AV Lithofacies, Depositional Environment, Burial History and Calculation of Organic Richness from Wireline Logs: A Study of the Barnett Shale in the Delaware Basin, Pecos Co., West Texas, and Comparison with the Barnett Shale in the Fort Worth Basin*

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Search and Discovery Article #110083 (2009)
Posted August 5, 2009

*Adapted from oral presentation at AAPG Annual Convention, Denver, Colorado, June 7-10, 2009

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Abstract

Studies of core and logs through the Barnett Shale in Pecos County in the southern part of the Delaware Basin have allowed us to compare the lithofacies and depositional environment of the Mississippian in this area with that in the Fort Worth Basin. Overall, mudrock facies are similar although, in contrast, the studied core contains no skeletal debris layers. Limestone concretions were not seen, but there is substantial dolomite in many horizons. Total clay contents are broadly similar. There is more bioturbation than in the Fort Worth Basin. Agglutinated foraminifera, *Tasmanites*, radiolarians, conodonts and echinoid spines are present. The transition zone between the Barnett and the Woodford Formation is a chert rather than a carbonate, as reported in the northern part of the Delaware Basin. This transition zone is regionally referred to as the "Mississippian Limestone". Recognizing this, we made cross-sections, isopach maps, and structure maps based on well-log correlations penetrating the Barnett Shale in Pecos, Reeves, Culberson, and Hudspeth counties. We then use published methods to calculate organic richness from wireline logs. We built a 1-D burial history of the cored well using “Genesis” software, making use of vitrinite reflectance data. Constructing the burial history is crucial for being able to track likely diagenetic changes in the shale with time. These diagenetic changes in turn control hydrocarbon generation, overpressuring, natural fracturing, petrology and petrophysics, and present-day mechanical rock properties, all of which are important factors in determining whether Barnett Shale gas in the Delaware Basin will be economic.

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June 8, 2009

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Motivation

- Prolific gas production from Barnett Shale in FWB

- Operators investigating Barnett in Delaware Basin

- Very little published geological data about Delaware Basin

- Geological characterization key for identifying gas sweet spots

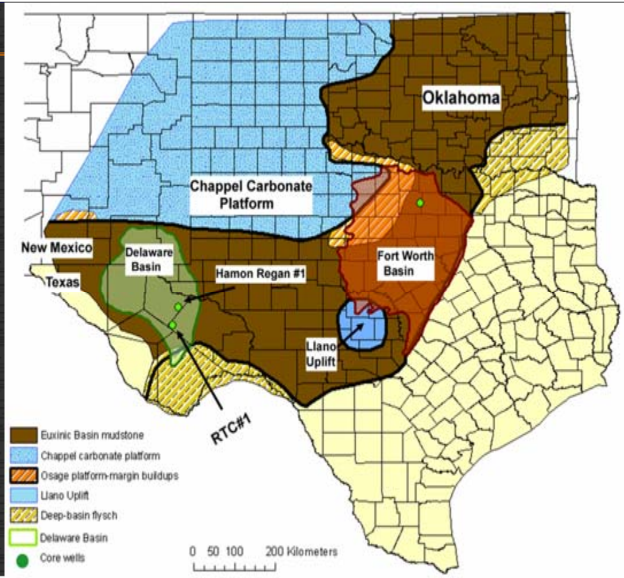
Outline

- Lithofacies
- Comparison (Delaware Basin and Fort Worth Basin)
- Depositional environment
- Transition zone
- Organic richness calculation from well logs
- Estimating gas content from original TOC and hydrocarbon potential
- Conclusions

Study Area

Basin Study

Barnett Shale



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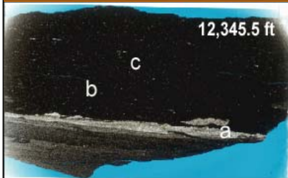
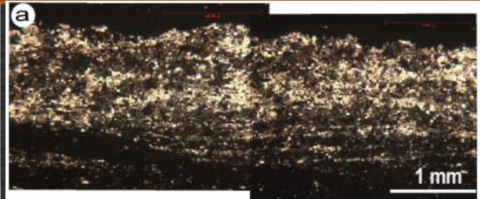
- Lithofacies Identification of Barnett Shale in Delaware Basin

Presenter's Notes: In this study, we recognize three general lithofacies on the basis of mineralogy, fabric, biota, and texture:
Can we say Barnett Shale at Delaware basin is true Shale or siliceous mudstone?
(Shale is defined as having fissility (Folk, 1980)

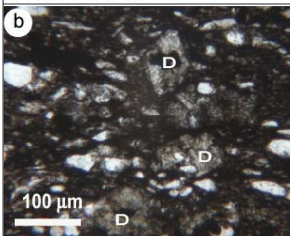
Laminated Mudrock Facies



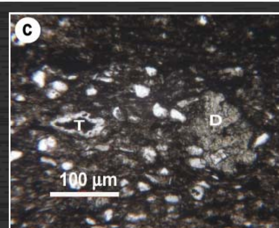
laminated mudrock fabric with silt layers at the bottom of the section



(a). Layer truncation and asymmetry could be caused by currents.



(b). Dolomite rhombs (D) commonly with organic centers. Timing is unclear: Some grow over the foliation, others are wrapped by it.



(c). Flattened *Tasmanites* (T) and dolomite rhomb overgrowing detrital quartz. Fabric wraps around lower part of rhomb.

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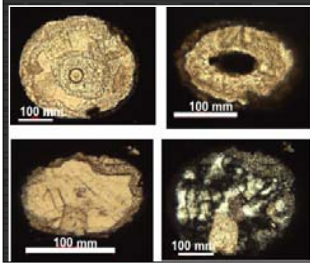
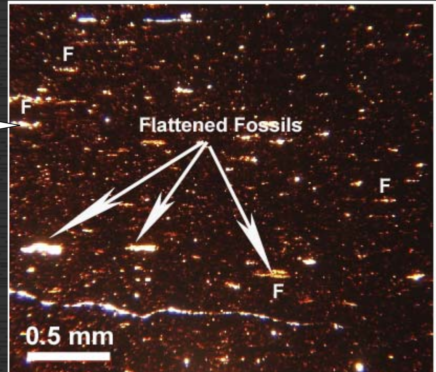
Micro-Laminated Mudrock Facies

Very thick thin section of compacted laminated mudrock.

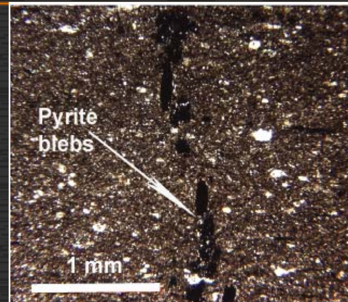


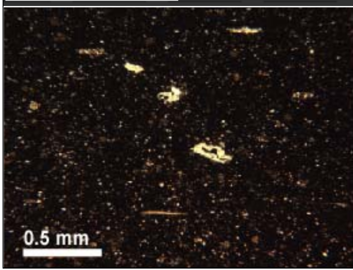


Fossils are mostly flattened (F) but some (at right) have retained their shape

Fossils are flattened as a result of compaction.

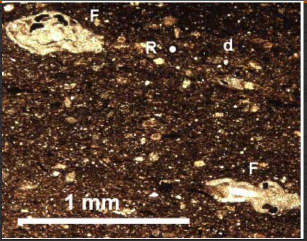
Unlaminated Mudrock Facies



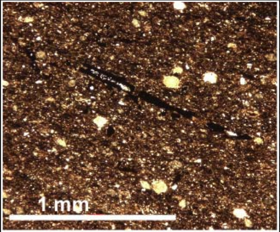


Unlaminated mudrock with agglutinated forams and conodonts

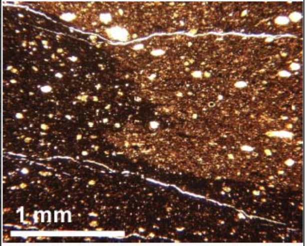
Argillaceous mudrock facies



Forams (F), radiolarians (R), detrital quartz silt (d) and dolomite rhombs in argillaceous matrix.

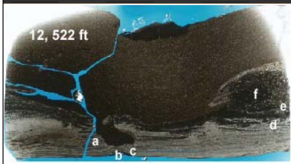


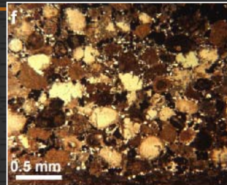
Echinoid spines replaced by pyrite with calcite in the center. Both longitudinal and cross sections.



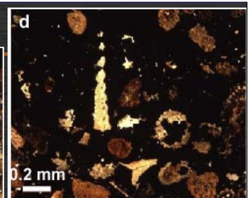
Layering at high angle to flattening fabric.

Coated Phosphate Accumulations

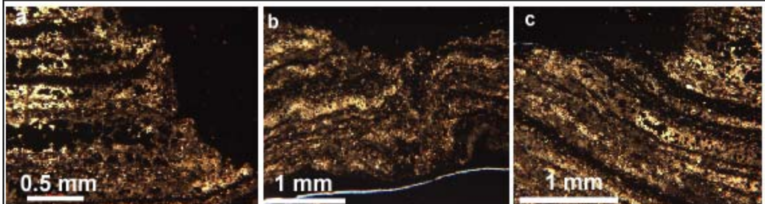




Coated phosphate grains



Radiolarians, conodonts and phosphate grains in pyrite nodule.



Layers of pyrite and carbonate are overlain by siliceous mudrock. At the boundary a layer of pyrite with phosphate nodules is present. The layers are deformed and truncated.

Pyrite Framboids

- Pyrite occurs as framboids, which is the key to

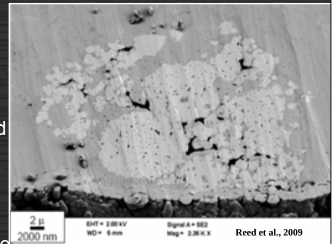
-Understanding the water column chemistry in ancient strata

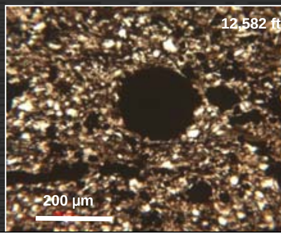
- identifying the depositional environment

- Pyrite framboid size: 1-18 µm (mean 5 µm) formed in a euxinic water column (Wilkins et al, 1997)

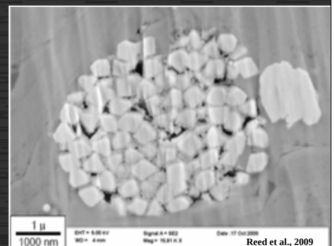
➢1-50 µm (mean 10 µm): formed in an oxic environment (Wilkins et al, 1997; Black Sea)

➢ The most dominant framboid size of Barnett Shale in FWB is (~1 µm) (Loucks and Ruppel, 2007)



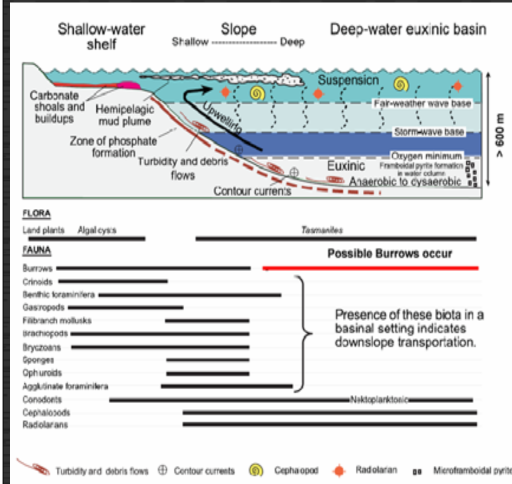


Large and small pyrite framboids



Presenter's Notes: Wilkin et al., (1996) stated that pyrite framboid size distribution may be used to indicate whether fine-grained sedimentary rocks were deposited in an anoxic or an oxic environment.
Pyrite occurs in all intervals of the Barnett Shale in the RTC#1 core and also occur as framboids, which is the key to identifying the depositional environment.
Pyrite framboids have been cited as a key to understanding water-column chemistry in ancient strata (Wilkin et al., 1996, 1997; Hawkins and Rimmer, 2002; Bond et al., 2004).

Depositional Environment

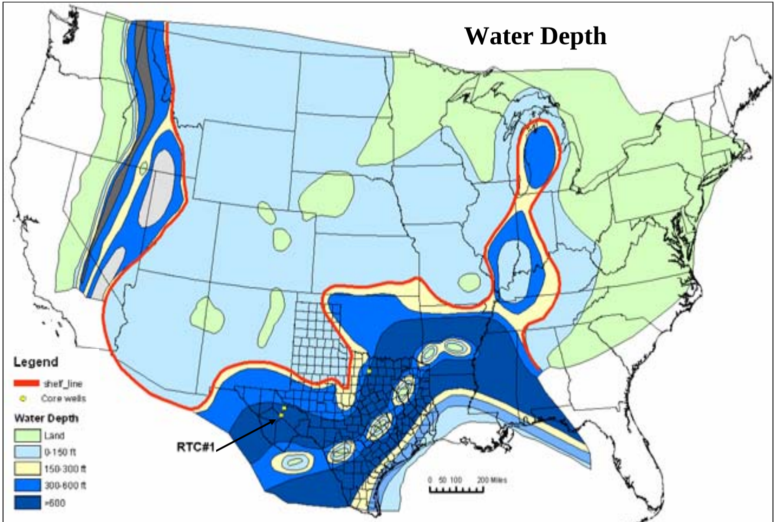


- The RTC#1 rocks are from a more distal basin setting, with underlying deep-water cherts.
- Fossil assemblage transported from adjacent shelves and upper slope by turbidity and debris flows or by suspension settling.
- Unlaminated textures are present in some core intervals; could possibly be explained by basin upwelling.

After Loucks and Ruppel, (2007)

Presenter's Notes: The presence of these biota (agglutinated foraminifera, gastropods, brachiopods, bryozoans, and sponges), in the deep basin setting might indicate downslope transportation.

Possible burrows occur in some intervals of the RTC#1 core. These were possibly formed by organisms transported from the shelf to the basin along with sediment. These organisms would have lived for a short time creating bioturbation and then died out due to the anoxic environment. Another interpretation: the basin is turning over, creating an oxygenated environment for organisms to live for a period of time when the oxygen is available. These organisms would then die out when the environment becomes anaerobic.



RTC#1 Well is located in the distal part of basin, where water depth is below oxygen minimum and storm wave base.

Map modified from Gutschick and Sandberg (1983)

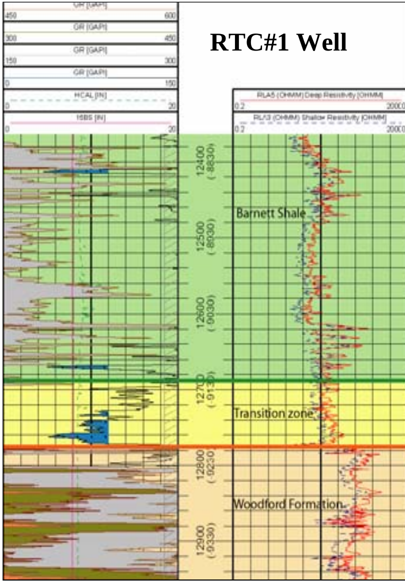
Presenter's Notes: the southern part of the Delaware Basin where the RTC#1 well is located is in the deepest part of the basin where the water depth is greater than 600 ft

Key differences between the Barnett Shale in Delaware Basin and FWB

Comparison

- There are no coarse skeletal debris layers
- More bioturbation (Basin turning over might explain the presence of bioturbation)
- Depths range from 7000 ft to 18,000 ft in Delaware Basin, but ~3000 ft to 8000 ft in FWB
- The average TOC is 2.90 %, but in FWB is 3.9% -4%
- Different sizes of pyrite framboids * Very low to no calcite content
- Gas content ranges between 100-145 scf/ton in Delaware Basin, but it 190-529 scf/ton in FWB (Jarvie, 2009)
- Variation in the TOC content, which might be explained as a difference in (1) O.M. input to the water column; (2) O.M. preservation in the sediments

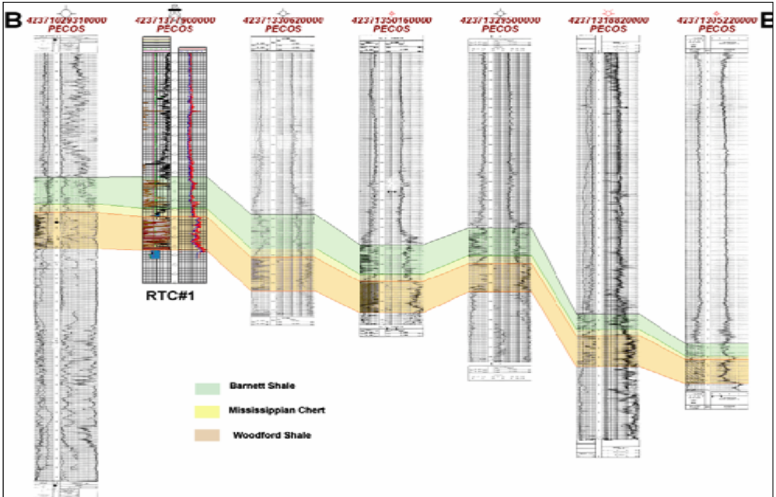
Presenter's Notes: Depths range from 7,000 ft (2133 m) along the western edge of the Delaware Basin to 18,000 ft (5486 m) along the basin axis. However, depths to the Barnett Shale within the FWB are shallow and start from approximately 3000 ft and reach 8000 ft at most.
The average TOC, based on 177 samples for the RTC#1 core, is 2.90 %. This is lower than the average TOC at the FWB.
plotting the ratio of Titanium / Aluminum (Ti/Al) versus depth can give an idea about the sediment source and whether it comes from one or more different sources.
the preservation of organic matter in sediments might be changeable through time. This could be determined from the organic matter production rate which shows high nitrogen contents on the total nitrogen isotope scale.



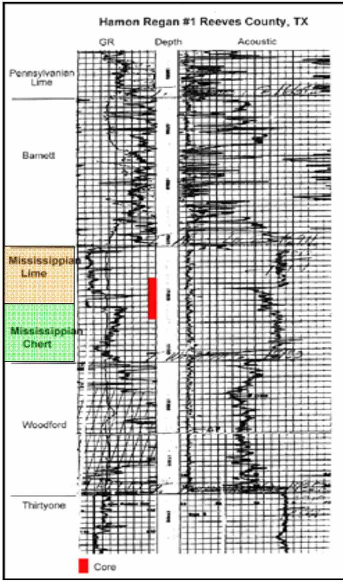
Transition Zone

The transition zone is commonly chert at the location of the RTC#1 well

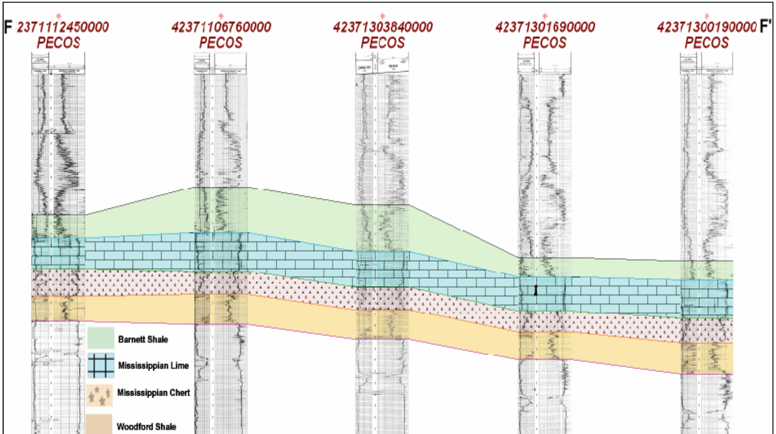
Presenter's Notes: GR and acoustic logs show the transition zone between the Barnett shale and Woodford Formation is a mix of carbonate and chert. The chert has the same signal as in the RTC #1 well and the carbonate has a low reading in the GR log. After examining the thin sections, this carbonate is identified as a dolomite.



Cross section BB' through RTC#1 where the transition zone between the Barnett Shale and Woodford Formation is interpreted as chert.



The transition zone is a mix of chert and lime in different parts of the basin

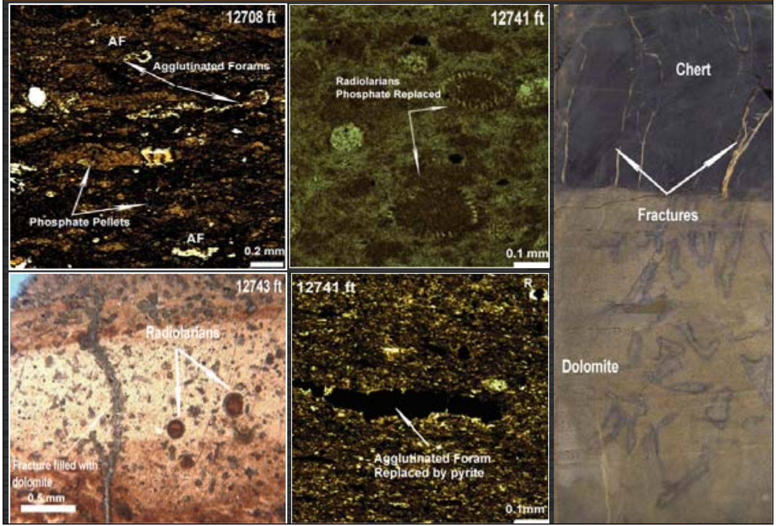


Cross section FF' across the Pecos County where the transition zone between the Barnett Shale and Woodford Formation is a mix of Mississippian chert and Mississippian lime.

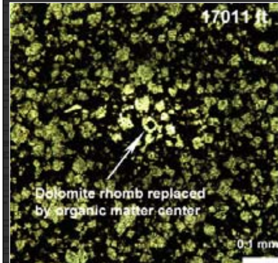
Presenter's Notes: Chert is an early diagenetic product. This mixed zone of Lime and Chert is probably caused by pressure dissolution that caused the chert to replace the lime.

Transition zone

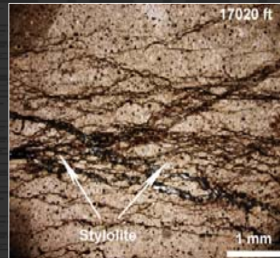
RTC#1

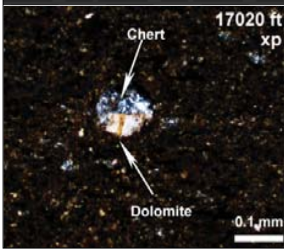


Transition zone (Hamon Regan)



Probably this dolomite is a diagenetic product or it might be generated from an anerobic oxidation of organic matter.



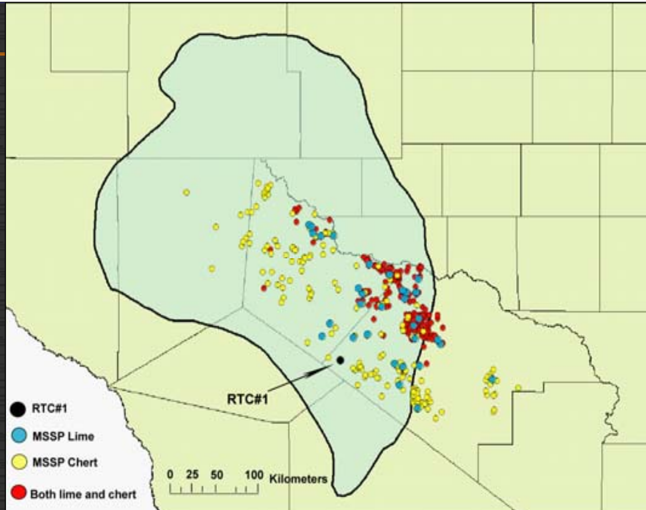


Stylolites resulted from compaction and pressure dissolution which may have provided a source of silica for chert to replace the dolomite in the transition zone.

Presenter's Notes: Some dolomite rhombs have organic centers suggesting that they nucleated on organic matter and were probably an early diagenetic product. It is difficult to tell which mineral replaces which.

There is no evidence for calcite at this interval. Instead, many ferrous carbonate clasts are dominant.

It is hard to point what is the background matrix at this zone



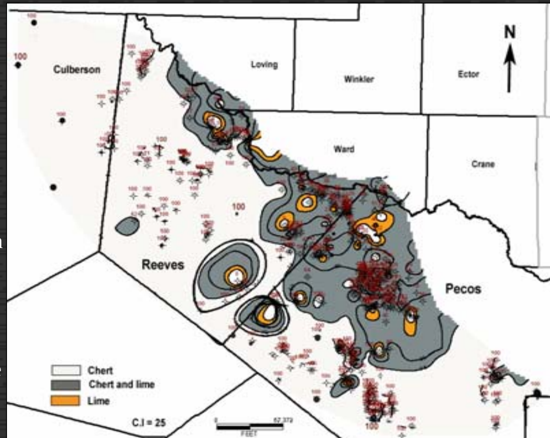
Location map showing the distribution of the Mississippian wells that are rich in lime, chert, and mix of lime and chert

Presenter's Notes: Location map showing the distribution of the Mississippian wells that are rich in Lime, chert, and mix of Lime and chert.

Map showing the distribution of chert, lime, and mixed chert/lime wells

Interpretation:

- This zone has undergone diagenetic processes that caused extensive rock replacement as a result of burial depth.
- The limestone was generated on the shelf, eroded, and then was transported to the basin to mix with the chert that was formed in the basin. A replacement process between the chert and the limestone then began.



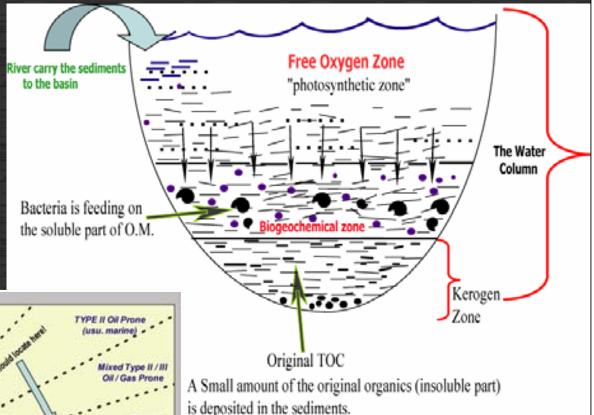
Presenter's Notes: The presence of stylolites in the Hamon Regan #1 well could be a result of compaction and pressure dissolution, where fluids rich in silica might have been transported to replace the carbonate in the transition zone. Based on the scope of this study it is difficult to tell which rock was formed first.

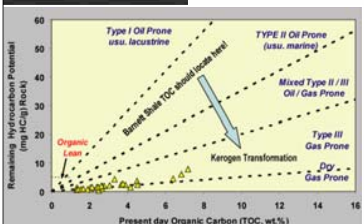
Calculation of the Gas content for the Barnett Shale in Delaware Basin

Calculation of Barnett Shale Gas Content

Methodology

• Back calculation for the original TOC

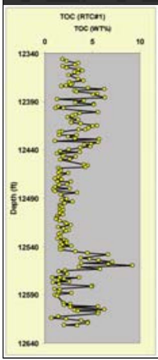


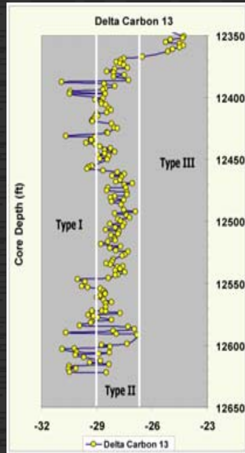


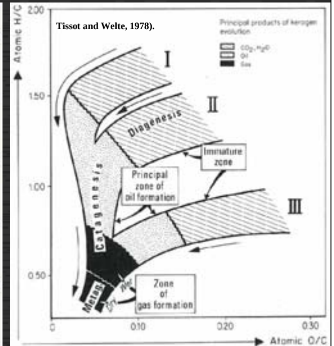
Kerogen type

Assumption

- The higher the peak of δC13, the higher the rank of kerogen type (more aromatic)







~ 14% type I kerogen, ~ 81% type II kerogen and ~ 5% type III kerogen

Presenter's Notes: It is not possible to differentiate between the kerogen types when the samples are thermally mature and are located in the gas window.

Variation in the TOC values with depth is largely consistent with the variation in the δ C13 for the RTC#1 well.

As the type of kerogen increases, the kerogen structure becomes more aromatic, which gives a higher value on the δC13 scale.

For example, type (I) kerogen is more aliphatic rich, which gives lower δC13 peak; type (II) kerogen has an increase in the aromatic benzene rings, which give higher reading than type (I) in the δC13 scale and so on for type III and type VI.

Equations

$$HI_o = \left(\frac{\%\ \text{type I}}{100} \times 750\right) + \left(\frac{\%\ \text{type II}}{100} \times 450\right) + \left(\frac{\%\ \text{type III}}{100} \times 125\right) + \left(\frac{\%\ \text{type IV}}{100} \times 50\right) \quad (1)$$

(Jarvie, 2007)

$$TR_{HI} = 1 - \frac{HI_{pd}\,[1200 - HI_o\,(1 - PI_o)]}{HI_o\,[1200 - HI_{pd}\,(1 - PI_{pd})]} \quad (2)$$

$K = TR_{HI} * C_R$

Type I= 50%
Type II= 15%
Type III= 0%
K= 19.5%
(Burnham, 1989).

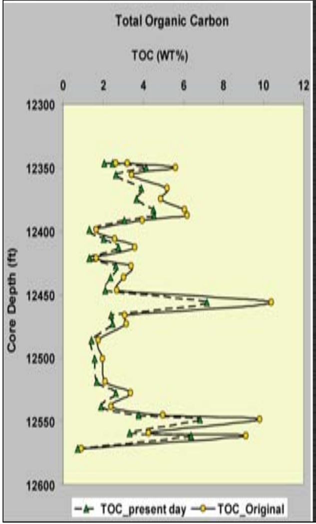
$$TOC_o = \frac{HI_{pd}\left(\frac{TOC_{pd}}{1+k}\right)(83.33)}{\left[HI_o\,(1 - TR_{HI})\left(83.33 - \left(\frac{TOC_{pd}}{1+k}\right)\right)\right] - \left[HI_{pd}\left(\frac{TOC_{pd}}{1+k}\right)\right]} \quad (3)$$

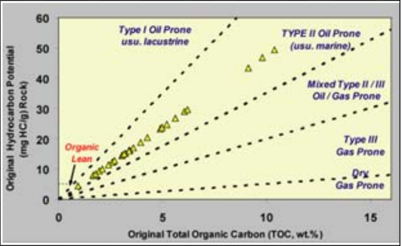
S_{2o}= (HI_OX TOC_O)/ 100 ➔ (4) (Ruble, 2009) (4)

Gas yield = (S_2o) - (S_{2r}) ➔ (5)

Presenter's Notes:
TR HI= the fractional conversion derived from original hydrogen index
HIo= Original Hydrogen Index
HIpd= Present day Hydrogen Index
C_R = the residual carbon at high maturity
PIo= Original Production Index
PIpd= Present day production Index (the ratio of S1 to S1 + S2 from Rock- Eval data) PI= (S1/ (S1+S2)
1200= a constant value; maximum amount of hydrocarbons that could be formed assuming 83.33% carbon in the hydrocarbons

Calculation of Barnett Shale Gas Content



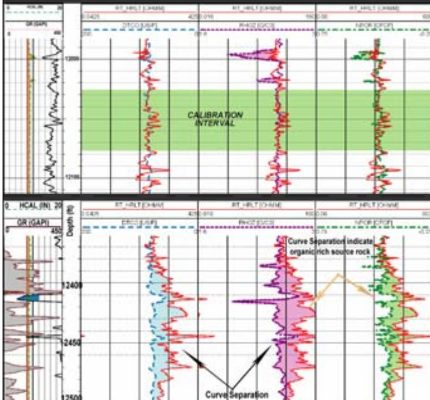


- Gas content of the RTC#1 is estimated to be 110.64 scf/ton based on calculating the original TOC and hydrocarbon potential

- 90% of the generated hydrocarbon left the system

Organic Richness from Wireline Logs

Methodology



- Method based on overlay of deep resistivity log with sonic log.

1) Matching overlay in immature source rock.

2) Separation between the two logs is an indication of source-rock organic matter.

- Neutron and Density logs can be used if borehole is in good condition.

Passey et. al., (1990)

$$\Delta \text{Log } R = \log 10 = (R/R_{baseline}) + 0.02 * (\Delta t - \Delta t_{baseline}) \text{ “Sonic”}$$

$$TOC = \Delta \text{Log } R * 10^{(2.297 - 0.1688 * LOM)}$$

$$\Delta \text{Log } R_{Neu} = \log_{10}(R/R_{baseline}) + 4 * (\Phi N - \Phi N_{baseline}) \text{ “Neutron”}$$

$$\Delta \text{Log } R_{Den} = \log 10(R/R \text{ baseline}) - 2.50 * (\rho_{b-} \rho_{baseline}) \text{ “Density”}$$

Presenter’s Notes:

Δ log R= the separation of sonic/resistivity curves,

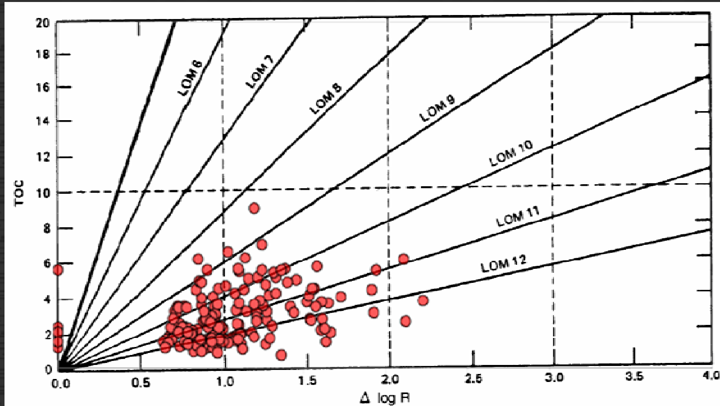
R baseline = the resistivity matching to the Δt baseline, when the sonic and resistivity curves overlay in non source rock interval

0.02 = the ratio of sonic/resistivity scale (50 µsec/ft per one resistivity cycle)

2.297 & 0.1688 = parameters are determined empirically in clay rich rock by Passey et al., (1990).

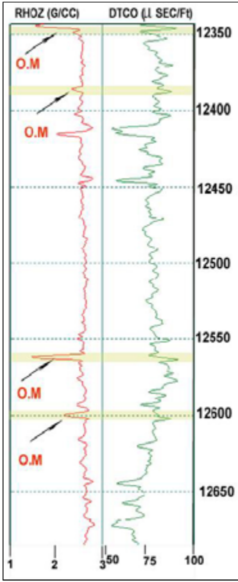
The Δt baseline is constant along the entire well; however, the R baseline is changeable in order to baseline the two curves.

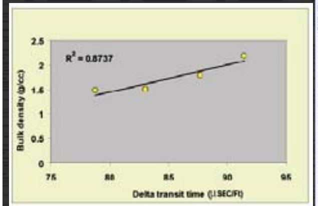
Level Of Maturity (LOM)

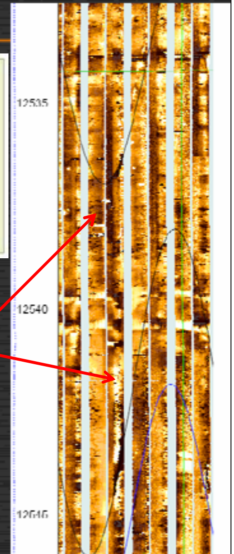


Apparent variation in maturity arises because the shale is heterogeneous and the kerogen is a mixture of types I, II, and III, which may suggest different depositional environments.

Organic Matter

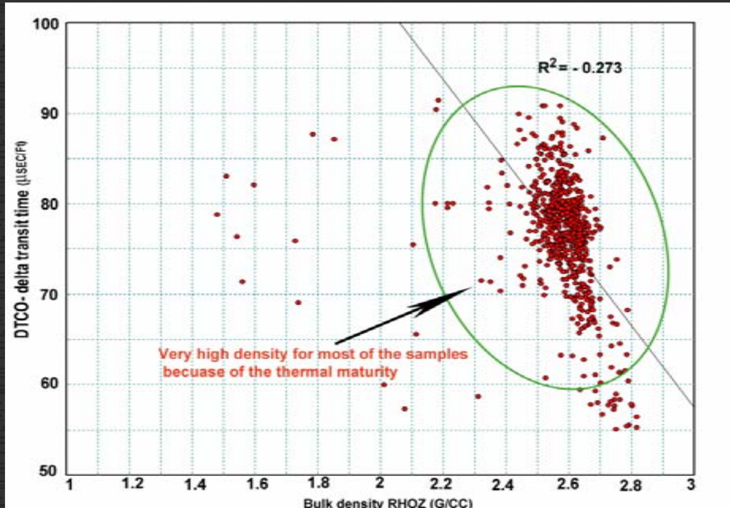






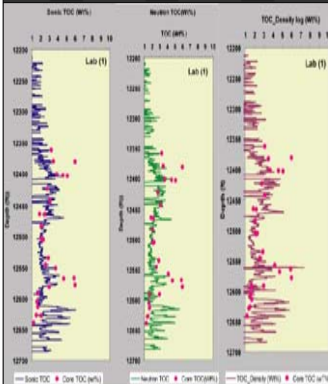
Non-continuous laminae

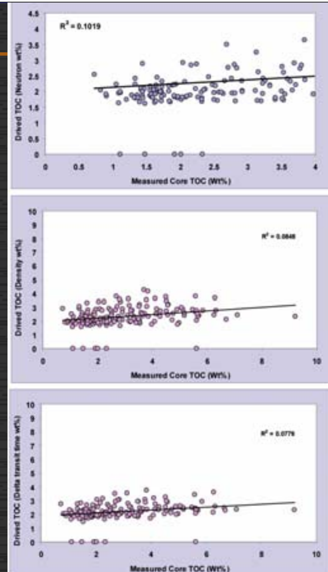
High Thermal Maturity of Examined Samples



Presenter's Notes: Plot of photoelectric factor (PEF), sonic delta transit time and caliper. The high peaks of the PEF refer to the solid particles associated with the sediments, which are most likely organic matter. Caliper logs should be used with PEF in order to separate between the washout areas and the organic matter layers. Solid organic matter should give high delta transit time; therefore Δt log should be used with the PEF to identify this organic matter.

Correlation





weak correlation because :

- Large missed core intervals
- Sample locations for measured TOC
- Different types of kerogen are present in Barnett Shale (Mix of types I, II, III)

Conclusions

- High organic content, laminae, small pyrite framboids suggest anoxic conditions
- RTC#1 well is located in the distal part of basin, where water depth is below oxygen minimum and storm wave base
- The short depositional events of oxygenated sediments transported from more proximal setting
- Cherts in transition zone indicate deep-water distal setting
- The mix of Mississippian Lime and Chert between the Barnett Shale and Woodford Formation probably suggests a diagenetic process that causes chert to replace the carbonate by the process of pressure-dissolution

Conclusions

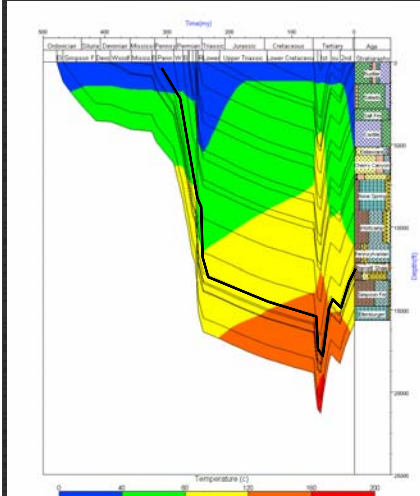
- Back calculating for the original TOC and hydrocarbon potential helped in estimating the gas content for the Barnett Shale at the location of RTC#1 well
- Estimating the TOC from wireline logs is not an accurate method to apply for the Barnett Shale because it has a mix of different kerogen types. However, it is a good tool to use in order to know the location of O.M.-rich intervals.
- Barnett Shale in Delaware Basin has potential as a gas play but it is deeper than in the FWB – wells more expensive

Acknowledgments

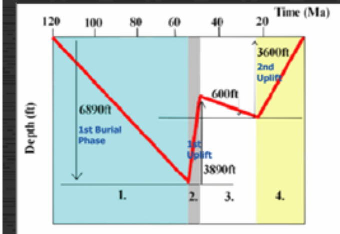
- Ford Foundation
- Jackson School of Geosciences
- Bureau of Economic Geology
  - Permian Basin Geological Synthesis Project
  - STARR
- Pioneer Natural Resources
- MJ Systems
- Supervisors
  - Dr. Fisher, Dr. Groat
- Colleagues
  - Kitty Milliken, Tongwei Zhang, Harry Rowe, Fred Wang

1-D Burial Model for the Delaware Basin at the location of the RTC#1 well

Burial History Model for Delaware Basin at the location of the RTC#1 well

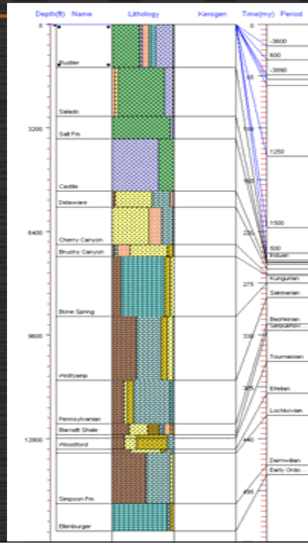


Note temps are in centigrade (200°F ≈ 90°C)



New revised burial history for the Delaware Basin at the location of RTC#1 (modified from Sinclair 2007)

Lithological column created in Genesis 4.8 for RTC#1



Location map showing the Delaware Basin wells that have similar lithology