Hydrogen Index as a Maturity Proxy - Some Pitfalls and How to Overcome Them*

Mark H. Tobey[1] and Catherine E. Campbell[2]

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[1]Encana Oil and Gas (USA) Inc., Denver, CO
[2]Robert L. Bayless, Producer, Denver, CO (ccampbell@bayless-cos.com)

Abstract

Rock-Eval hydrogen index (HI) is often used to compare relative maturities of a source horizon across a basin. Usually, there are several measurements from the source horizon at a single well, and the mean hydrogen index is calculated, or the S2 is plotted against TOC. The slope of the best fit line through that data is used as the representative HI for that well (sometimes referred to as the 'slope HI' methodology). There is a potential flaw in both these methodologies; however, that renders the calculated HI as misleading if the source horizon being examined is not relatively uniform in source quality, vertically in the stratigraphic column. From a geologic perspective, it would be unusual for the source rock quality not to vary vertically in the stratigraphic column. Organic matter input, preservation, dilution, and sediment accumulation rate typically vary in many depositional environments over the millions of years required to create a thick source rock package. Nevertheless, there are source rocks which do display remarkable source-quality uniformity from top to bottom of the stratigraphic package. We have examined source rocks from several basins where the source quality is relatively uniform over the stratigraphic column, and source rocks where the source quality varies greatly over the stratigraphic column. Methodologies to assess hydrogen index at specific wells for these two scenarios differ. Most geoscientists may not be familiar with why a single technique is not suitable for both these scenarios, or how to correctly use hydrogen index as a relative maturation proxy in the case where source rock quality is not uniform. We will demonstrate how to determine if your source rock quality is uniform or varied relative to HI over the stratigraphic column, and how to assign a hydrogen index to the different source facies when that source rock quality is not uniform. Further we will illustrate how to estimate the original hydrogen index of the different source facies and assign each a transformation ratio. The transformation ratio is a better proxy for relative maturity, since different source facies may have different present-day hydrogen indices, but their present-day transformation ratio should be quite similar.

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Hydrogen Index as a Maturity Proxy

Some pitfalls and how to overcome them

Mark Tobey: Encana Oil and Gas
Cat Campbell: Robert L. Bayless, Producer

Outline

- The issues with Hydrogen Index
- Background
- Best practices
- Case studies
- Recommendation

Presenter's notes: For unconventional plays, understanding source rock maturity is essential to constraining the area of interest, depending on what petroleum fluid is being targeted (oil, condensate, dry gas).

HI Pitfall

- Source rock mineralogy is typically <u>not</u> uniform through a sedimentary column …
- Amount (**TOC**) and quality (**Hydrogen Index**) of organic matter is typically <u>not</u> consistent.
- A single hydrogen index for a source rock sedimentary column at a well is usually <u>not</u> a valid relative maturation index.

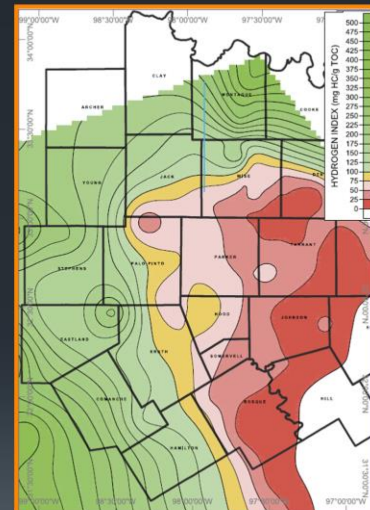
Presenter's notes: The Hydrogen Index pitfall is based on the idea that source rocks are not uniform through a sedimentary column. Hydrogen Index varies, sometimes significantly, based on the source rock quality as well as maturity. Hydrogen Index is often used as a maturity proxy, but with significant variation potentially coming from changes in rock quality, it may not be the best tool. With a varied stratigraphic column, such as seen the Green River formation show in the photo, applying a single Hydrogen Index to a well is not truly representative of the maturity at that location.

Source rock mineralogy is typically <u>not</u> uniform through a sedimentary column … nor is source rock TOC and hydrogen index typically uniform through a sedimentary column …

This photo is from the Green River formation in the Mahogany Bench interval and includes data from a core of that zone. It shows the extreme variation in TOC and HI over a small interval.

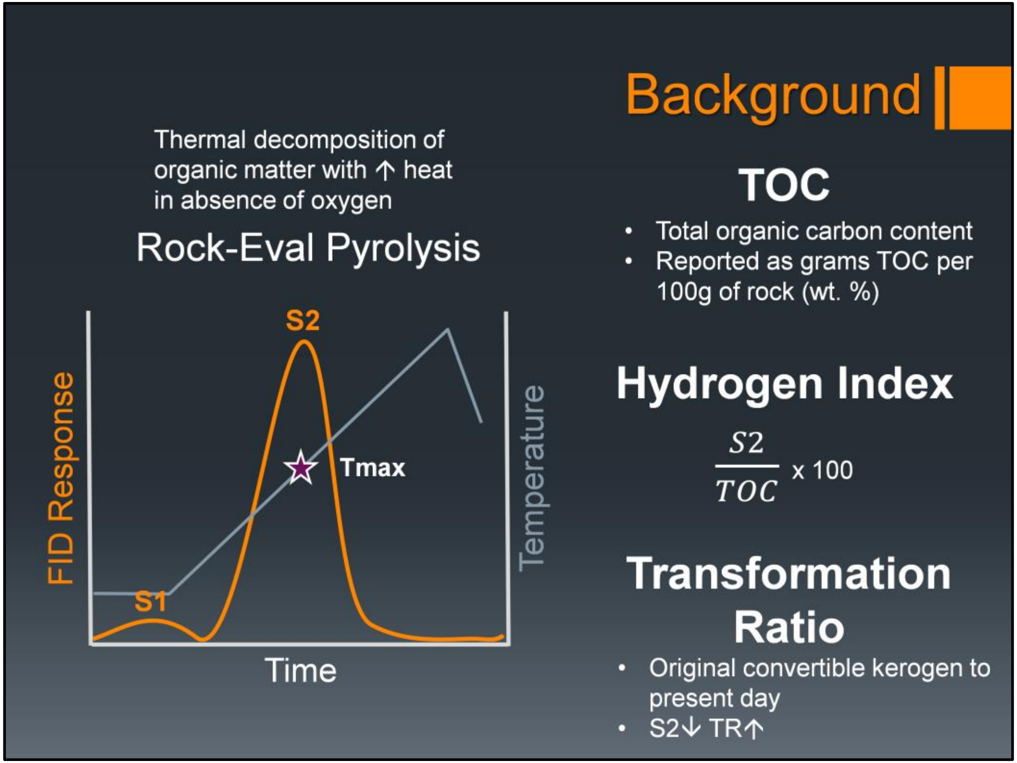
Objective

- Source rock maturity map-exploration tool
- Hydrogen Index-maturity proxy
  - Map relative maturity
- Caution
  - Uniform original HI rare in nature
    - Vertically
    - Laterally



Barnett Shale- Jarvie et al. (2007)

Presenter's notes: Using HI as a maturity tool without understanding how original HI varies through a vertical sediment column and/or across a basin can be misleading.
For unconventional plays, understanding source rock maturity is essential to constraining the area of interest, depending on what petroleum fluid is being targeted (oil, condensate, dry gas).



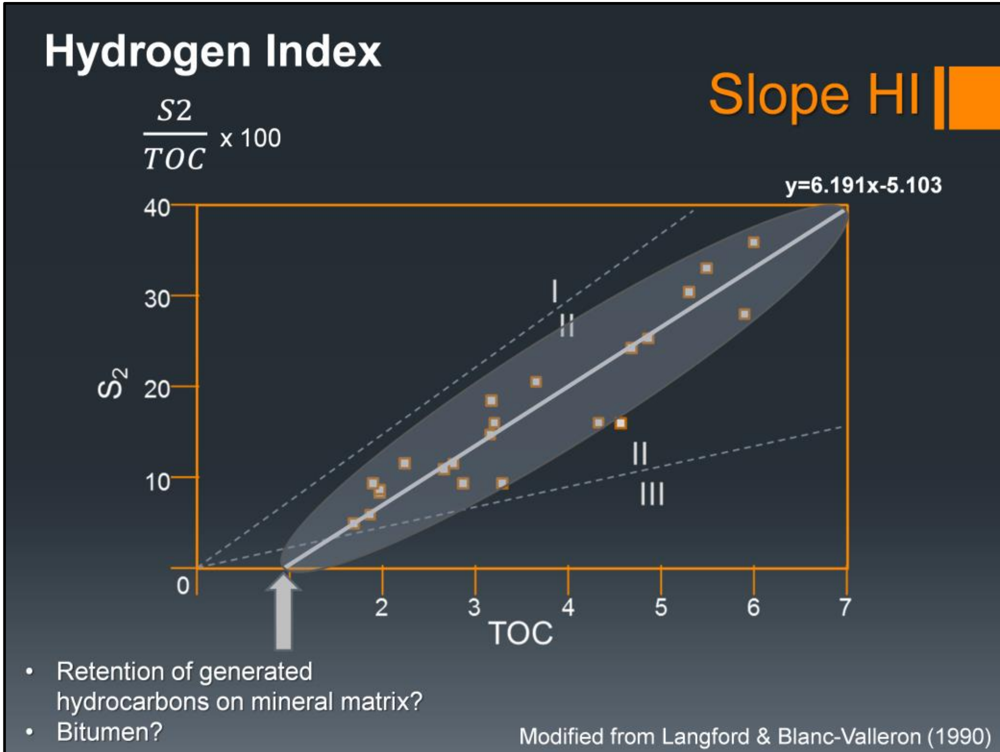
Presenter's notes:

- Pyrolysis is the thermal decomposition (cracking) of organic matter with increasing heat in the absence of oxygen.
- Rock-Eval pyrolysis is an analytical tool where the oil within the rock is thermally distilled (S1) and the convertible kerogen within the rock is cracked or pyrolyzed to oil and gas (S2) in order to quantify the remaining generative potential (quality) of the source rock.
- The greater the generative potential (S2) relative to the TOC, the greater the Hydrogen Index. As a SR matures, its Hydrogen Index decreases, so Hydrogen Index can be used as relative maturation parameter.
- Tmax, the temperature at which the S2 peak crests, is also a relative maturation indicator. The higher the Tmax temperature, the greater the thermal maturity of the SR.
- Transformation ratio is a ratio based on present day convertible kerogen that remains in the rock relative to the original convertible kerogen in the rock. As S2 decreases, or more organic matter has been converted to oil and gas, the transformation ratio increases.

Best Practice

- Calculate hydrogen index (HI) of **solvent extracted** rock. Why?
  - You want the hydrogen index to be measure of how much of the original convertible kerogen remains, which is a maturation proxy … <u>not</u> a measure of that <u>PLUS</u> any high boiling oil in the rock.
- Tmax is a maturation proxy too. Why not map that instead of HI?
  - Tmax can be mapped. Screening the data to the most kinetically well-behaved data assists in removing Tmax outliers. However, the TOC and S2 measurements are more robust.

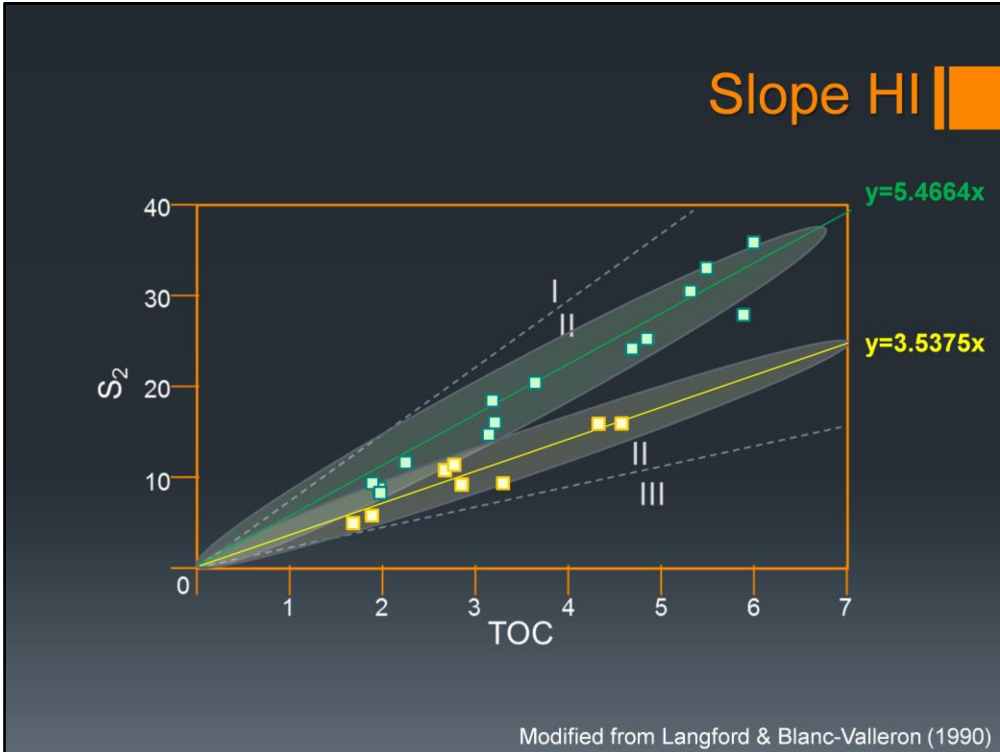
Presenter’s notes: You want the hydrogen index to be measure of how much of the convertible kerogen has converted, which is a maturation proxy … not a measure of that PLUS any high boiling oil in the rock.
S2 and TOC can be measured accurately, whereas the measurement of Tmax is made by an algorithm within the instrument software.



Presenter's notes: Because Hydrogen Index is a ratio of S2 and TOC, the slope of a cross-plot of S2 vs. TOC is often used as a means of estimating source rock HI for a sedimentary column at a single well (slope HI method). The slope of the line through all the data, even if it does not intersect the origin, is used as the mean HI of that sedimentary column.

In this example the slope is 6.191, which when multiplied by 100 (HI=S2/TOC x 100) give an HI of 619.

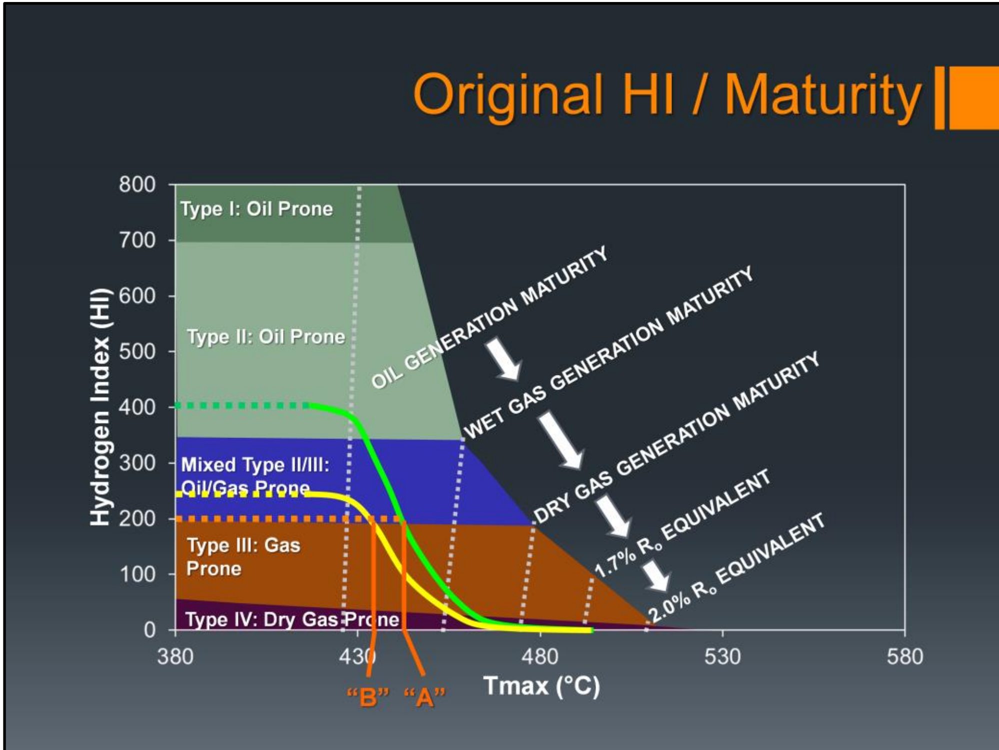
- However, often, the best fit line will not intersect the origin, and there have been explanations proposed that this is likely due to the retention of generated hydrocarbons on rock the mineral matrix, coking, or the presence of pyrobitumen.
- An alternative explanation which makes more sense from both a geologic and pyrolysis standpoint is that the best fit line should go through the origin and the data may require more than one line to characterize the HI of the kerogen from multiple samples.
- As TOC approaches 0, S2 should approach 0 because there's no TOC.
- In this plot, the authors suggest a single line which does not intersect the origin, which would imply that these rocks with TOCs < 1% would not generate any observable HCs, even though the derived HI of 619 suggests a high quality, lower maturity source rock. That is unlikely.



Presenter's notes: We would argue that a more plausible explanation is that the source rock quality is not uniform through the sedimentary column, and the data could be represented by at least 2 lines, with different slopes (different hydrogen indices) which do intersect the origin, as would be expected.

2 distinct qualities of source rock exist in the data, one with an HI of 547 (green) and one with an HI of 354 (yellow).

Our explanation is also more plausible when one is working with solvent extracted rock, from which all the bitumen has been removed from the rock matrix.

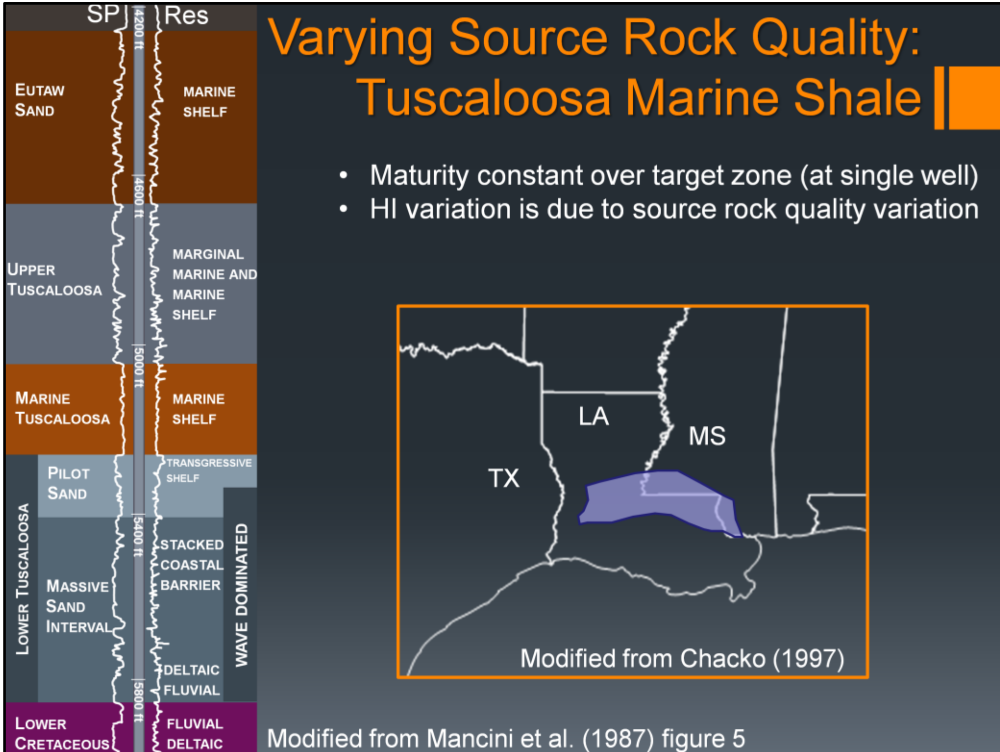


Presenter's notes: The ideal path by which a source rock's hydrogen index might change with increased maturation is illustrated here:

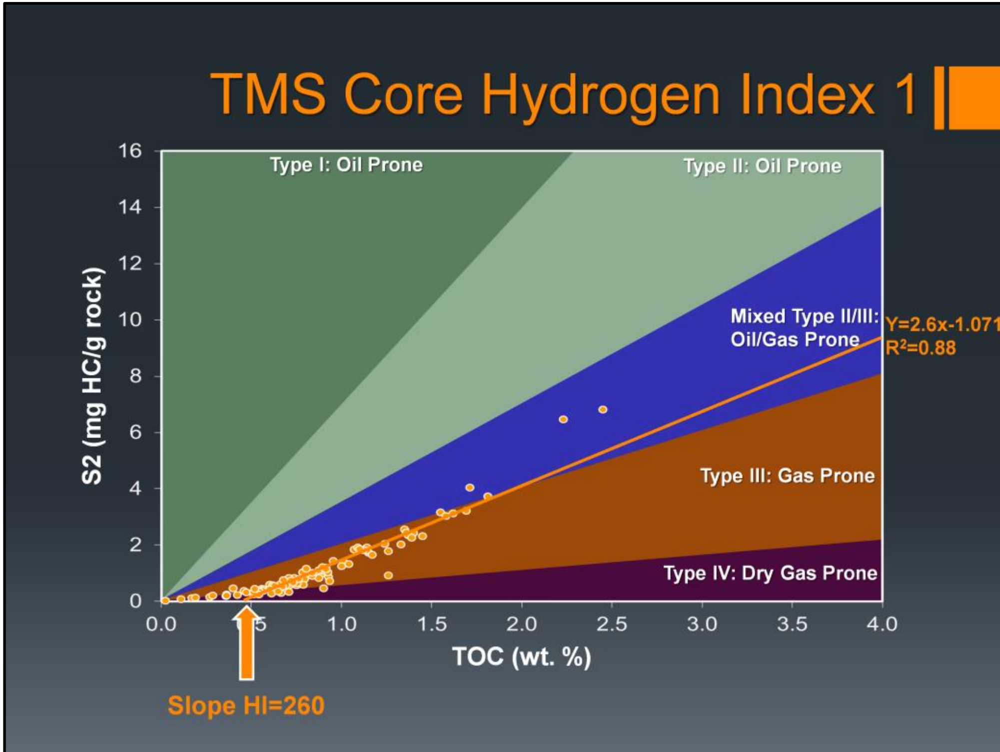
- The green line represents a kerogen with an original HI of ~400, and you can see how its HI decreases with increasing Tmax (maturity)
- The yellow line represents a kerogen with an original HI of ~250, and you can also see how its HI decreases with increasing maturity

If you believed that the source rock was uniform over your well, as represented by the green line, and the present day HI was 200, you would calculate a relative maturity of "A."

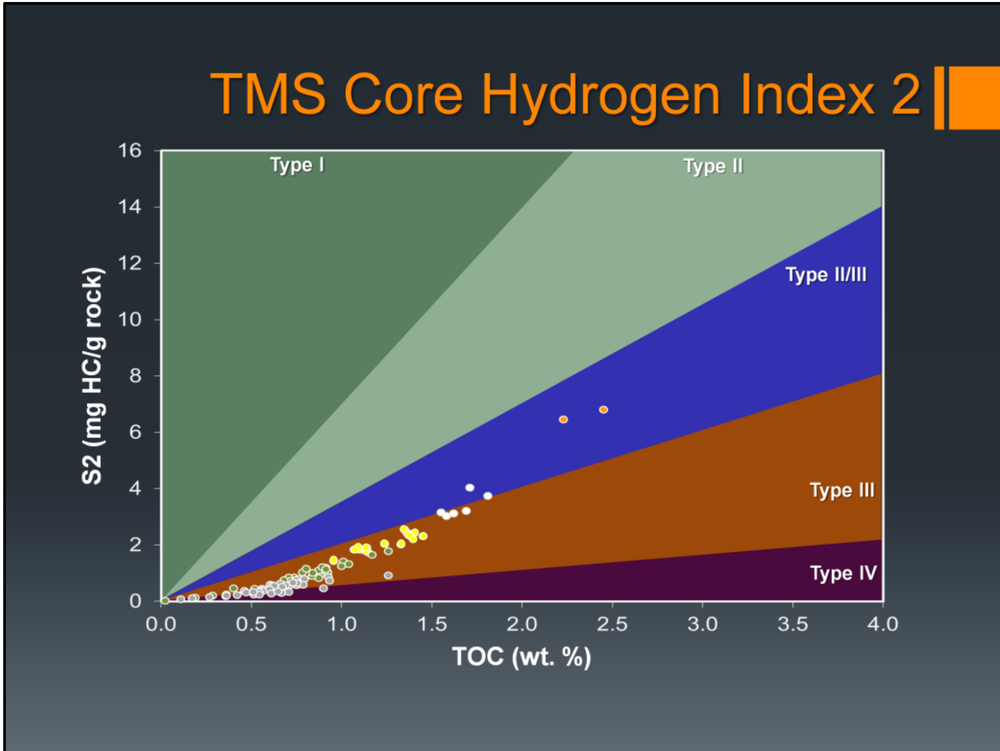
However, if the source rock was not uniform, and the present day HI of 200 was due to a high weighting of the source rock represented by the yellow line, its actual relative maturity would be closer to maturity "B."



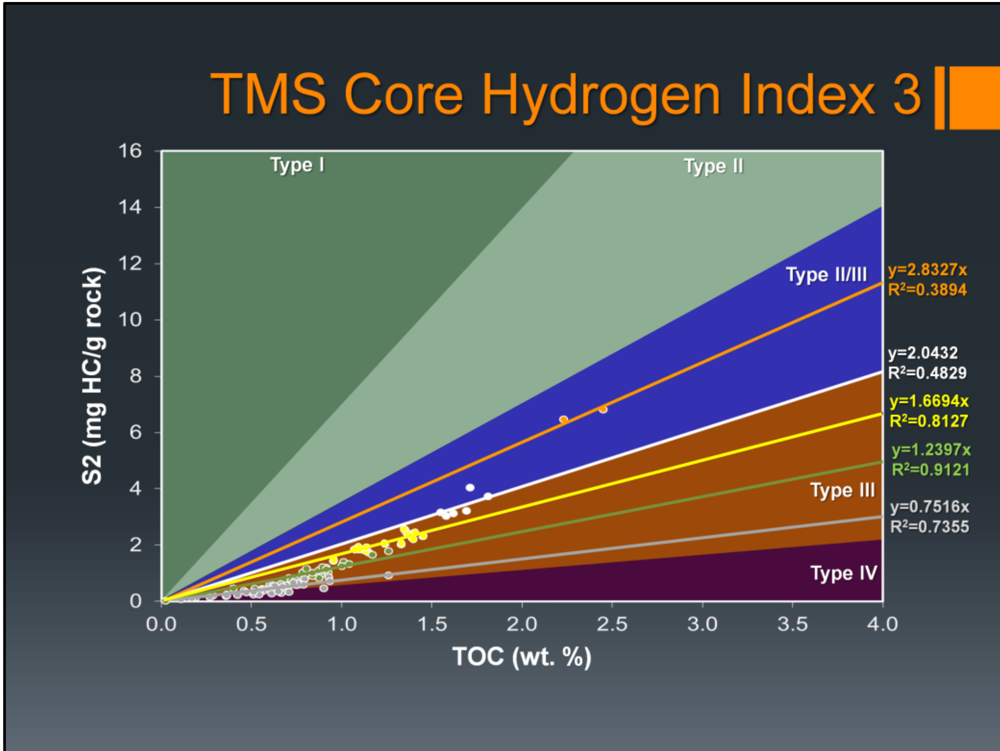
Presenter's notes: Here is a case study in the Tuscaloosa Marine Shale. A core from a single well was examined. Over the depth interval sampled, the TMS thermal maturity is essentially constant, but we will see variation in the SR HI.



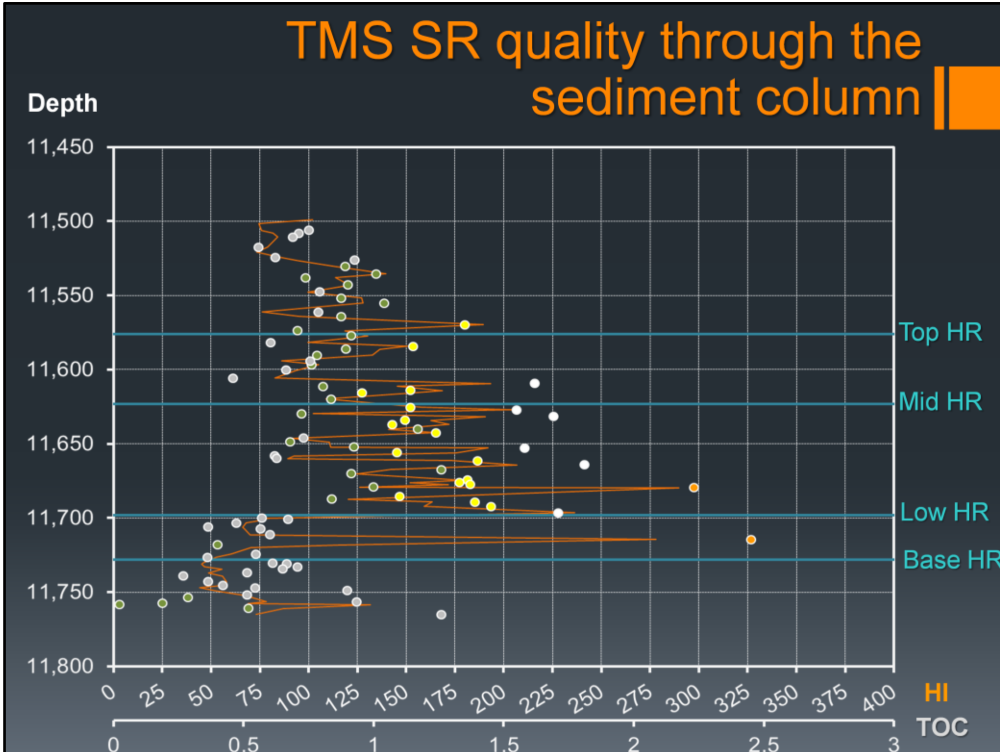
Presenter's notes: Applying the slope-HI methodology the TMS source rock data over the entire cored interval results in a line which does not intersect the origin, and yields a slope-HI of ~260.



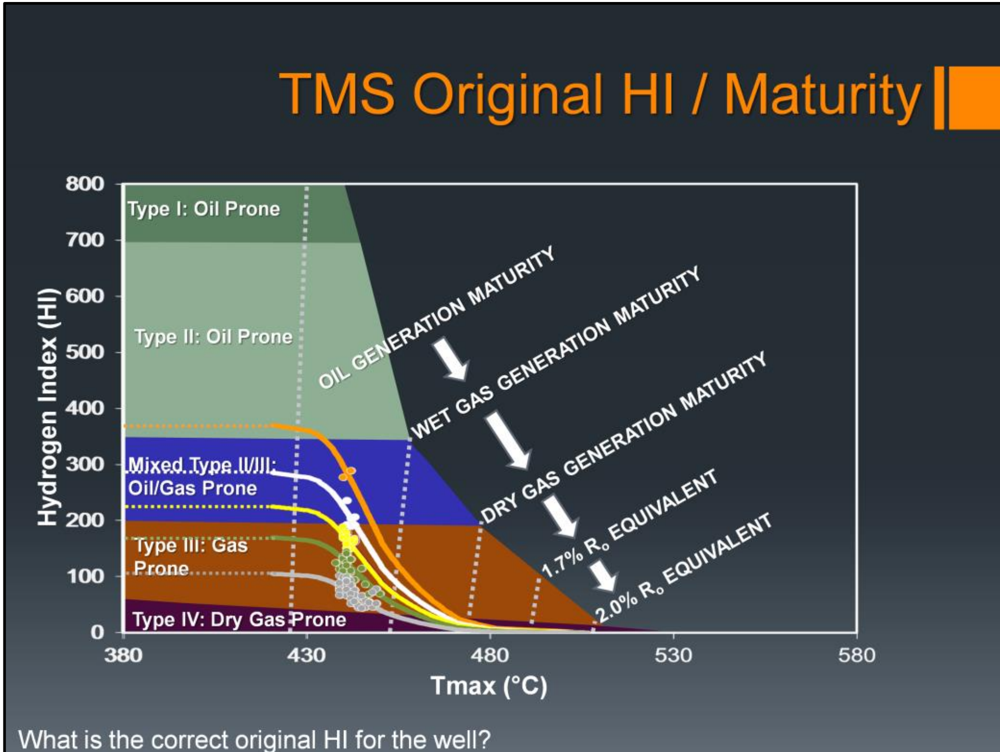
Presenter's notes: However, the source rock quality over the cored interval varies, and at least 5 lines which intersect the origin, with HI slopes ranging from 283 to 75 describe the data more correctly, as seen in the next slide.



Presenter's notes: At least 5 lines intersecting the origin, with HI slopes ranging from 283 to 75 describe the data more correctly.

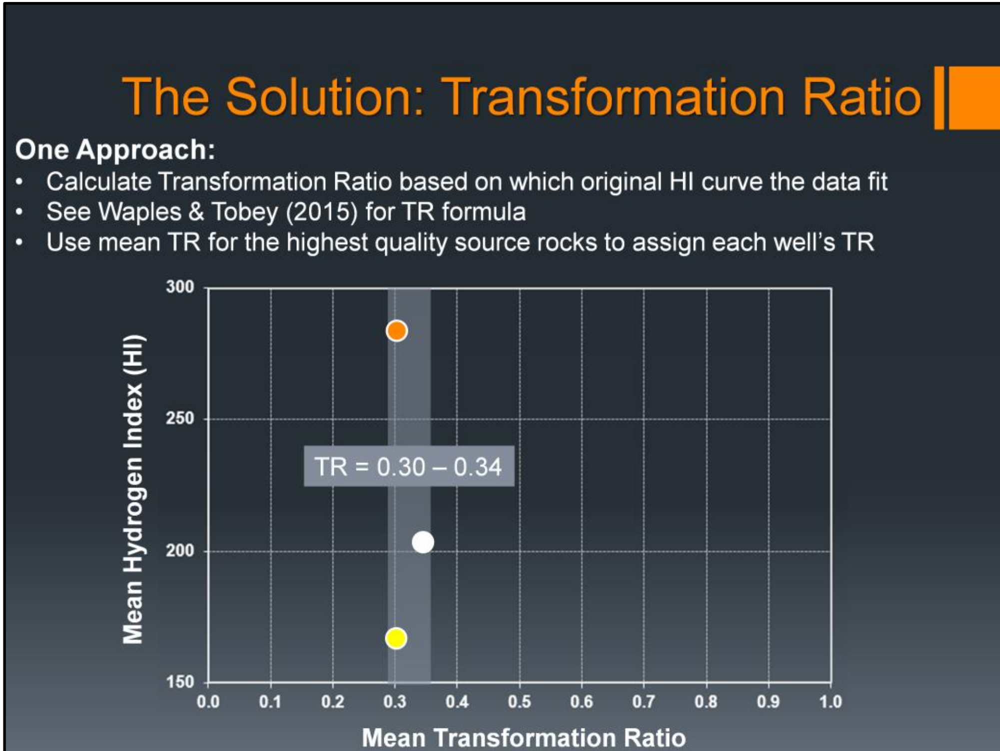


Presenter's notes: This plot illustrates that the hydrogen index and TOC of the TMS source rock is not uniform through the sediment column.
What HI do you use for this well?
If you only had three data points you would likely draw the wrong conclusion.



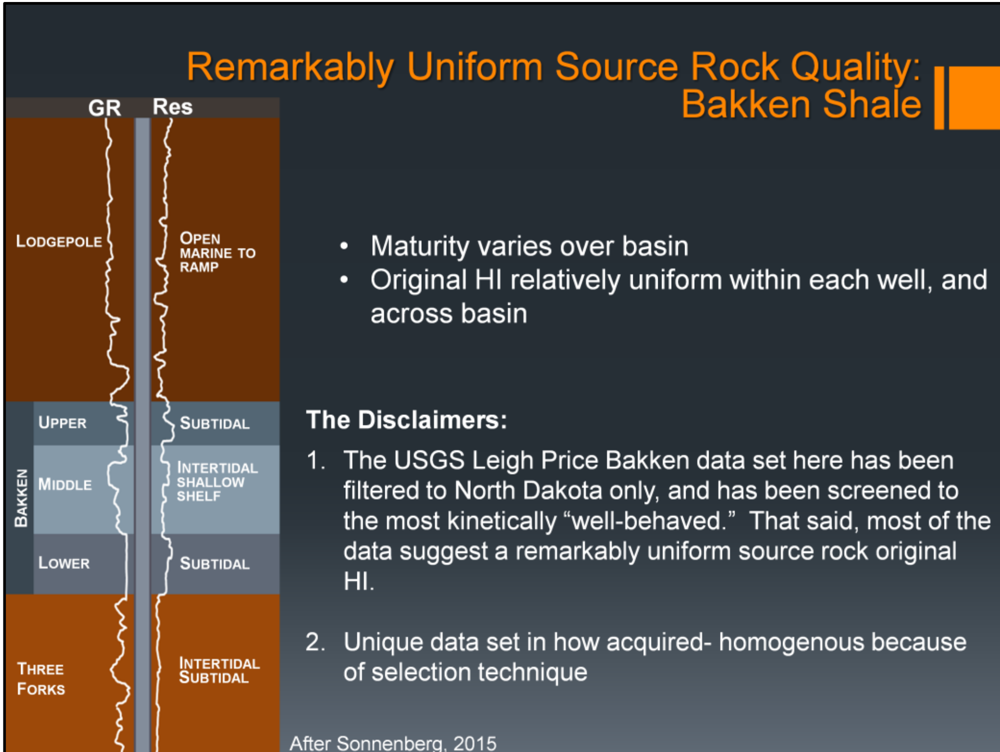
Presenter's notes: Present day Hydrogen Index varies significantly, while maturity (Tmax) does not. This plot illustrates that the original HI of the TMS at this single well also varies significantly. So, we cannot use a single well HI to compare relative maturity for TMS basin unless we know which original HI the data represents.

So what is the solution if we don't want to depend solely on Tmax as a maturity proxy but want to use the HI measurement, which is more robust (since TOC and S2 can be measured accurately)?



Presenter's notes: Transformation ratio should be relatively constant at the same maturity, even while the present day hydrogen index may vary, if the original hydrogen index of each source rock sample can be determined.

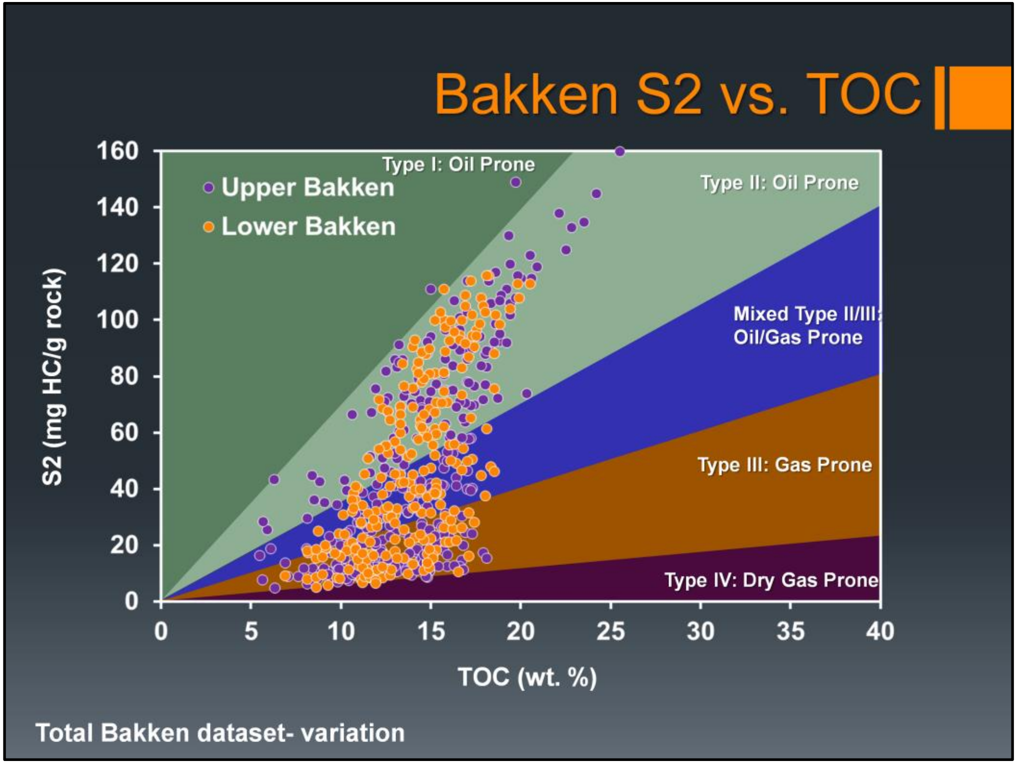
1. Calculate the transformation ratio for each sample based upon which original HI curve the data plot with in previous plot
2. Calculate the mean transformation ratio for the highest quality source rocks
3. Use the mean transformation ratio of the means of the highest quality source rocks as a relative maturation proxy and map TR across the basin
4. In this example, approximately 1/3 of the convertible kerogen has been converted.



Presenter’s notes: The main point of this talk is to demonstrate that source rock quality varies through the sedimentary column, so assigning a single HI to a sedimentary column is problematic.

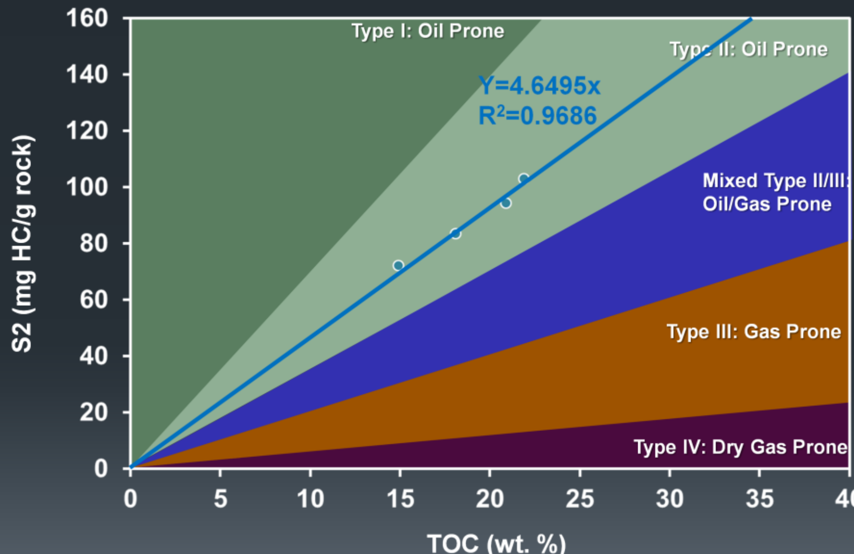
As often occurs in geology, exceptions to the rule can be found, where the source rock sedimentary column has a remarkably uniform HI. That exception is illustrated by the Leigh Price Bakken data set. That sample set was meticulously high-graded to the darkest rock chips within each cuttings interval, so that may account for the apparent uniformity.

It is possible that if those cuttings samples were not high-graded and analyzed “as is” that more variation would have been observed for the Leigh Price wells.



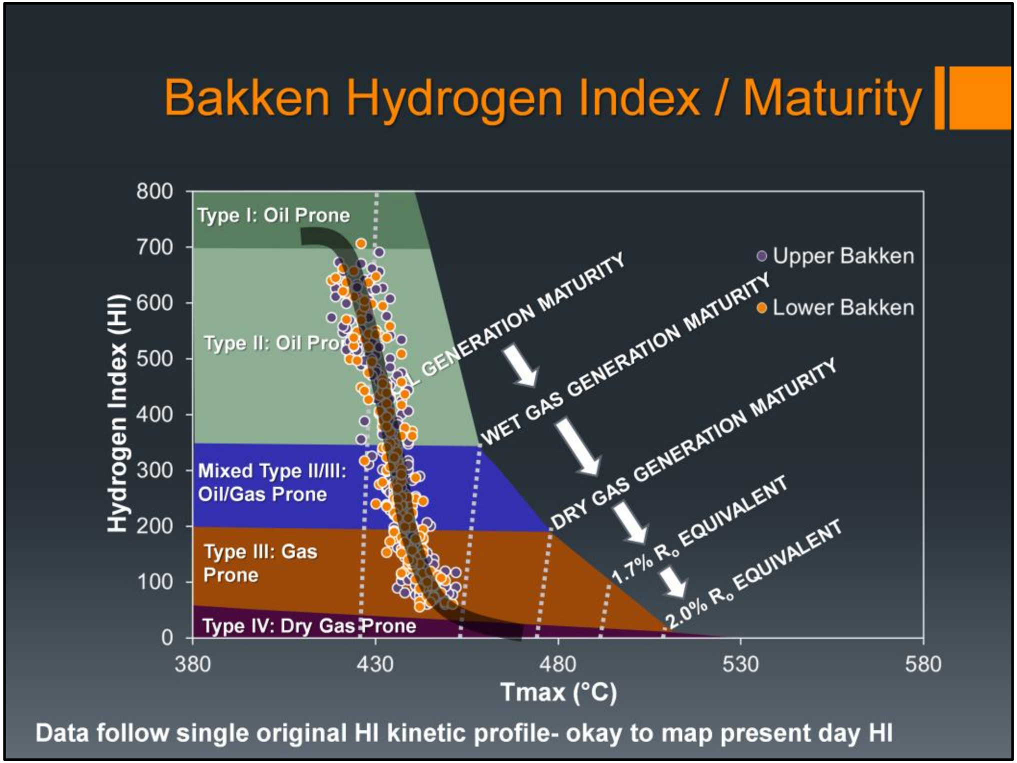
Presenter's notes: The total Bakken data set from many wells across the basin vary greatly in HI and TOC. If looked at on a well-by-well basis, the data from a single well would suggest a single slope-HI line that intersects the origin. Thus at each well the source rock has a uniform HI is apparently controlled by maturity. That is what we see in the next slide.

Bakken S2 vs. TOC



Single well- single slope HI indicating uniform HI controlled by maturity

Presenter's notes: Single well example from the Bakken on an S2 TOC plot. These data suggest a single slope-HI line that intersects the origin. Thus at each well the source rock has a uniform HI is apparently controlled by maturity rather than source rock variation.



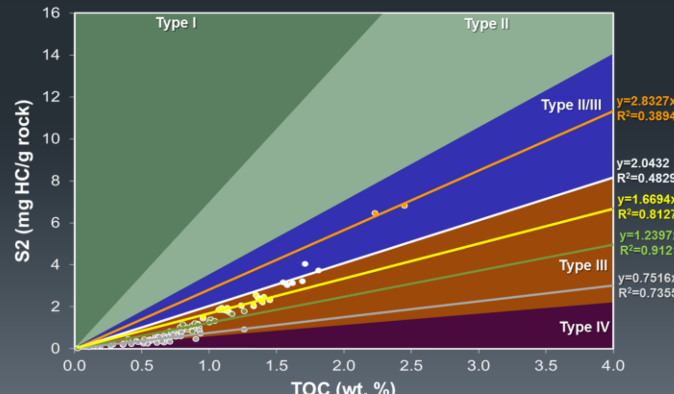
Presenter's notes: The data in general follow a single original HI kinetic profile in which the present day HI decreases regularly with increasing maturity.

- In this case, because all the data suggest a single original HI, mapping present day HI would be a reasonable maturity mapping proxy.
- However, best practice would be to use the Transformation Ratio, as illustrated with the TMS example, since the Bakken example is more often the exception, rather than the rule. We should point out as well that the Bakken data set here was filtered to the most kinetically "well-behaved," but almost of the data fell along a single original HI curve.

Application Summary

1. Determine HI using the slope-HI methodology

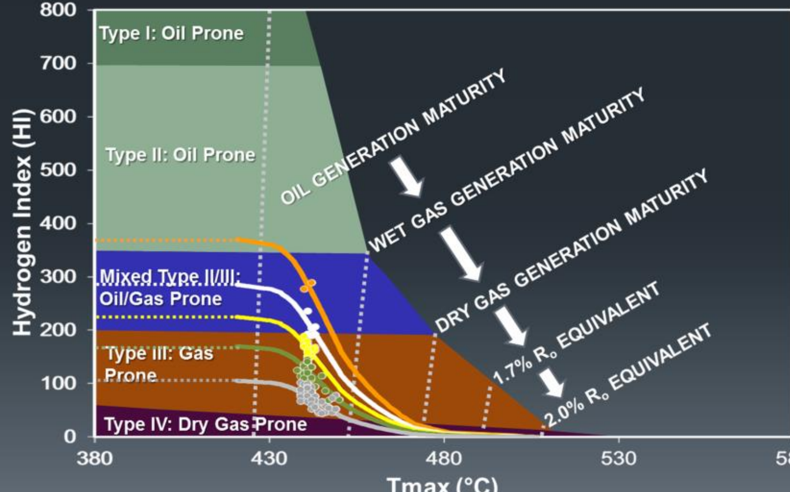
- Fit data to lines that intersect the origin for each well
- There will likely be multiple intervals with differing present-day hydrogen indices
- Intervals likely have same maturity if interval being examined </= 300' thick.



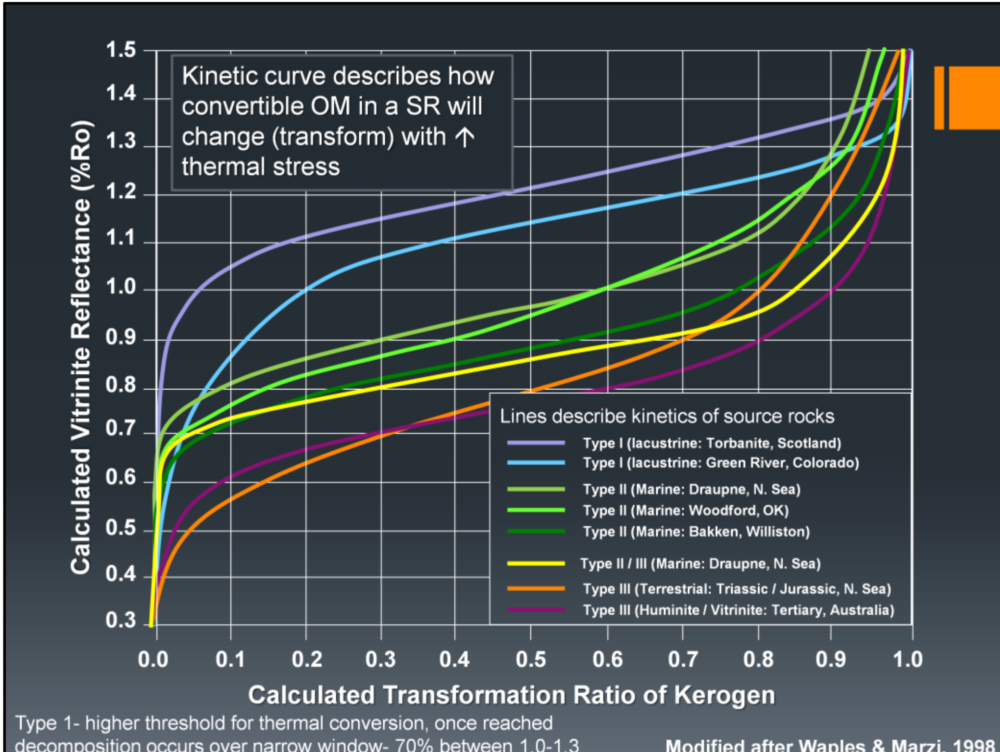
Presenter's notes: If your data aren't as well behaved as the Bakken, what do you do? The first step is to determine the Hydrogen Index using the slope-HI methodology. Plot the data on an S2-TOC graph and fit lines to the data that intercept the origin. There will likely by multiple lines representing different present-day hydrogen indices. One note, maturity will likely not be a factor if the section being evaluated is less than about 300' in thickness.

Application Summary

2. Cross-plot HI vs. Tmax data. Determine to which original HI kinetic curve the data fit and assign those data that original HI.



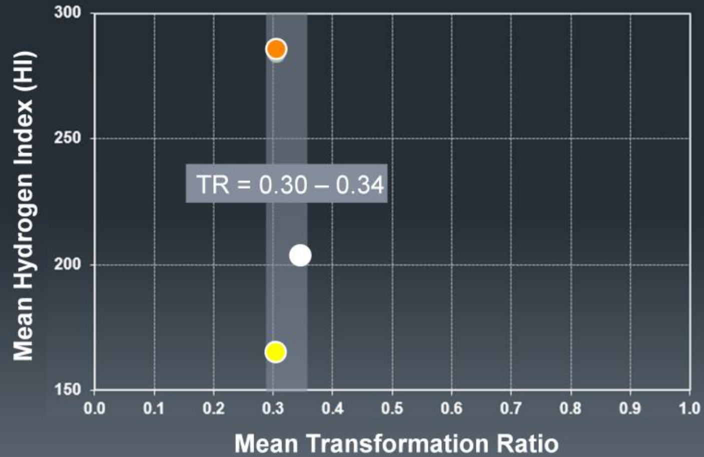
Presenter's notes: The second step is to cross plot the Hydrogen Index and Tmax data and determine to which original HI kinetic curve the data fit. This is done based on using the kinetic curves shown on the next slide, or approximations of those kinetic lines. Based on the kinetic curve, determine the original HI value for each group of data. For example in these data, the original HI values range from just over 100 to 375.



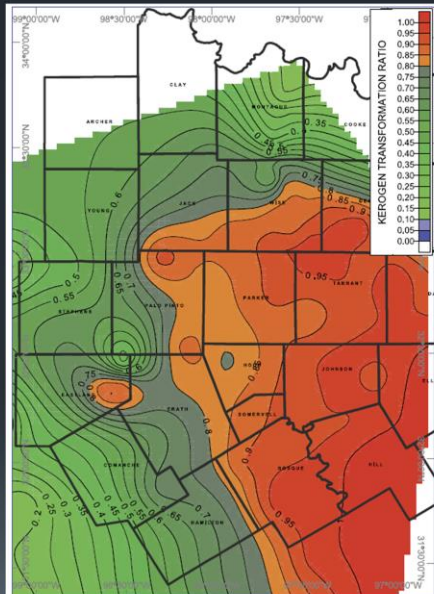
Presenter’s notes: This slide illustrates the extent to which different kerogen types from different source rocks decompose to yield oil & gas at different thermal stresses. These are compiled from published data for kerogen kinetics for a number of source rocks, as published by Waples and Marzi, 1998.
The kinetics of each source rock are described by these lines, which show the change in kerogen transformation with increased thermal stress represented by vitrinite reflectance.
Type I kerogens have a higher threshold for thermal conversion, but once that threshold is reached, decomposition occurs over a relatively narrow window (e.g., 70% of total decomposition occurs between 1.0-1.3% Ro for Green River shale). Type II kerogens have in general a lower threshold for thermal conversion but for some decomposition occurs over a greater temperature range than others. For example, the Woodford undergoes ~50% of its decomposition between 0.85-1.10% Ro.

Application Summary

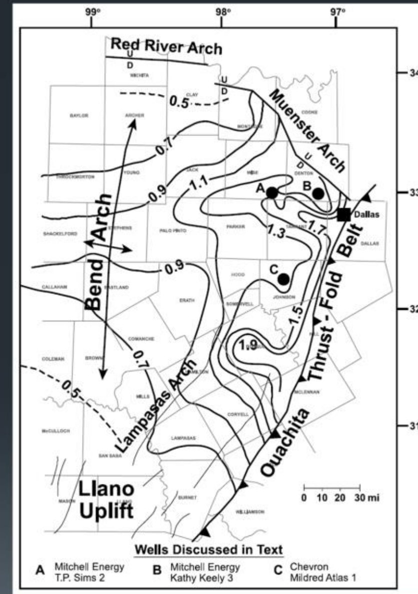
3. Calculate Transformation Ratio for each well using assigned original hydrogen index for the data. Map transformation ratio across basin as a maturity proxy.



Presenter's notes: The final step is to determine the Transformation Ratio for the well using the assigned hydrogen index for the data. The source for the transformation equation is Waples and Tobey, 2015. That presentation offers the equation and an explanation of the variables. The Transformation Ratio is calculated on a well-by-well basis and is then mapped across the basin as maturity proxy. The Transformation Ratio will be more uniform for a well than Hydrogen Index or Tmax.

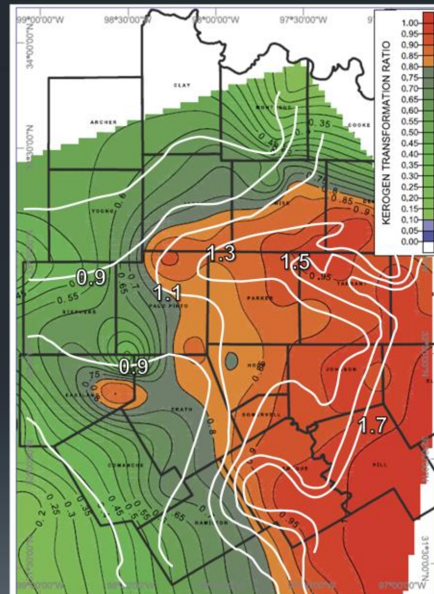


Barnett Shale Transformation Ratio
Jarvie et al. (2007)



Barnett Shale Vitrinite Reflectance
Montgomery et al. (2005)

Presenter's notes: These two maps show maturity trends in the Barnett shale. Jarvie et al (2007) contoured the Transformation Ratio and Montgomery et. Al. (2005) the Vitrinite Reflectance. Both show a similar maturity trend.



Modified from Jarvie et al. (2007) and Montgomery et al. (2005)

Presenter’s notes: An overlay of the vitrinite data on the Transformation Ratio data.

Why? Because it's NOT all the same!

Gneudna

GR Shale

THANK YOU!

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