and 14-34 contain coals in the Fort Union section. The 1-28 well does not have coal present in the Fort Union. Through the coal bearing interval the geothermal gradient increases from a background of approximately 1.4 deg F / 100 feet to over 3.0 deg F / 100 feet.



Presenter's notes: Continuous temperature log and gamma ray data from the AEC 8-13 Yellow Point well showing the increased geothermal gradient through the Fort Union coaly section. The panel on the right is an expanded view of the coaly section showing how the temperature shifts higher through each individual coal. The yellow dashed line is a projection of the geothermal gradient above the coaly section downward, and shows a 10 deg F increase in temperature through the coaly section as compared to a non-coal temperature profile.

AEC 8-13 Yellow Point Calibration Plot
Modeled Temp & %VRo (LLNL*) vs Observed Data



Model Results: (Red = Temp, Pink = %VRo LLNL*)

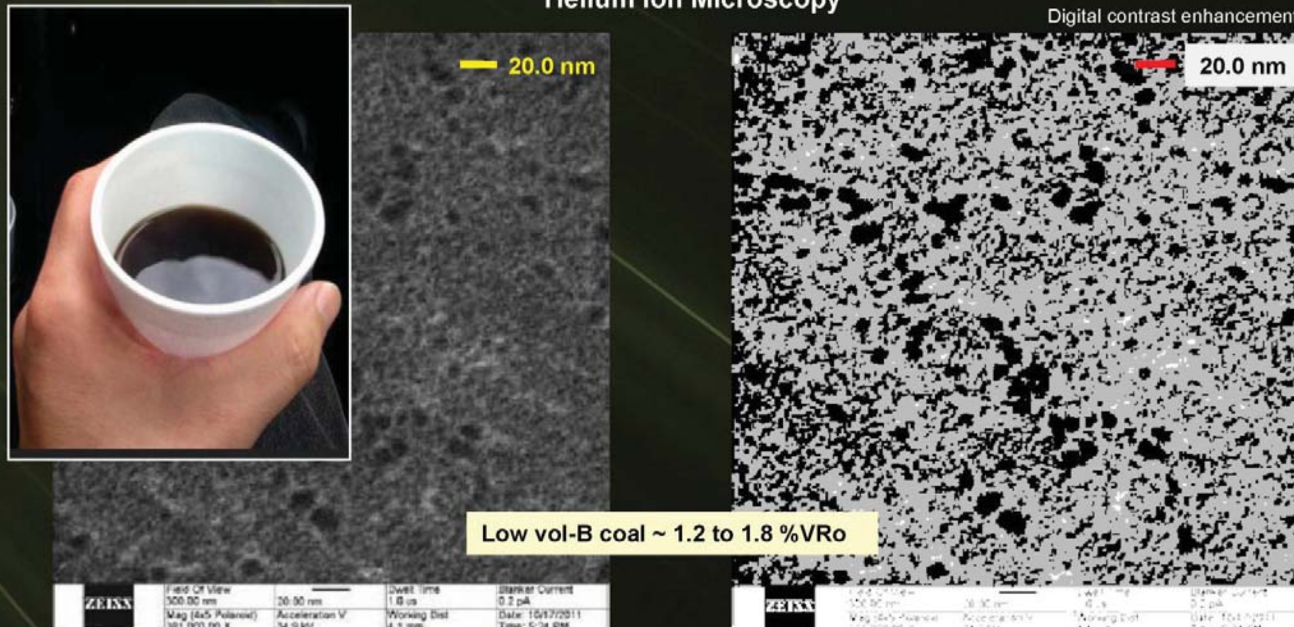
Observed Data: (black points = measured temperature)

*Lawrence Livermore National Labs kinetic model

Presenter's notes: AEC 8-13 Yellow Point Calibration plot (derived from burial model) showing modeled temperature (red) and modeled %VRo (magenta) as compared with the measured data from the continuous temperature log.

Why is Coal Such a Good Insulator?
Coal - Microporosity Size

Helium Ion Microscopy

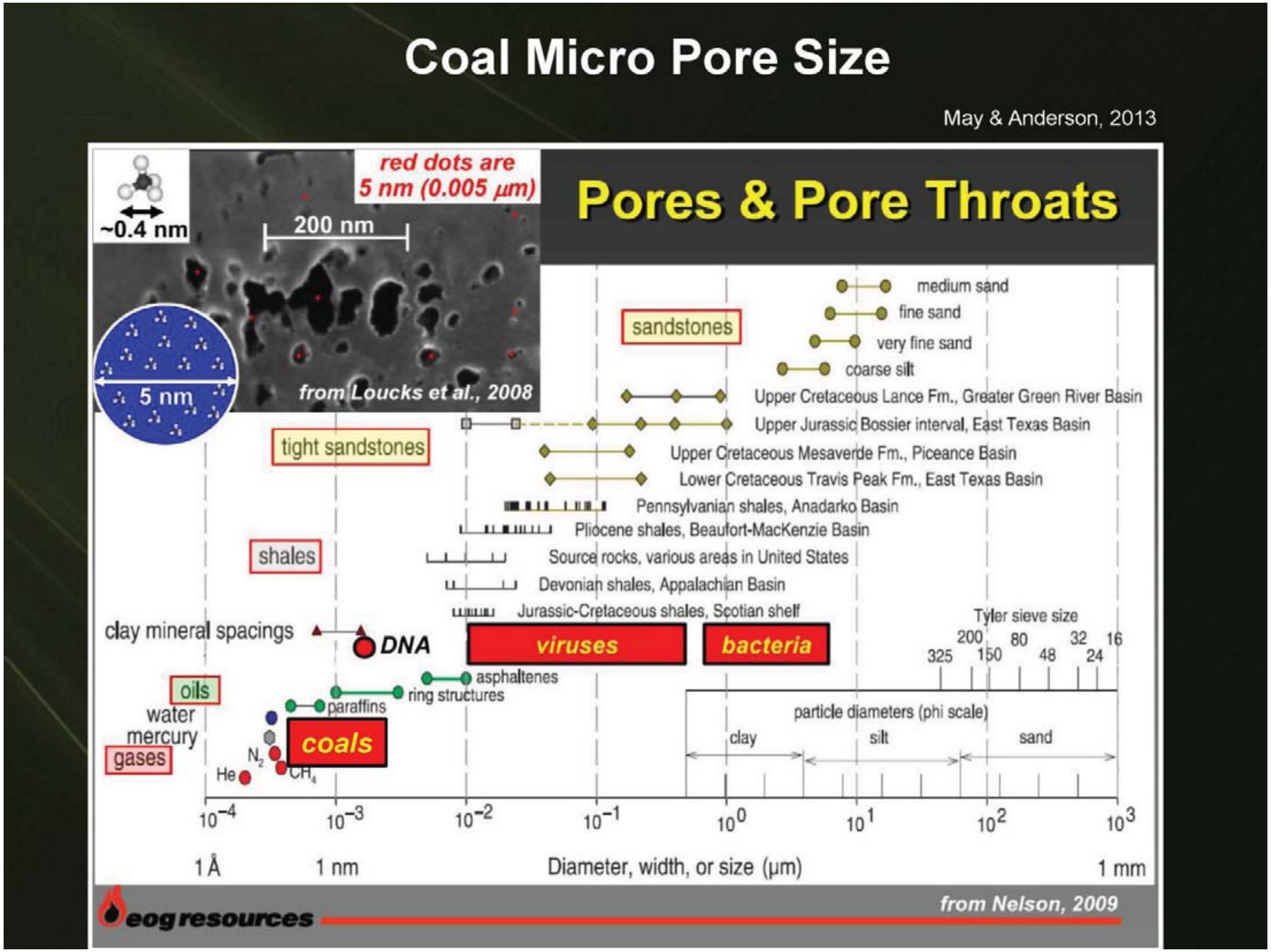


Coal micropores range from < 1 nm in diameter to occasionally several nanometers.

	CH_4	CO_2	H_20	N_2
Molecular Size (nm)	0.38	0.33	0.28	0.36
Thermal Conductivity ($W\ m^{-1}K^{-1}$)	0.03	0.015	~0.6	0.028

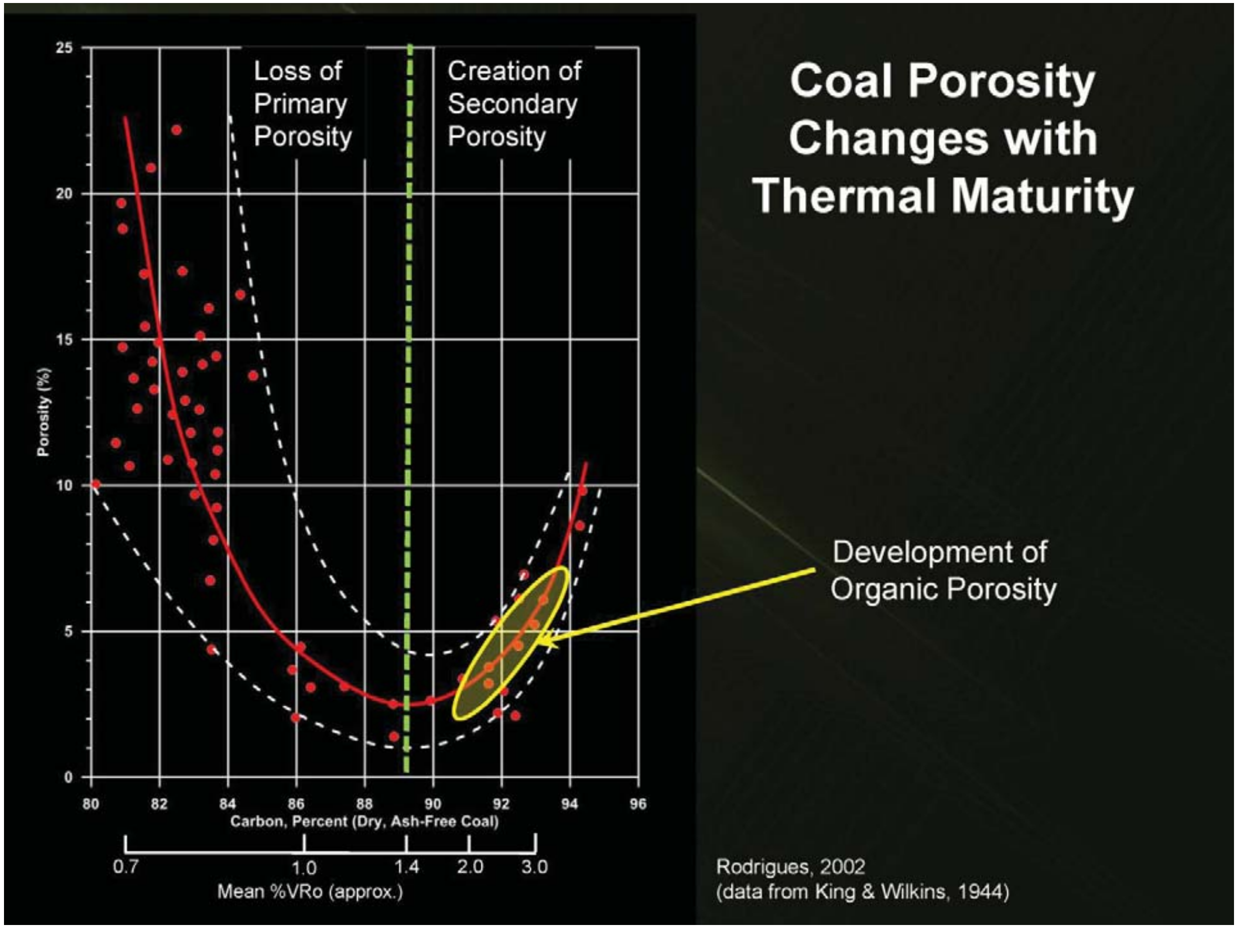
Coal HIM images from Kliewer and Walters, 2012

Presenter's notes: Thermal conductivity in coal is dependent on moisture content, the lower the moisture content (higher gas saturation) the lower the thermal conductivity. The nanoporosity when filled with low thermal conductivity gases (CH4, CO2, N2) lowers the overall thermal conductivity of the coal making it a very effective insulator. Helium Ion Microscopy (HIM) images from:
Kliewer and Walters, 2012, Geological Applications of Helium Ion Microscopy:
http://www.imaging-kit.com/applications/geological-applications-helium-ion-microscopy.



Presenter's notes: Comparison of rock type, hydrocarbon molecular size and pore throat sizes illustrating the very small (~1 nanometer) size of coal micro porosity.

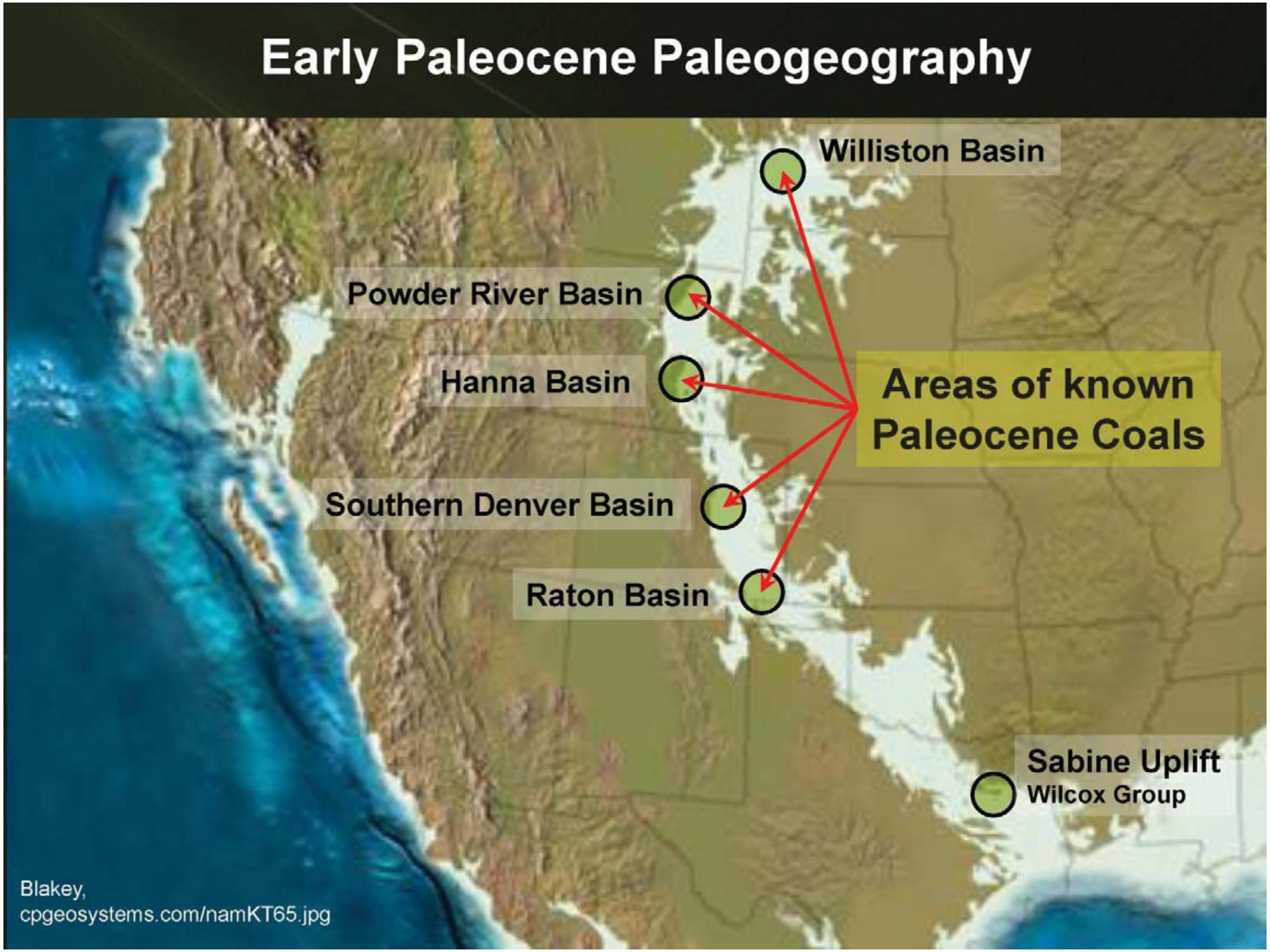
Nelson, P. H., 2009, It's a small world after all – The pore throat size spectrum, AAPG Search and Discovery Article #50218, posted January 19, 2010.



Presenter's notes: Coal porosity as compared with maturity and percent carbon (Rodrigues, 2002, and King and Wilkins, 1944). Porosity is reduced through early compaction and achieves a minimum porosity at 1.4 %VRo. Conversion of kerogen or breakdown of adsorbed and absorbed liquid hydrocarbons creates organic porosity and the porosity of the system increases. This model does not include porosity as the result of cleating.

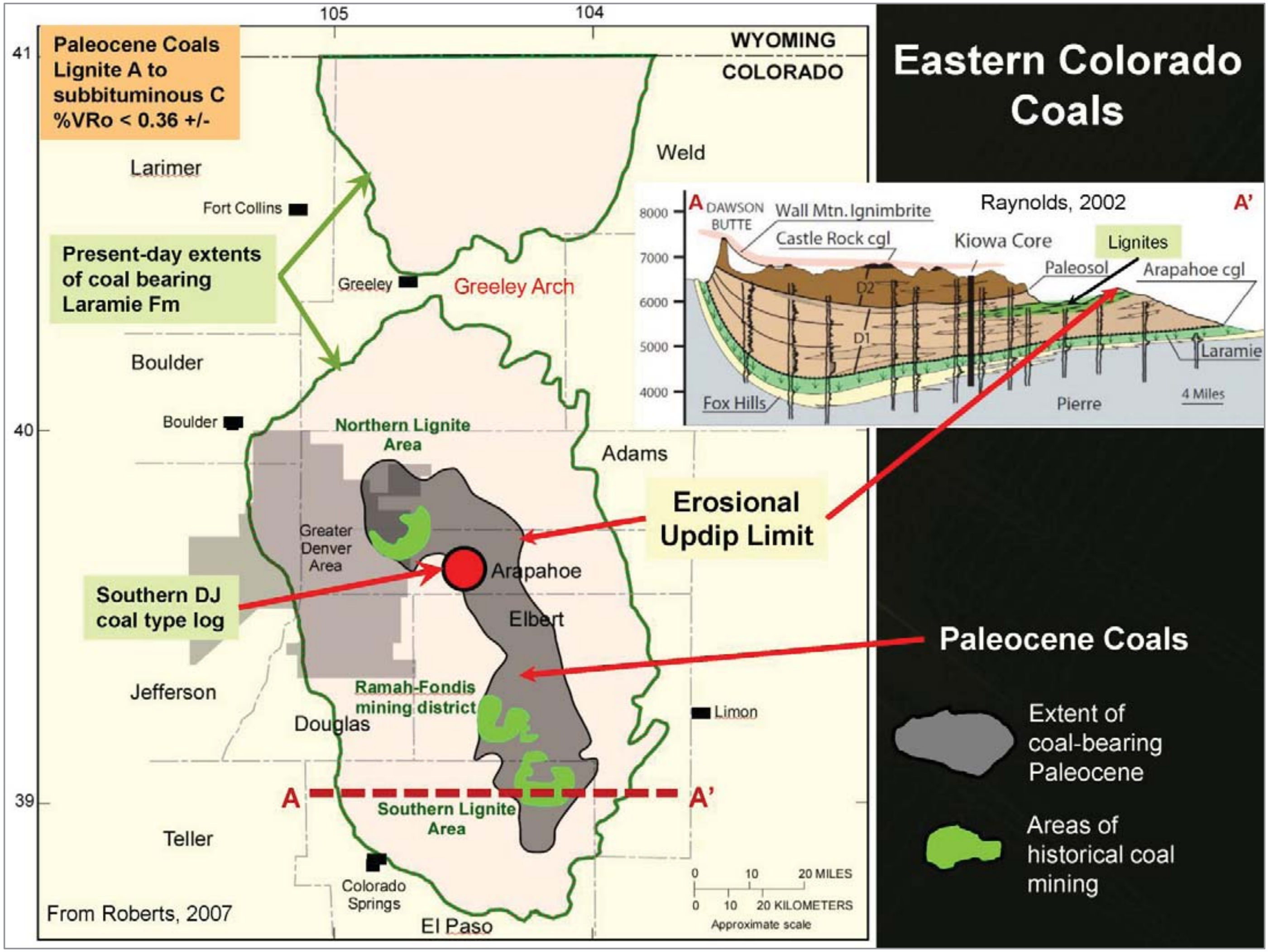
Rodrigues, C.F., Lemos de Sousa, M.J., 2002, The measurement of coal porosity with different gases, International Journal of Coal Geology v. 48, pp. 245-251.

King, J.G., Wilkins, E.T., 1944. The internal structure of coal. Conf. Ultra-fine Structure of Coals and Cokes, London, 1943. The British Coal Utilization Research Association, London, pp. 46– 56.



Presenter's notes: Distribution of shallow marine seaway (and possible lacustrine) depositional environments and the presence of known Paleocene lignitic coals at approximately 65 ma.

Paleogeography from R. C. Blakey: http://www.cpgeosystems.com/namKT65.jpg.



Presenter's notes: Distribution of coals and coal bearing section in eastern Colorado (Roberts, 2007). Coal bearing, late Cretaceous Laramie Formation shown in tan and areas rich in Paleocene coal shown in gray. The up-dip extent (to the east) of the Paleocene lignitic coal is the present-day erosional limit and the down-dip extent (as shown) is the economic mining limit of 200 feet. The Paleocene lignites extend further to the west. Paleocene lignites of the lower Denver Formation (D1) are shaded green on cross section A-A' (Raynolds, 2002).

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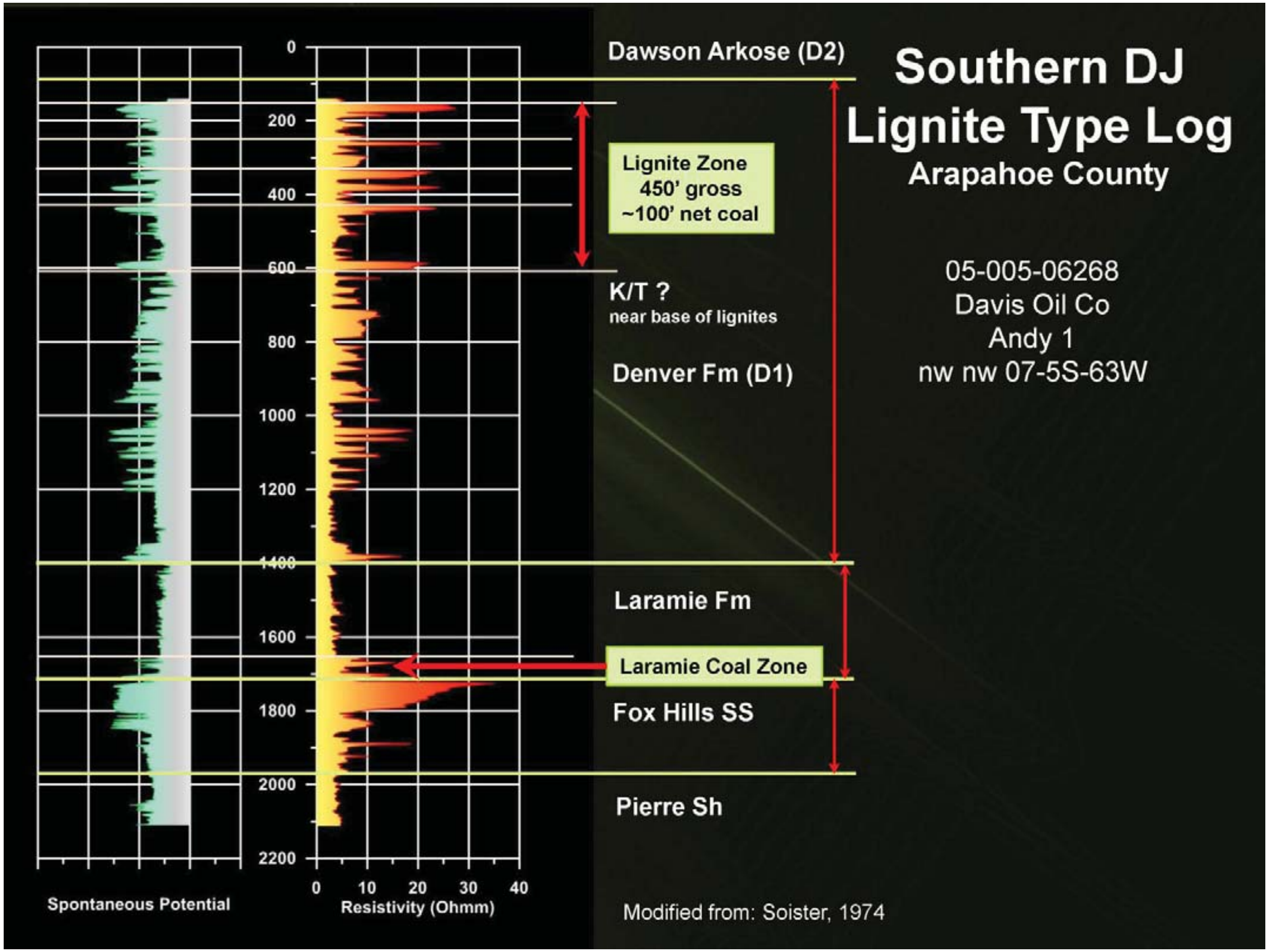
Roberts, S.B., 2007, Coal in the Front Range Urban Corridor—An Overview of Coal Geology, Coal Production, and Coal Bed Methane Potential in Selected Areas of the Denver Basin, Colorado, and the Potential Effects of Historical Coal Mining on Development and Land-Use Planning: U.S. Geological Survey Digital Data Series DDS-69-P.

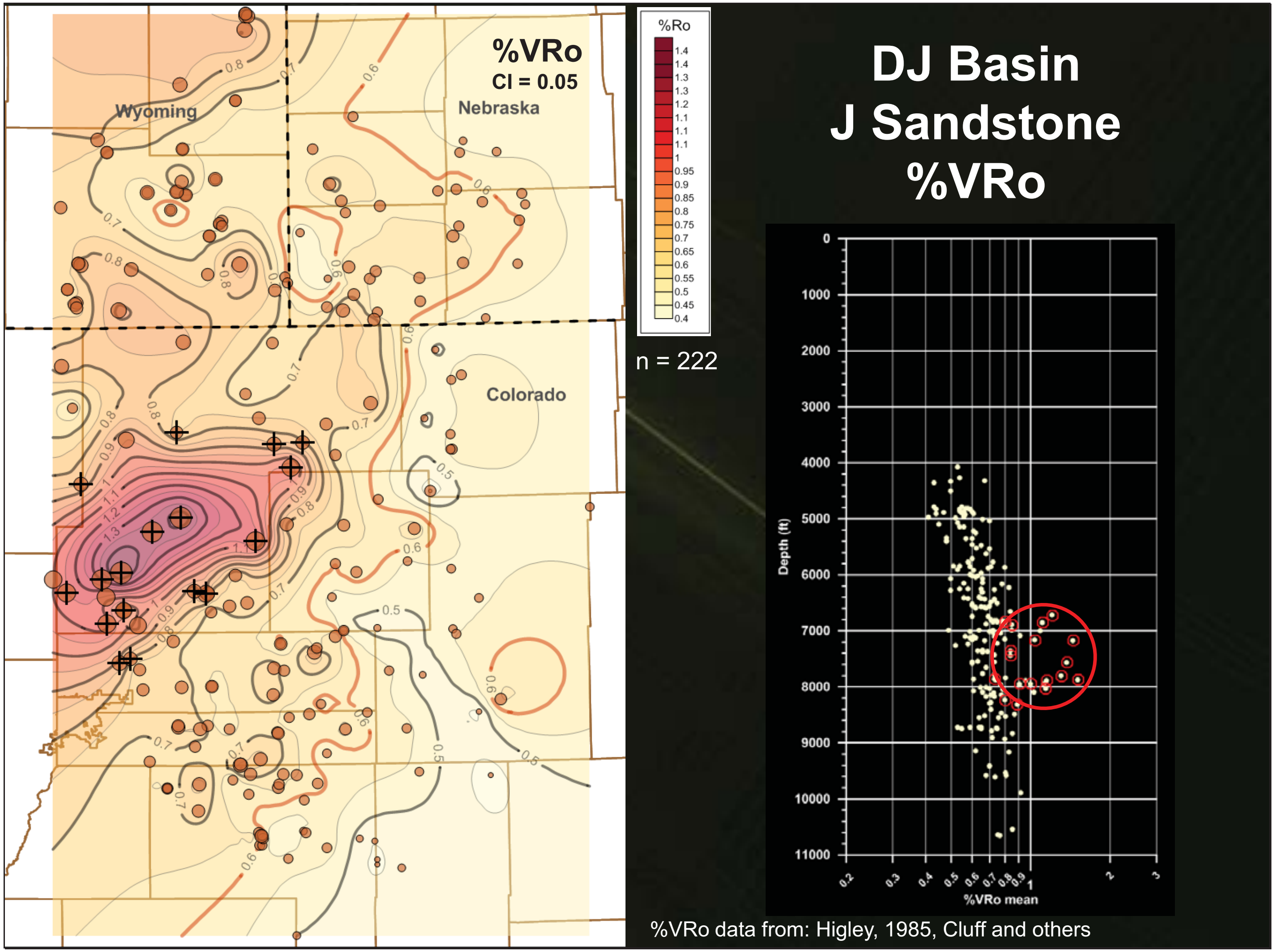
Raynolds, R.G., 2002, Upper Cretaceous and Tertiary stratigraphy of the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, no. 2, p. 111-134.



Presenter's notes: Southern DJ basin type log; Davis Oil, Andy 1, nw nw 07-5S-63W. The Paleocene lignite zone is approximately 450 to over 500 feet thick with laterally varying amounts of coal (100' in this well). The K/T boundary is very close to the base of the lignite zone. Log modified from Soister, 1974.

Soister, P.E., 1974, A preliminary on a zone containing thick lignite beds, Denver basin, Colorado. U.S. Geological Survey Open-File Report 74-27, 48 p., plate 2.

Building the Regional %VRo Map



Presenter's notes: Vitrinite reflectance map (%VRo) constructed from multiple data sources, Higley, 1985, Hallau and Cluff (multiple years) and proprietary industry reports. Outliers (inside red circle) on Depth vs. %VRo cross-plot are shown as "plus" symbols on the %VRo map.

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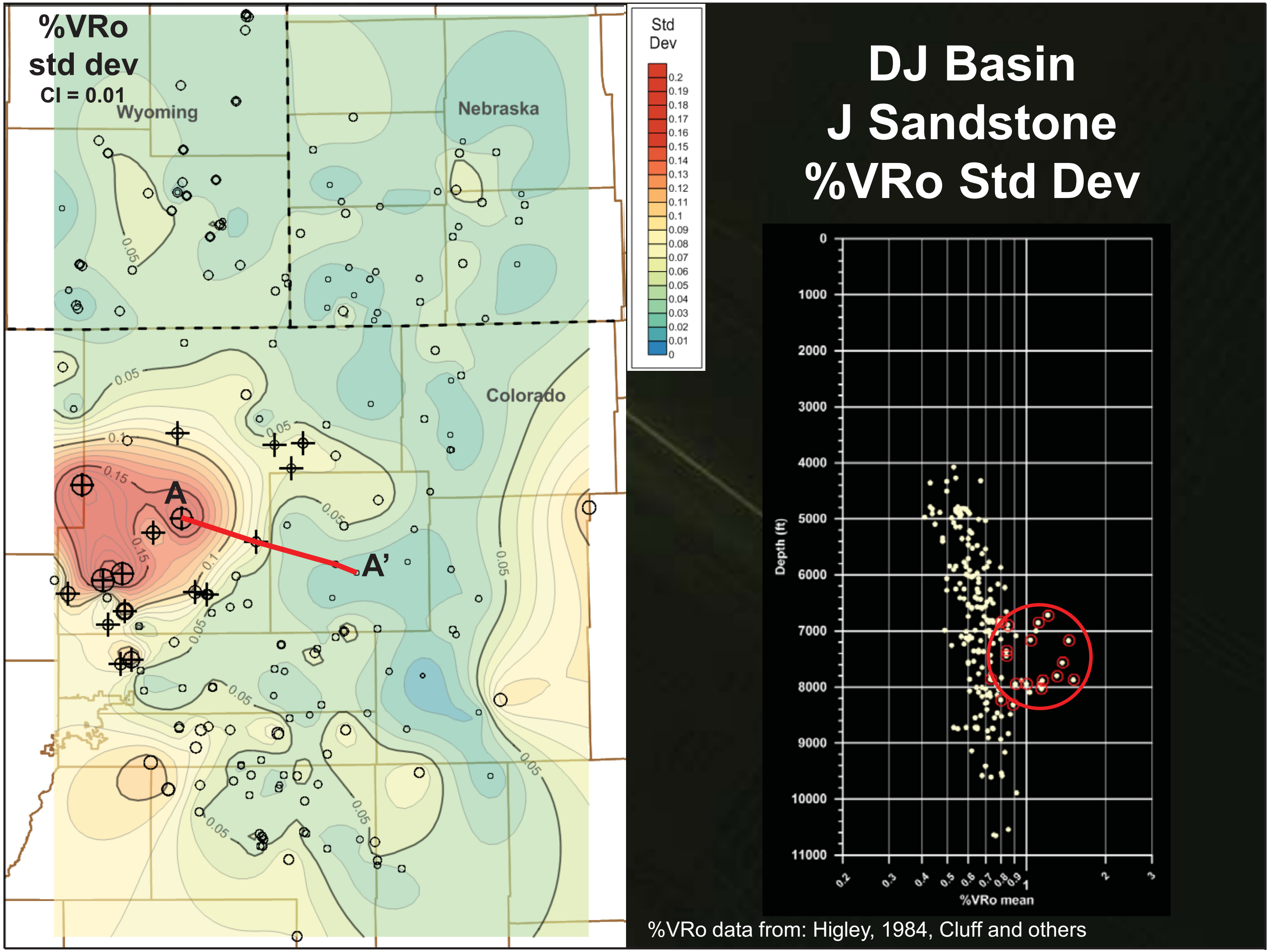
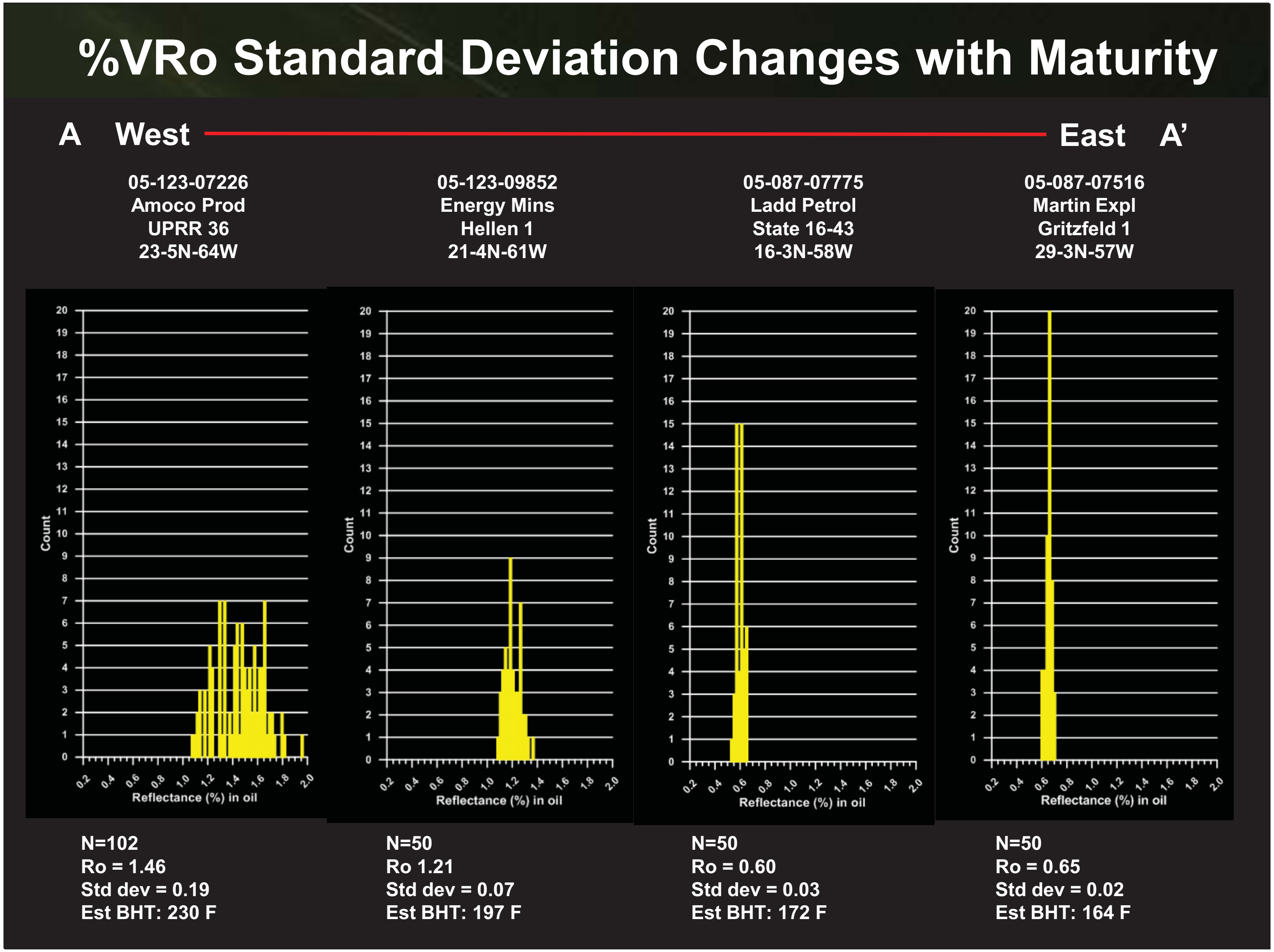
Hallau, D.G., Vitrinite reflectance off Cretaceous coaly material and thermal maturity of the Niobrara Formation, DJ Basin, Colorado, USA. In press, RMAG currently untitled publication, RMAG.

Higley, D.K., et al, 1985, Isoreflectance map of the J Sandstone in the Denver basin of Colorado, U. S. Geological Survey, Open File Report 85-384.

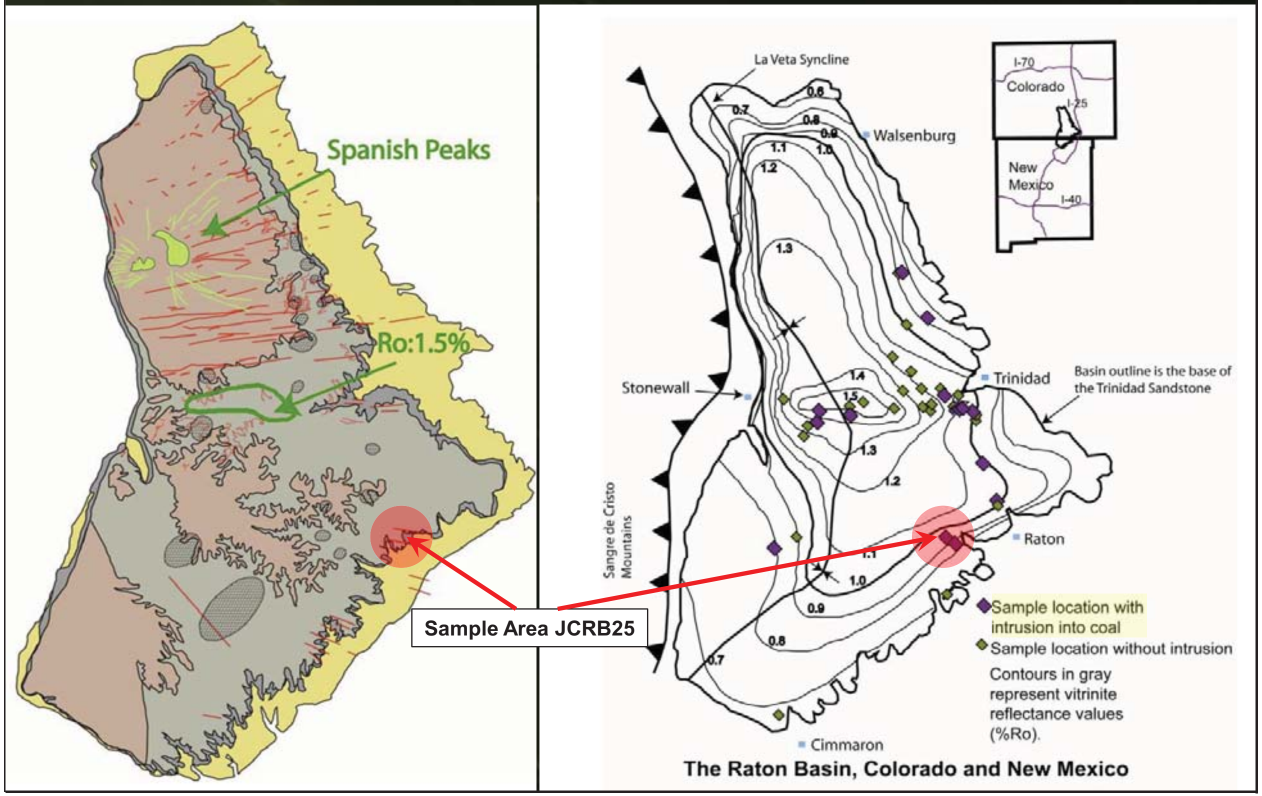


Presenter's notes: Vitrinite reflectance standard deviation map constructed from multiple data sources, Higley, 1984, Hallau and Cluff (multiple years) and proprietary industry reports. The same field of outliers shown on the previous slide are repeated here illustrating the increasing uncertainty with mean %VRo with increasing maturity in the greater Wattenberg field area, Weld, county, Colorado.



Presenter's notes: Vitrinite reflectance histogram "cross-section" A-A' (location shown as red line on previous slide). It is uncertain as to why the error increases with increasing maturity but this phenomenon has also been recognized in the Raton Basin. This may be related to slight differences in the devolatization of coal macerals at higher thermal maturity or it may be due to the difficulty in maceral identification at higher levels of thermal maturity.

Raton Basin – "Normal %VRo" vs Contact Effects

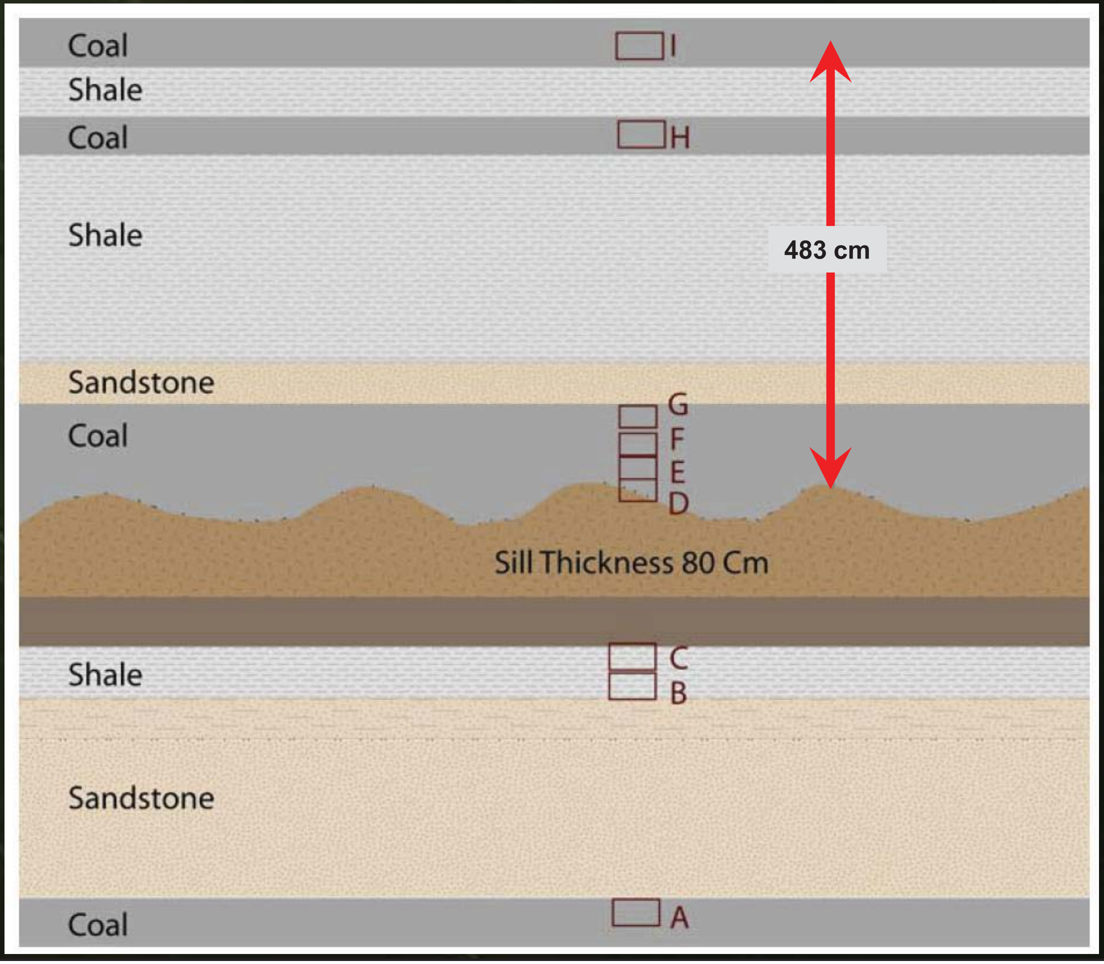


Presenter's notes: Raton basin regional geology (Flores and Bader, 1999) and %VRo (Cooper, 2006), showing the location of sample JCRB25; a coaly section affected by sill injection.

Flores, R.M., and Bader, L.R., 1999, A summary of Tertiary coal resources of the Raton basin, Colorado and New Mexico, in U.S. Geological Survey Paper 1625-A Chapter SR.

Cooper, J.R., 2006, Igneous intrusions and thermal evolution in the Raton basin. CO-NM: Contact metamorphism and coal-bed methane generation, University of Missouri-Columbia Master of Science Thesis, 249 p.

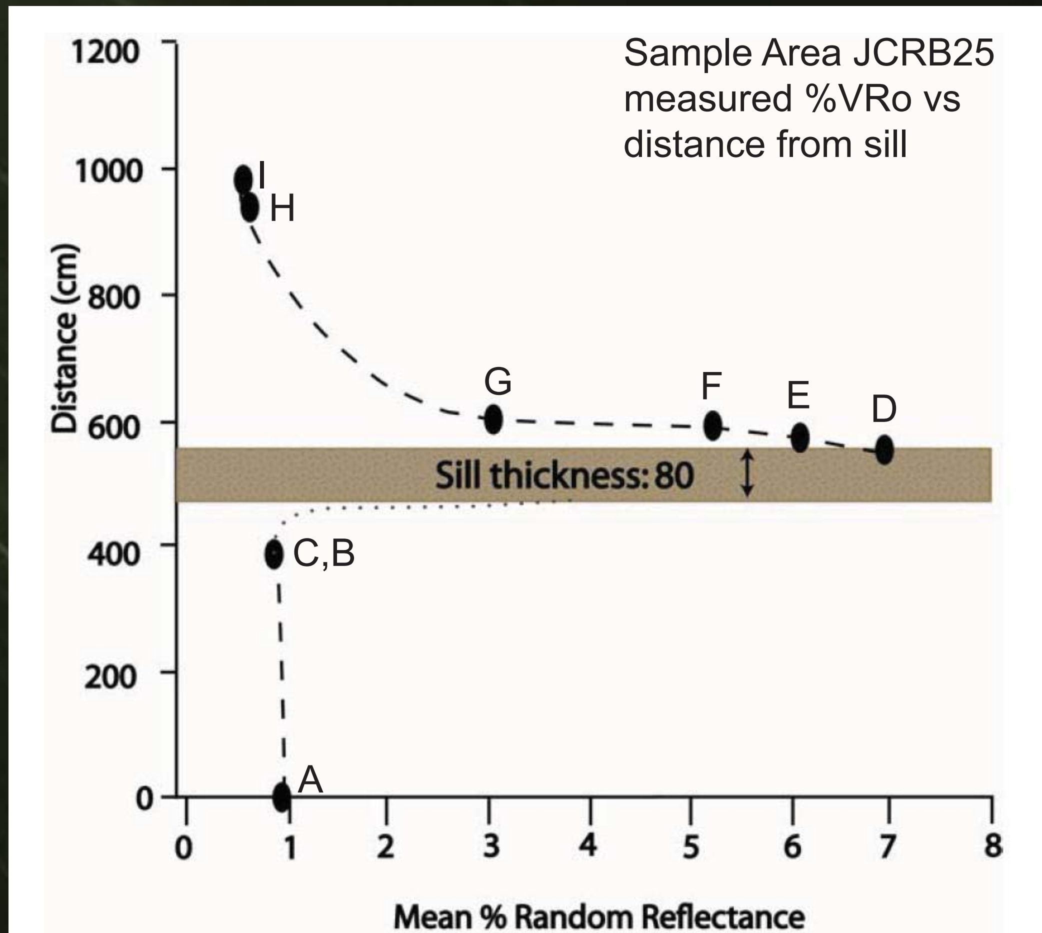
Raton Basin – "Normal %VRo" vs Contact Effects
Single Sill Example – Area JCRB25



Cooper, 2006

Presenter's notes: Schematic diagram showing coal vitrinite sampling locations in vicinity of igneous sill.

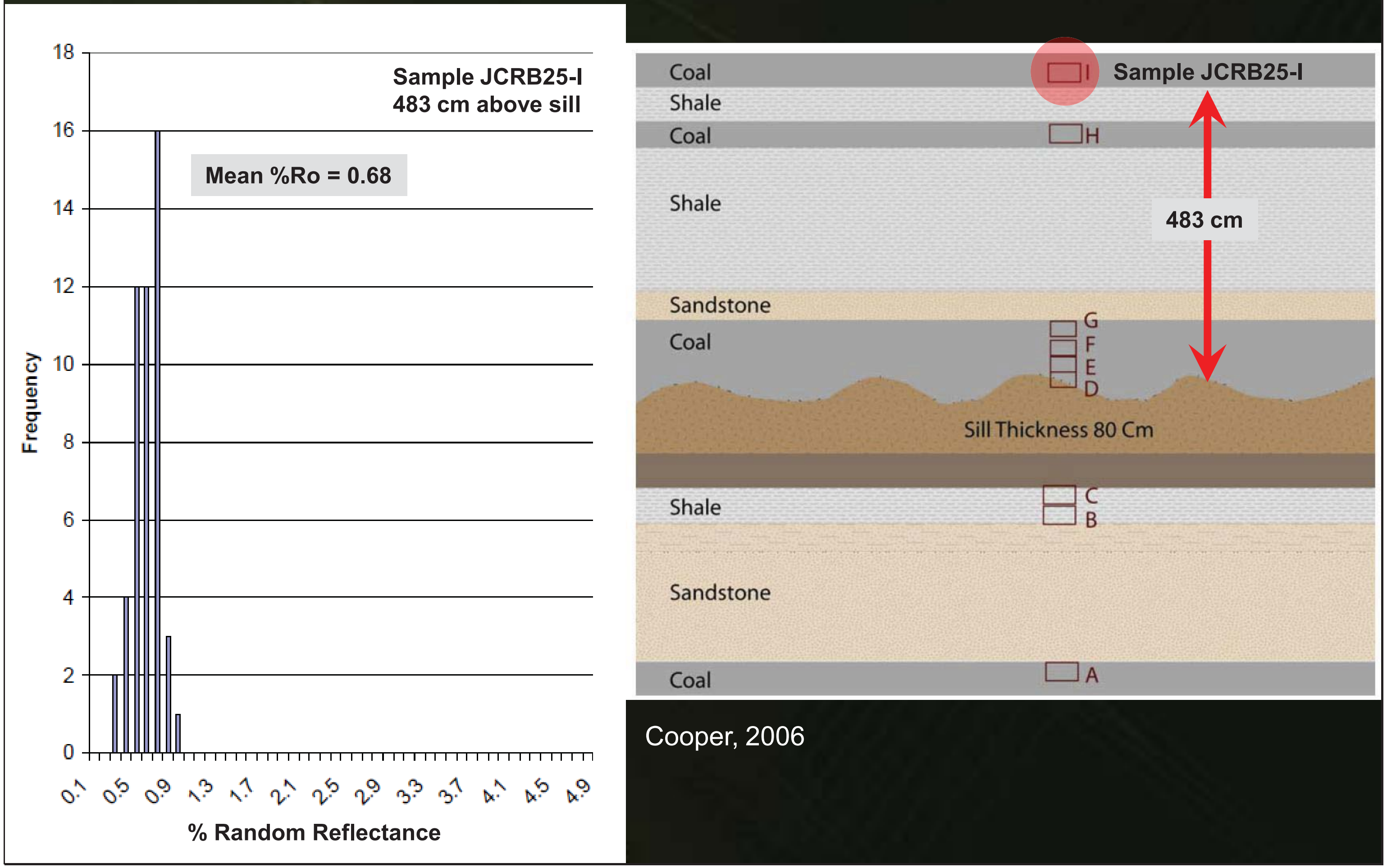
Raton Basin – "Normal %VRo" vs Contact Effects
Single Sill Example – Area JCRB25



Cooper, 2006

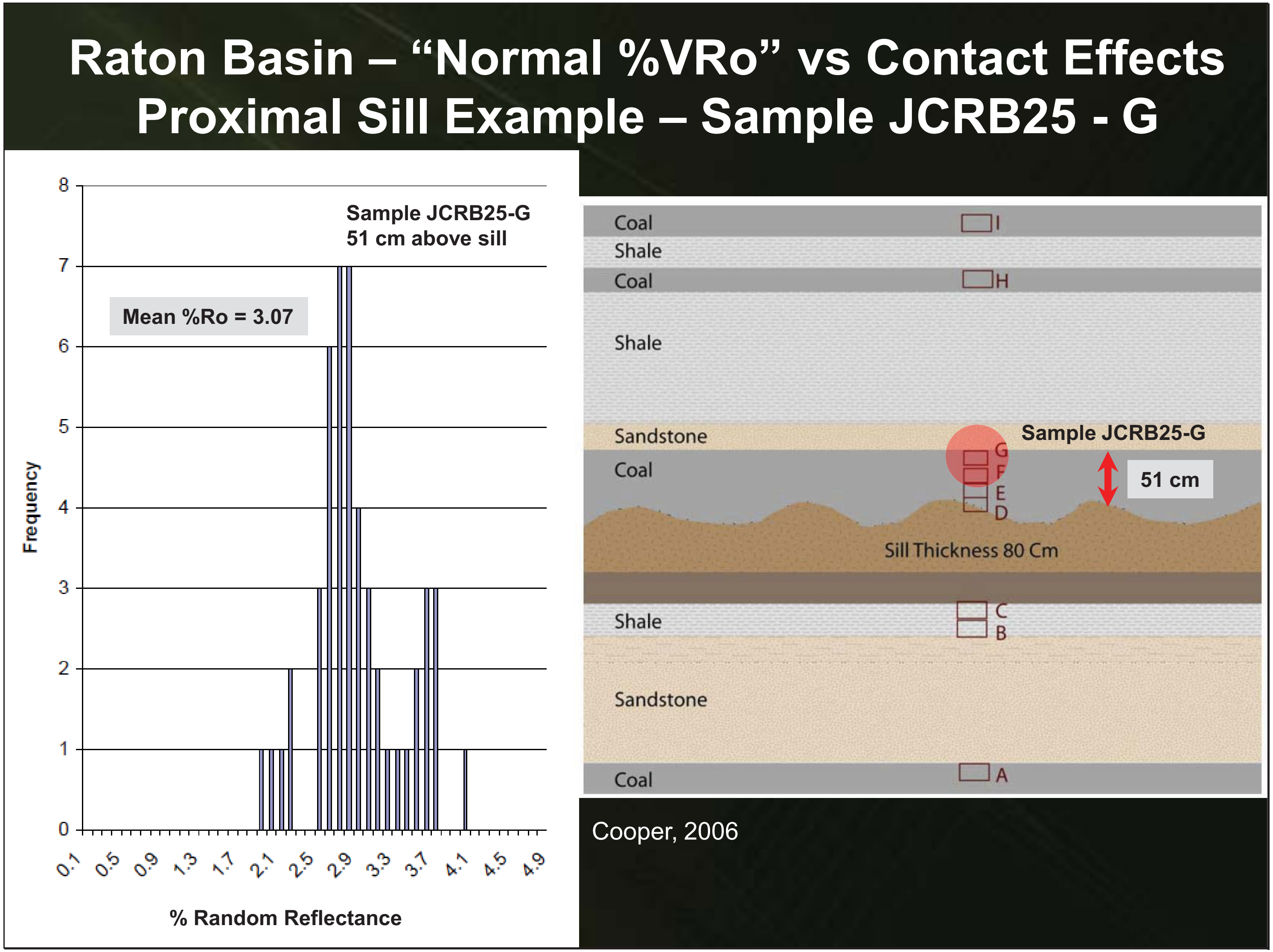
Presenter's notes: Increasing mean vitrinite reflectance with increasing proximity to igneous sill.

Raton Basin – "Normal %VRo" vs Contact Effects Distal Sill Example – Sample JCRB25 - I

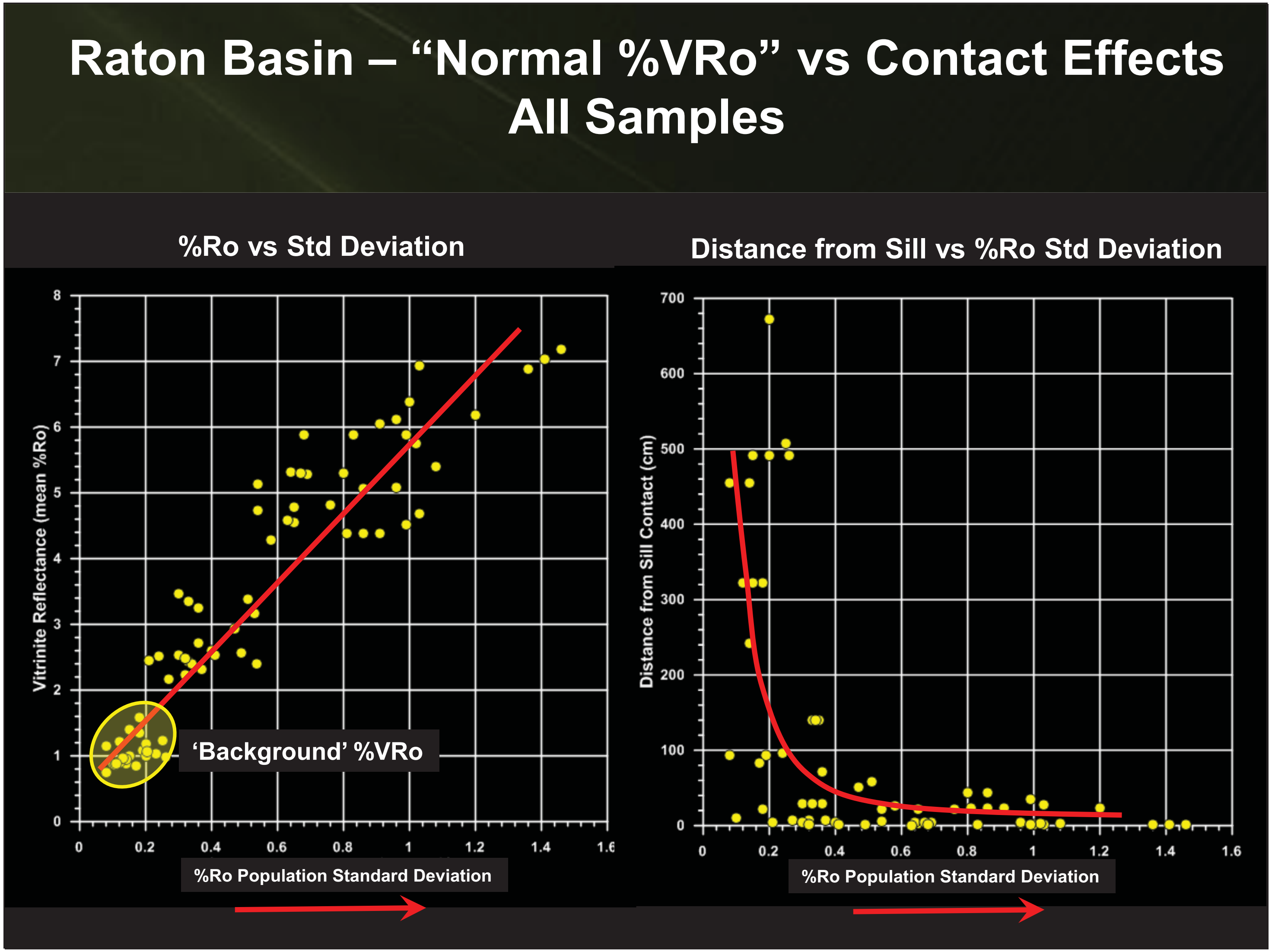


Cooper, 2006

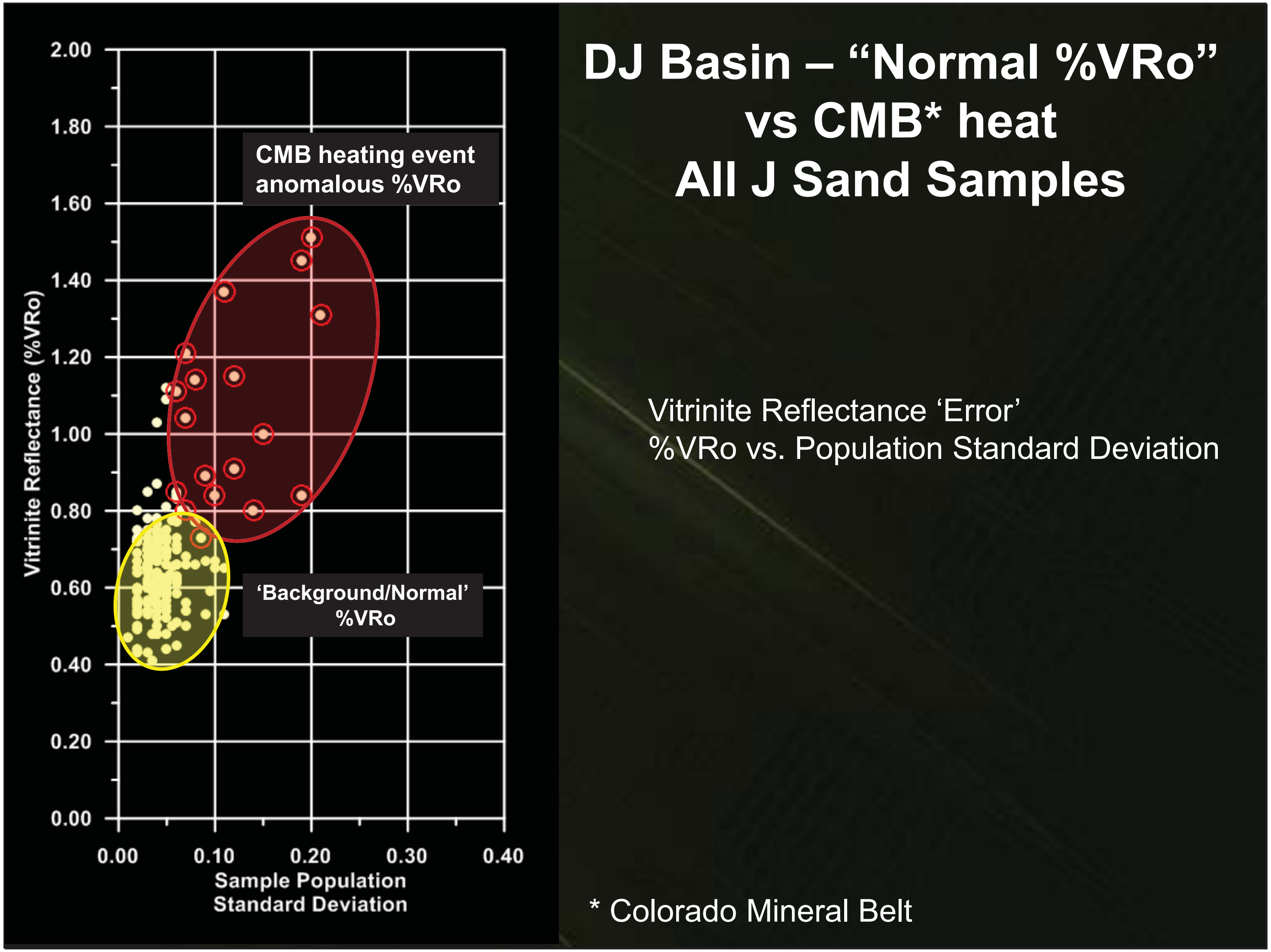
Presenter's notes: Vitrinite reflectance histogram (sample JCRB25-I). This vitrinite population in this sample (483 cm above the sill) is similar in shape to that of many other samples that are not proximal to thin sills in the Raton basin study by Cooper, 2006.



Presenter's notes: Vitrinite reflectance histogram proximal to sill (sample JCRB25-G, 51 cm above sill) show considerable histogram spread (increasing standard deviation).

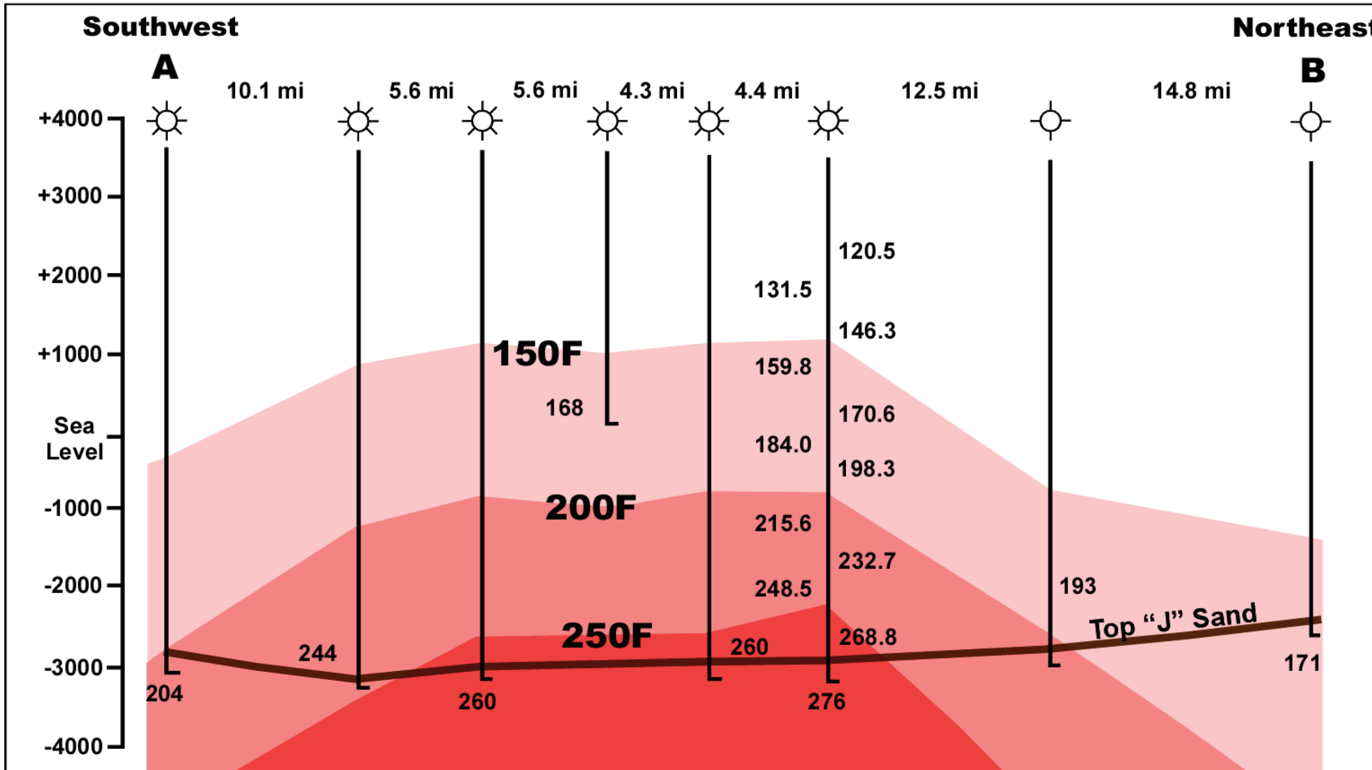


Presenter's notes: Cross-plots of all vitrinite data published by Cooper, 2006. %Ro population standard deviation vs Vitrinite Reflectance (left) shows a strong relationship with increasing population standard deviation with increasing mean %Ro. The "background" %Ro values are shown inside the yellow highlight. %Ro population standard deviation vs Distance from Sill Contact (cm) shows increasing %Ro population standard deviation with proximity to the igneous sill heat source.



Presenter's notes: DJ basin sample population standard deviation vs vitrinite reflectance plot. The "background" vitrinite populations are shown highlighted in yellow and the high standard deviation outliers are highlighted in red. The points shown in red are located within the Wattenberg field area. This area is geothermally warmer than areas outside the field and vitrinite reflectance indicates a higher level of thermal maturity (with much higher mean %VRo standard deviation).

DJ Basin – "Normal %VRo" vs CMB Heat Pulse Heating event @ Oligocene-Miocene or younger

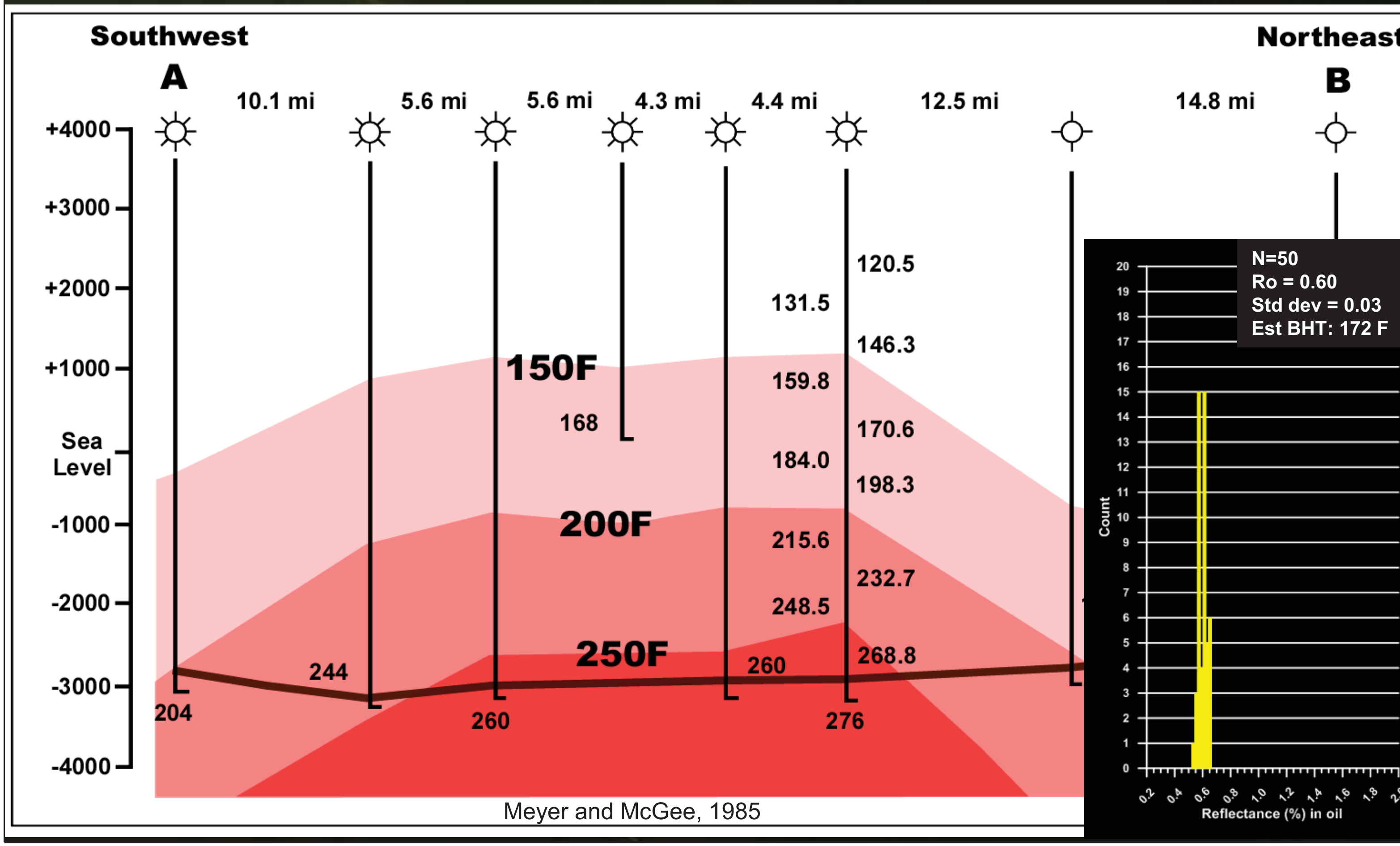


Meyer and McGee, 1985

Presenter's notes: Temperature cross-section trending southwest to northeast across Wattenberg field (Meyer and McGee, 1985) illustrating the elevated temperatures in the field area.

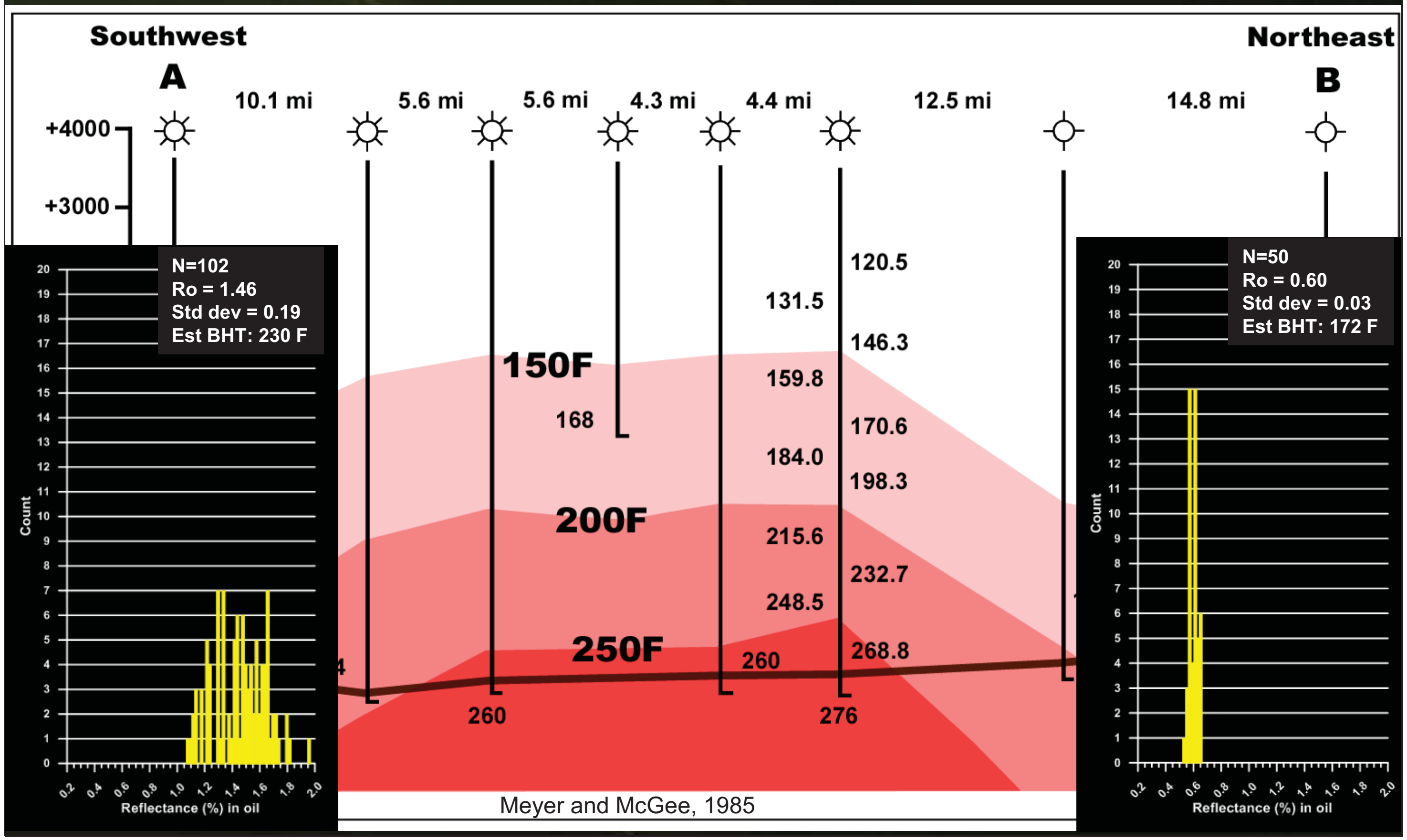
Meyer, H.J., and McGee, H.W., 1985, Oil and gas fields accompanied by geothermal anomalies in the Rocky Mountain Region, AAPG Bulletin, V. 69, No. 6, p. 933-945.

DJ Basin – "Normal %VRo" vs CMB Heat Pulse
Heating event @ Oligocene-Miocene or younger



Presenter's notes: Placement of a "normal" vitrinite histogram outside the effect of the Wattenberg heat anomaly.

DJ Basin – "Normal %VRo" vs CMB Heat Pulse Heating event @ Oligocene-Miocene or younger



Presenter's notes: Placement of an anomalously high standard deviation vitrinite histogram within the effect of the Wattenberg heat anomaly. The unanswered question is; will vitrinite histograms behave "normally" (with tight distributions) with regular burial in an environment of constant heat flow or will the standard deviation of vitrinite populations rapidly increase at mean %Ro greater than 0.8, with or without an anomalous heating event (either the CMB event or in the case of the Raton basin, the injection of an igneous sill).

Vitrinite Reflectance Errors and Data Quality

- Quantity (minimum of 20 measurements)
- Quality of samples (poor polish, pitted)
- Size (particles larger than measuring spot, not small particles)
- Type (vitrinite-like organic materials, correct particle identification)
- Pure samples (core is better, cuttings may be contaminated with mud additives, etc)
- Thermal maturity (anisotropy, >1% VRo)
- Reflectance suppression/enhancement (e.g., alginate, oxidizing environs)

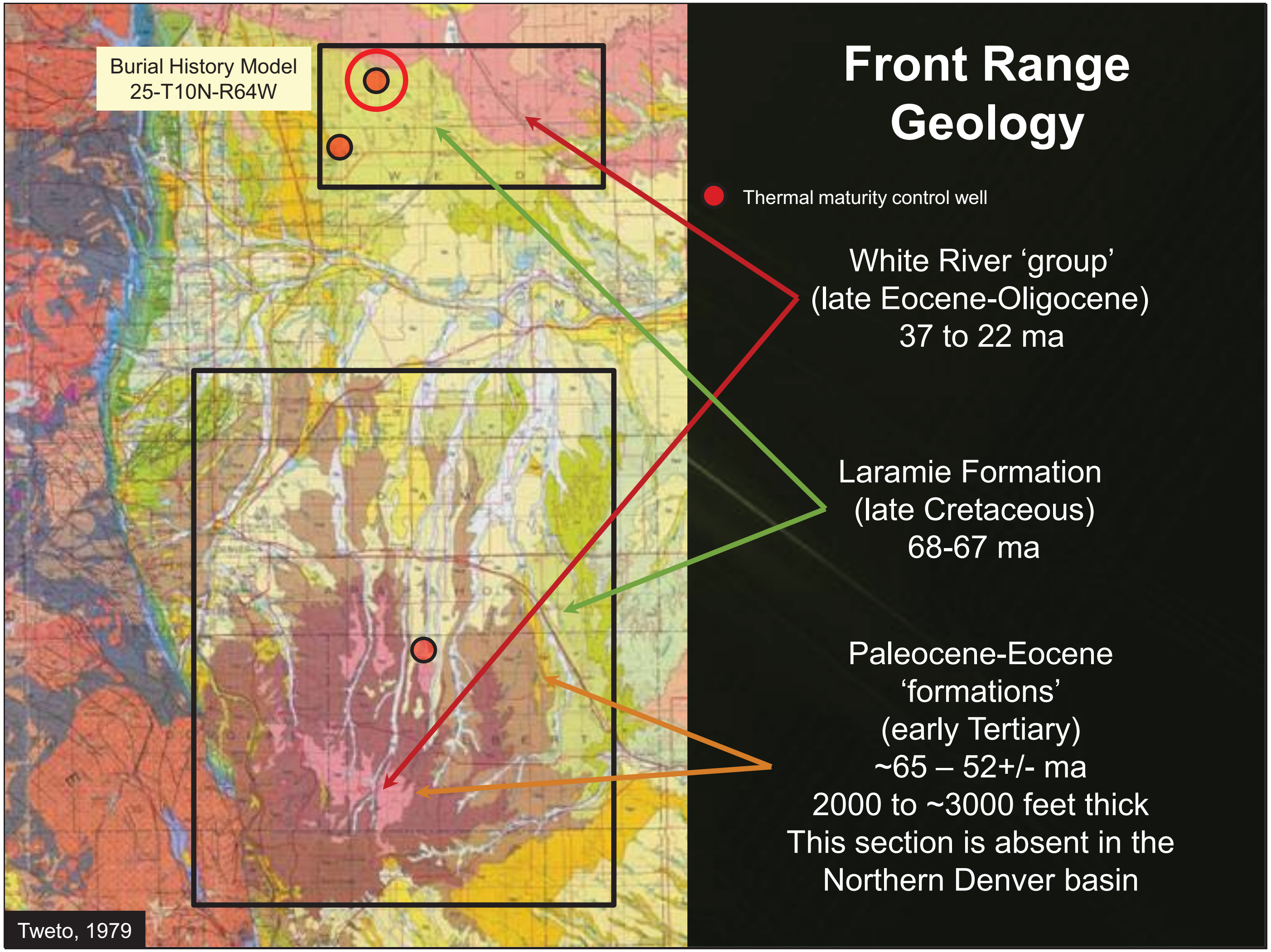
Modified from Cardott, 2012

Presenter's notes: Vitrinite reflectance errors and data quality.

Cardott, B.J., 2012, Introduction to vitrinite reflectance as a thermal maturity indicator, AAPG Search and Discovery Article #40928, posted May 21, 2012.

Post Cretaceous Geohistory
Eastern Colorado

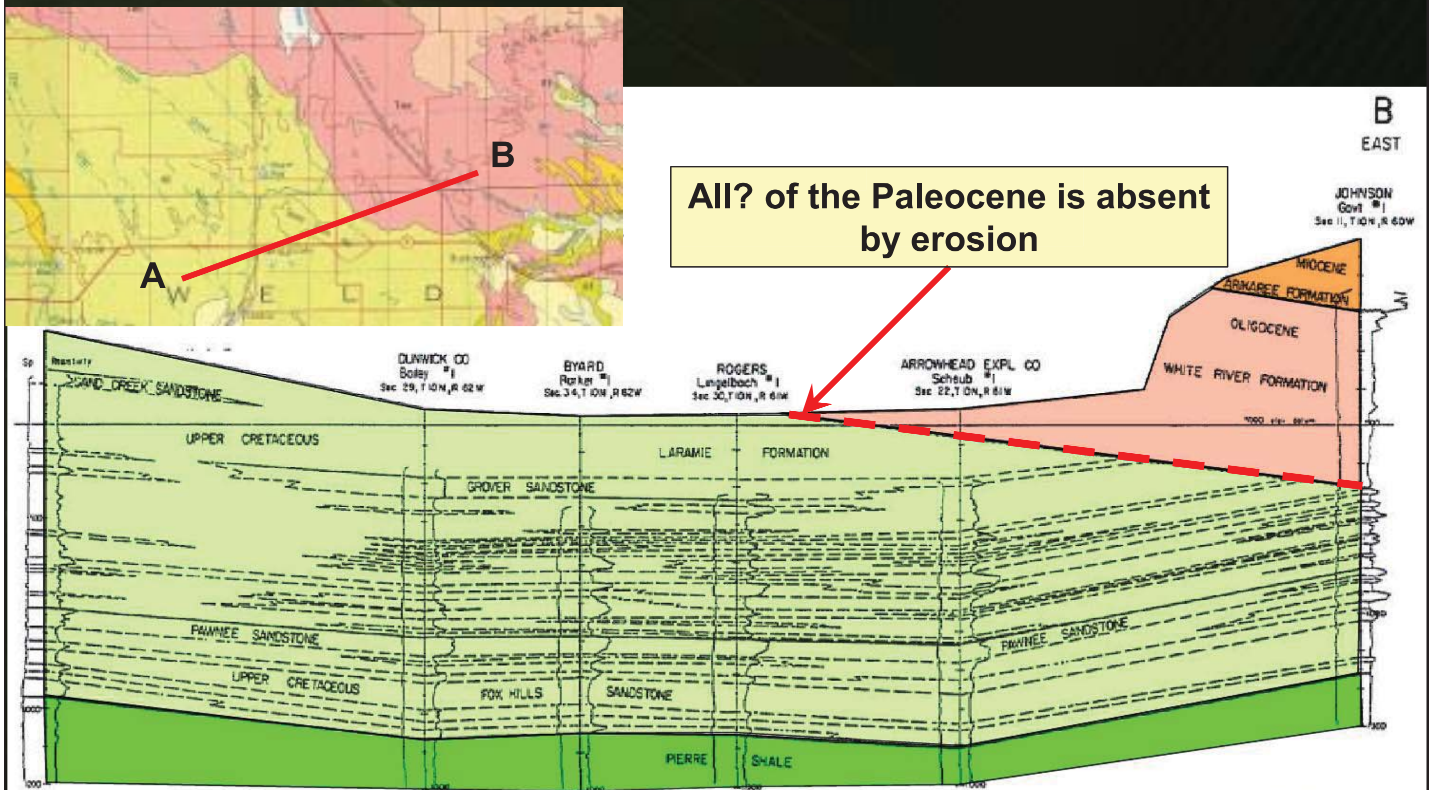
Presenter's notes: Post Cretaceous Geohistory of Eastern Colorado



Presenter's notes: Front range of Colorado geologic map (Tweto, 1979), illustrating the different geohistories of the northern vs. the southern DJ basin. In the southern DJ basin approximately 2800-3000 feet of Paleocene is present (brown colors on map) between the Laramie Formation (light green) and Eocene units (pink) such as the White River Formation and Castle Rock Conglomerate.

Tweto, Ogden, 1979, Geologic Map of Colorado, U. S. Geological Survey .

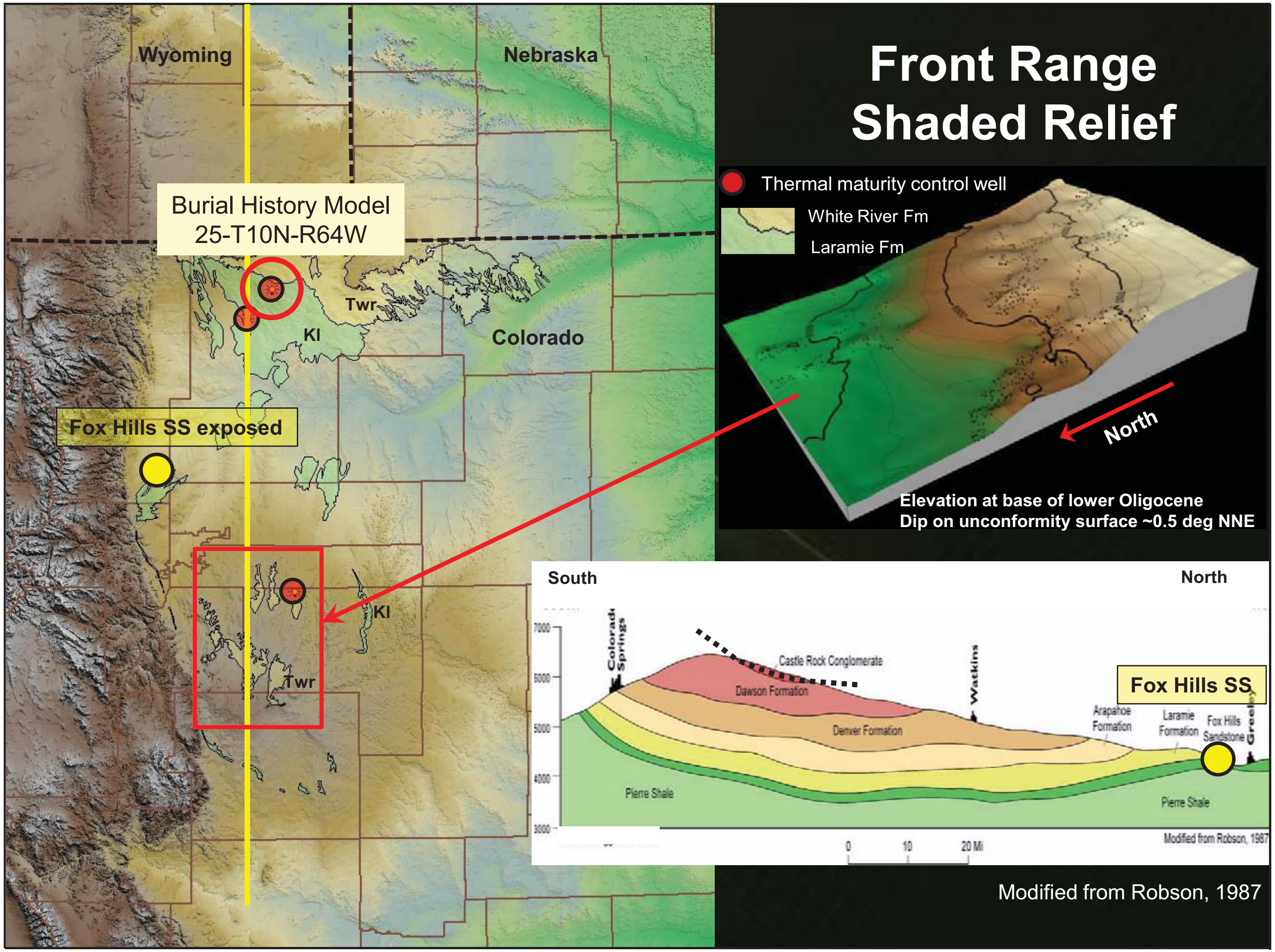
Northern Denver Basin – Cross Section



Reade, 1978

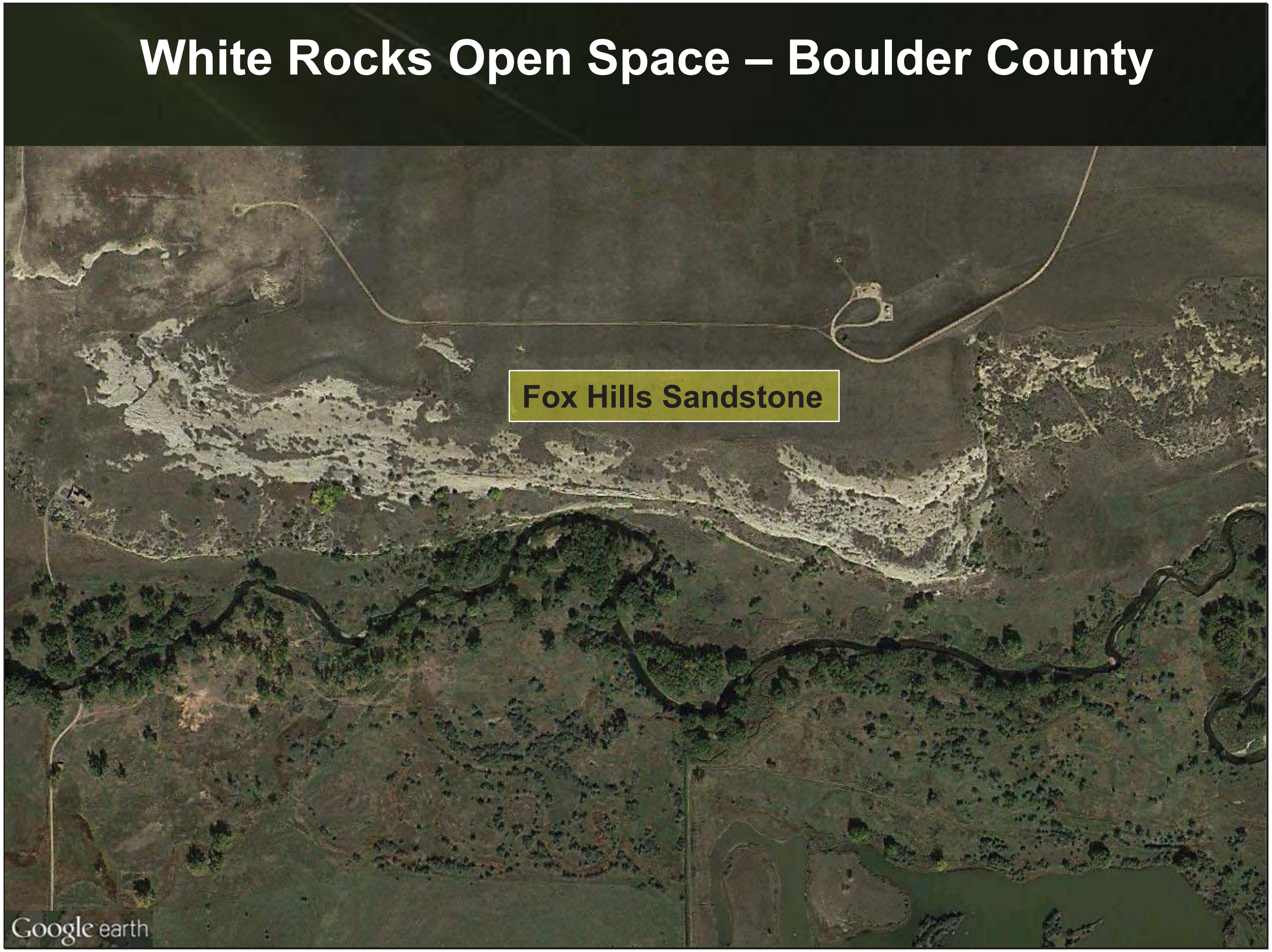
Presenter's notes: Cross-section A-B (Reade, 1978) illustrating the unconformable relationship between the Laramie Formation and the overlying White River Formation. The entire Paleocene section has been removed by erosion or non-deposition.

Reade, H.L., 1978, Uranium deposits: Northern Denver Julesburg basin, Colorado; in Energy Resources of the Denver Basin, Rocky Mtn. Assoc. of Geologists Guidebook, pp. 161-171. Pruit, et al, eds.



Presenter's notes: Shaded relief map of eastern Colorado with outcrops of Tertiary White River Group and Laramie Formation posted. The elevations of the basal White River contact was used to produce the block diagram (upper right) which shows the dip of the post-Paleocene unconformity dipping approximately 0.5 degrees to the north-north-east. This is in agreement with the cross-section of Robson, 1987.

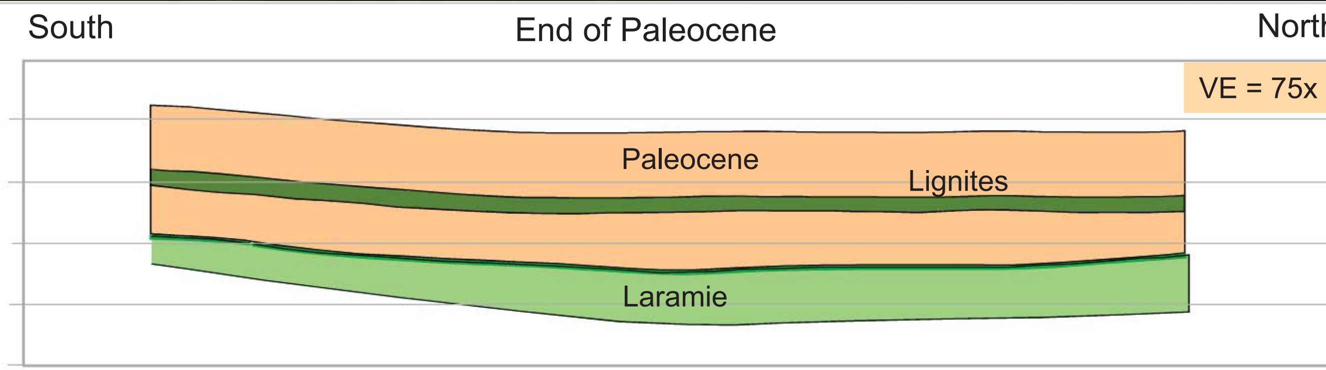
Robson, S.G., 1987, Bedrock aquifers in the Denver basin, Colorado; a quantitative water-resources appraisal, U. S. Geological Survey, Professional Paper 1257.



Presenter's notes: Exposure of Fox Hills Sandstone located approximately 5.6 miles east-north-east of boulder, Colorado. (Latitude: 40.05360, Longitude: -105.16091).

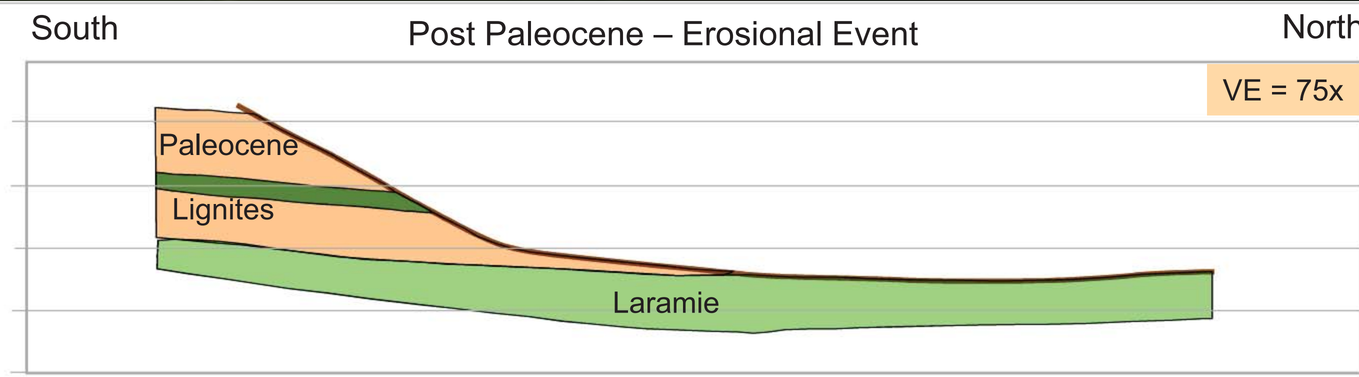
Google earth imagery date: 10/6/2014.

Geohistory & Stratigraphic Correlations Southern vs Northern Denver Basin



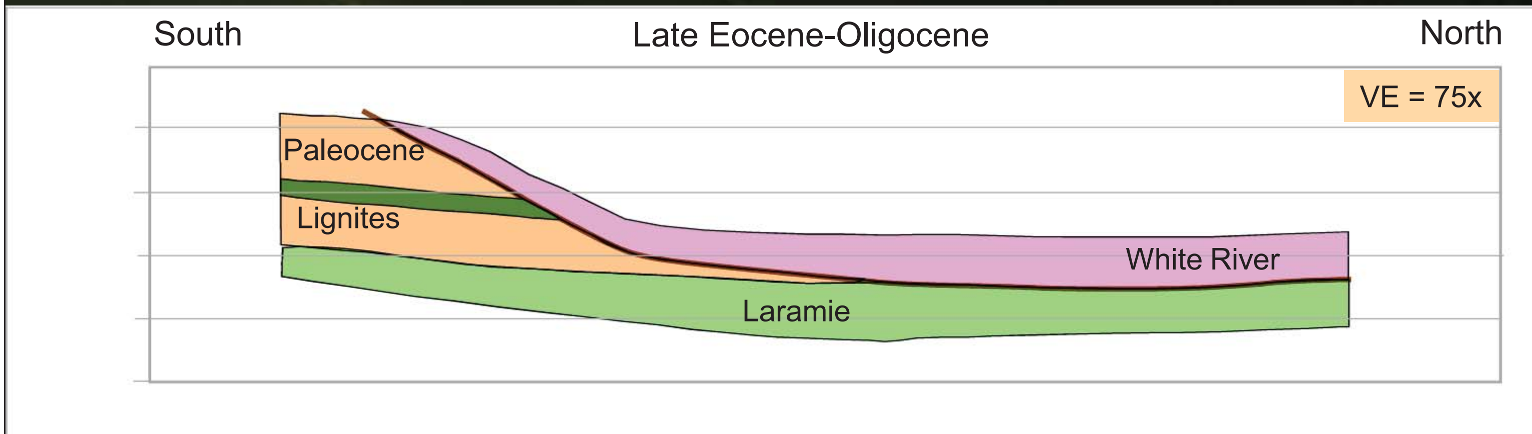
Presenter's notes: Schematic development of the western DJ basin. Shown here is a simplistic representation of a north-south cross section (yellow line on earlier slide) of the western DJ basin at the end of Paleocene and prior to post Paleocene uplift and erosion.

Geohistory & Stratigraphic Correlations
Southern vs Northern Denver Basin



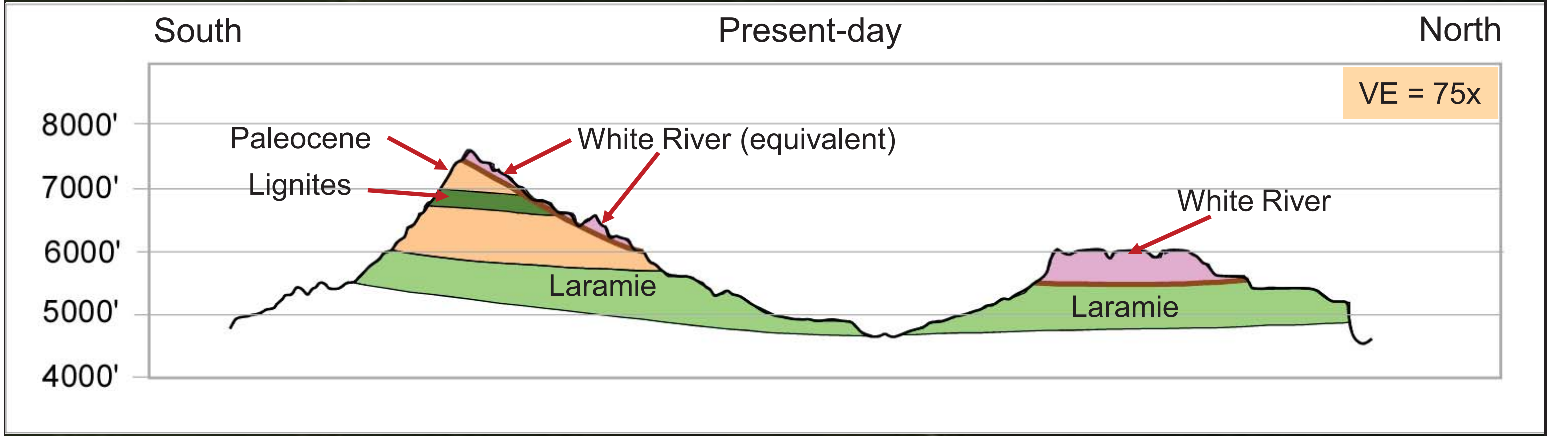
Presenter's notes: Schematic development of the western DJ basin. Shown here is a simplistic representation of a north-south cross section of the western DJ basin at the end of post Paleocene uplift and erosion. Note 75x vertical exaggeration.

Geohistory & Stratigraphic Correlations
Southern vs Northern Denver Basin

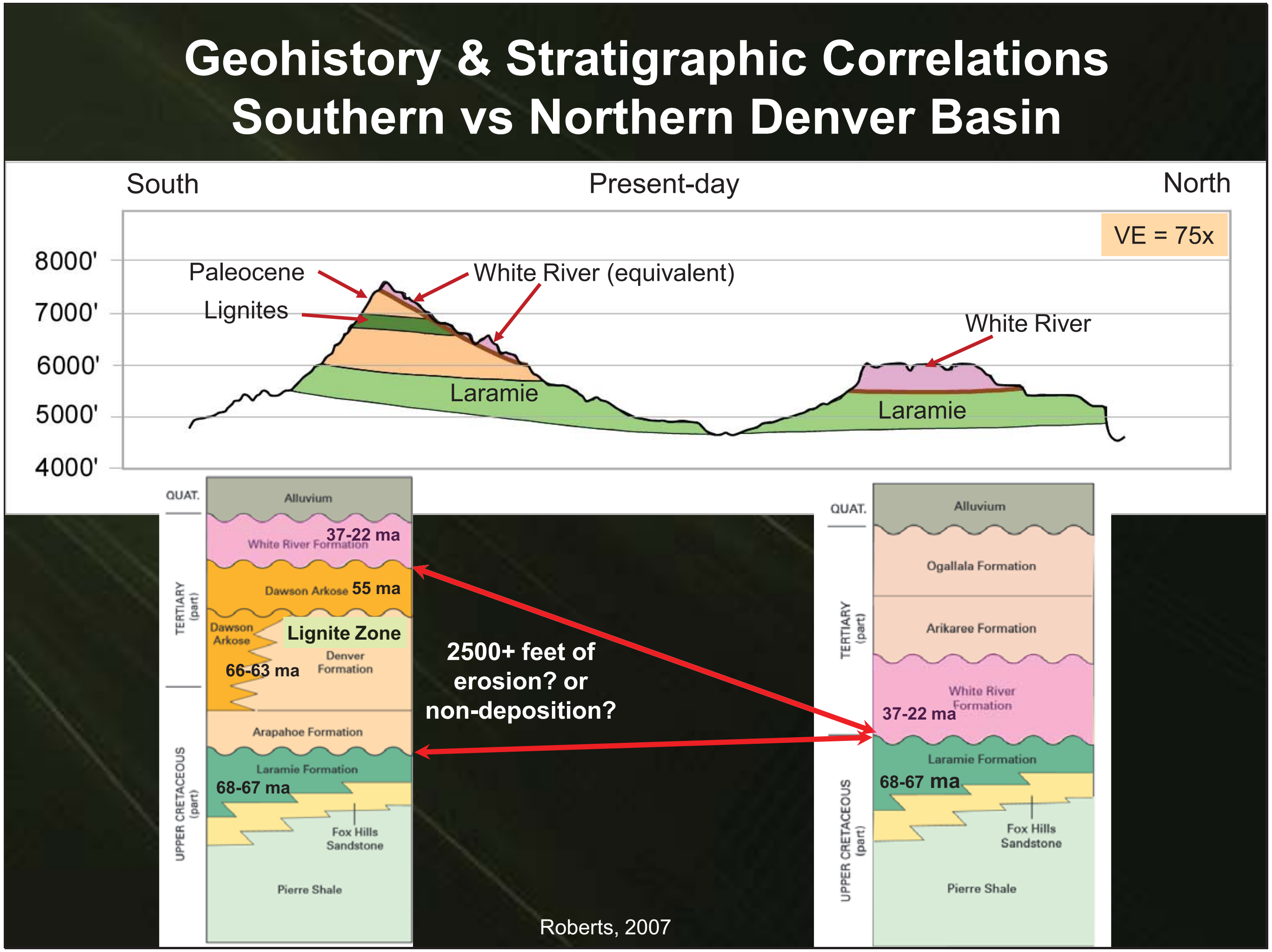


Presenter's notes: Schematic development of the western DJ basin. Shown here is a simplistic representation of a north-south cross section of the western DJ basin at the end of Eocene-Oligocene White River Group deposition.

Geohistory & Stratigraphic Correlations
Southern vs Northern Denver Basin

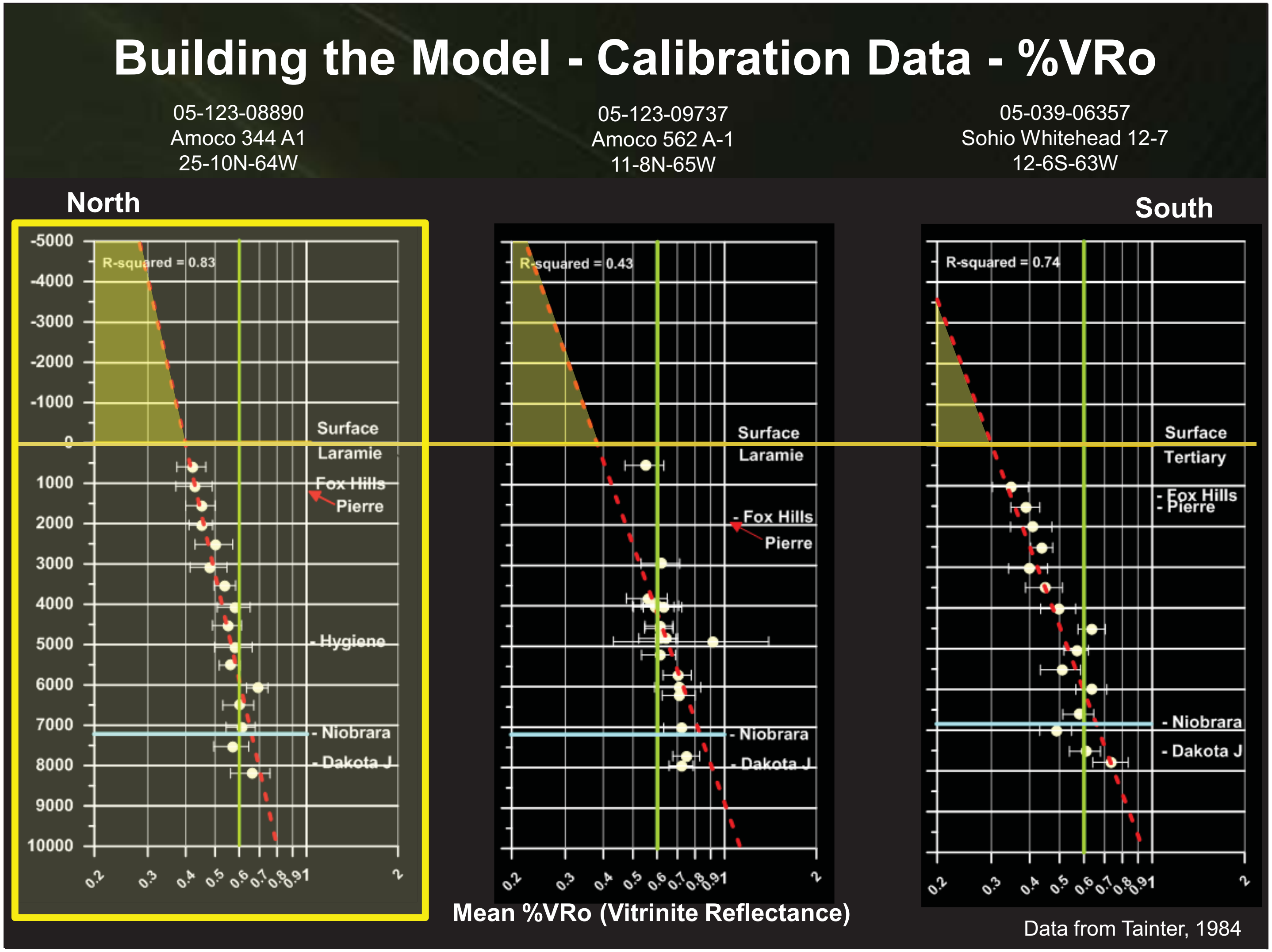


Presenter's notes: Schematic development of the western DJ basin. Shown here is a simplistic representation of a north-south cross section of the western DJ basin at present-day.



Presenter's notes: Comparison of the present-day stratigraphic columns representing the southern DJ basin vs the northern DJ basin (Roberts, 2007).

Roberts, S.B., 2007, Coal in the Front Range Urban Corridor—An Overview of Coal Geology, Coal Production, and Coal Bed Methane Potential in Selected Areas of the Denver Basin, Colorado, and the Potential Effects of Historical Coal Mining on Development and Land-Use Planning: U.S. Geological Survey Digital Data Series DDS-69-P.



Presenter's notes: Calibration data used in construction of geohistory and burial history model. Within the DJ basin there are only a few "control wells" where continuous vertical sampling of %VRo maturity data is available. The three wells shown represent the best, continuous vertical sampling of vitrinite reflectance data and were taken from Tainter, 1984. In these plots (logarithmic %VRo vs linear depth), the best fit (dashed red) (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

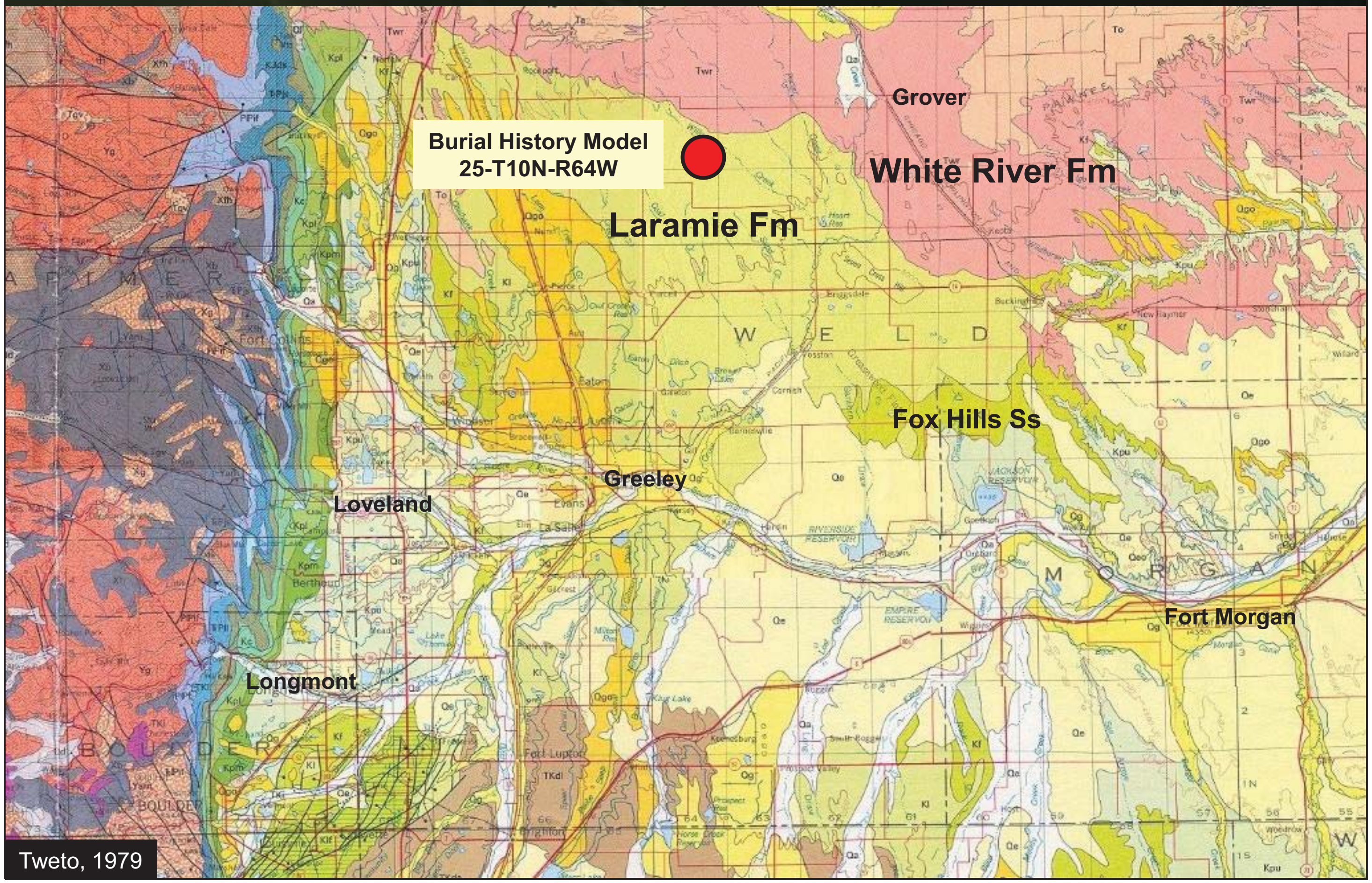
is projected above the present-day surface (0 depth in feet). The intercept with the Y-axis at 0.2 VRo is an indication of erosional magnitude (Dow, 1977). The interpretation is that the amount of uplift/erosion decreases from north to south and is in agreement with the observations from geologic mapping. The data set outlined in yellow was used to build the burial history model shown in following slides.

Tainter, P.A., 1984, Stratigraphic and paleostructural controls on hydrocarbon migration in Cretaceous D and J sandstones of the Denver basin, in Hydrocarbon source rocks of the Greater Rocky Mountain Region, RMAG 1984, pp. 339-354.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, no. 2, pp. 79–99.

Amoco 344A1 Model Location

sw sw 25-10N-64W

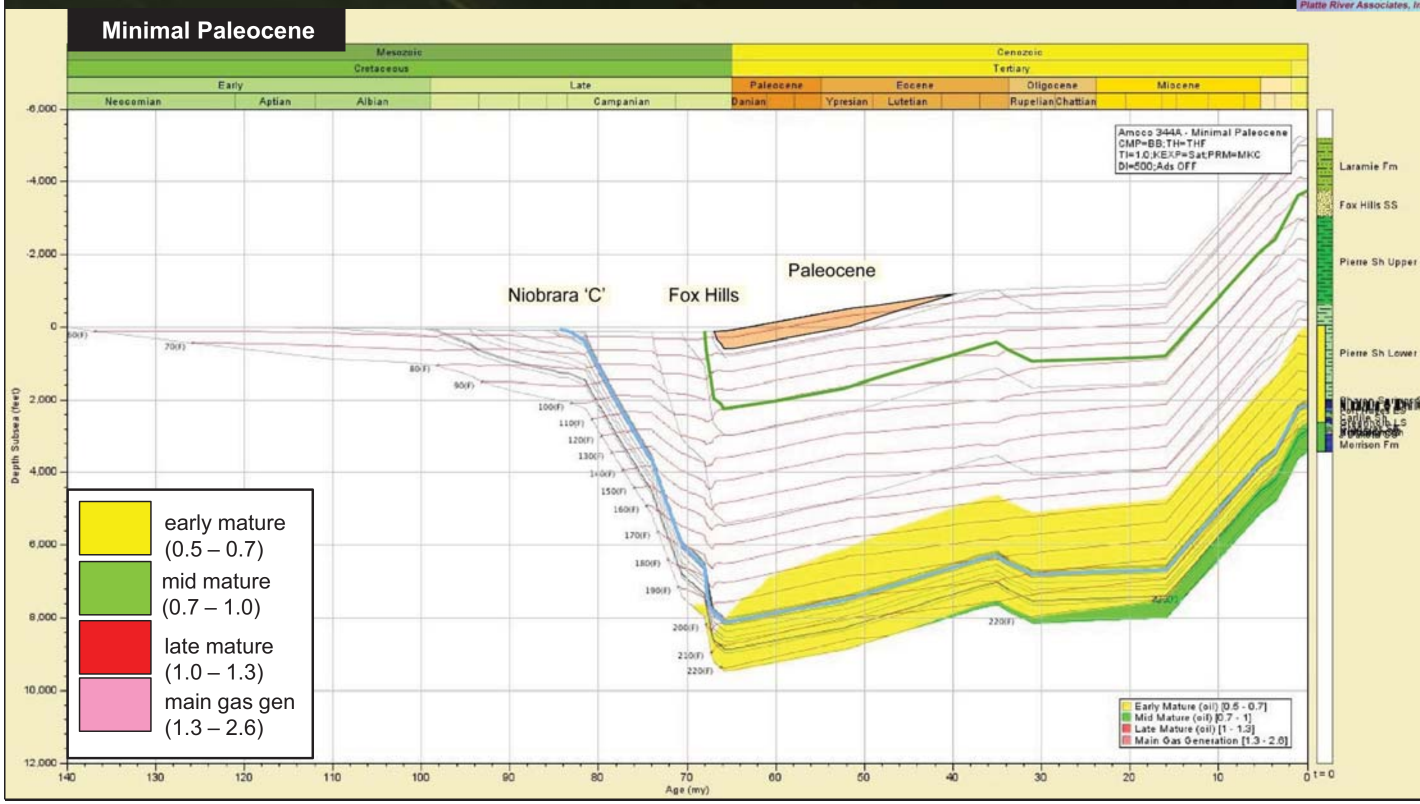


Presenter's notes: Location of Amoco 344A1 well burial history model. The well is spud in the Laramie and there is no Paleocene stratigraphy preserved in this area. Colorado geologic map (Tweto, 1979).

Tweto, Ogden, 1979, Geologic Map of Colorado, U. S. Geological Survey .

Amoco 344A1 – Burial History Scenarios

1 Model – 4 Scenarios



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) burial history plots – 1 model with 4 scenarios.
Shown above (scenario 1) with the deposition of only a minimal amount of Paleocene, the Niobrara "C" (blue marker) does not enter the mid mature oil window; only a small amount of oil would have been generated.
In all scenarios, all other parameters; heat flow model, rock properties, etc. were held constant.
Model built with Platte River Associates, BasinMod: October 2014 release.

Amoco 344A1 – Burial History Scenarios

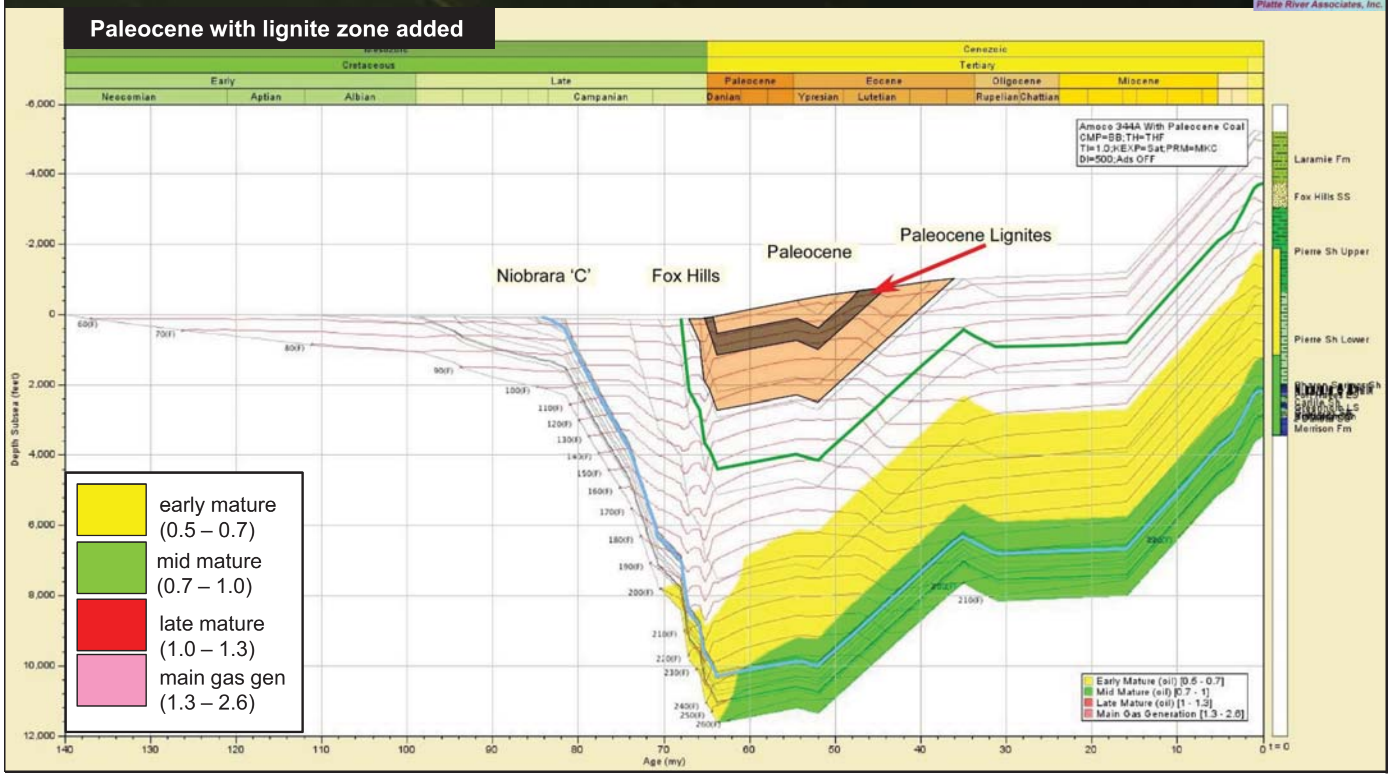
1 Model – 4 Scenarios

Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) burial history plots – 1 model with 4 scenarios.

Shown above (scenario 2) with the added deposition of ~3000 feet of Paleocene that DOES NOT include any coal or coaly material, the Niobrara "C" (blue marker) just enters the top of the mid mature oil window; significant quantities of oil are generated but barely enough to expel any liquid hydrocarbons from the kerogen rich shaly marls into the chalks (reservoirs).

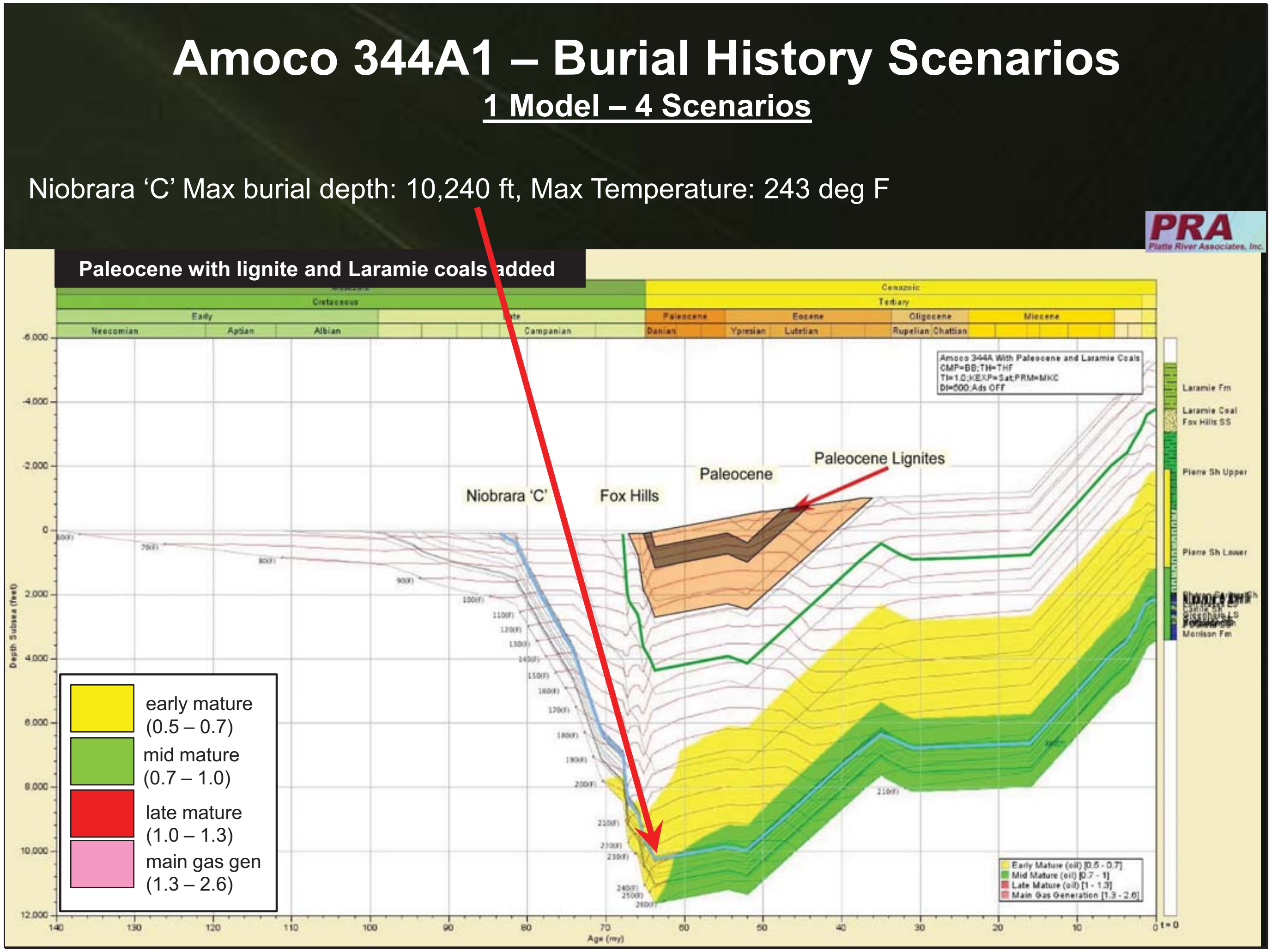
Amoco 344A1 – Burial History Scenarios

1 Model – 4 Scenarios



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) burial history plots – 1 model with 4 scenarios.

Shown above (scenario 3) with the added deposition of ~3000 feet of Paleocene that DOES include 100 feet of lignite within a 400 foot thick shaly section, the Niobrara "C" (blue marker) is now well into the mid mature oil window; significant quantities of oil are generated and expelled from the kerogen rich shaly marls into the chalks (reservoirs).



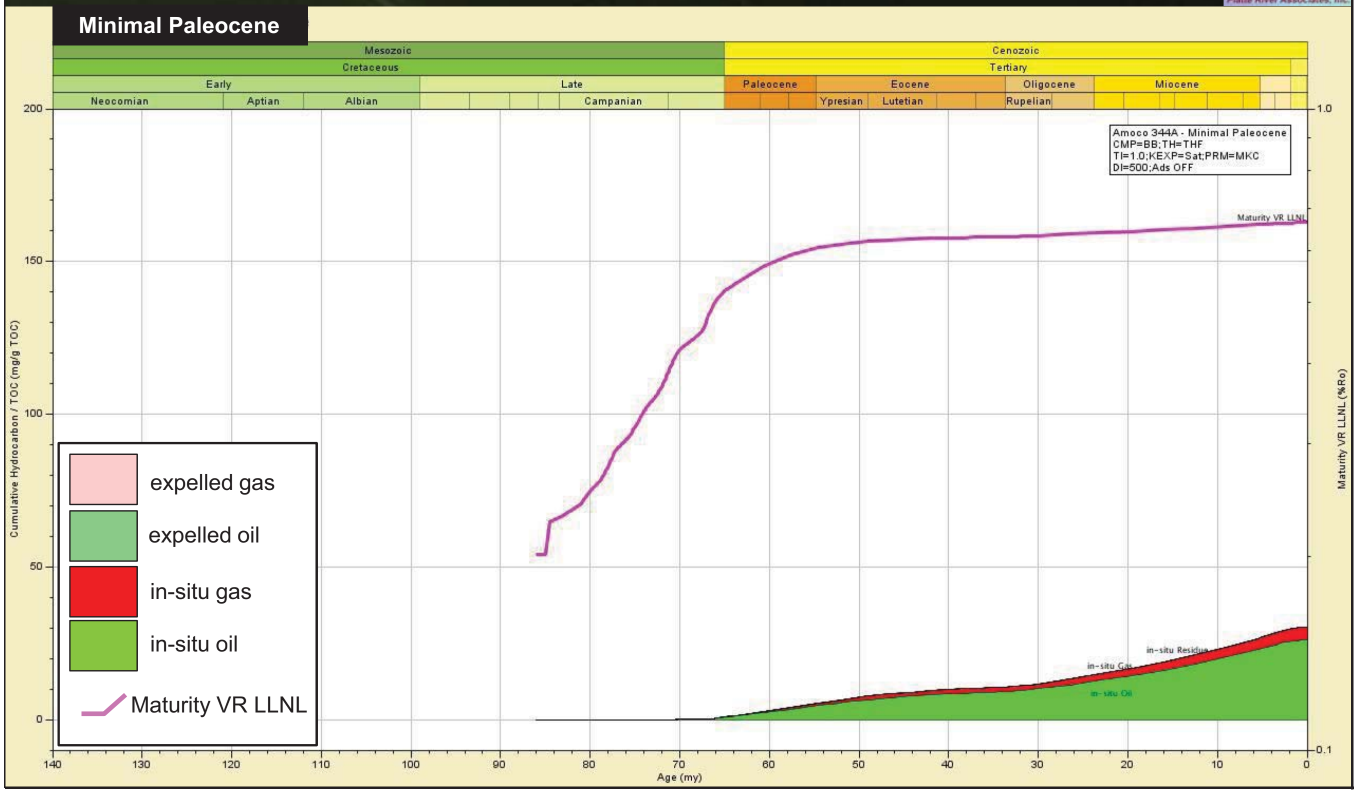
Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) burial history plots – 1 model with 4 scenarios.

Shown above (scenario 4) the same as scenario 3 but with the addition of a thin (25 foot) thick Laramie coal section (included in green marker) . As with scenario 3, the Niobrara "C" (blue marker) is now well into the mid mature oil window; significant quantities of oil are generated and expelled from the kerogen rich shaly marls into the chalks (reservoirs). However, the addition of the thin Laramie coal does not significantly change the generation and expulsion picture.

Amoco 344A1 – Cumulative Generated Hydrocarbons

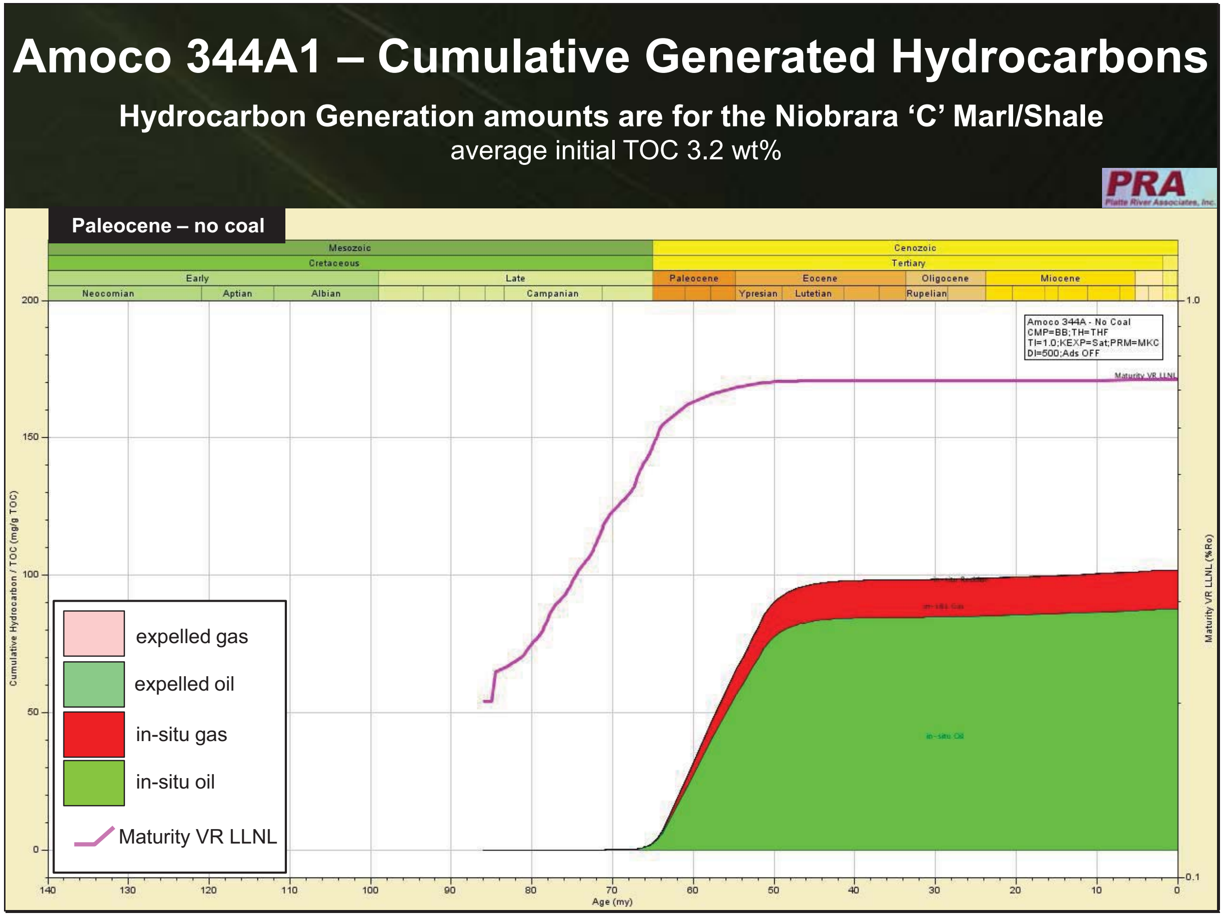
Hydrocarbon Generation amounts are for the Niobrara 'C' Marl/Shale

average initial TOC 3.2 wt%



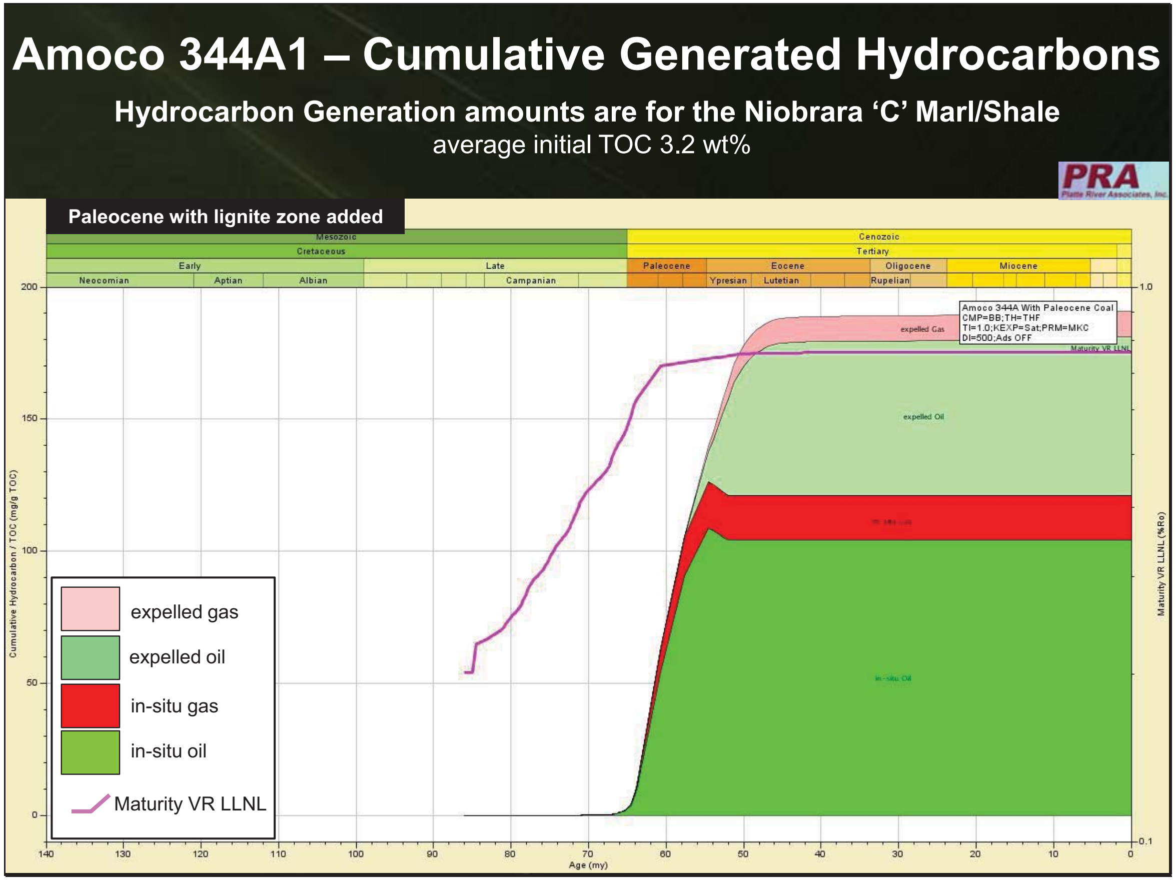
Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) cumulative generated hydrocarbons plot for the Niobrara "C" Marl – 1 model with 4 scenarios.

Shown above (scenario 1) with the deposition of only a minimal amount of Paleocene, the Niobrara "C" (blue marker on burial history plot) does not enter to mid mature oil window; only a small amount of oil would have been generated. While some hydrocarbons have been generated, no hydrocarbons have been expelled. Calculated maximum %VRo is approximately 0.67.



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) cumulative generated hydrocarbons plot for the Niobrara "C" Marl – 1 model with 4 scenarios.

Shown above (scenario 2) with the added deposition of ~3000 feet of Paleocene that DID NOT include any coal or coaly material, the Niobrara "C" (blue marker on burial history plot) just enters the top of the mid mature oil window; significant quantities of oil are generated but barely enough to expel any liquid hydrocarbons from the kerogen rich shaly marls into the chalks (reservoirs). While significant hydrocarbons have been generated, no hydrocarbons have been expelled. Calculated maximum %VRo is approximately 0.73.



Presenter’s notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) cumulative generated hydrocarbons plot for the Niobrara “C” Marl – 1 model with 4 scenarios.

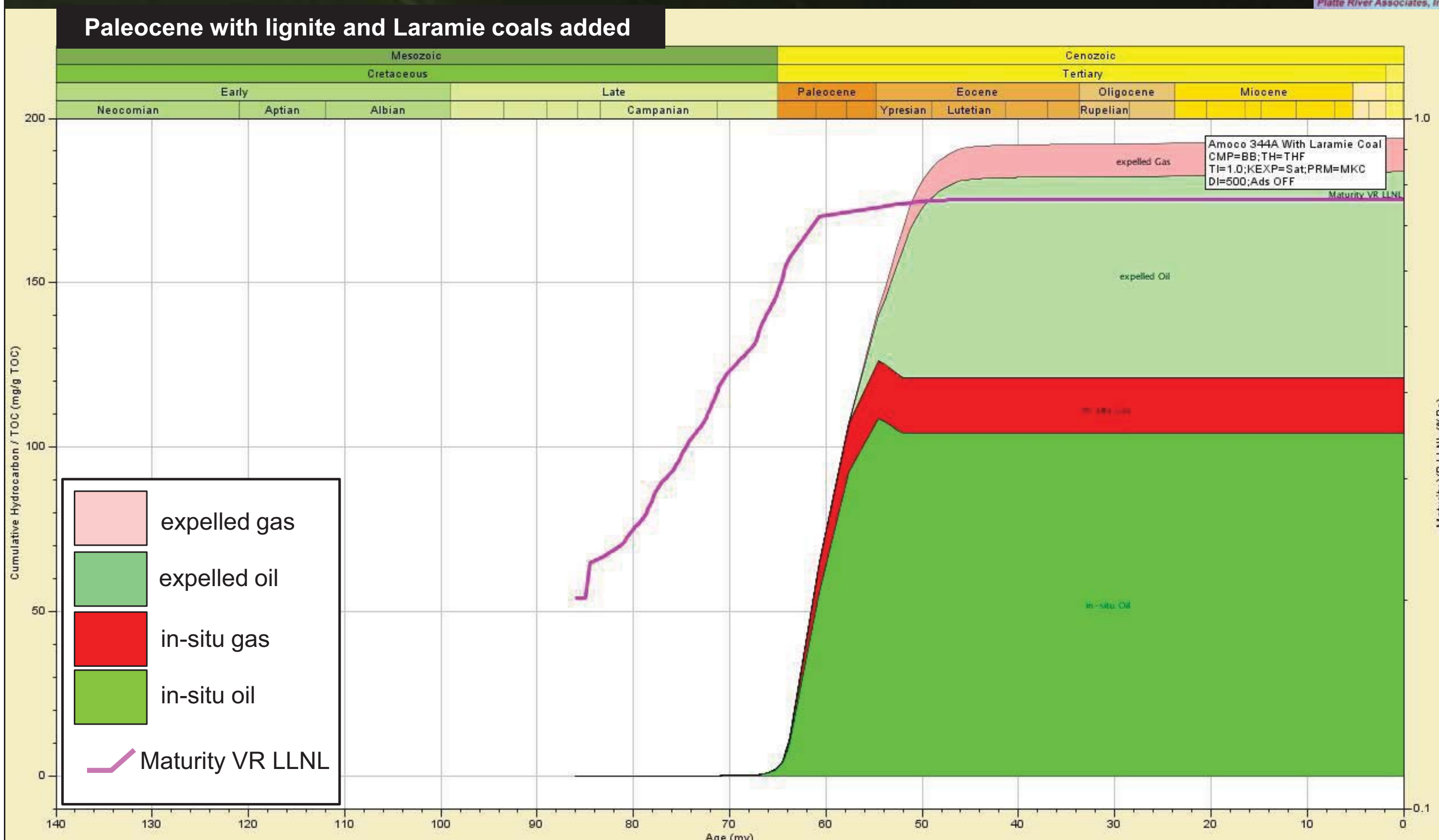
Shown above (scenario 3) with the added deposition of ~3000 feet of Paleocene that DOES include 100 feet of lignite within a 400 foot thick shaly section, the Niobrara “C” (blue marker on burial history plot) is now well into the mid mature oil window; significant quantities of oil are generated and expelled from the kerogen rich shaly marls into the chalks (reservoirs). Significant hydrocarbons have been generated and expelled from the source horizons. Calculated maximum VRo is approximately 0.77.

Level of conversion (Transformation ratio) is about 65%.

Amoco 344A1 – Cumulative Generated Hydrocarbons

Hydrocarbon Generation amounts are for the Niobrara 'C' Marl/Shale

average initial TOC 3.2 wt%



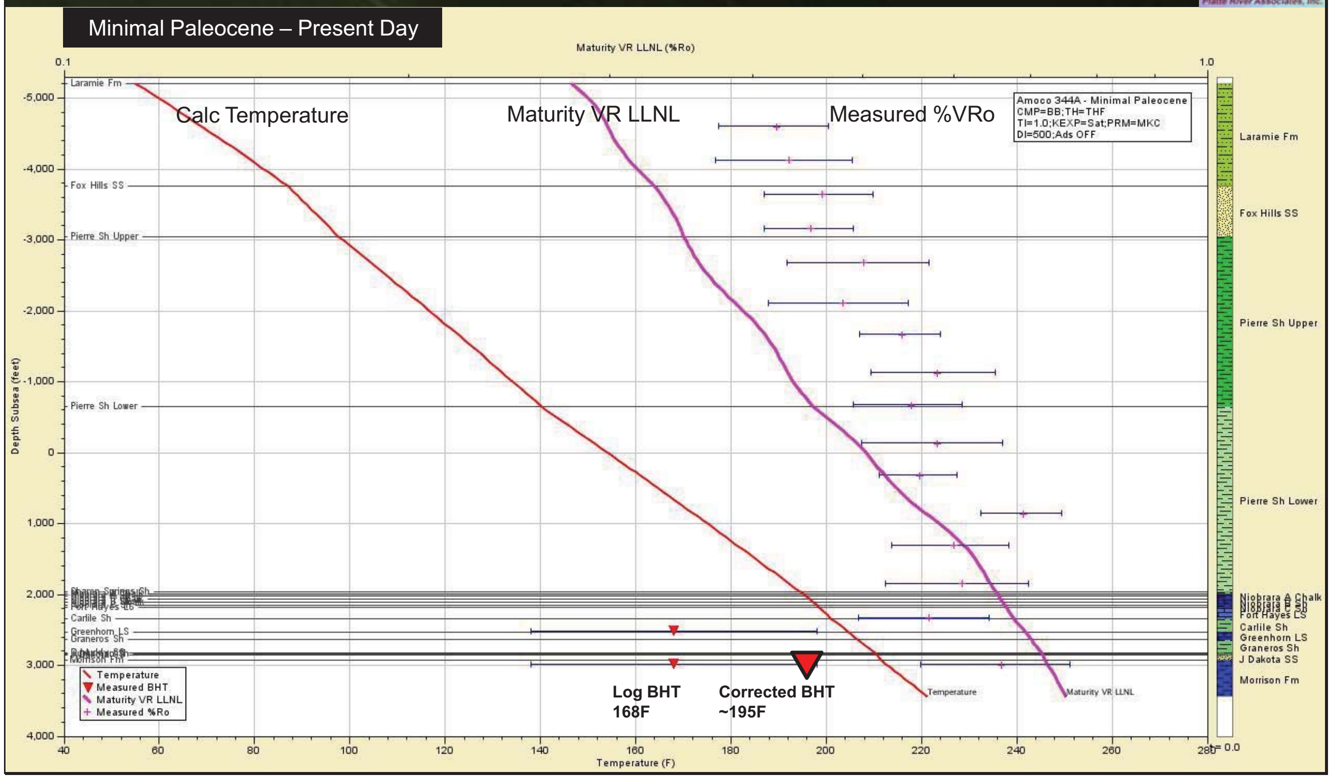
Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) cumulative generated hydrocarbons plot for the Niobrara "C" Marl – 1 model with 4 scenarios. (Presenter's notes continued on next slide)

Presenter’s notes continued from previous slide)

Shown above (scenario 4) the same as scenario 3 but with the addition of a thin (25 foot) thick Laramie coal section (included in green marker) . As with scenario 3, the Niobrara “C” (blue marker on burial history plot) is now well into the mid mature oil window; significant quantities of oil are generated and expelled from the kerogen rich shaly marls into the chalks (reservoirs). However, the addition of the thin Laramie coal does not significantly change the generation and expulsion picture. Significant hydrocarbons have been generated and expelled from the source horizons. Calculated maximum %VRo is approximately 0.77.

Level of conversion (Transformation ratio) is about 65

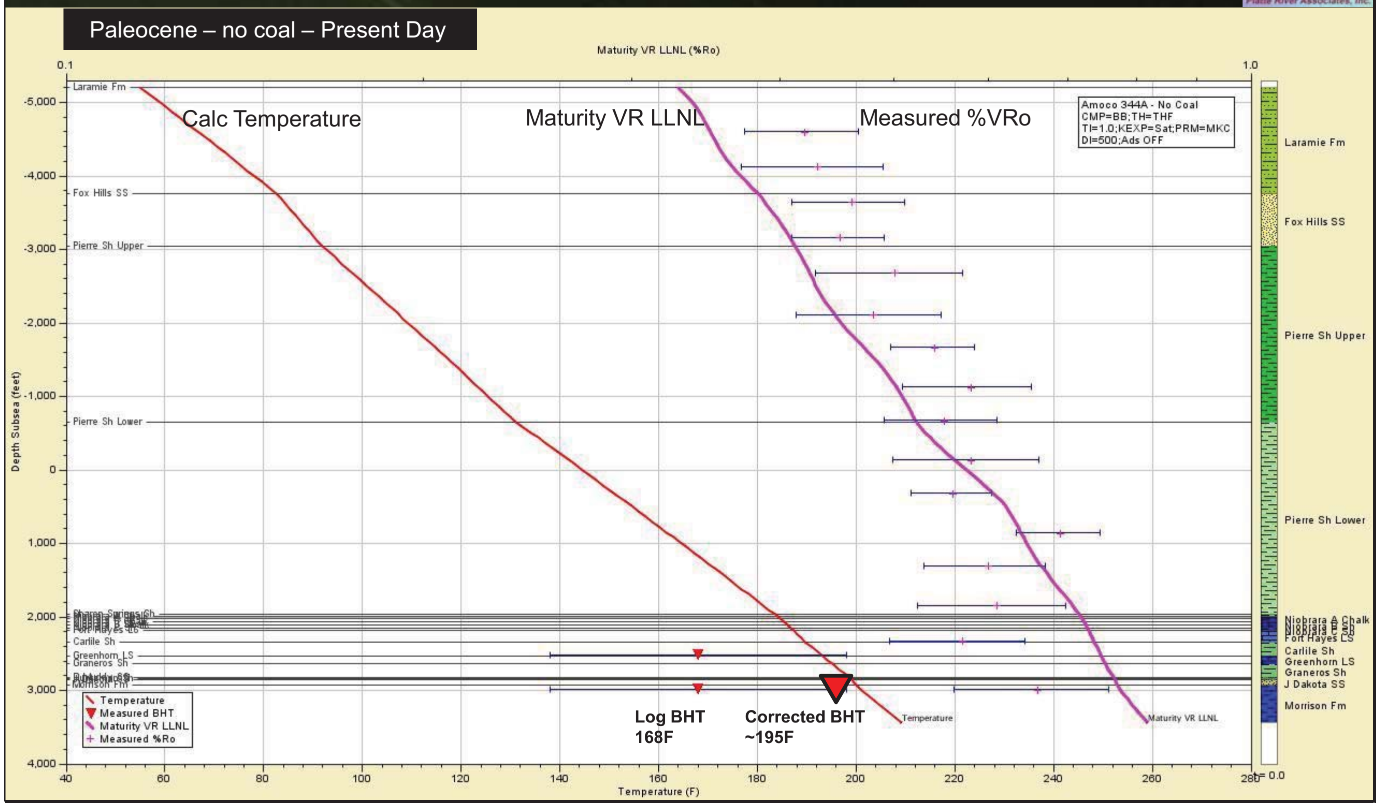
Amoco 344A1 – Calibration



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) calibration plot – 1 model with 4 scenarios.

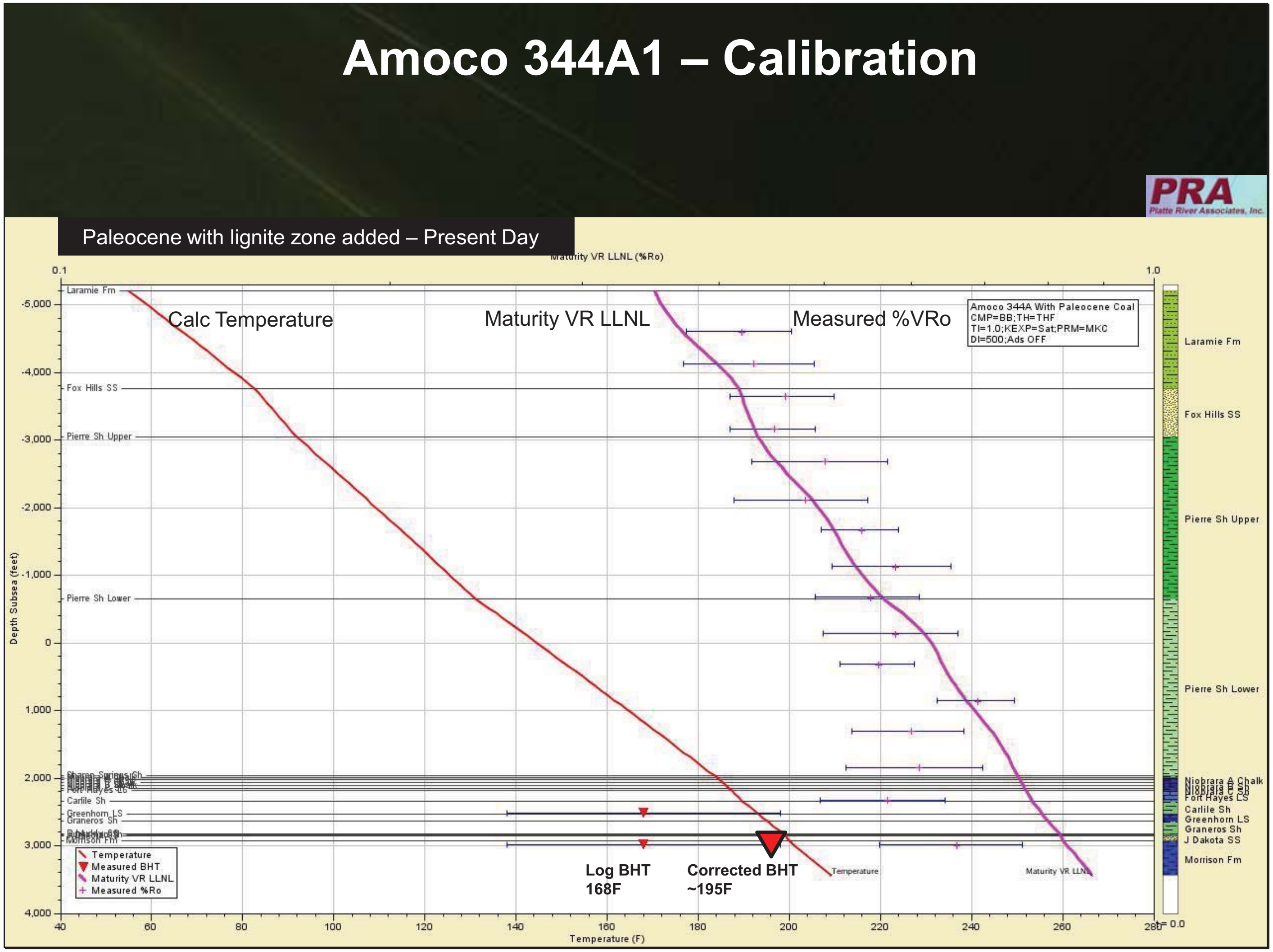
Shown above (scenario 1) with the deposition of only a minimal amount of Paleocene, the modeled temperature and vitrinite reflectance values do not match very well to the observed present-day temperature and measured vitrinite reflectance data.

Amoco 344A1 – Calibration



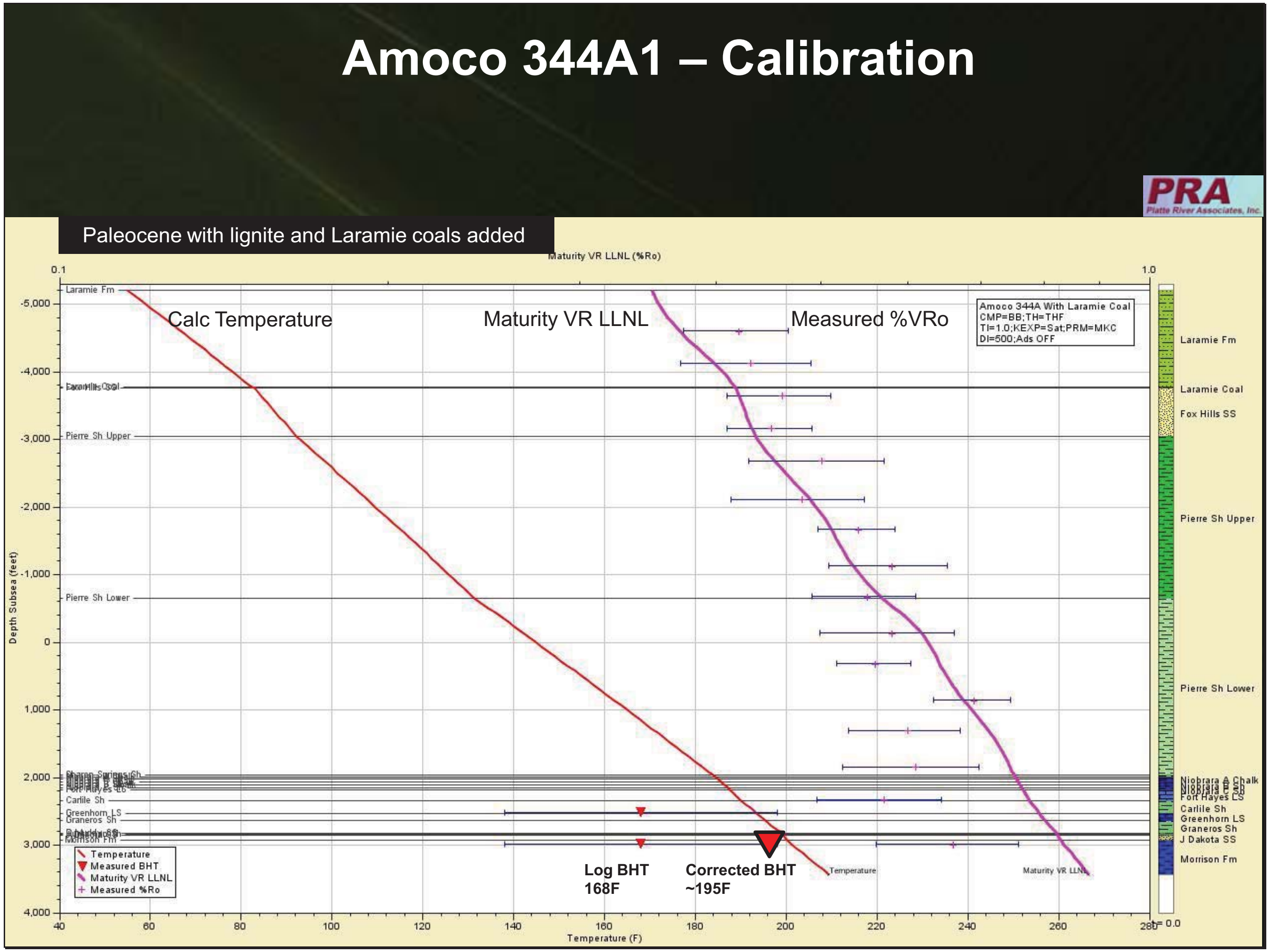
Presenter’s notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) calibration plot – 1 model with 4 scenarios.

Shown above (scenario 2) with the added deposition of ~3000 feet of Paleocene that DID NOT include any coal or coaly material. Modeled temperature and vitrinite reflectance data begin to fit the observed data.



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) calibration plot – 1 model with 4 scenarios.

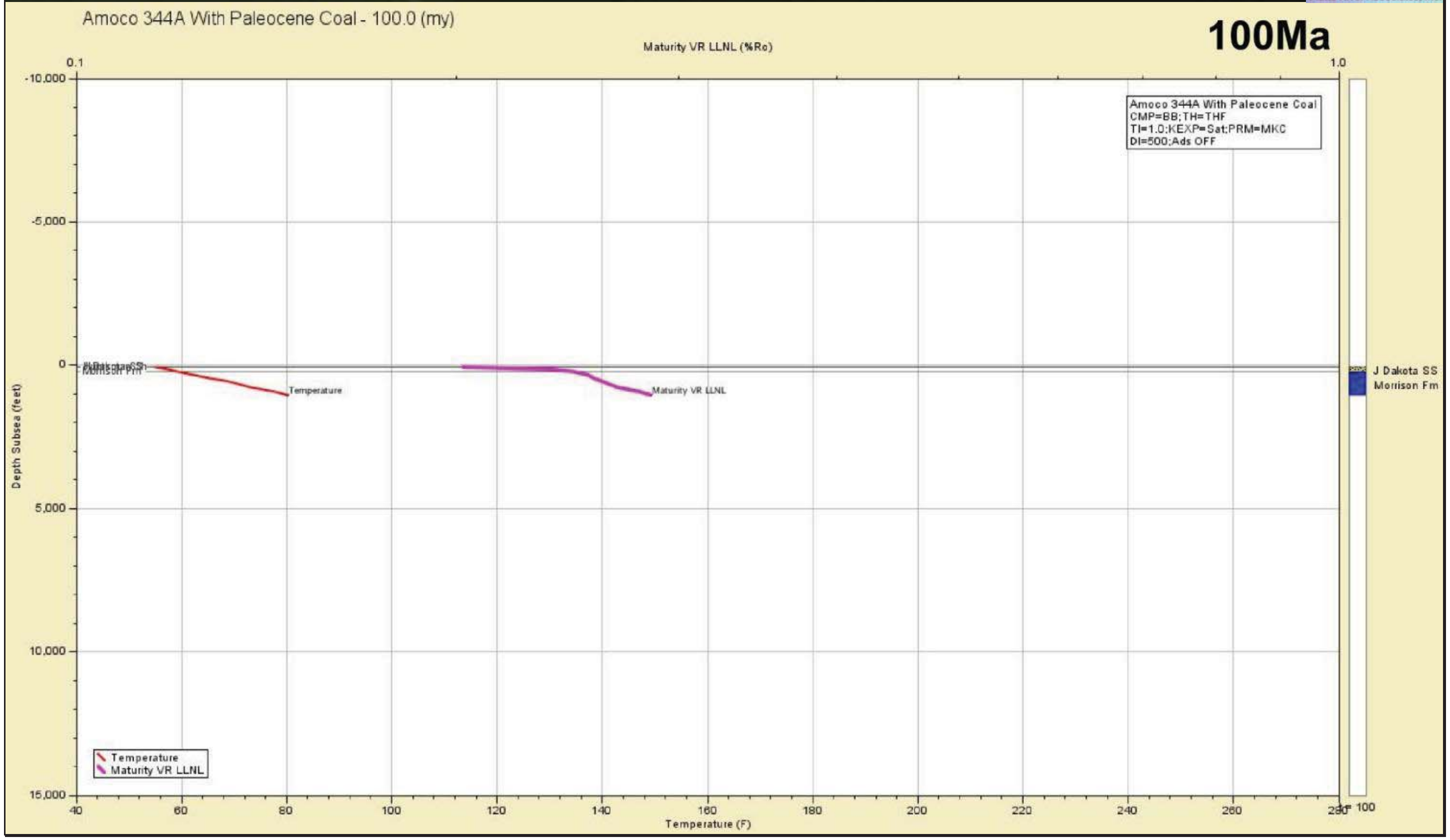
Shown above (scenario 3) with the added deposition of ~3000 feet of Paleocene that DOES include 100 feet of lignite within a 400 foot thick shaly section. Modeled temperature and vitrinite reflectance data fit the observed data much better than scenario 2.



Presenter's notes: Amoco 344A1 (API: 05-123-08890, TRS: 25-10N-64W) calibration plot – 1 model with 4 scenarios.

Shown above (scenario 4) the same as scenario 3 but with the addition of a thin (25 foot) thick Laramie coal section. There is no significant change in the modeled present-day temperature and vitrinite reflectance data verses the observed data comparing scenario 3 and scenario 4.

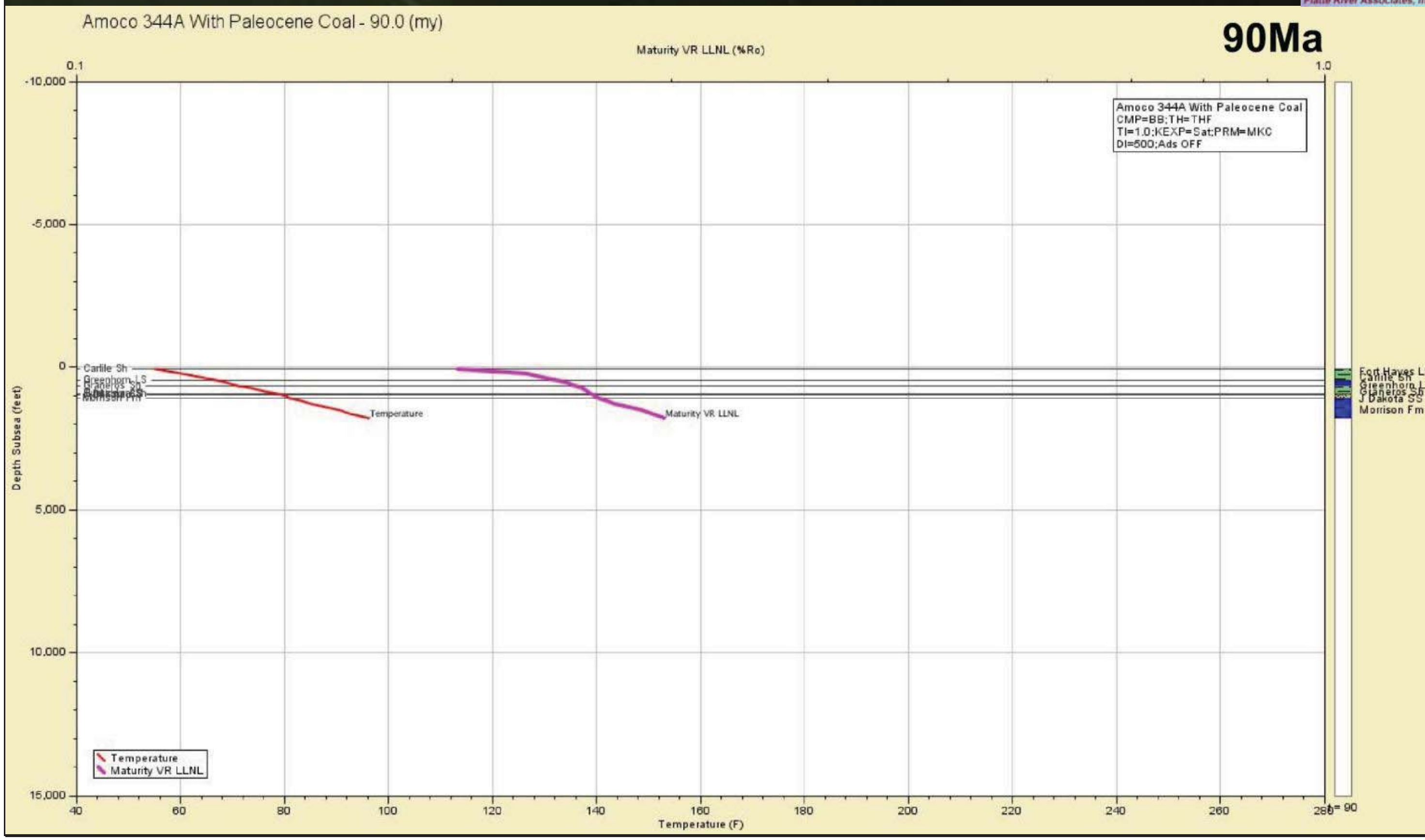
Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')



Presenter's notes: Amoco 344A1 depth plot through time (100ma slice). The next 10 slides represent a time slices showing burial of sediment through time and calculated temperature (red) and vitrinite reflectance (magenta). The time slices are: 100ma, 90ma, 80ma, 70ma 65ma, 60ma, 50ma, 40ma, 30ma, 20ma, 10ma and Present-day.

Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara ‘C’)

PRA
Platte River Associates, Inc.



Presenter’s notes: Amoco 344A1 depth plot through time (90ma slice).

Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara ‘C’)

Presenter’s notes: Amoco 344A1 depth plot through time (80ma slice). Reference dots have been added at the Niobrara “C” bench level for better visualization. The red dot shows the calculated temperature and the magenta dot shows the calculated %Ro at Niobrara “C”.

Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (70ma slice). This time slice shows the dramatic increase in temperature due to the rapid deposition of the Pierre shale units. The Niobrara "C" has not entered the oil window.

Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (65ma slice). The Niobrara "C" would have just entered the top of the oil window and minor amounts of hydrocarbons are being generated.

Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (60ma slice). The Niobrara "C" is within the oil window and hydrocarbons are being generated but not expelled.

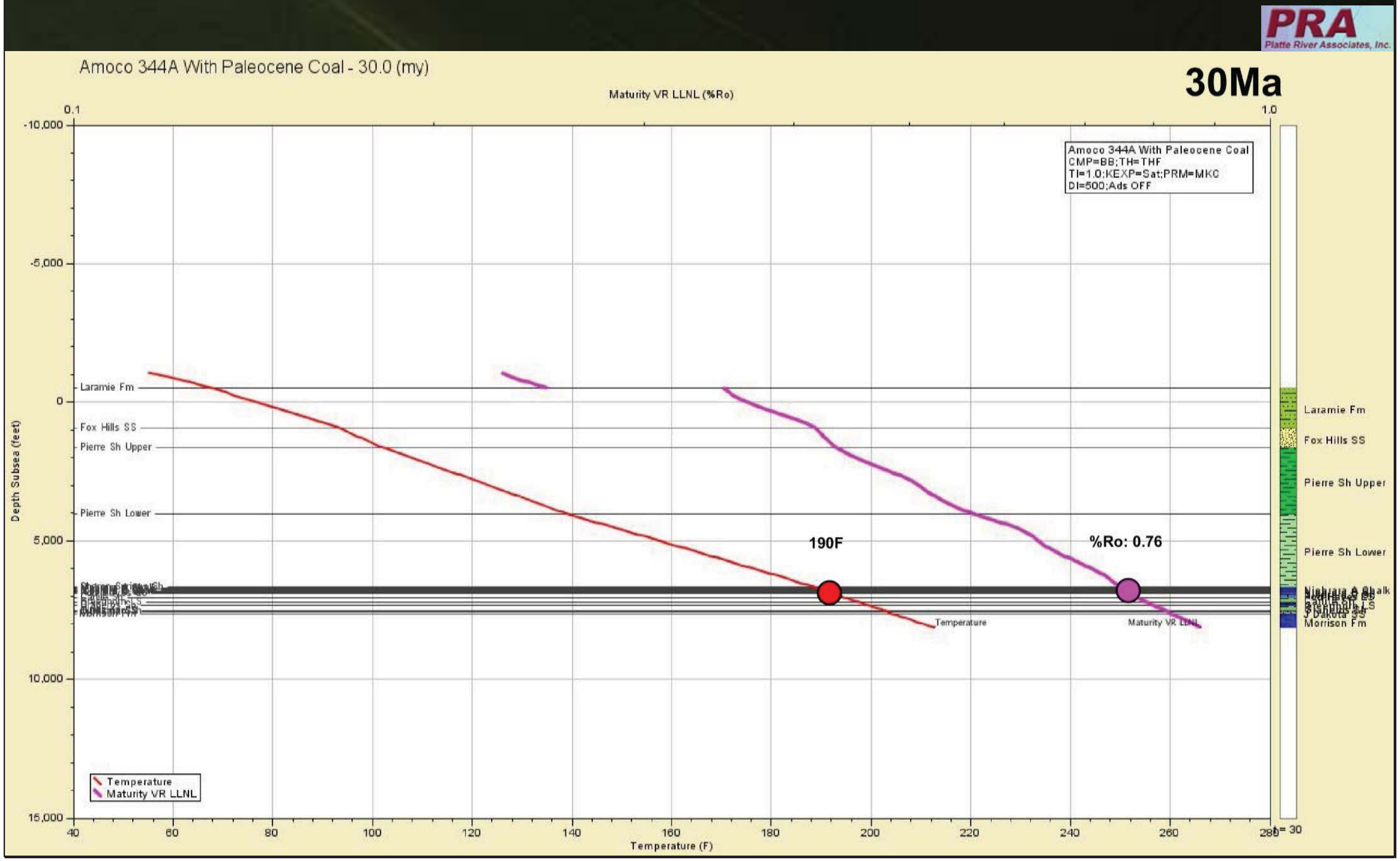
Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (50ma slice). The Niobrara "C" is within the oil window, near maximum burial, hydrocarbons are being generated and expelled.

Amoco 344A1 – Depth Plot – Thru Time Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (40ma slice). Early uplift begins, hydrocarbon generation slows.

Amoco 344A1 – Depth Plot – Thru Time Calculated Temperature & %VRo (at Niobrara ‘C’)



Presenter’s notes: Amoco 344A1 depth plot through time (30ma slice). Uplift and erosion continues.

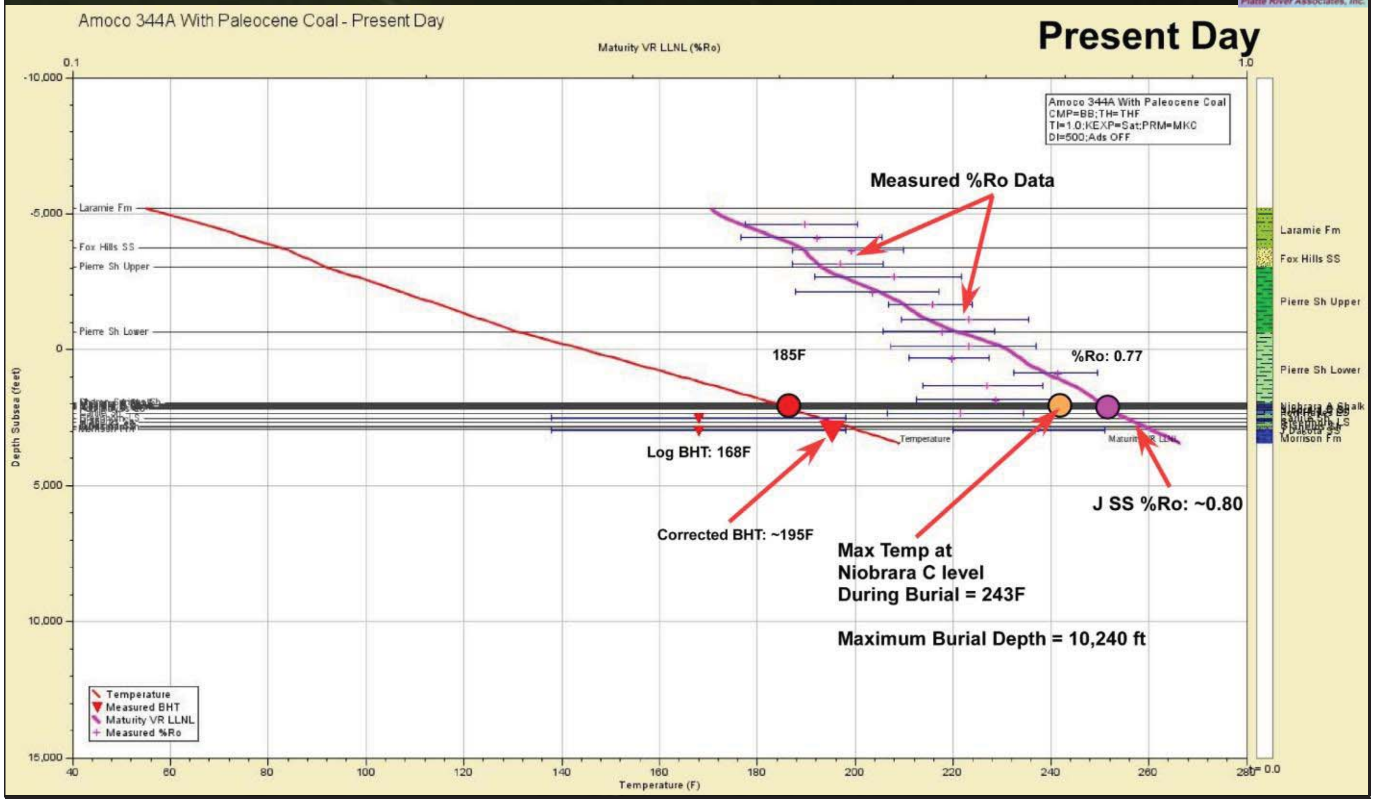
Amoco 344A1 – Depth Plot – Thru Time Calculated Temperature & %VRo (at Niobrara 'C')

Presenter's notes: Amoco 344A1 depth plot through time (20ma slice). Uplift and erosion continues.

Amoco 344A1 – Depth Plot – Thru Time Calculated Temperature & %VRo (at Niobrara ‘C’)

Presenter’s notes: Amoco 344A1 depth plot through time (10ma slice). Uplift and erosion continues.

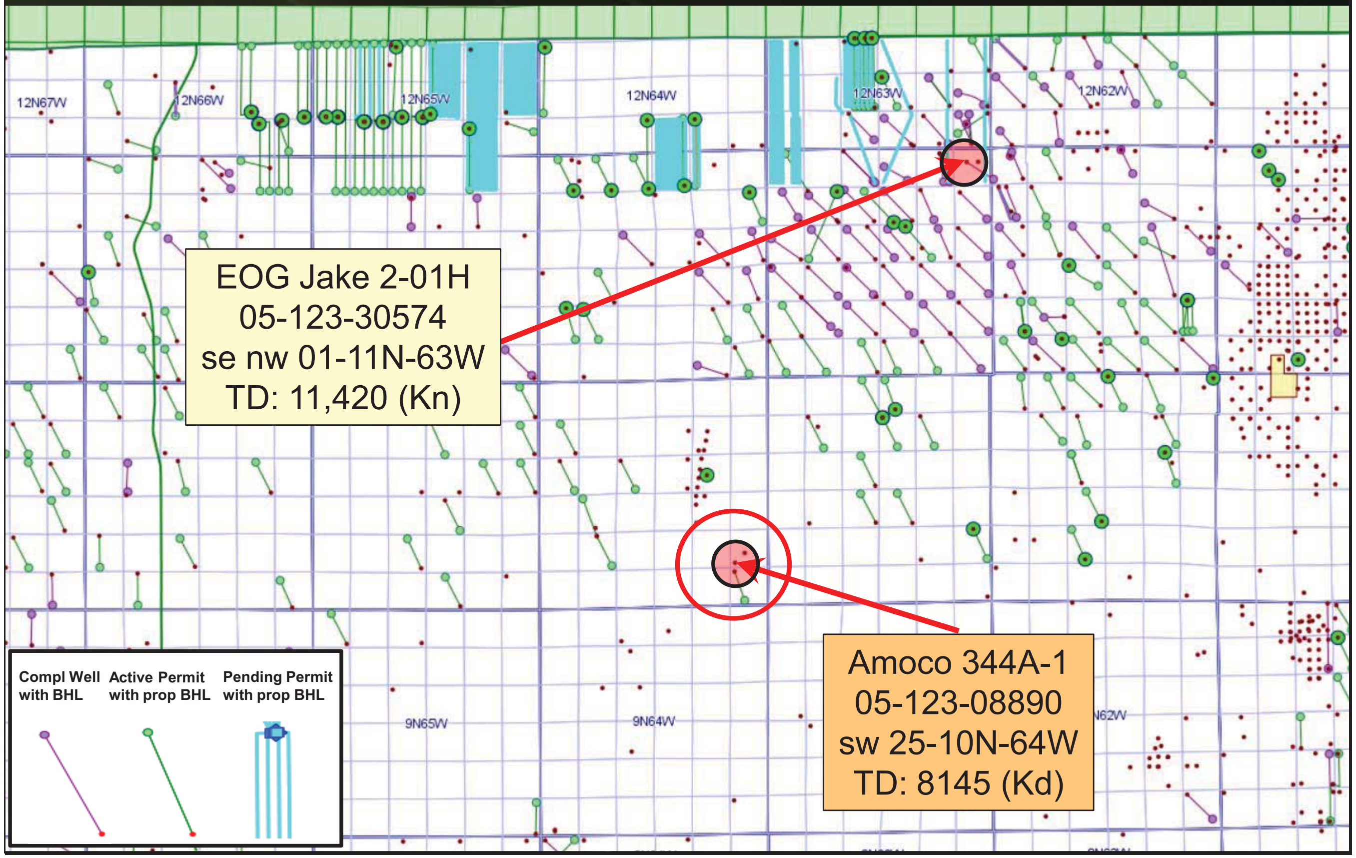
Amoco 344A1 – Depth Plot – Thru Time
Calculated Temperature & %VRo (at Niobrara 'C')



Presenter's notes: Amoco 344A1 depth plot through time (Present-day slice). Uplift and erosion to present-day surface. This slide compares the modeled results with the observed data; bottom hole temperature (measured and corrected) and modeled &Ro with measured vitrinite data. It also shows the modeled maximum burial depth of 10,240 feet with a maximum temperature at Niobrara "C" of 243 deg F. The calculated %Ro at J Sandstone level is approximately 0.80 %Ro which is in good agreement with the measured %Ro data (see %VRo map).

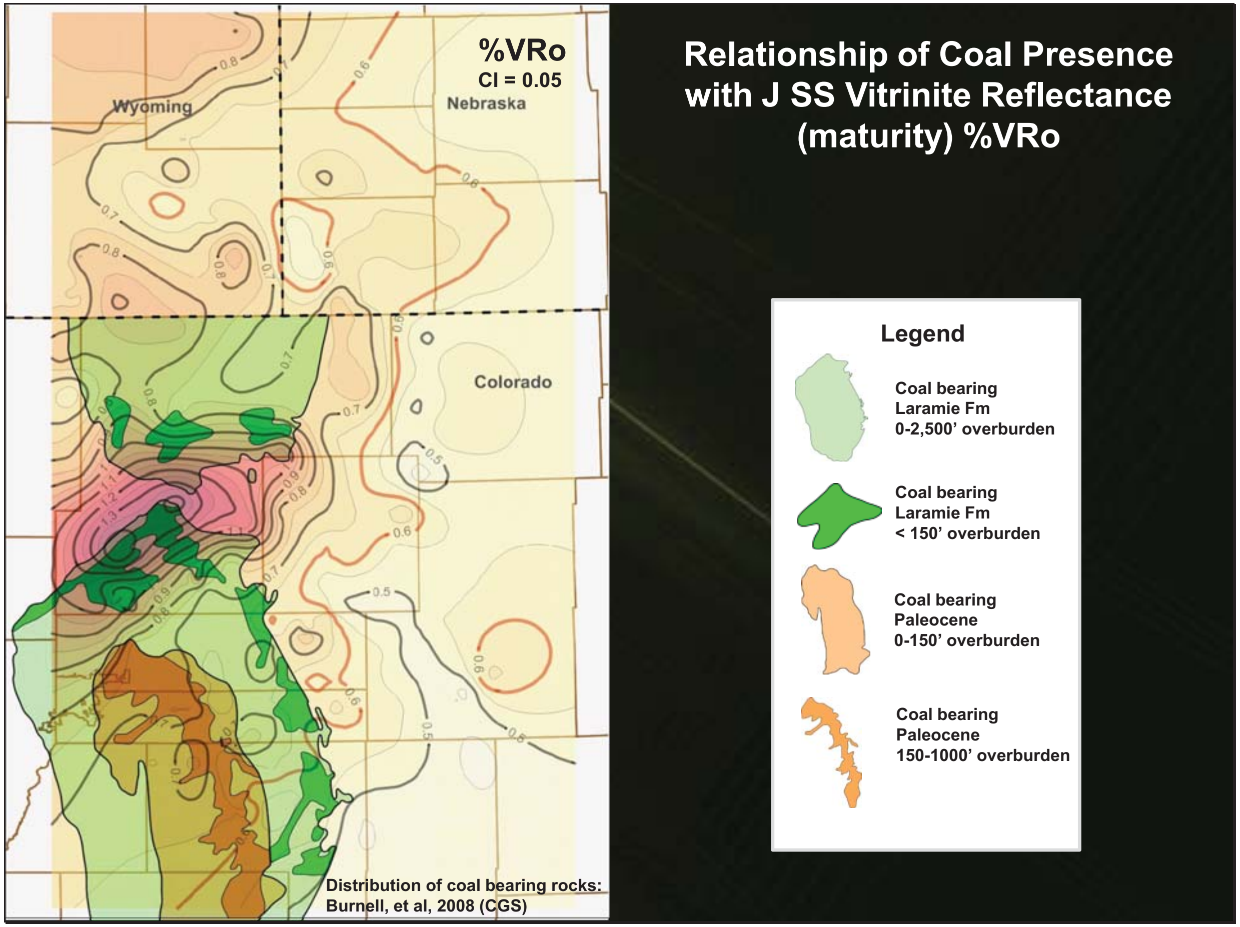
Amoco 344A1 – Location Map and E&P Activity

COGIS, 04/2015



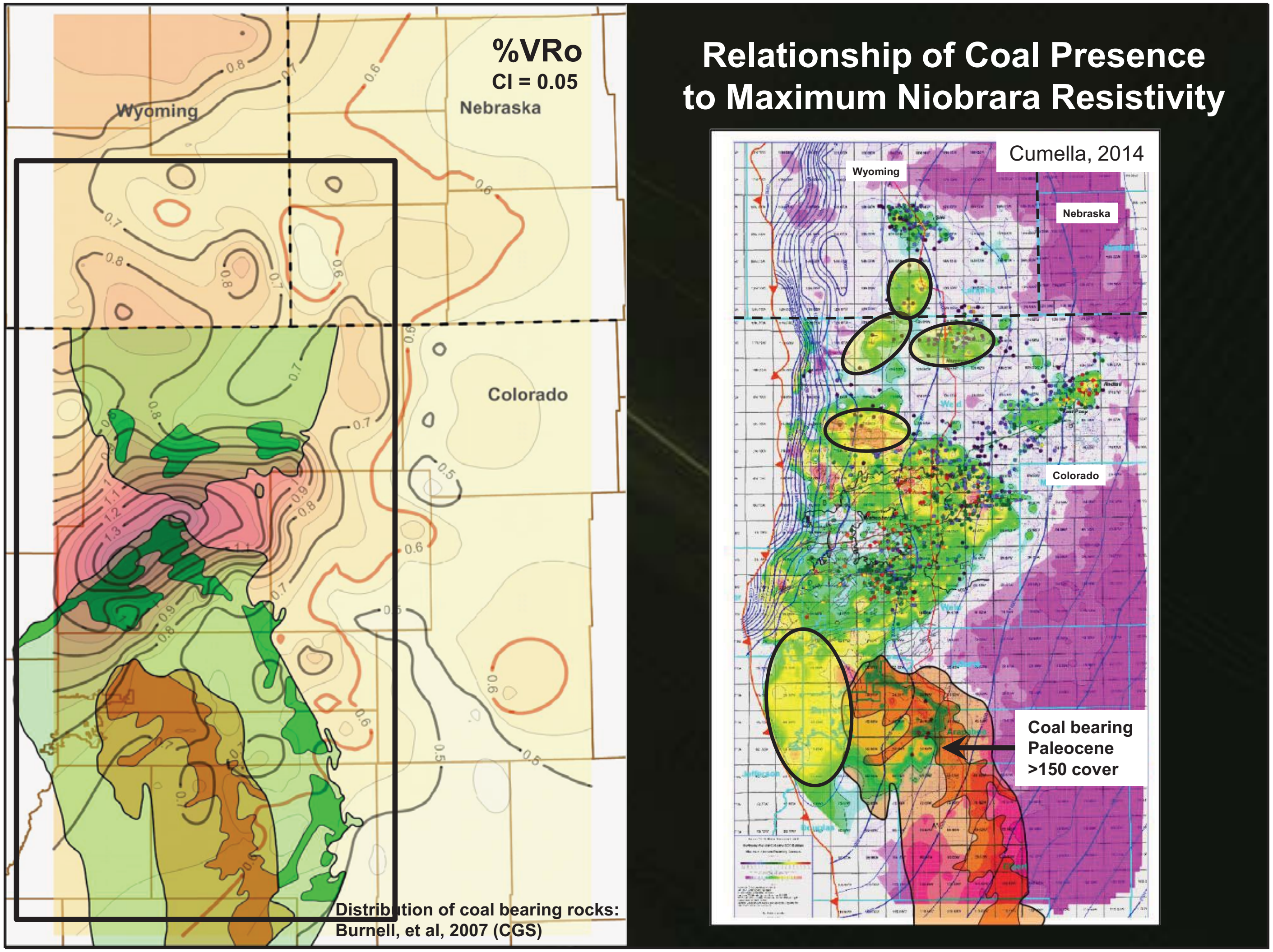
Presenter's notes: Location map (COGIS, 04/2015) showing the position of the Amoco 344A1 modeled well and its position relative to recent Niobrara play activity in the northern DJ basin.

Colorado Oil & Gas Conservation Commission (COGIS, accessed 04/2015) http://dnrwebmapgdev.state.co.us/mg2012app/



Presenter's notes: Relationship of coal presence (Burnell, et al, 2008) to J sandstone maturity (%VRo). This slide shows an overlay of both Paleocene and Laramie coals with J Sandstone maturity expressed as %VRo. There appears to be minimal correlation of coal presence with thermal maturity except with the possibility of a %VRo contour "pull out" as seen in the southwestern part of the map where the presence of the Paleocene coaly section appears to be coincident with an area of higher maturity.

Burnell, J.R., et al., 2008, Colorado mineral and energy industry activities, 2007, Colorado Geological Survey, Information Series 77, p. 26.



Presenter's notes: Relationship of coal presence to J sandstone maturity (%VRo) and Niobrara maximum resistivity (Milne, J.J. and Cumella, 2014). The right hand panel of this slide compares Niobrara maximum resistivity (another maturity proxy) with J Sandstone %VRo. The black box on the left panel is the approximate area shown on the maximum resistivity map.

(Presenter's notes continued on next slide)

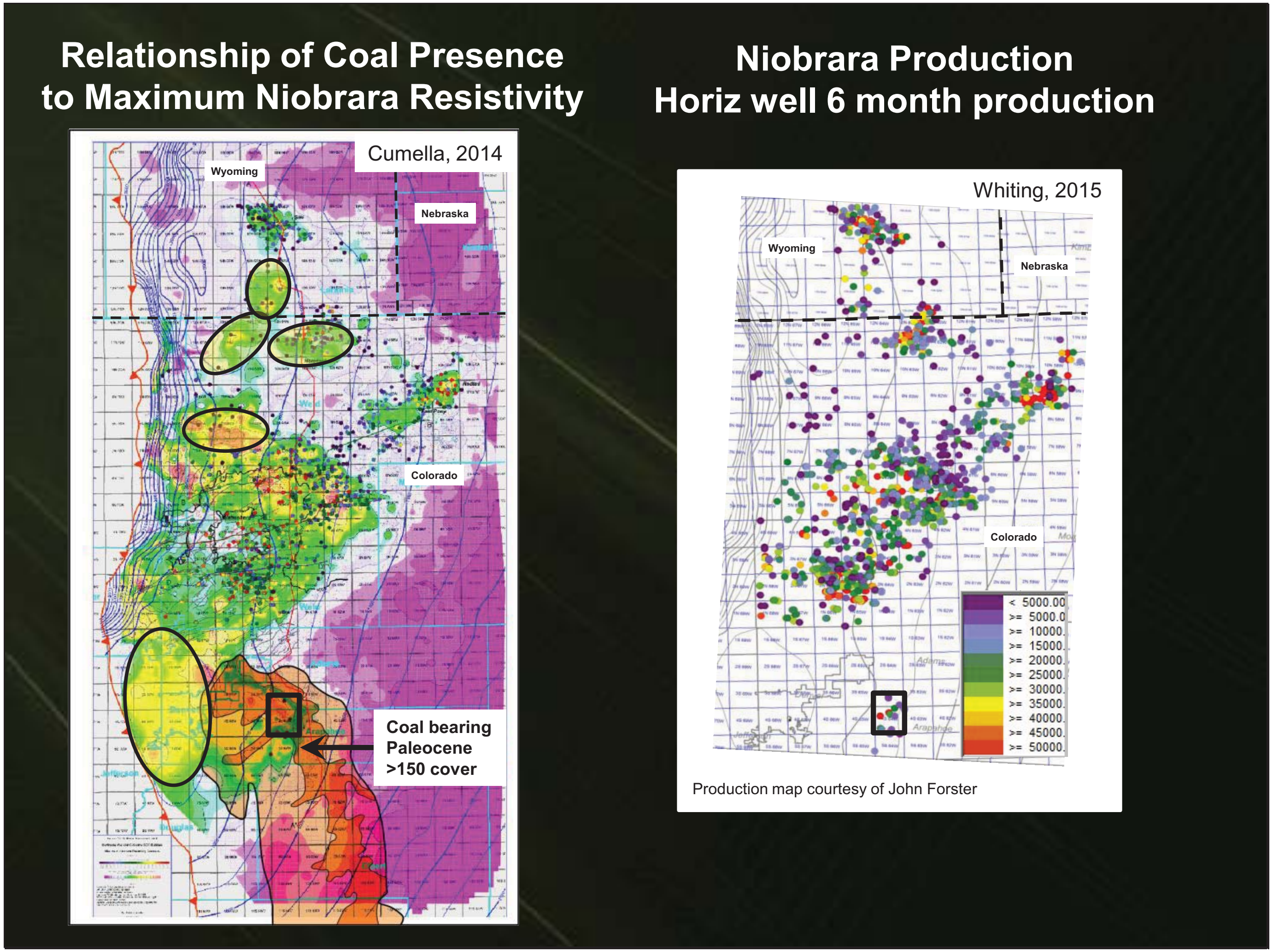
(Presenter's notes continued from previous slide)

This slide adds an additional overlay of the Paleocene coals that are buried the deepest and potentially the thickest (due to erosion of the section to the east). The juxtaposition is in the area of highest Niobrara maximum resistivity in the southern DJ basin.

The area with present-day coal-bearing Paleocene has been juxtaposed on the maximum resistivity map and there is a good correlation of elevated Niobrara resistivity with the presence of coal. This area also in part corresponds to the higher %VRo 0.7 contour pullout.

This slide shows highlighted areas of anomalous Niobrara maximum resistivity that may be explained by the presence of Paleocene coals that were eroded sometime before the White River Group rocks were deposited. The inference is that not all of the areas that appear more mature are due to local higher heat flow but may be the result of preserved of heat within the system due to the insulating effect of coal whether it is present today or not.

Milne, J.J. and Cumella, S.P., 2014, DJ basin horizontal Niobrara play, in J.P. Rogers, J.J. Milne, S.P. Cumella, D. Dubois, P.G. Lillis, eds., Oil and gas fields of Colorado 2014: RMAG pp. 190-235.



Presenter's notes: Comparison of Niobrara maximum resistivity (with Paleocene coal overlay) with Niobrara horizontal well 6 month production map (Forster, 2015 unpublished map). The black box (on both maps) outlines the area of recent Niobrara activity in the southern DJ basin. The area of successful activity is in an area of elevated Niobrara resistivity and corresponds to an area of thick Paleocene cover containing insulating coal.

Conclusions

- Coals have very low thermal conductivity (by 10x)
- 1st Derivative of temperature can be used to identify low thermal conductivity rocks such as coal and source rocks
- The presence and persistence of coals in the sedimentary stack can significantly affect thermal maturity, especially at critical maturity thresholds
- Not all maturity anomalies are the result of local basement heat sources
- There is a good correlation between present-day Paleocene coals and Niobrara resistivity

- Caveat 1: Presence or absence of underlying salts?
- Caveat 2: "All models are wrong, but some are useful"
  George Box (a famous Bayesian), 1951

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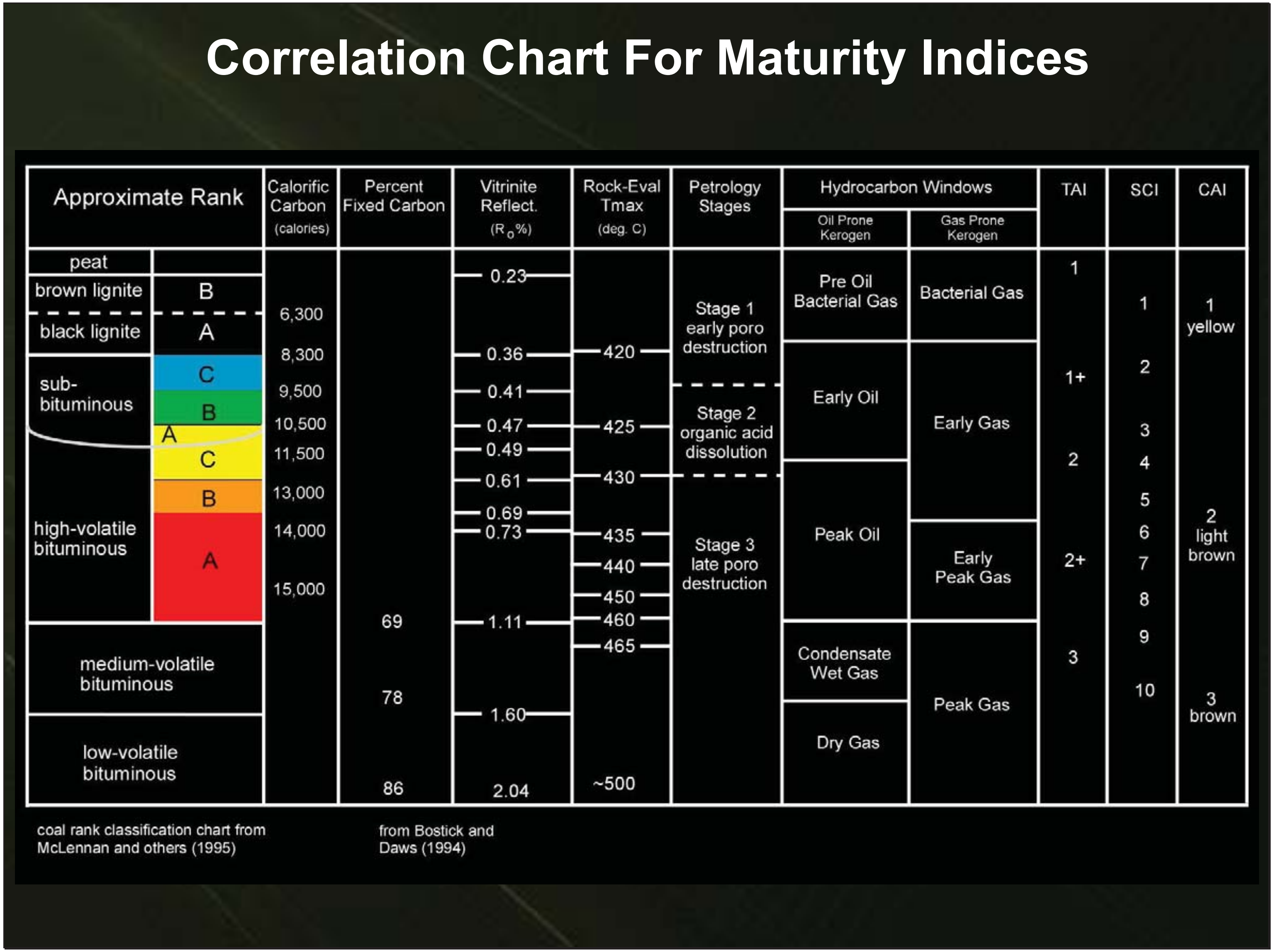
- Platte River Associates, Inc.
- USGS Core Research Center
- Special thanks to John Forster and Jay Scheevel

Thank You

Extra Slides



Presenter's notes: Composite correlation chart for maturity indicies.