

Geological and Geochemical Attributes of Paleozoic Source Rocks and Their Remaining Potential for Unconventional Resources in Erg Oriental Algerian Sahara*

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Abstract

The Erg Oriental in Algeria refers to the western part of the Ghadames basin that extends across Algeria, Tunisia, and Libya. There is significant oil and gas production from Berkine and Illizi of southeastern Algeria. The Paleozoic sedimentary section of these basins reveals significant petroleum source rocks within Lower Silurian (Llandovery) and Upper Devonian (Frasnian) strata that were deposited along the northern shelf of the African Craton. These source facies are primarily black shale, extending across North Africa to the Middle East and correlating with major worldwide anoxia events. Analogues are reported all around the world, including North and South America, Russia, Pakistan, and China. It is estimated that more than 10% of the world's petroleum reserves are derived from Paleozoic source rocks, primarily Silurian and Devonian in age.

Although the source-rock potential of these hot shales was identified in some of the earliest exploration reports in North Africa, their potential for shale oil/gas resources only emerged recently. On-the-ground assessments for their unconventional resource potential have yet to be conducted.

Mineral and organic attributes of the Silurian and Devonian source rocks in the Berkine/ Illizi basin are analogous to the Silurian-aged source rocks in the Permian, Anadarko, and Michigan basins, and the Devonian source rocks to the Marcellus, Woodford, and Bakken in the U.S.

Silurian and Devonian organofacies are mostly sapropelic (type II kerogen). The Silurian has an abundance of graptolites, and the Devonian contains acritarchs and spores. Both contain organofacies with predominantly spores and pollens and frequent thin layers of Tasmanaceae algae (type I), deposited in the shallow-marine environment of Gondwana's epicontinental seas. Younger Paleozoic source rocks (Carboniferous) are mainly ligno-humic (type III kerogen) that originated from terrestrial land plants.

The organic content of Silurian and Devonian black shales of the Erg Oriental is appropriately assessed through conventional techniques (% TOC); however, maturity measures (Vitrinite Ro%) show inconsistencies with depth of burial. Vitrinite Ro% is particularly unrealistic when

compared to the thermal stress of the recovered hydrocarbon fluids. This is due to an absence of vitrinite macerals for measurement. Most commonly exinite is misidentified as vitrinite, leading to higher-than-normal reflectance readings. RockEval pyrolysis displays reliable results in the oil window but fails to differentiate the condensate- or dry-gas-generation windows.

This presentation highlights the importance of source rock maturity in the context of unconventional resource assessment, discusses the limitations of commonly used maturity markers (R_o , T_{max}) and examines alternatives to mitigate some pitfalls. The study shows that the organic matter has undergone a complex geological history, with differences occurring due to local burial depth variations during the Carboniferous. It also points out the good, remaining oil potential for the Upper Devonian on three quarters of the studied area, and the fact that the Silurian hot shale (up to 10% TOC) is mostly in the gas window. Silurian and Devonian hot shales have provided for huge oil and gas resources in Illizi's and Berkine's conventional reservoirs but importantly hold significant unconventional resources yet to be developed.

Selected References

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Williams, J.H., 2010, Evaluation of well logs for determining the presence of freshwater, saltwater, and gas above the Marcellus Shale in Chemung, Tioga, and Broome Counties, New York: U.S. Geological Survey Scientific Investigations Report 2010–5224, 27 p., Website accessed August 16, 2013. <http://pubs.usgs.gov/sir/2010/5224/>

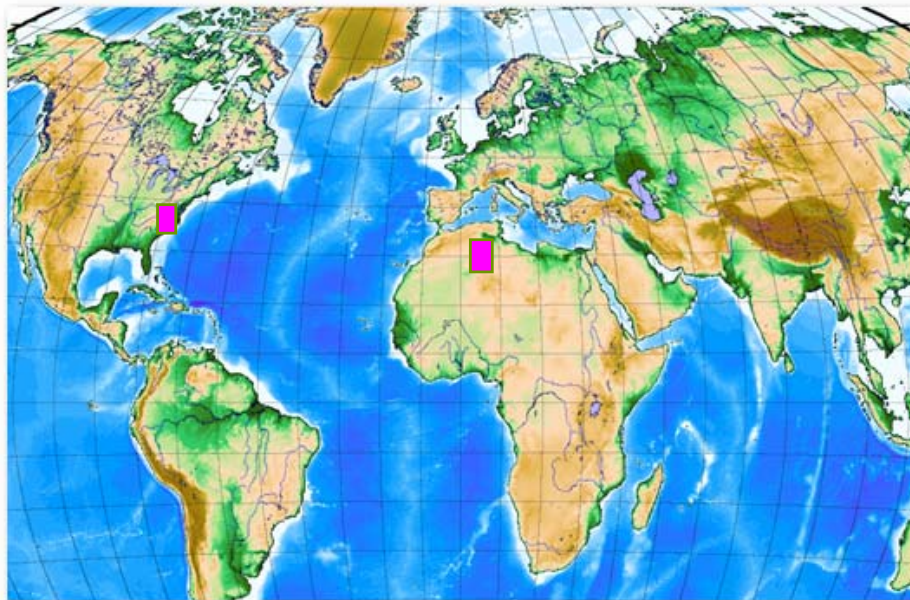
Geological and Geochemical Attributes of Paleozoic Source Rocks and Their Remaining Potential for Unconventional Resources in Erg Oriental Algerian Sahara

A. Chaouche

Objectives

- The Paleozoic SR deposition in Algeria and equivalents in the eastern US basins
- The predominance of algal/bacterial organic matter input
- The impact of structured and amorphous kerogen on shale oil/shale gas reservoirs
- Ambiguity in SR maturity assessment
 - Limited terrestrial input impedes Ro% measurement
 - Bitumen/kerogen effect on pyrolysis Tmax°C
- Fluid maturity markers complementing Ro% / Tmax°C
- Frasnian & Silurian of Illizi/ Berkine as shale reservoir rocks.

Index Location Map



Eastern US basins - Illizi Berkine: What is the common link?

- Environment of Deposition
- Paleozoic Paleogeography
- Organic matter type productivity/preservation

Although epicontinental or epeiric seas are virtually absent from earth today their predominance in the Paleozoic was the prime factor of an un-precedented development of biodiversity

Glacial ice that melted by the end of Ordovician induced major transgressive events that extended from the Appalachian of North America to the Caucasian in Asia

Utica represents a major transgression across the eastern Unites States with shale indicating a tremendous influx of organic material

Silurian radioactive shale is another significant transgressive event that occurred across North Africa extending to the Arab peninsula.

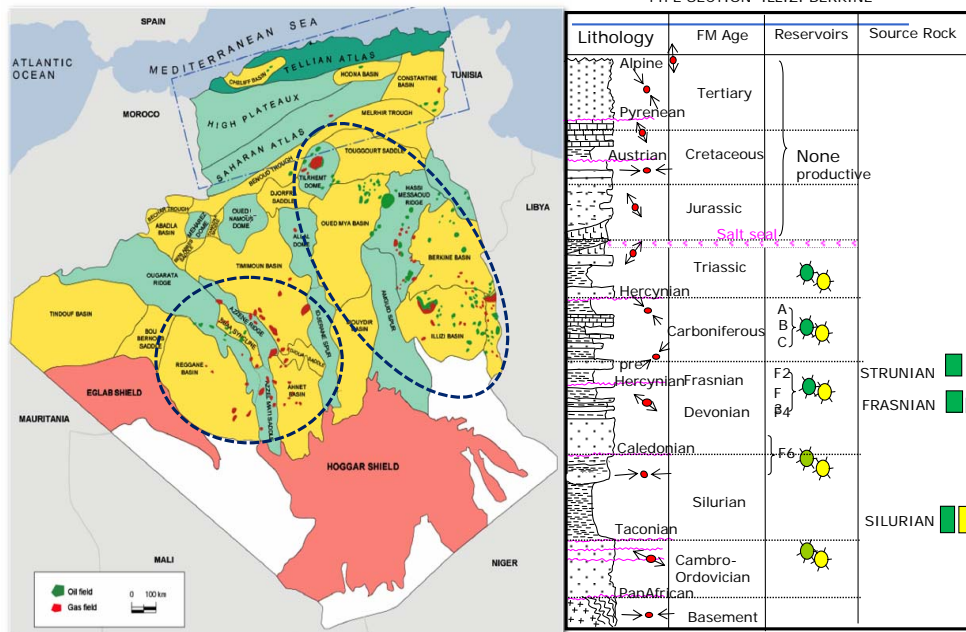
Because of the low relief of the shelf, even a minor sea level rise caused widespread transgressions

Organic productivity was dominated by algal blooms: widespread *G. prisca* algae of Ordovician in U.S. or the graptolites of the Silurian in north Africa and Middle East

Similar conditions prevailed during Marcellus and Frasnian shale deposition even if the compressive movements of the Caledonian and Acadian initiated structural highlands that restricted water circulation

Algerian Oil and Gas Field Distribution

TYPE SECTION ILLIZI BERKINE

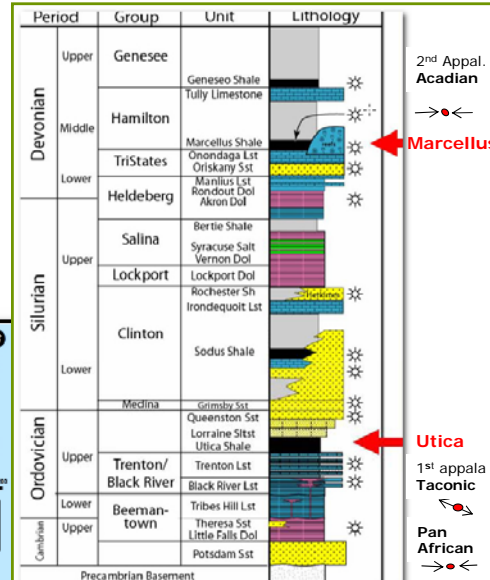


Presenter's notes: The distribution of oil and gas fields shows two main provinces belonging to the Saharan plate: mainly oil in the Eastern province (Triassic) and gas in the western province. The Atlassian domain remains underexplored: so far only few small oil fields have been discovered; significant reserves are yet to be discovered in conventional traps, and huge shale potential is still untouched.

Eastern US Basins



Type section

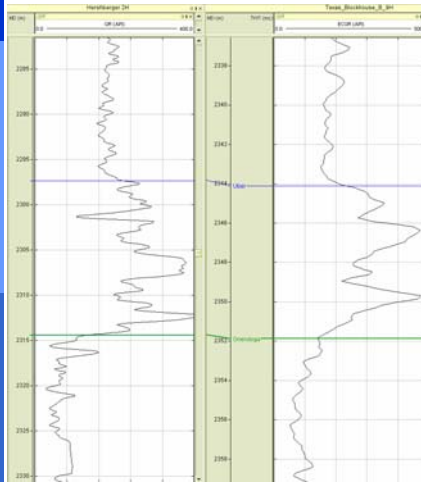


Presenter's notes: Distribution of fluids within the Eastern U.S., as shown in the type section, mimic the Algerian Paleozoic oil and gas discoveries where source rocks have equivalent geological age and basins shaped by the same structural events.

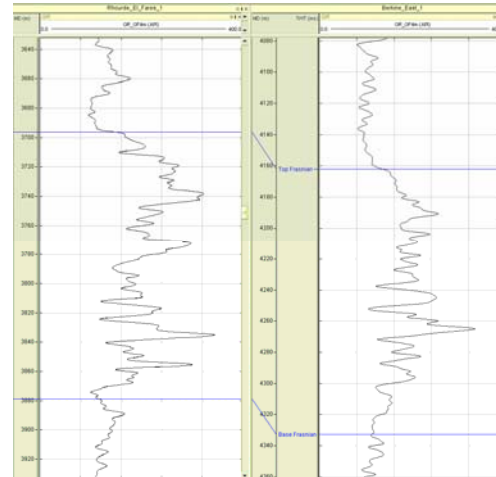
Gamma Ray Response—N. America & N. Africa



Marcellus - USA

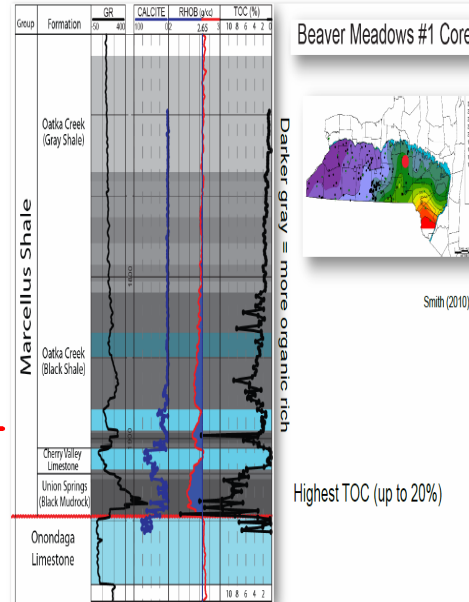
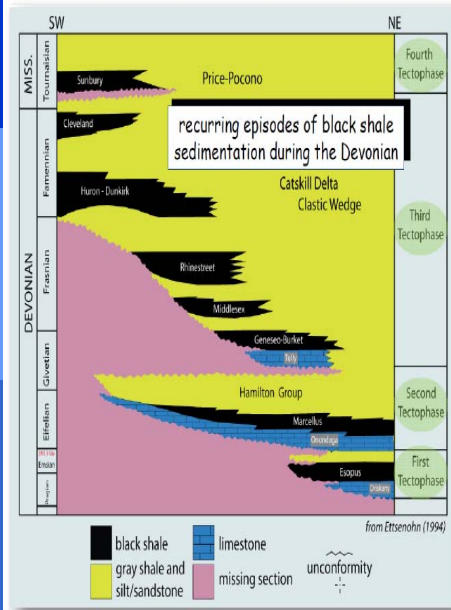


Frasnian – Algeria



Presenter's notes: The analogy in sedimentary deposits is well expressed by the gamma ray response that shows recurrent pulses of high gamma related to periods of highstand.

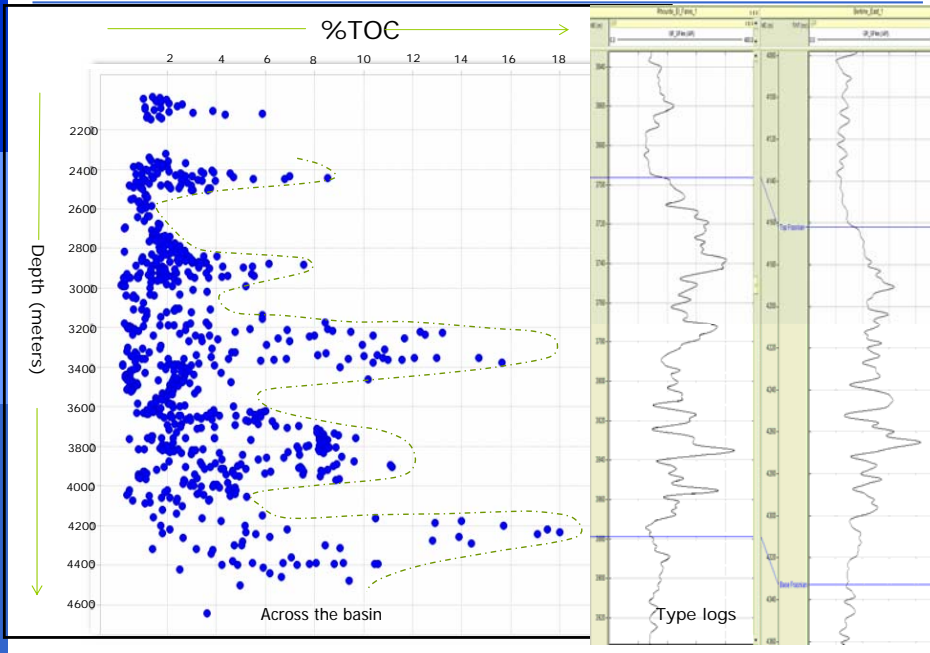
Marcellus shale – TOC /Gamma Ray correlation



J H Williams USGS 2010

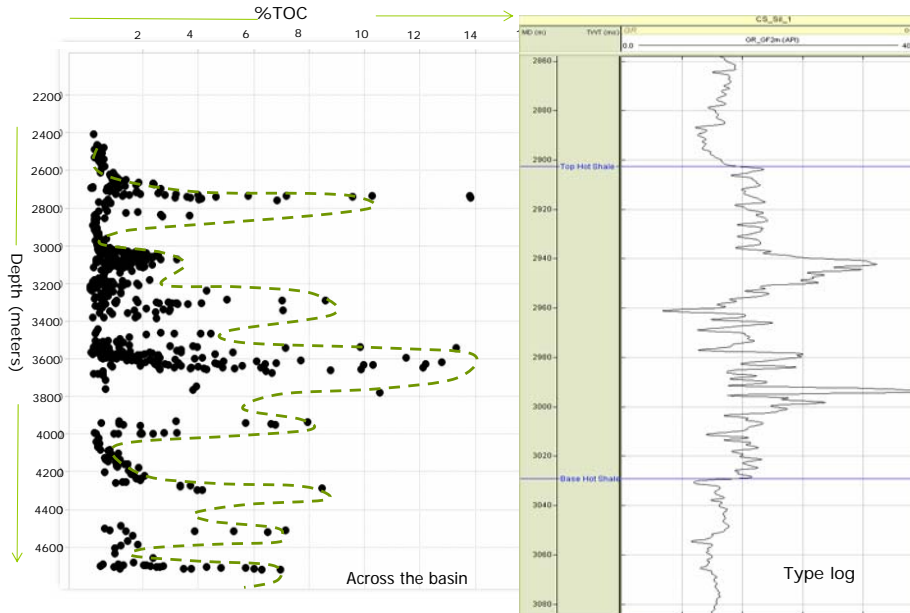
Presenter's notes: The organic matter content of the Marcellus (Eifelian) correlates with the recurrent episodes of transgression that marked the Devonian and can be traced back to the Algerian sedimentary deposits (Frasnian). Yet, the major transgressive event at the base of Marcellus seems to be diachronic in time, having occurred in Early Devonian in U.S. and Middle Devonian in Algeria.

TOC & Gamma Ray in the Frasnian Radioactive shale



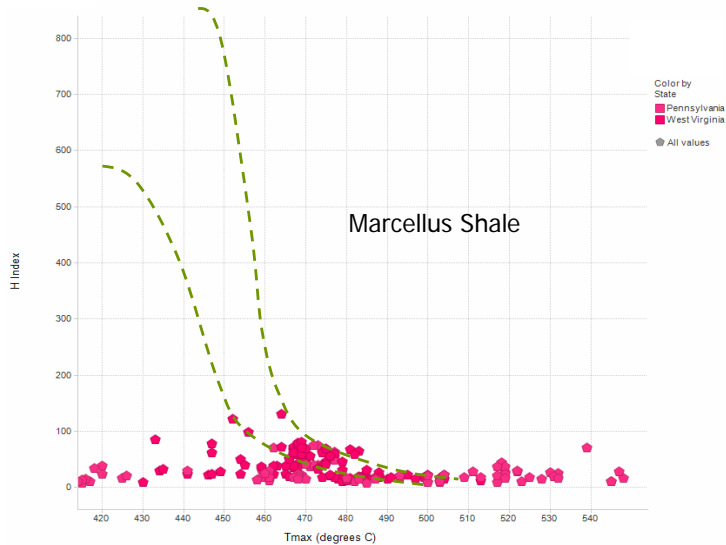
Presenter's notes: TOC versus depth cross-plot for the Frasnian radioactive shale confirms TOC /Gamma ray correlation, with high gamma ray pulses matching the abundance of organic content.

TOC & Gamma Ray in the Silurian Radioactive Shale



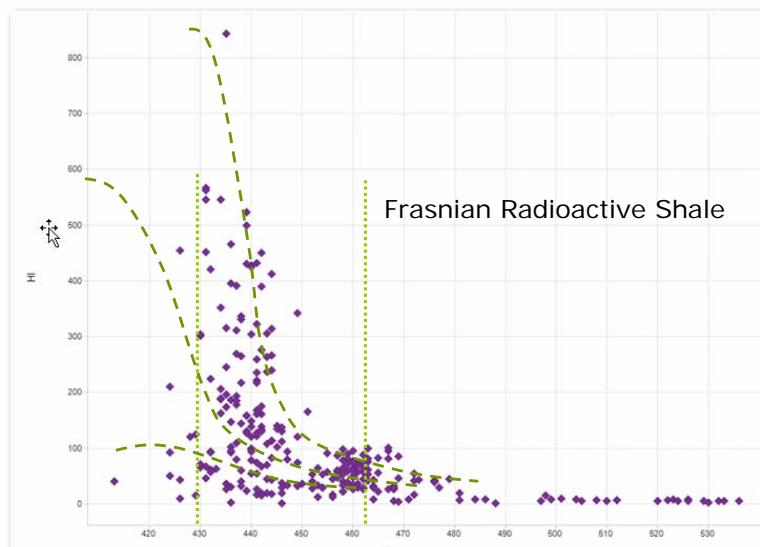
Presenter's notes: The Silurian radioactive shale marks a significant transgressive event that followed the Pan-African peneplanation. Three major pulses are recorded in the western Algerian basins and the two first are present across all of North Africa. A good correlation has been established between TOC and gamma ray .

HI: The Marcellus Shale is Highly Mature



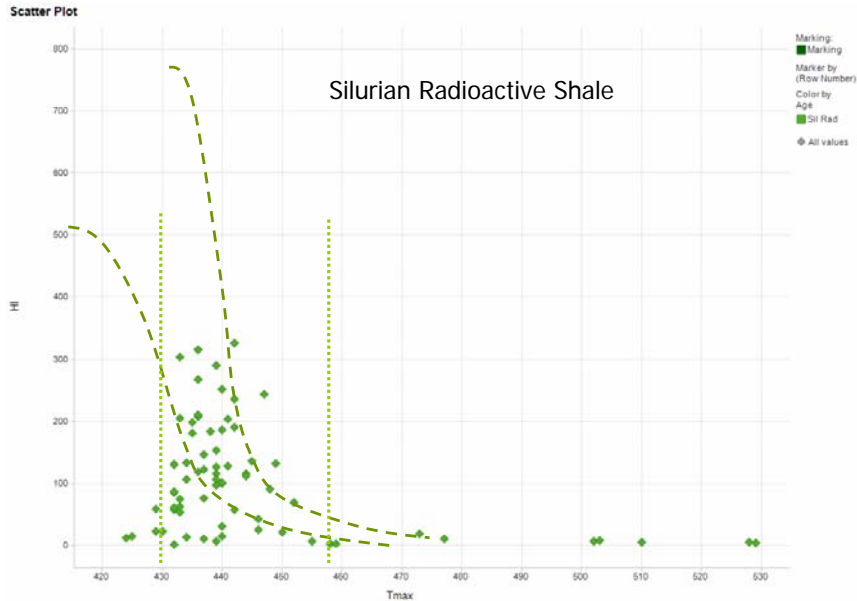
Presenter's notes: The HI /Tmax⁰C of Marcellus shale shows clearly an advanced organic-matter transformation, verified by the high gas potential of Marcellus.

Hydrogen/ Tmax°C Of The Frasnian Illizi /Berkine



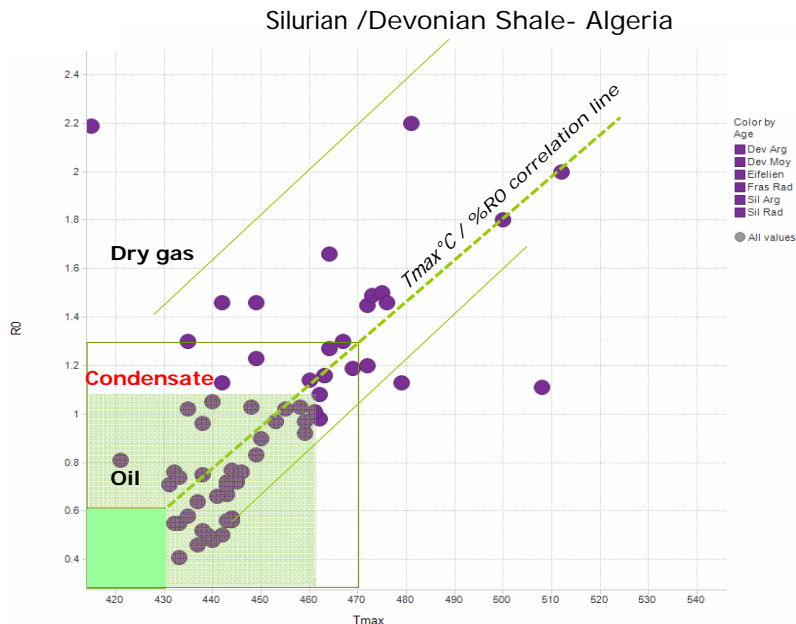
Presenter's notes: Frasnian radioactive shale of Algeria may have experienced a much lower organic matter transformation compared to its counterpart, Marcellus, in U.S., suggesting a remaining liquid potential.

Hydrogen/ Tmax°C Of The Silurian Illizi /Berkine



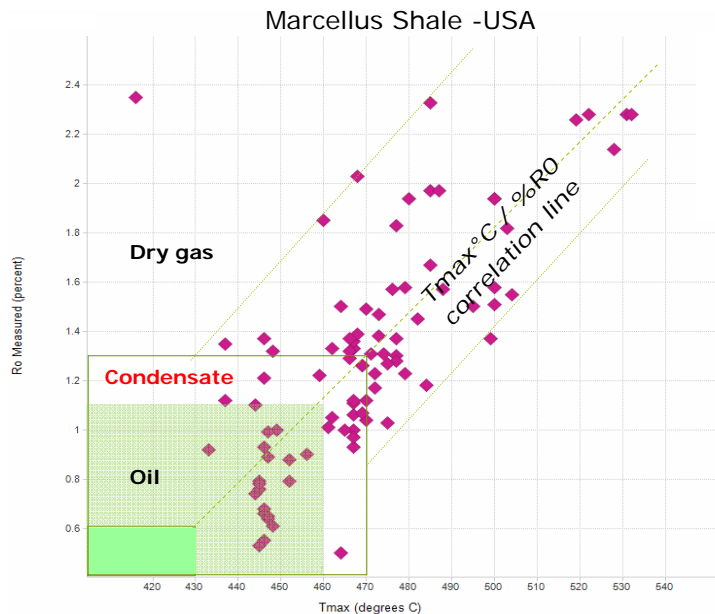
Presenter's notes: Silurian radioactive shale have been penetrated mainly in the Illizi basin, with only few penetrations in the Berkine at locations where the depth is not excessive. Hydrogen index, compared to the Frasnian, shows a moderate organic matter transformation, with liquid hydrocarbon still present in the source rock.

R_o Does Not Correlate to T_{max} °C in Older Shales



Presenter's notes: The R_o/T_{max} correlation is somewhat tentative; it seemingly is not conclusive for maturity assessment of Frasnian and Silurian radioactive shales. The lack of true vitrinite in Silurian and Devonian sediments presents a difficulty; for R_o performed on bitumen often overestimates the maturity reading.

Absence of R_o / T_{max} °C Correlation

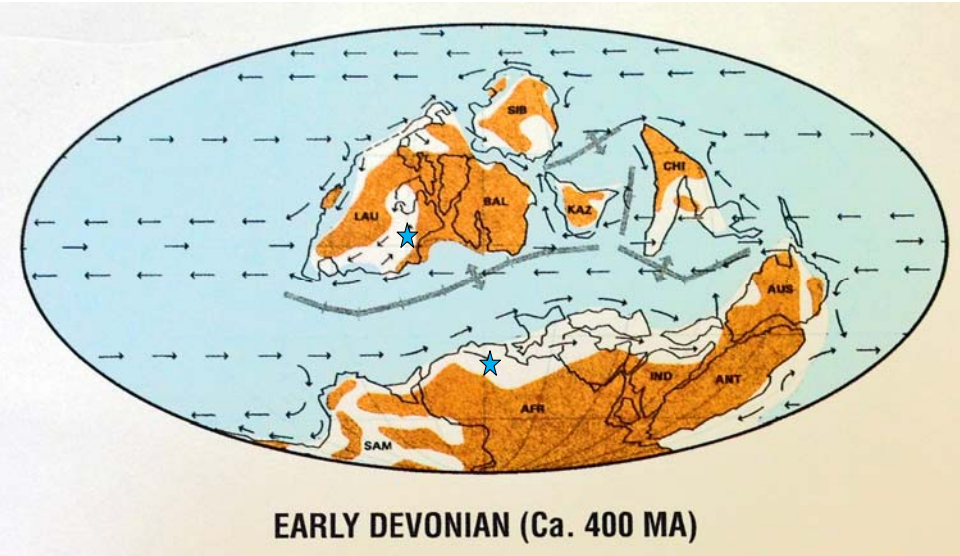


Presenter's notes: Marcellus Shale shows similar scatter and divergence in R_o / T_{max} °C correlation for the reasons notes earlier for Frasnian and Silurian radioactive shales.

The Late Appearance of Land Plants in Paleozoic SR

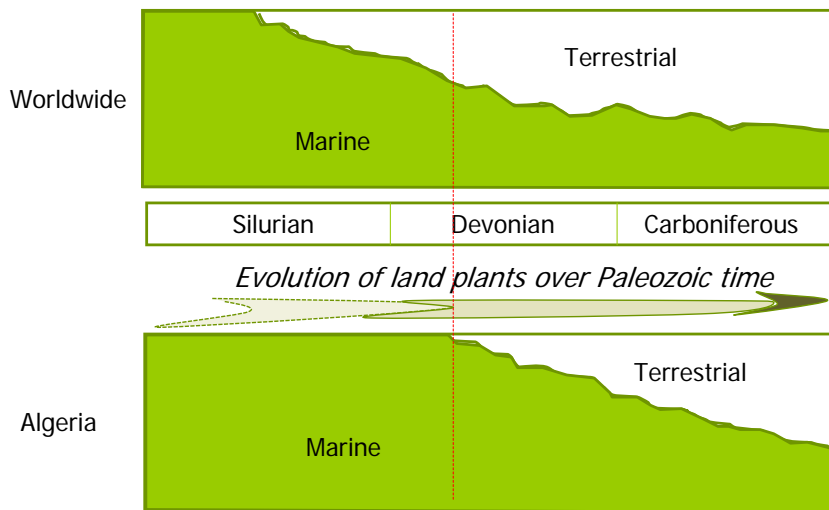
- In the absence of “true and universal thermal maturity marker” %Ro of vitrinite reflectance has been used for maturity assessment of all source rocks of different ages and lithologies.
- Vitrinite macerals (such as Collinite and Corpocollinite) may be rare or absent in Paleozoic source rocks. Therefore true measures of Vitrinite reflectance are difficult.
- Vitrinite may be confused with bitumen. This results in an overestimation of thermal maturity.
- RockEval Tmax°C fails to compensate for the Ro deficiency because of its own pitfalls: effect of free hydrocarbons present in the source rock, mineral matrix and thermal effect on the S2 peak.

Paleo-latitude position - impact on organic input: Frasnian & Marcellus



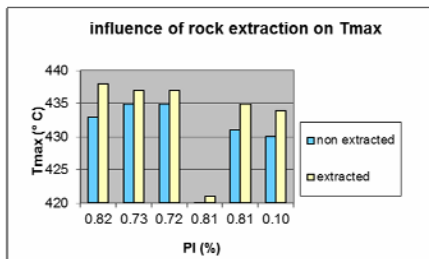
Presenter's notes: Paleo-latitude position and paleo-environment conditions of Laurasia suggest possible earlier development of land plants in eastern US basins than in Gondwana for Algerian basins.

Land plant appearance & presence in the Organic Input



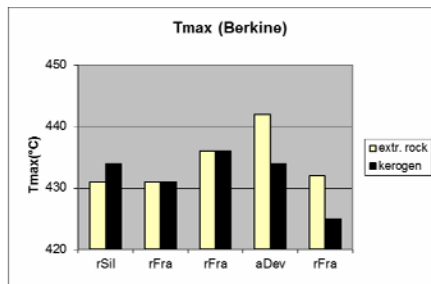
Presenter's notes: The relatively late apparition of land plants and their rareness in the palynofacies of Paleozoic in Algeria indicates the limitations of vitrinite reflectance as thermal maturity marker for SR in Illizi /Berkine.

Pyrolysis Tmax °C Pitfalls



1- Effect of Free Hydrocarbons on S2 Peak
Typical SARA SR extract

Sat	Aro	Res	Asp
47.8	4.3	46.0	1.8
34.8	15.8	41.0	8.4
23.1	27.8	46.5	2.6
32.7	22.7	40.9	3.7



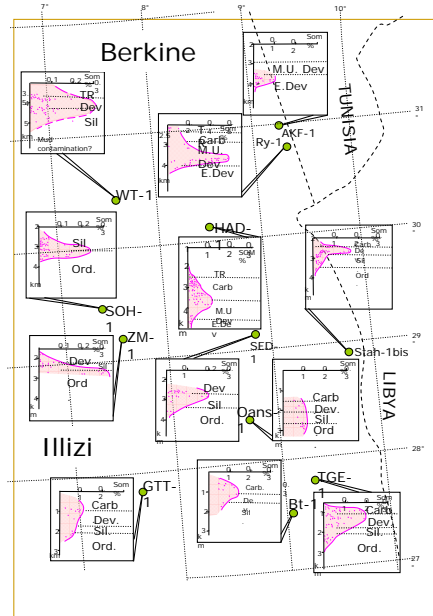
Data-- M. Vandenbroucke 2003

2 Effect of Mineral Matrix on RockEval Tmax°C

3-Thermal effect broadening peak S2 inducing false reading.

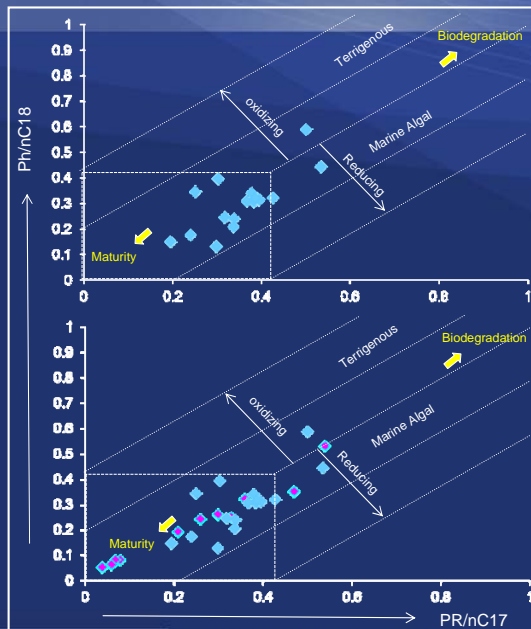
Presenter's notes: RockEval Tmax°C pyrolysis can be useful from the onset to the end of oil window if performed on samples from water-based mud drilled wells. Mixing data from oil-based and water-based muds yields conflicting results with variations in Tmax °C exceeding 5°C (Vandenbrouk, 2005). Tmax°C based on extracted kerogen may yield better results, but cost is less effective. Alternative would be a combination of maturity markers, including the soluble organic matter.

Soluble Organic Matter as a Maturity Indicator



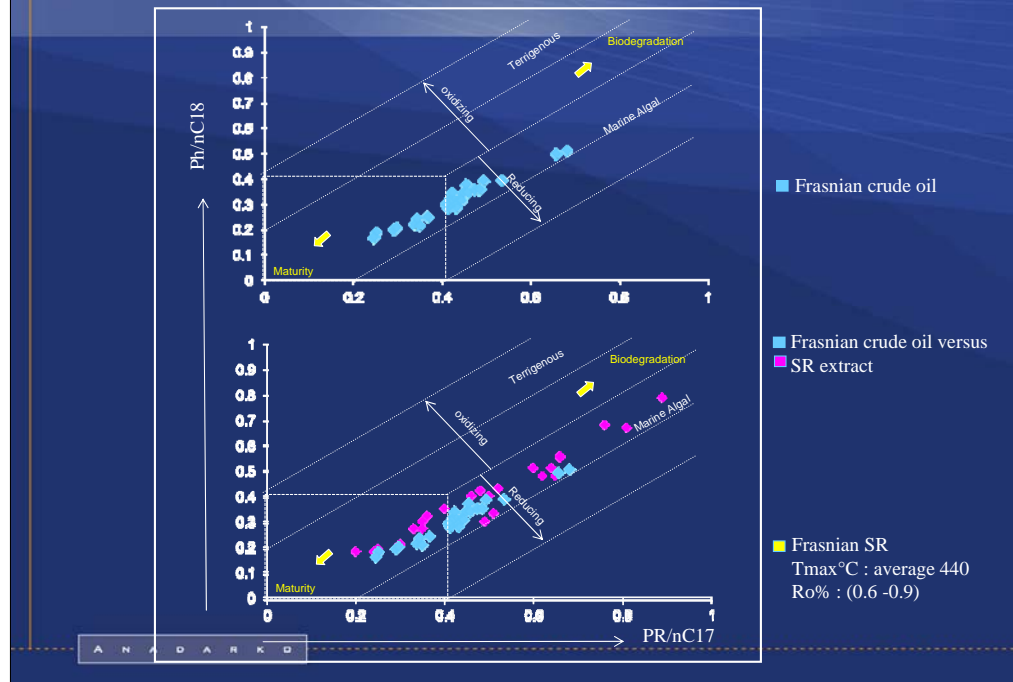
Presenter's notes: Organic matter extract can accurately assess maturity where samples are taken from water-based mud drilled wells and selected in the SR intervals.

Silurian: Oil to Source rock



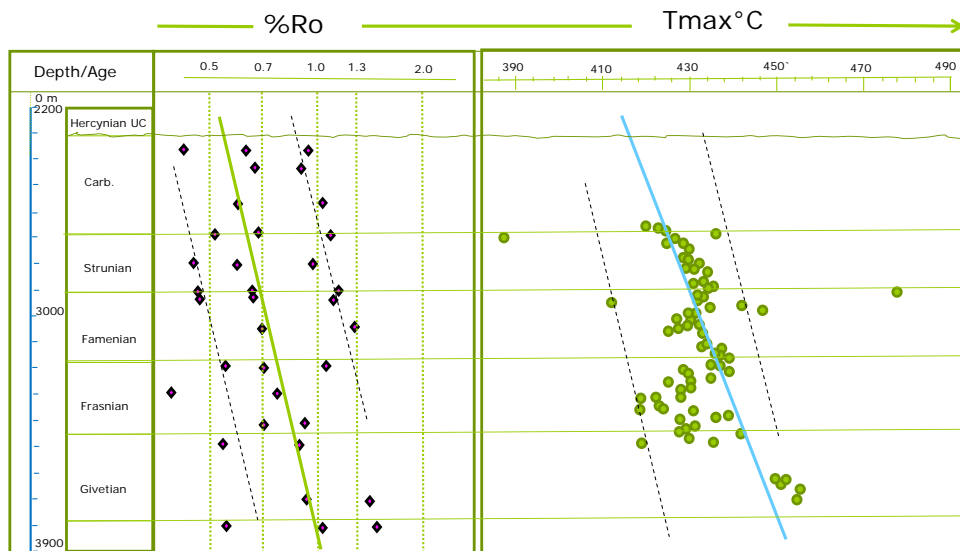
Presenter's notes: The overlap of maturity markers from soluble organic matter and oil indicates the range of thermal stress experienced by oil and the SR.

Frasnian : Oil to Source Rock

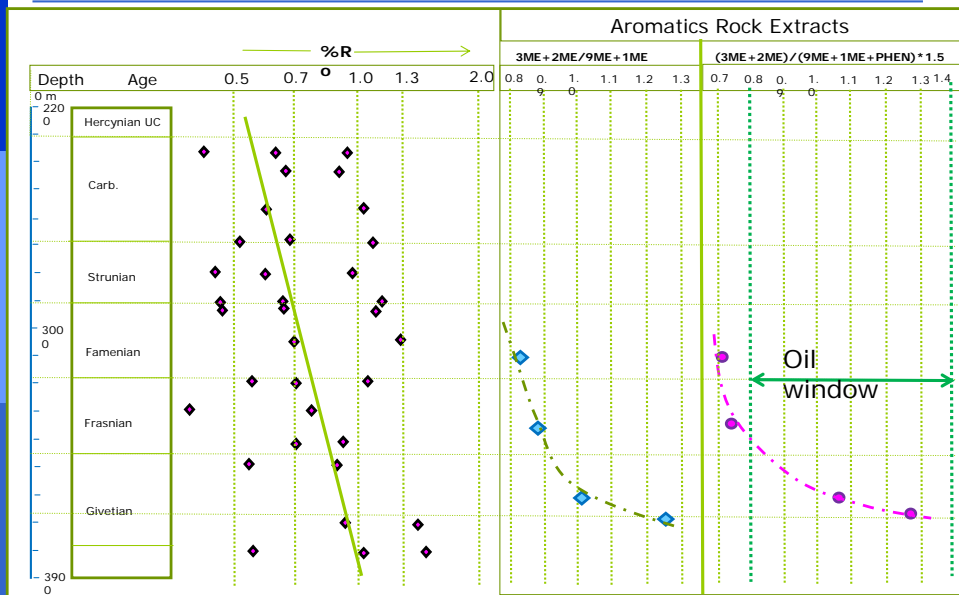


Presenter's notes: Rock extract from Frasnian SR and oil from Frasnian SR: maturity in the oil window range.

Berkine--what is the correct maturity trend?



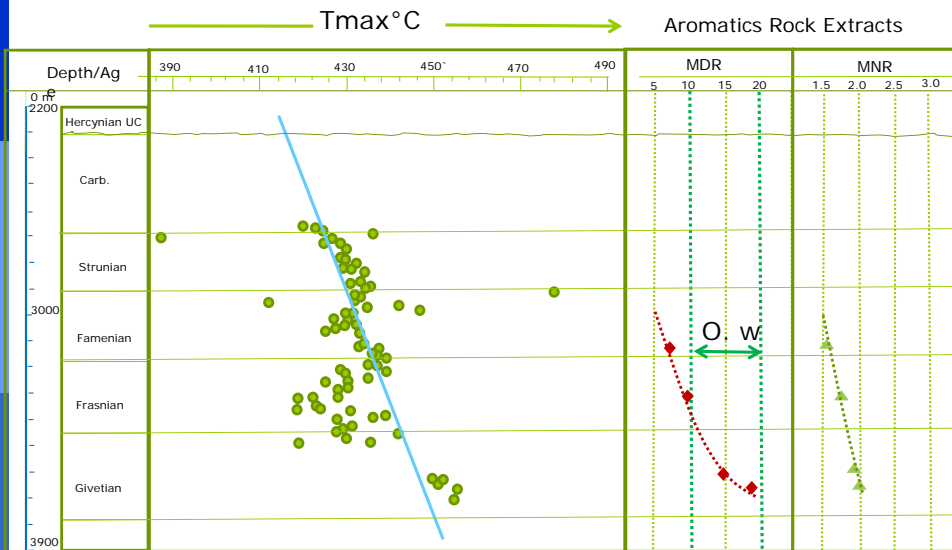
Phenanthrenes & MPI as substitute...



PHENANTHRENES: $\frac{(3ME+2ME)}{(9ME+1ME)}$

MPI-1 PHENANTHRENES: $\frac{(3ME+2ME)}{(9ME+1ME+PHEN)} * 1.5$

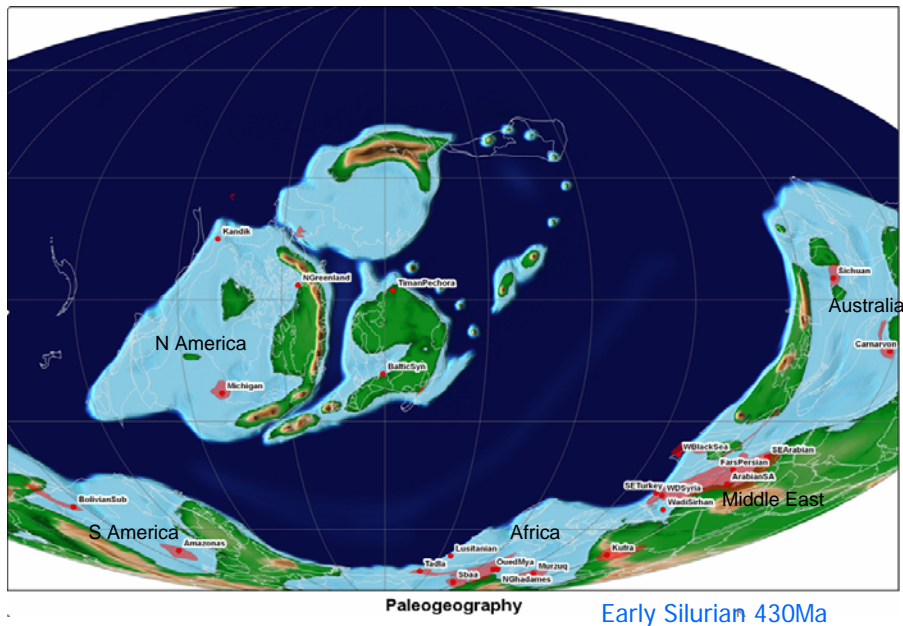
...Or Dibenzothiophenes and Naphtalene



MDR: 4-ME DIBENZOTHIOPHENE/ 1-ME DIBENZOTHIOPHENE

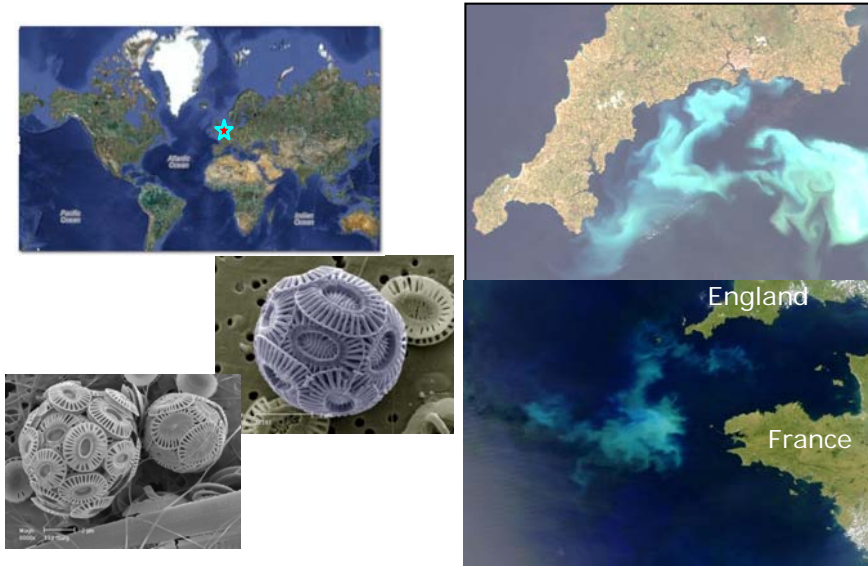
MNR: 2-ME NAPHTALENE/ 1-ME NAPHTALENE

Importance of Structured Kerogen for Shale Reservoirs in Algeria



Presenter's notes: Paleogeography of Africa and North America in the Early Silurian showed optimal conditions for a development of planktonic and algal organic matter. Note the wide distribution of the shallow water on the continental margins and their relations to seaways, enhancing biodiversity and organic productivity.

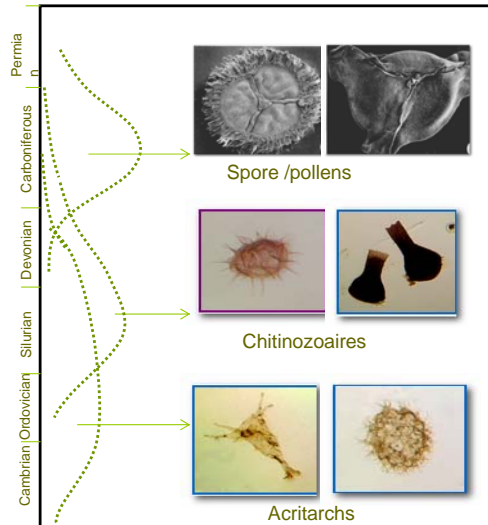
Modern Analogy: Algal Blooms Near England and France



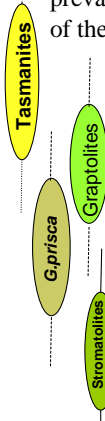
Reservoir Forming Coccolithophores: Blooms of *Emiliania huxleyi*, captured by satellite, are shown just off the coast of the United Kingdom. (U.S. Department of Energy Genome Programs, <http://genomics.energy.gov>.)

Presenter's notes: Algal bloom can develop in a very short time, given a combination of optimum factors-- nutrients, sun light, temperature, etc., that cause rapid increase in the population of algae and in their accumulation in an aquatic system.

Paleozoic Structured Kerogen



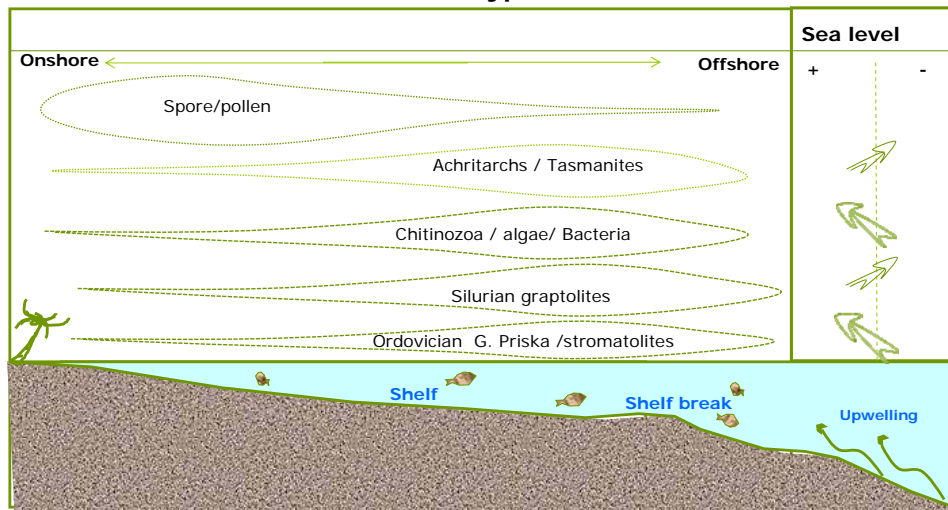
Remains from the Paleozoic palynomorphs suggest that labile kerogen dominated by marine algae and micro-phytoplankton was prevalent in the organic matter input of the Paleozoic source.



Presenter's notes: Palynological assemblages of these episodes showed a predominance of organic content derived from very shallow marine dominated by algal and plankton material. The structured kerogen, represented by Acritarchs, Chitinozoans, spores and pollens in the palynomorphs, is often associated with amorphous organic content as part of bacterial and the labile fractions. Other representative types include graptolites and Tasmanite cysts that should have clear and distinctive markers within oil fractions and biomarkers.

Structured Kerogen and its Potential in Shale Reservoirs

Paleozoic Facies Type



Marine transgressive and regressive cycles controlling the algal bloom of Paleozoic epicontinental seas

Presenter's notes: Typical and unique palynofacies developed in response to the transgressive/regressive cycles that occurred on very low relief shelf that extended deep into the continent; the high organic productivity resulted from the algal blooms, and the organic-matter preservation was a result of productivity exceeding the consumption. The shelf break is another high productivity/ organic matter preservation zone where upwelling is the driving mechanism

Conclusions

- Devonian Shales of Algeria and Eastern US (Appalachian, Illinois, and Michigan) basins were deposited in shallow-marine environments.
- The low-relief shelves allowed extensive transgressions. Multiple algal bloom events provided significant organic deposits in a very short time. Truly anoxic conditions were exceptional and rare, and organic matter was preserved whenever productivity exceeded consumption.
- The Paleozoic organic-rich units were identified and correlated on geophysical logs by their higher gamma and increased neutron response.
- Distinctive lithology of organic-rich units consist mainly of structured organic content showing predominantly Chitinozoa/Acritarch and Graptolites for the Silurian and Chitinozoa/Spore Pollen and Tasmanites for the Devonian will have specific shale reservoir characteristics.
- In the absence of universal and independent maturity markers, Vitrinite Reflectance and Pyrolysis RockEval must be supported and refined by indications from soluble organic matter.
- It is fundamental for shale exploration to narrow the maturity and transitions between organic phases.

Acknowledgment

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Questions

