

Regional Upwelling During Late Devonian Woodford Deposition in Oklahoma and Its Influence on Hydrocarbon Production and Well Completion*

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Search and Discovery Article #80410 (2014)**

Posted October 6, 2014

*Adapted from oral presentation given at AAPG Education Directorate Woodford Shale Forum, Oklahoma City, Oklahoma, May 29, 2014.

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Abstract

The Woodford Shale in Oklahoma is an organic-rich, dark grey Upper Devonian to Lower Mississippian marine mudstone that is a major hydrocarbon source rock. Since the mid-2000's, it has become a major unconventional resource play and a prolific producer of hydrocarbons across the state. In the deep parts of the Anadarko Basin, it reaches a thickness of more than 900 ft. (Amsden, 1975). Comer (2008) presented the most comprehensive regional depositional synthesis of the Woodford noting the importance of marine upwelling in the preservation of its high organic content and its generation of the “chert” facies that is so prevalent in the Arkoma and eastern margins of the Anadarko basins. The importance of understanding the lateral changes of its upwelling facies, that Comer noted, is probably not appreciated from an economic perspective, however. Changes in upwelling facies have an impact on drilling, completions and production and perhaps even in the timing of hydrocarbon generation.

Deep Marine Upwelling

Comer (2012) proposed that upwelling extant during Woodford time was the result of aridity and high evaporation rates within the shallow epicontinental seaway that existed across the southern U.S. at that time. High biologic production in surface waters resulted from the upwelling of deeper nutrient-rich waters to replace those lost by high evaporation rates. Hypersaline brines, in Comer's model, promoted density stratification and severely restricted vertical water circulation therefore enhancing bottom stagnation and organic matter preservation.

Our studies, while agreeing with Comer's basic premise of upwelling, suggest to us that aridity and high evaporation rates may not have been the primary driver for upwelling. We propose that upwelling during the late Devonian and early Mississippian Woodford time was more related to regional deep marine coastal upwelling, a function of Hadley circulation and the formation of, what was during the Devonian, a southeasterly Trade Wind blowing parallel to a west-facing North American craton.

Ancient coastal upwelling systems are recognized using a number of criteria. All coastal upwelling systems today are situated within the major trade wind belts on west-facing coastlines as were, presumably, the ancient ones. They are characterized by high organic productivity and high sedimentation rates (as high as 2 m/1ka) producing organic-rich sediments that exhibit little, if any, bioturbation under the upwelling zones. Sediments associated with these systems typically have elevated concentrations of phosphorite, and uranium and other metals. The sea-floor under modern upwelling zones are covered with opal-rich sediments because of the high productivity of silica-rich organisms such as radiolarians at low-latitudes and diatoms at high latitudes. Ancient examples contain abundant chert beds of biogenic origin. The high productivity of phyto- and zoo-plankton also leads to high fish production and concentrations of fish debris in sediments. Surface waters over upwelling zones are typically colder than surrounding regions and may therefore be typified by cold-water fauna (from Diester-Haass 1978).

Regional facies variations in the Woodford reflect a variety of factors. Paleogeography, submarine sediment dispersal systems, and position to upwelling currents all affected Woodford facies. Most of the Woodford facies can be explained in the context of proximity to a major late Devonian to early Mississippian upwelling center that existed to the southeast of Oklahoma.

General Lithofacies

The Woodford is mostly a non-calcareous organic-rich mudstone. Much of the Woodford across the Arkoma and southern portions of the Anadarko basins are dominated by chert-rich beds. The cherts formed as a result of the diagenetic alteration of siliceous microfossils, particularly radiolarians, the remnants of which are prevalent within thin sections of the Woodford chert. Like carbonates, the Woodford is composed of debris and organisms that lived primarily within the water-column or accumulated at the sea-floor. The only terrestrial component to most Woodford facies appears to have been transported as wind-blown dust. Besides radiolarians, other common fossils include *Tasmanites* (remains of green algae). Other much less common fossils include linguloid brachiopods, fish scales, shark coprolites, conodonts, and, in the northern portions of the Arkoma and Anadarko around the Nemaha Ridge, terrestrially derived wood fragments, goniatites, and rare bryozoan fragments. Trace fossils are locally abundant although, in most cases, not diverse.

In the context of a coastal upwelling model, the distribution of fossils and lithofacies within the Woodford can be explained and predicted. For instance, the distribution of the radiolarian-bearing chert facies within the Woodford is constrained to the Arkoma Basin and southern end of the Anadarko Basin. This facies is equivalent to the Arkansas Novaculite and is a direct indicator of coastal upwelling having formed just inland of the Late Devonian shelf-slope break. The dominance of radiolarians within beds marks the intervals and regions where coastal upwelling was most intense. Facies not deposited under the direct influence of upwelling are more fossiliferous. They commonly lack radiolarians but preserve organic-rich non-bioturbated mudstone facies that may alternate with two-dimensionally (*Nerites* ichnofacies) and three-dimensionally bioturbated intervals (*Zoophycos* ichnofacies). Such traces are typical of having formed under stressed conditions. Sediments within the Woodford reflect a combination of erosive and depositional processes that may reflect internal waves formed along pycnoclines, contourites, and/or sediment gravity flows that mobilized fluidized muds at the sediment-water interface. Sandstone and coarse siltstone beds composed of reworked conodonts, pyrite grains, fish debris, lingulids, and pyritized *Tasmanites* debris are common in some intervals and were likely concentrated by bottom currents.

Paleotopography

Paleotopography was important in the distribution of Woodford facies. The presence of the north-south trending Nemaha Ridge, which separates the Anadarko and Arkoma basins, prevented the distribution of the chert-rich upwelling facies so typical of the Arkoma Basin into the Anadarko Basin through most of Woodford deposition. The exception is the southernmost portion of the Anadarko Basin to which the Nemaha Ridge did not extend. As a result there are more bioturbated intervals within the Woodford west of the Nemaha Ridge than in the Woodford east of the Ridge. The deep upwelling facies also decreases rapidly from the Arkoma Basin northward onto the Cherokee Platform which was also a positive feature for much of Woodford deposition.

Drilling, Completions, and Production

Facies types in the Woodford have a big impact on the economics of a Woodford well. For instance, drilling through the chert-rich upwelling facies results in slower drilling and a reluctance on the part of drilling engineers to cut a core to evaluate that part of the Woodford. It is also the most brittle of the Woodford facies and the most prone to having developed natural fractures. It therefore can be expected to have the best fracture permeability and porosity and perhaps best potential liquids recovery. The 3-dimensionally bioturbated intervals, although individually thin (only a few centimeters to 30 centimeters thick), and often overlooked in whole core sampling, are generally non-reservoir facies (very low TOC, higher clay contents, more ductile). When stacked up into intervals of alternating bioturbated (non-reservoir) rock and unbioturbated (reservoir) rock, they create problems with frack initiation because of their ductility and can significantly reduce a well's EUR.

The presence of *Tasmanites* algae is also of interest. *Tasmanites* are nearly ubiquitous within the Woodford. They are present in association with the remains of radiolarian cysts but can also dominate the microfossil assemblage within the more distal portions of the deep upwelling facies (radiolarians are either not present or constitute minor fossil components). *Tasmanites* are so abundant within much of the Woodford that they must have been a major source for the hydrocarbons present within the formation. Recent studies suggest that the kinetics of hydrocarbon generation in beds that contain *Tasmanites* are different than beds containing other types of marine organics. Specifically, Vigran et al., 2008 showed that hydrocarbon generation within *Tasmanites*-enriched beds start generating hydrocarbons at significantly higher temperatures than other marine source rocks (Tmax as much as 15 degrees C higher than other non-*Tasmanites* bearing marine source rocks used in their study). This suggests that the onset of peak oil generation in Woodford beds dominated by *Tasmanites* will be higher than beds that are not dominated by *Tasmanites*.

Conclusions

Thermal maturity and thickness are important factors to producing hydrocarbons from the Woodford Shale. However, facies variability is significant over a regional area and is a factor in selecting landing zones, completions strategies, and prospecting for liquids recovery.

Acknowledgment

The authors thank Devon Energy for allowing the release and publication of this information. The authors also acknowledge Dave O'Bright and Chris Flenthope for their insightful discussions on Woodford production, facies, and economics.

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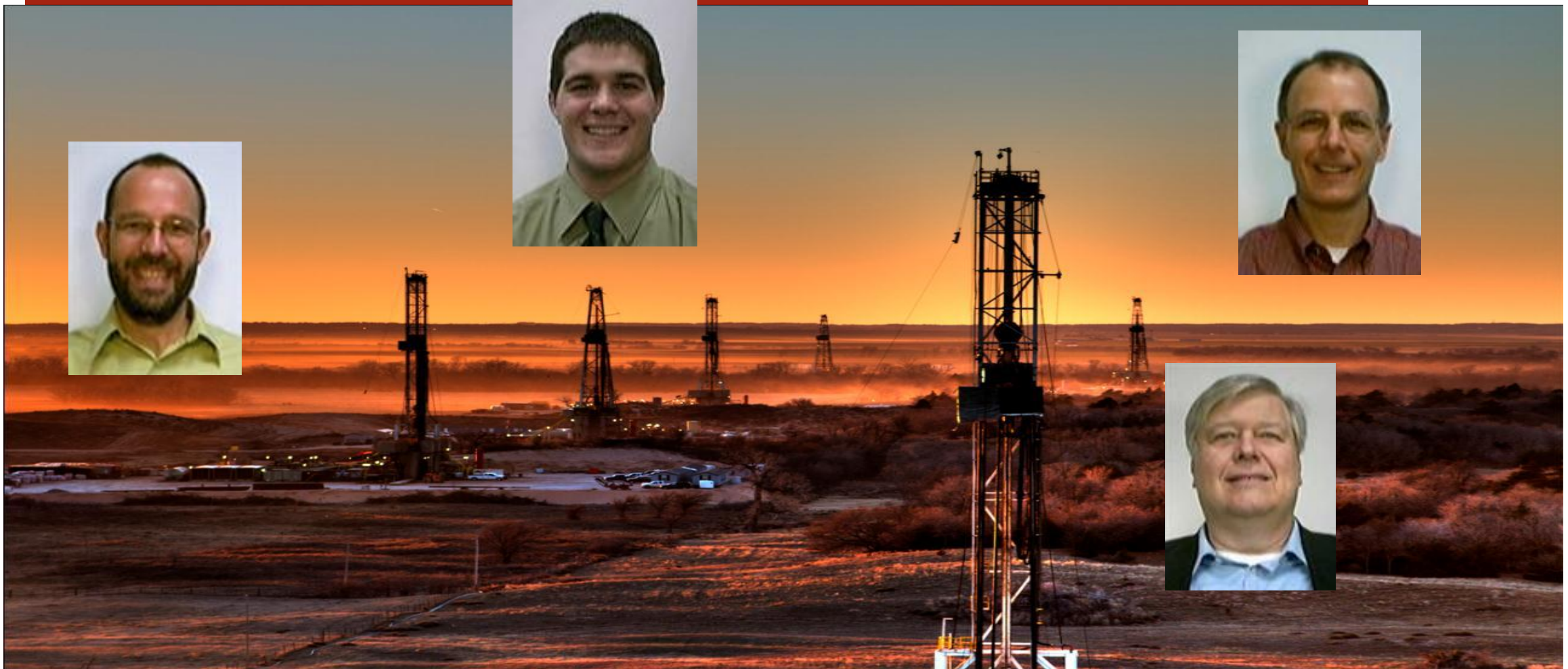
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Regional upwelling during Late Devonian Woodford deposition in Oklahoma and its influence on hydrocarbon production and well completions

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Special thanks to Dave O'Bright, Chris Flenthrope, Bill Coffey and Bob Olson, Devon Energy



Key points

- What is the Woodford?
 - Distribution
 - Production
- Environment of deposition (EOD)
 - Can facies variability be explained?
- Impacts of facies on production/completions
- Role of tectonics and paleotopography in Woodford production



What is the Woodford Shale?

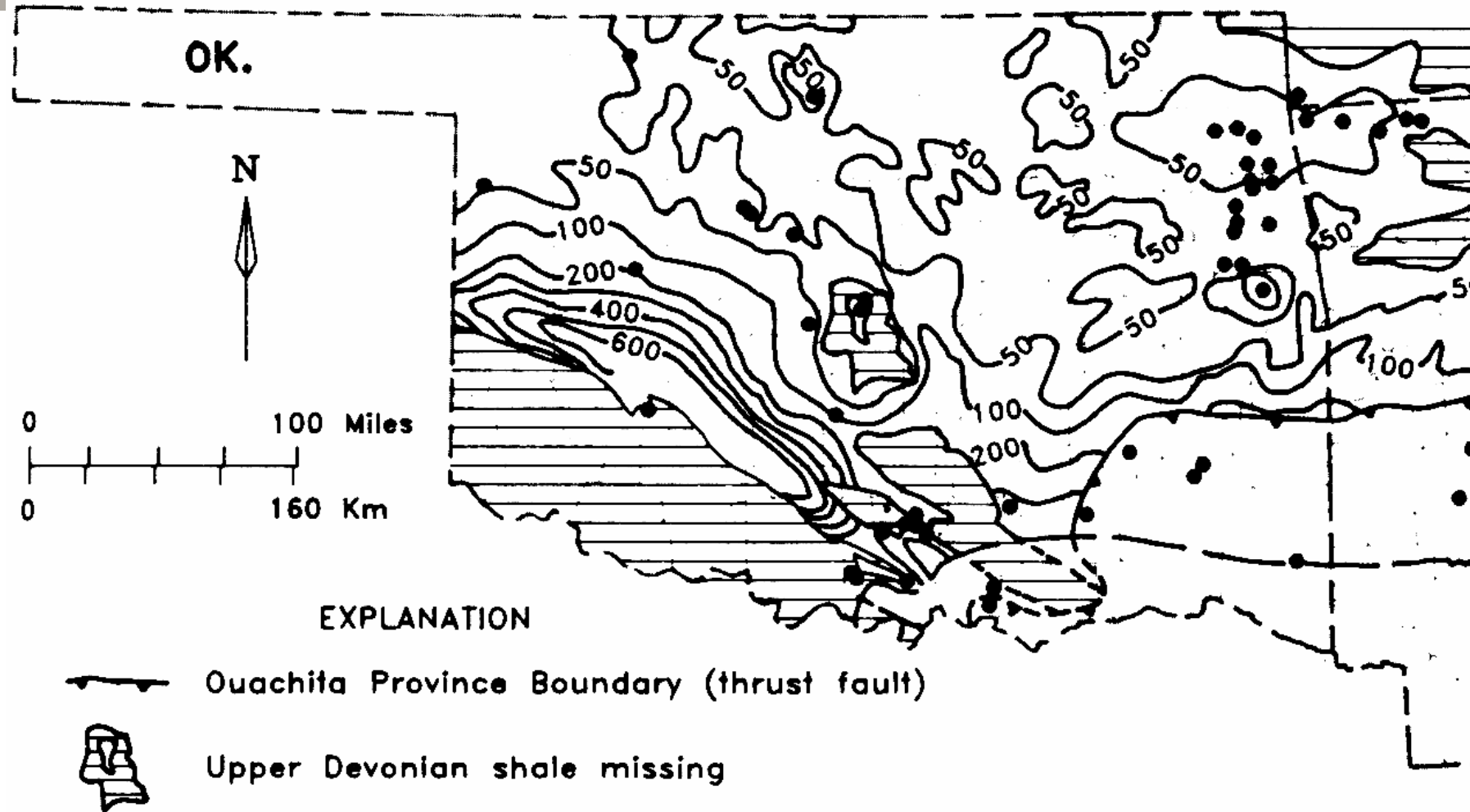
SYSTEM	UNIT
PERMIAN	U
	Leonardian
	L
	Wolfcampian
PENNSYLVANIAN	U
	Virgilian
	Missourian
	Desmoinesian
	M
MISSISSIPPIAN	L
	Atokan
	Morrowan
	Chesterian
DEVONIAN	U
	Meramecian
	Osagean
SILURIAN	L
	Kinderhookian
	Woodford – Chattanooga
SILURIAN	M
	Misener
SILURIAN	L
	Hunton Group
ORDOVICIAN	U
	Viola Ls.
ORDOVICIAN	M
	Simpson Group
ORDOVICIAN	L
	Arbuckle Group
CAMBRIAN	U
	Timbered Hills Gp. – Reagan Ss.
CAMBRIAN	M
PRECAMBRIAN	L
	Undifferentiated



What is the Woodford? - depends where one looks.

- Up to 600 ft thick
- Siliceous Mudstone
 - Mostly non-calcareous but can be slightly calcareous in some areas
- Chert-rich in some areas/intervals but not in others
- Generally non-fossiliferous, but in some areas/intervals fossils are quite common
- Organic-rich (up to 14%TOC) except in heavily bioturbated intervals
- From each Woodford well one can identify an “upper”, “middle”, and “lower” Woodford but they are not necessarily age-equivalents
- 3-10% porosity with nano-darcy scale matrix permeability

Woodford isopach map

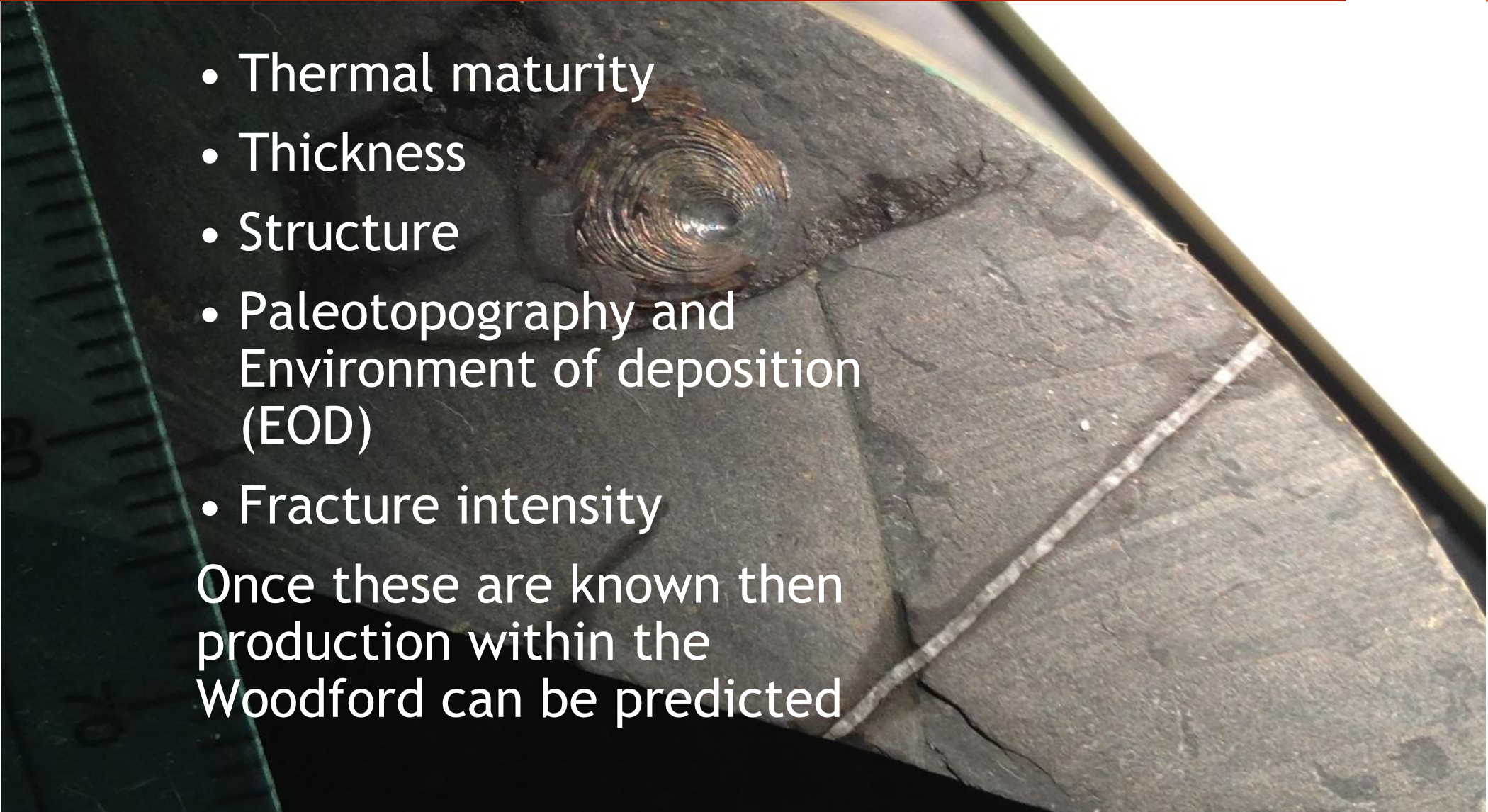


From Comer, J. B, 1992, Oklahoma Geological Survey, Circular 93, p. 70-93.

What accounts for Woodford production?

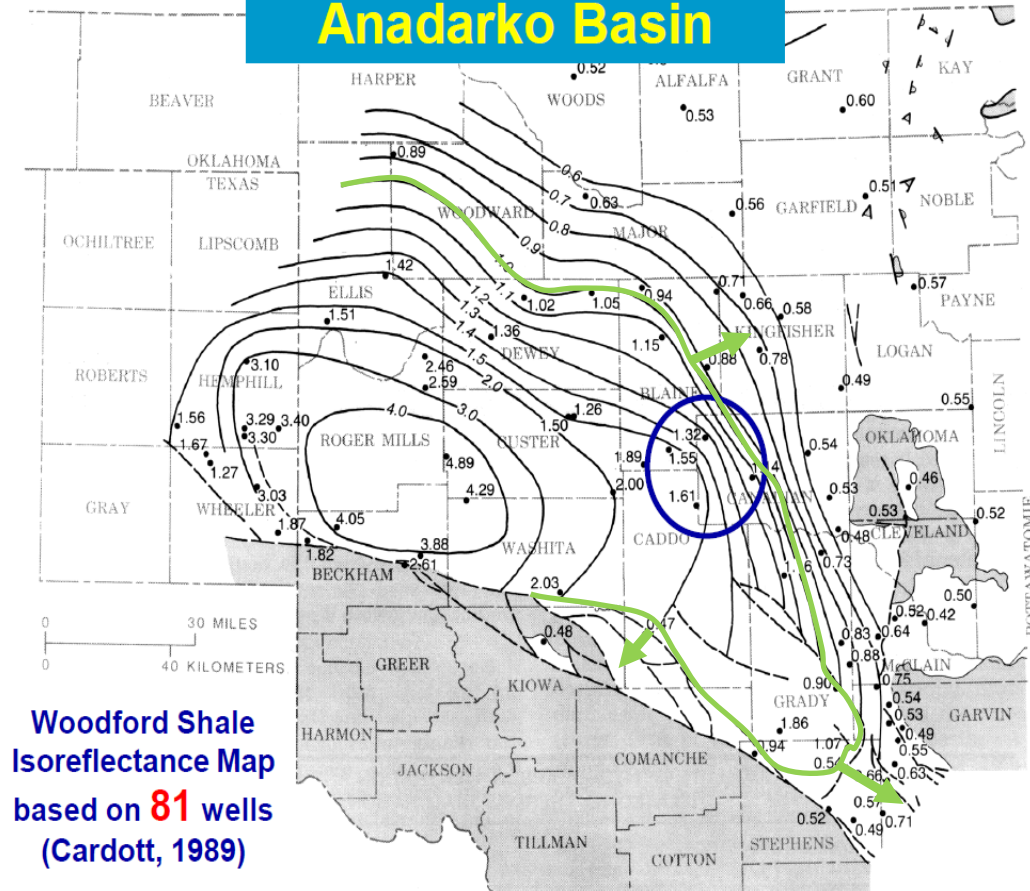
- Thermal maturity
- Thickness
- Structure
- Paleotopography and Environment of deposition (EOD)
- Fracture intensity

Once these are known then production within the Woodford can be predicted



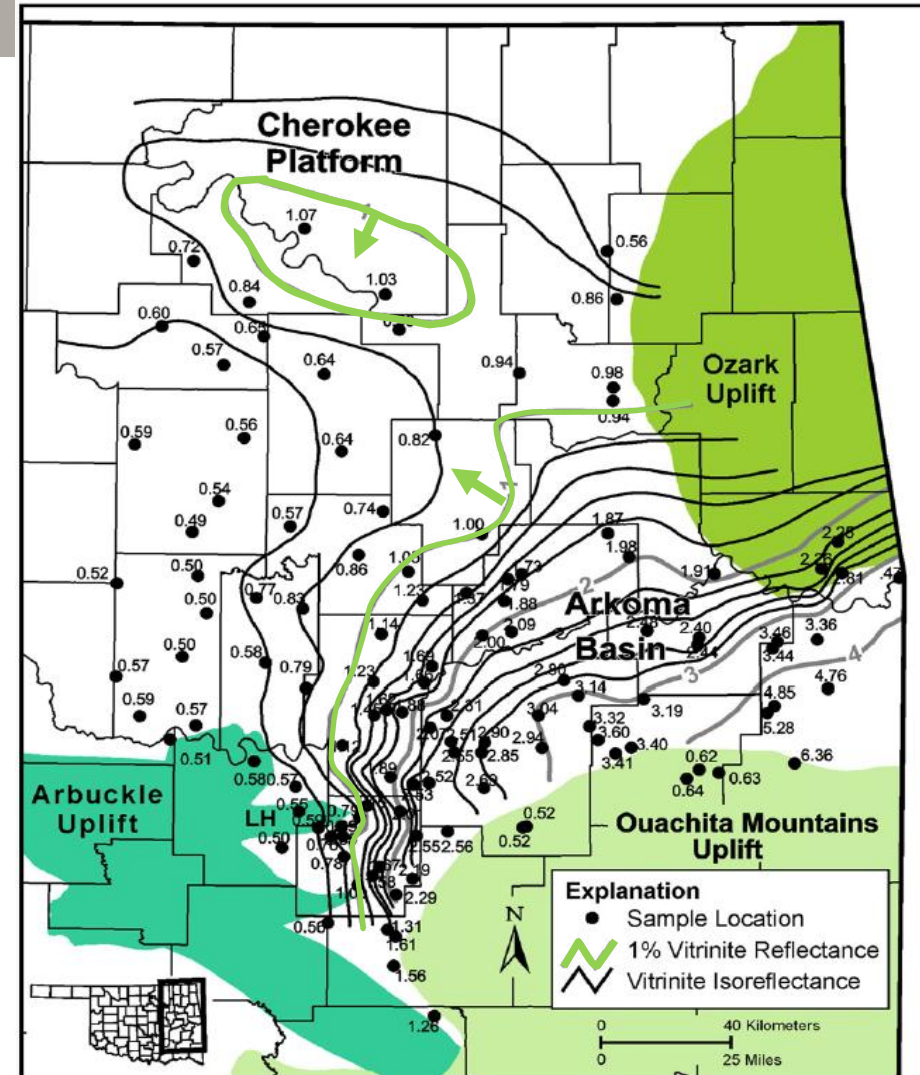
Thermal Maturity

Anadarko Basin

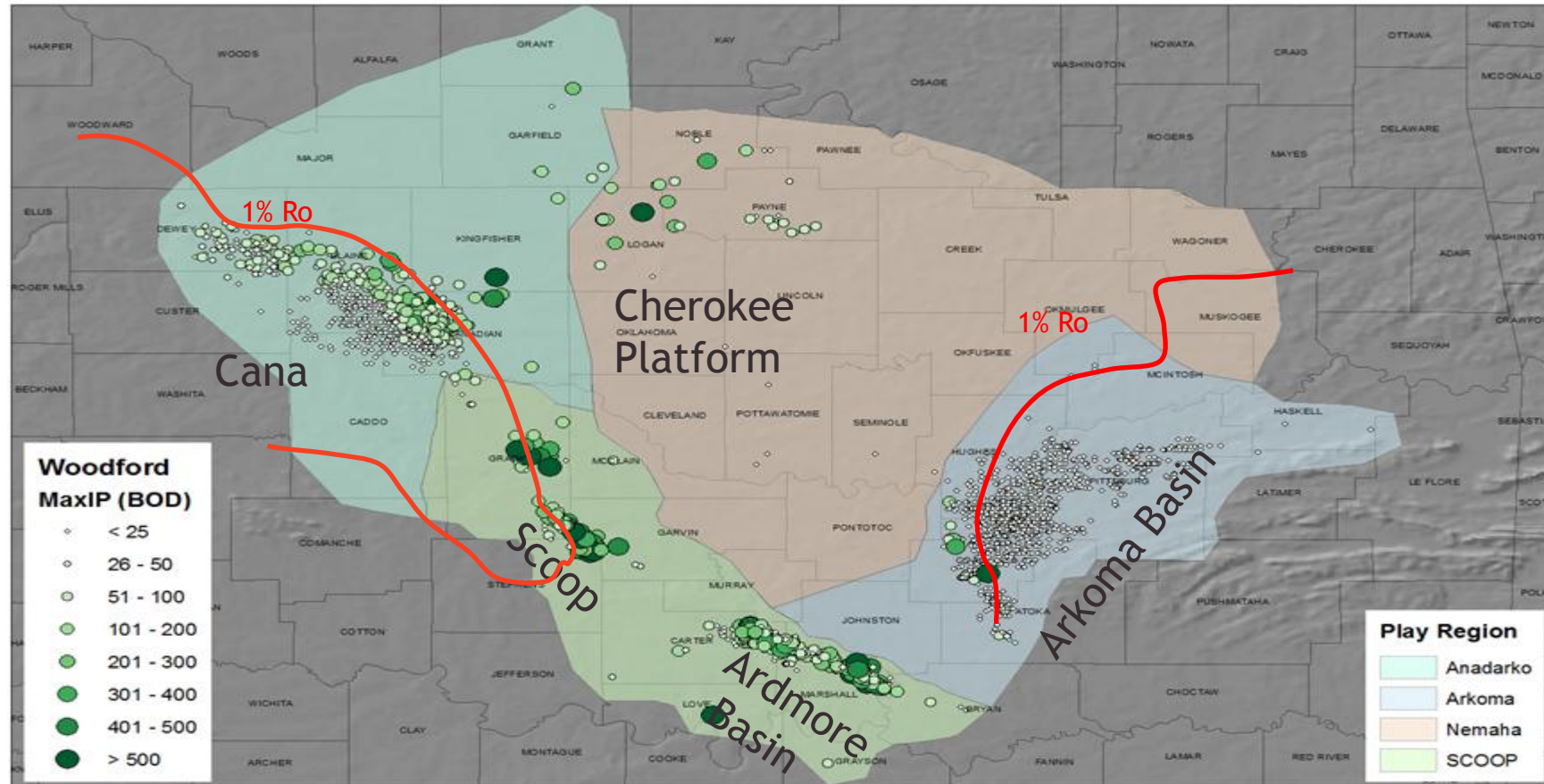


Woodford Shale
Isoreflectance Map
based on 81 wells
(Cardott, 1989)

<http://www.ogs.ou.edu/fossilfuels/pdf/2013CardAAPGWoodford.pdf>



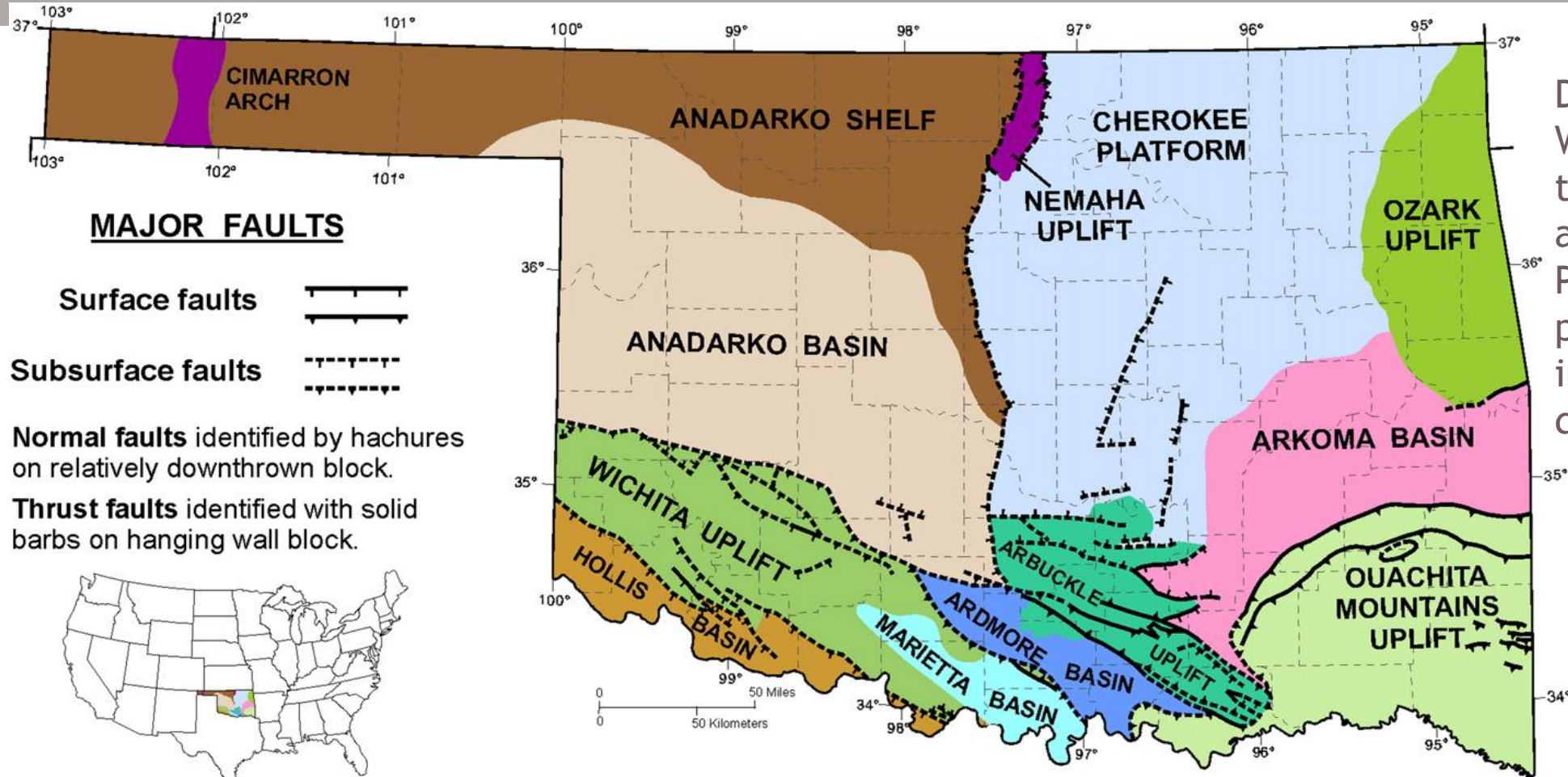
Woodford Max IP Oil (BOD)



**Woodford
MaxIP Oil 2001 - 2013**

<http://info.drillinginfo.com/oklahoma-oil-and-gas-woodford-scoop-wells-stamina/>

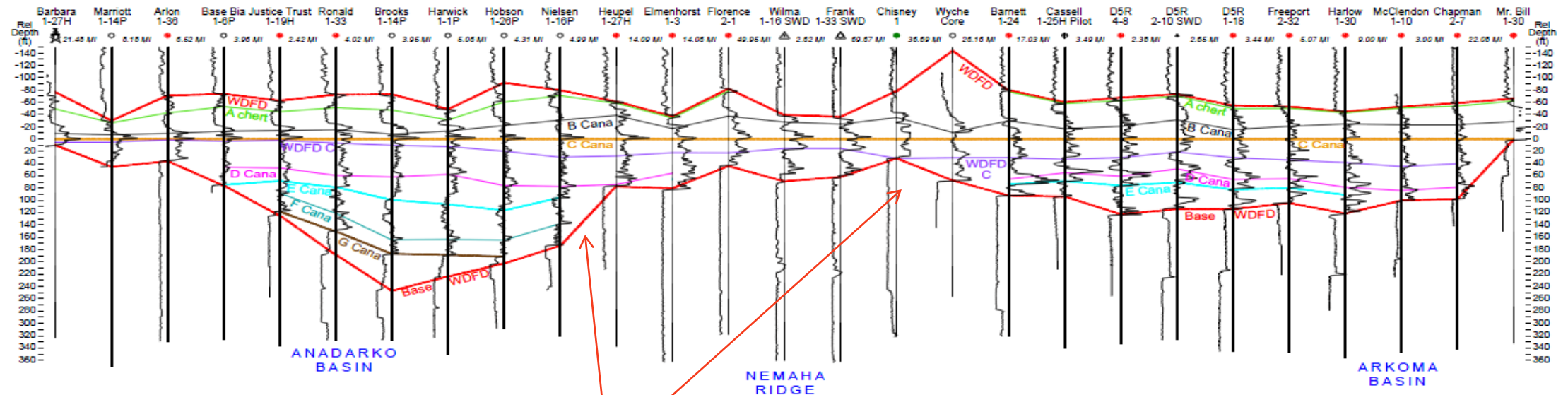
Paleotopography is important too...



During early Woodford deposition the Nemaha Uplift and the Cherokee Platform were positive and influenced Woodford deposition

From Cardott, B. J., 2012, Thermal maturity of Woodford Shale gas and oil plays, Oklahoma, USA, International Journal of Coal Geology, v. 103, p. 109-119

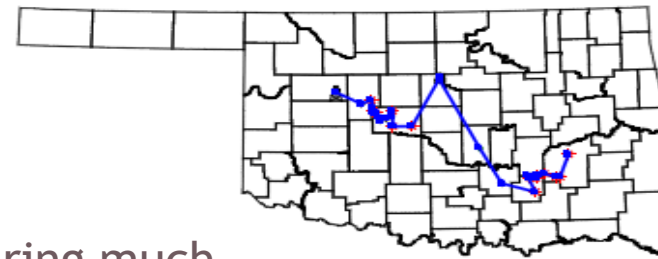
Paleotopography - Woodford deposition on-laped Nemaha Ridge and Cherokee Platform



Note on-lapping of facies

Figure 12. Cross section extending from the Barbara 1-27 core in the West Cana, Anadarko Basin (left) to the Mr. Bill core to the east in the Arkoma Basin.

Nemaha Ridge was positive during much of Woodford deposition

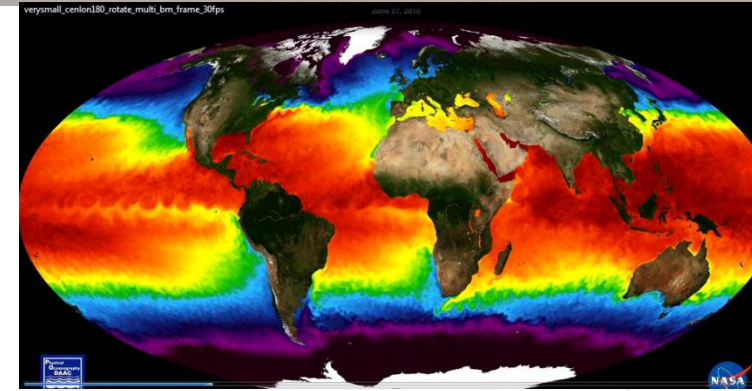
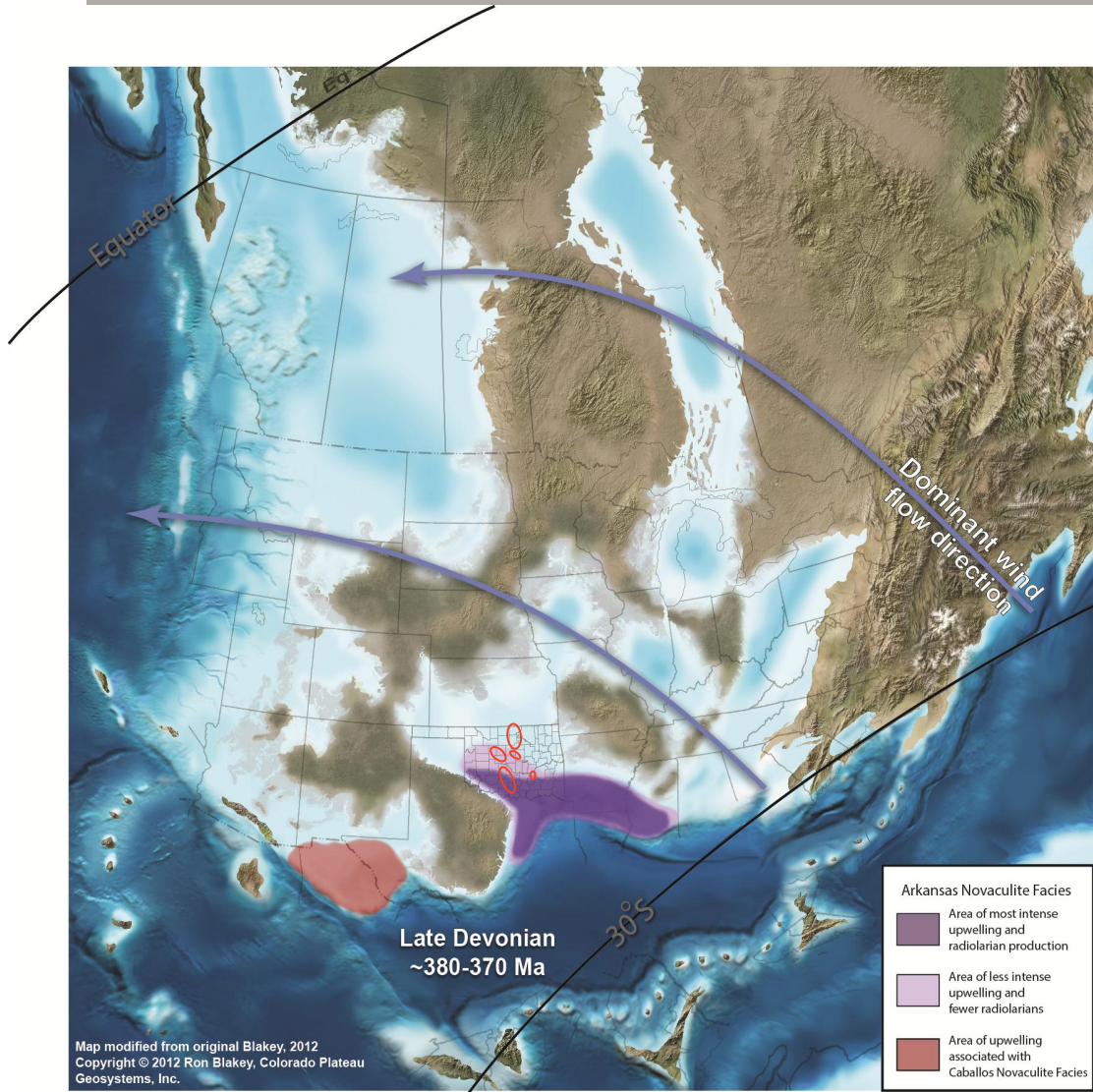


The Woodford is often characterized as being “cherty”

- Very indurated
- Bluish tint
- Mostly massive
- Diamictite-like with coarser grains (radiolarians, Tasmanites, and mudstone rip-ups floating in a finer grained matrix)
- Erosive bases with gradational to sharp tops
- Interlayered with laminated to faintly laminated siliceous mudstones that contain fewer radiolarians and more Tasmanites.



WDFD chert is derived from radiolarians but these are not the only source for chert.



Northridge (abundant silica in matrix)

radiolarian (siliceous skeleton of a single cell organism with extensions radiating from the body)

Tasmanites (large spherical fossil that represents the "body" of certain green algae)

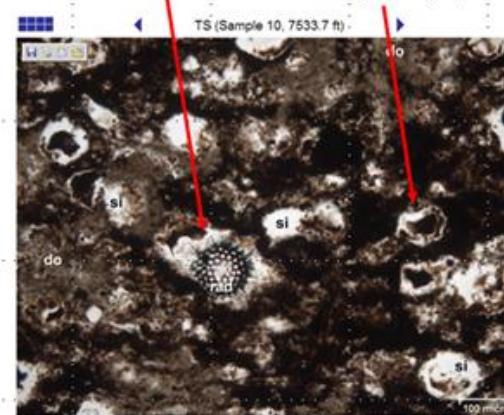
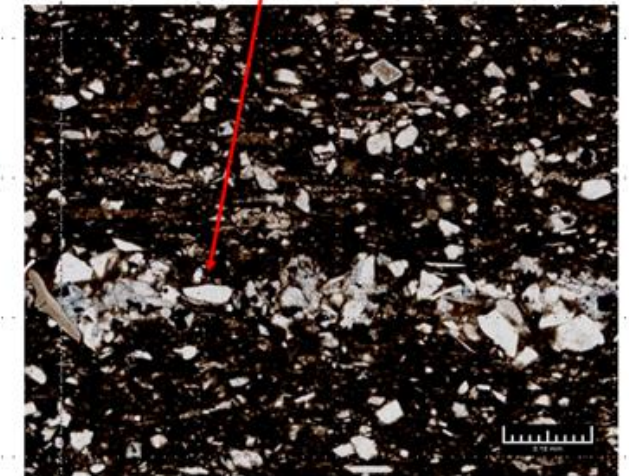


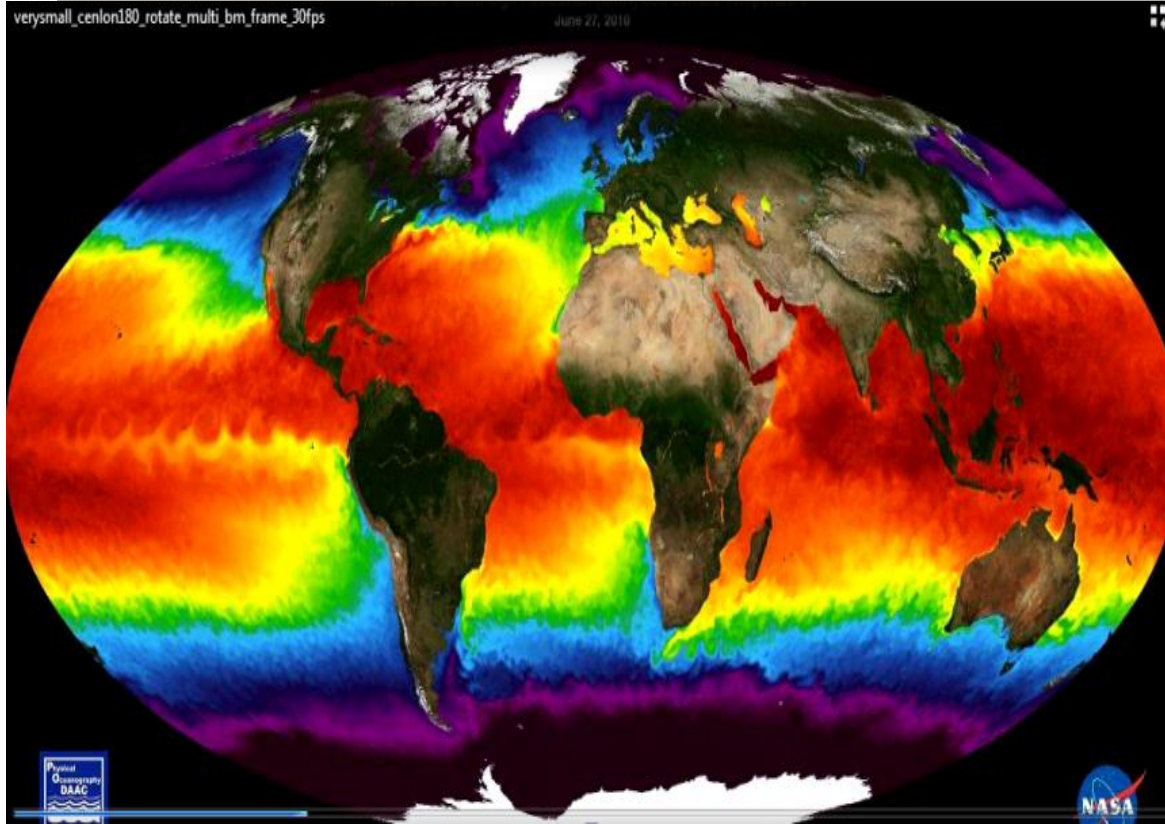
Image 12. Cherty microtexture at higher magnification. Lobate, irregularly shaped tasmanite cysts are fused and recrystallized to form a tightly cemented, brittle layer. Close inspection also reveals scattered radiolarian tests (rad) preserved in siliceous cement. Patches of dolomite (do) and replacive pyrite also contribute to porosity reduction and higher strength. Dark, opaque patches are organic and pyritic. (Plane polarized light. Scale bar = 100 microns)

Cana (less silica in matrix)

Detrital quartz (wind blown)



Woodford EOD - modern analogs are associated with coastal upwelling systems.

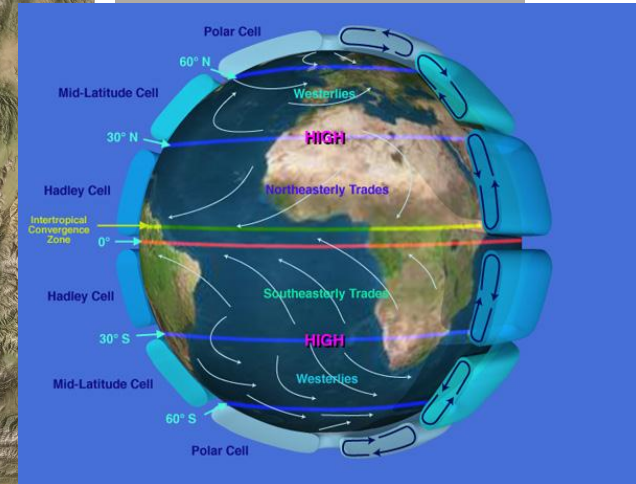
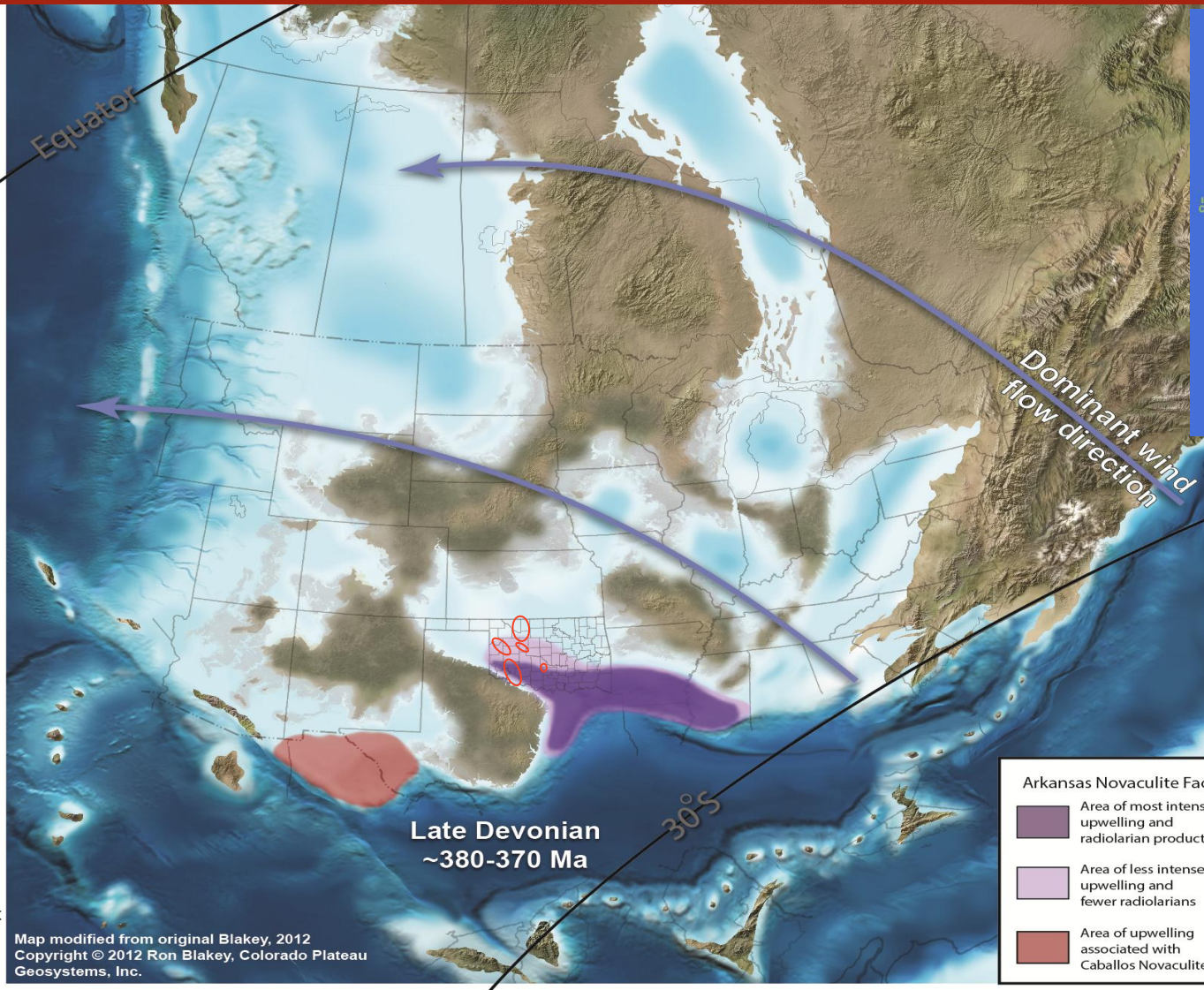


There are at least 5 major deep water upwelling systems in the world

- Some characteristics of coastal upwelling systems*:
 - Situated in major trade wind belts
 - Lower water temperatures
 - High organic productivity
 - Areas of high sedimentation rates up to 150- 200 cm/1000 yrs. (mostly derived from water column and not surface run-off)
 - Sediments have elevated concentrations of phosphorite and U and other metals
 - Sea-floor is covered with opal-rich sediments because of high productivity of silica-rich organisms such as radiolarians at low-latitudes and diatoms in high latitudes. Terrigenous sediments dilute opal concentrations.
 - High productivity of phyto- and zoo-plankton leads to high fish production and concentrations of fish debris in sediments

*(L.D-Haass, 1978, Sediments as Indicators of Upwelling, Springer-Verlag)

Woodford paleogeography



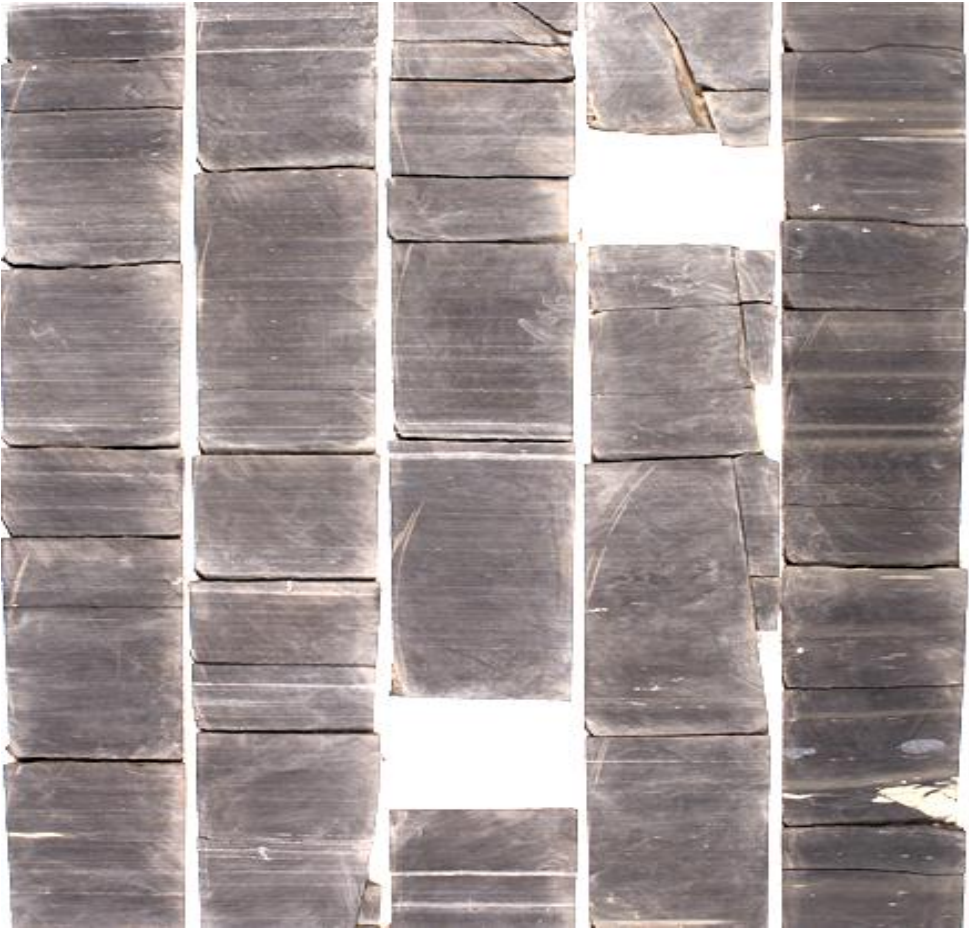
At a coastal upwelling zone, wind blow parallel to a coast, water at the ocean surface moves away from the coast and deep water rises up to take its place.
Courtesy of NOAA

Devonian southeasterly trade winds set up deep upwelling along west facing continental margins.

Abundance of chert beds decreases across the Nemaha Ridge and northward onto the Cherokee Platform

West

Cana - Anadarko Basin



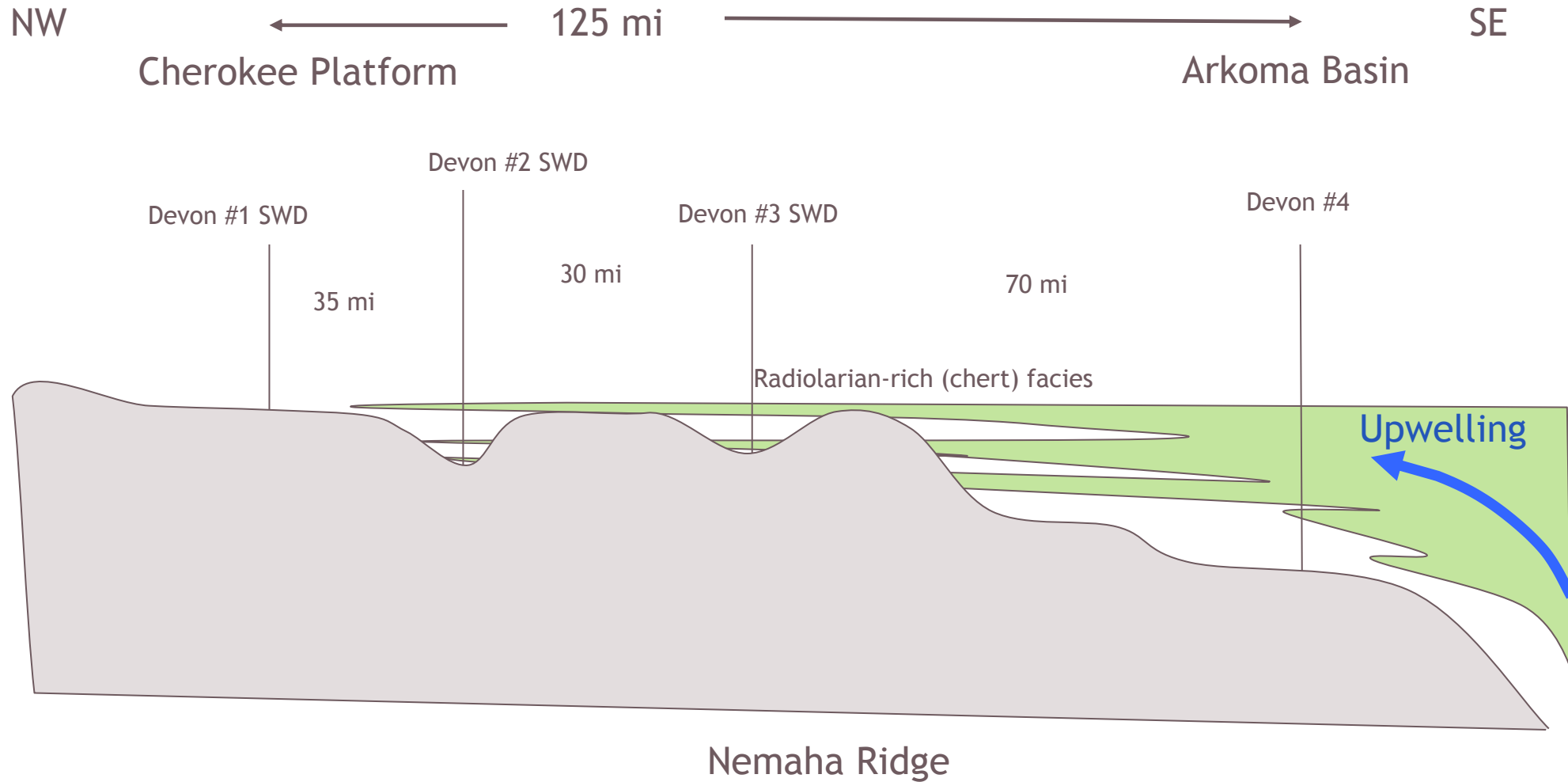
Northridge - Arkoma Basin

East

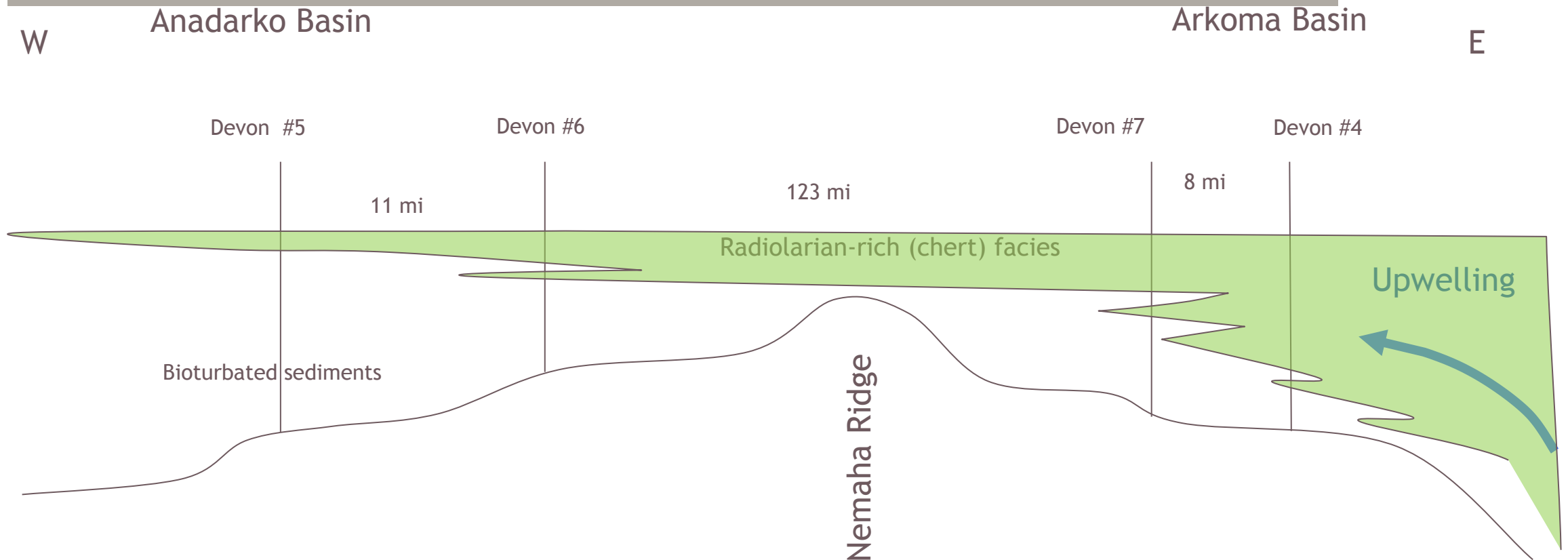


Note - Same stratigraphic unit depicted in both images (images enhanced to show detail)

As sea-level started to rise, the Woodford progressively on-lapped the Cherokee Platform



Paleotopography (Nemaha Ridge) also restricted deep upwelling currents



Nemaha Ridge and “shallow” Cherokee Platform disrupted upwelling currents resulting in the deposition of more oxygenated sediments and less chert on the Cherokee Platform and in the Anadarko Basin behind the Nemaha Ridge

Life Aquatic...west of the Nemaha uplift organisms flourished at times.



Arrows indicate bioturbated intervals alternating with darker, unbioturbated beds. Not all bioturbated zones are marked

Traces fossils are quite common in the lower half of the Woodford west of Nemaha Ridge and on Cherokee Platform

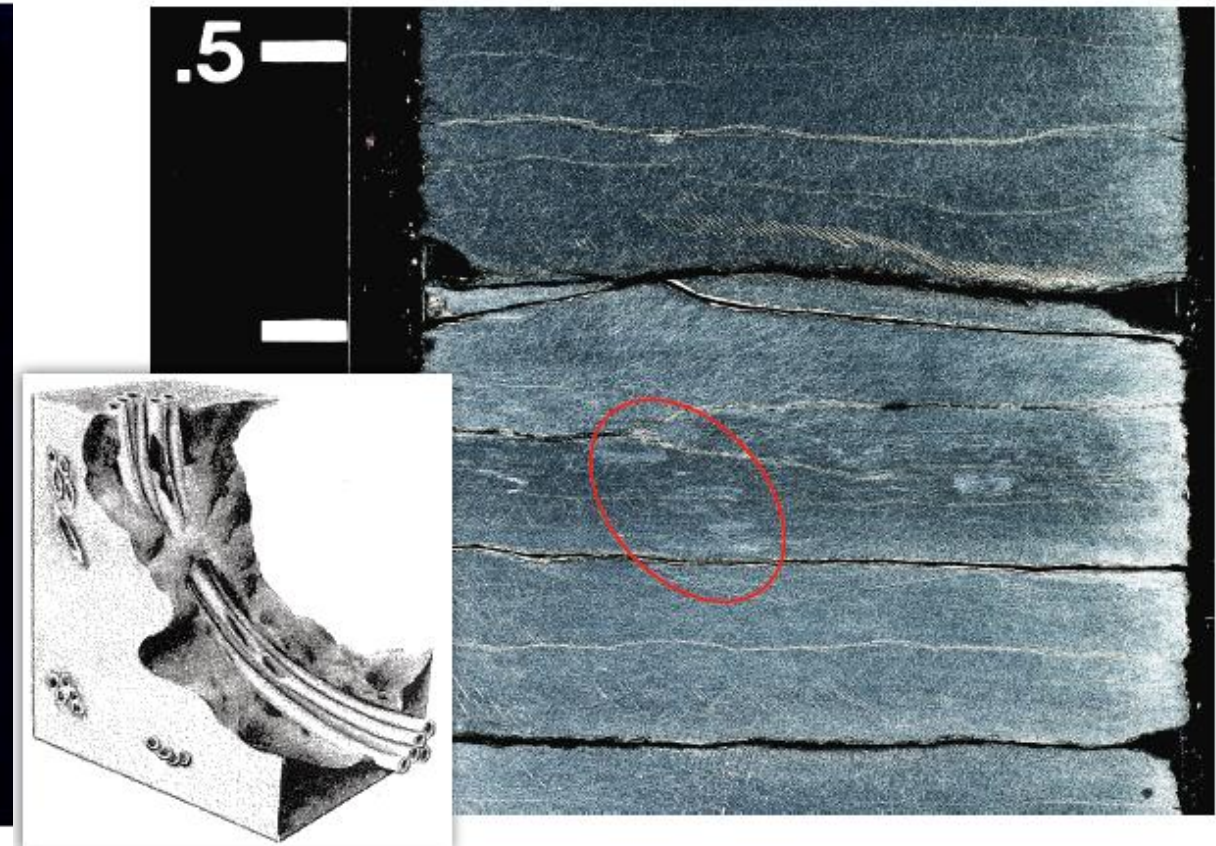
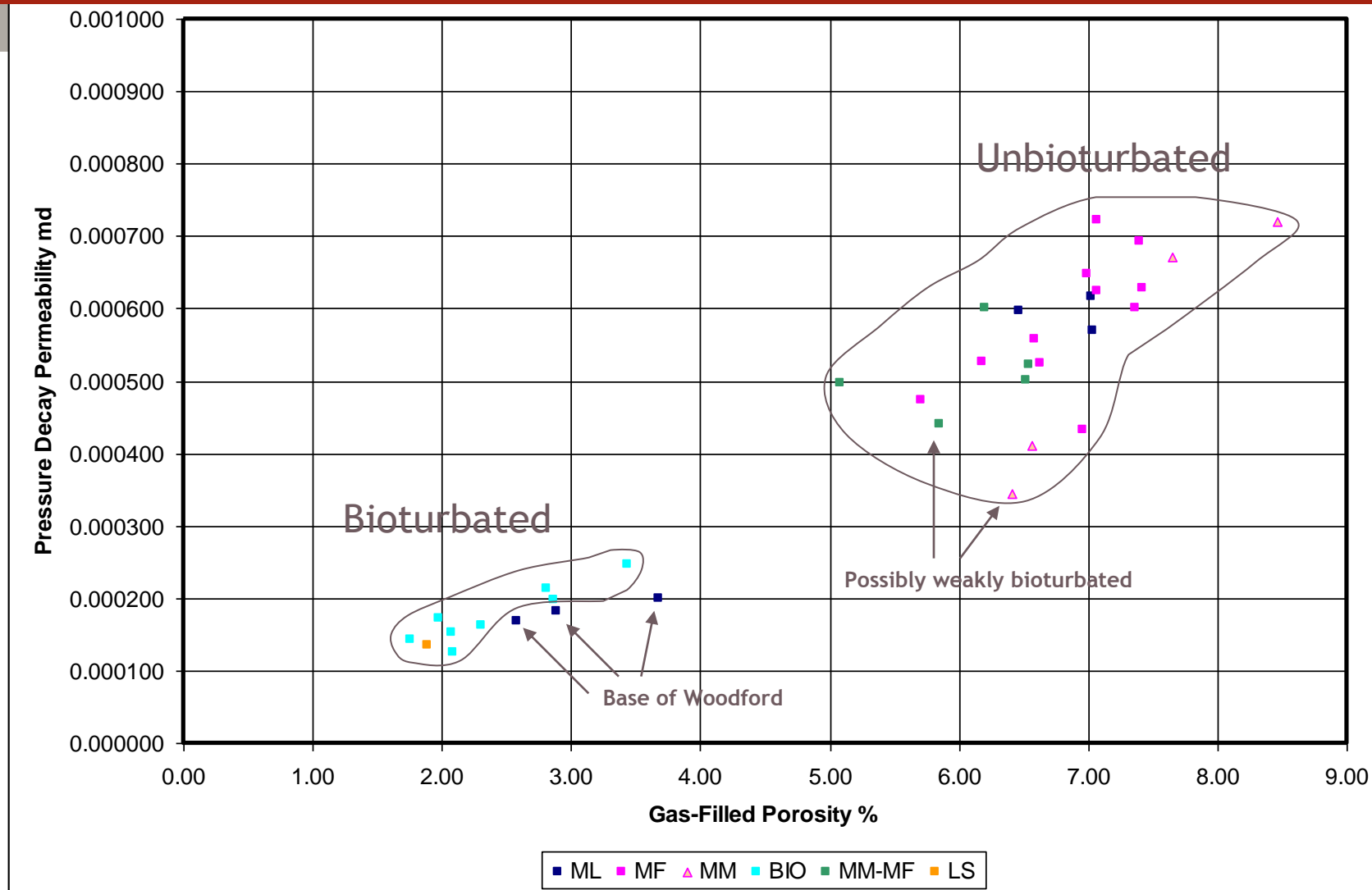
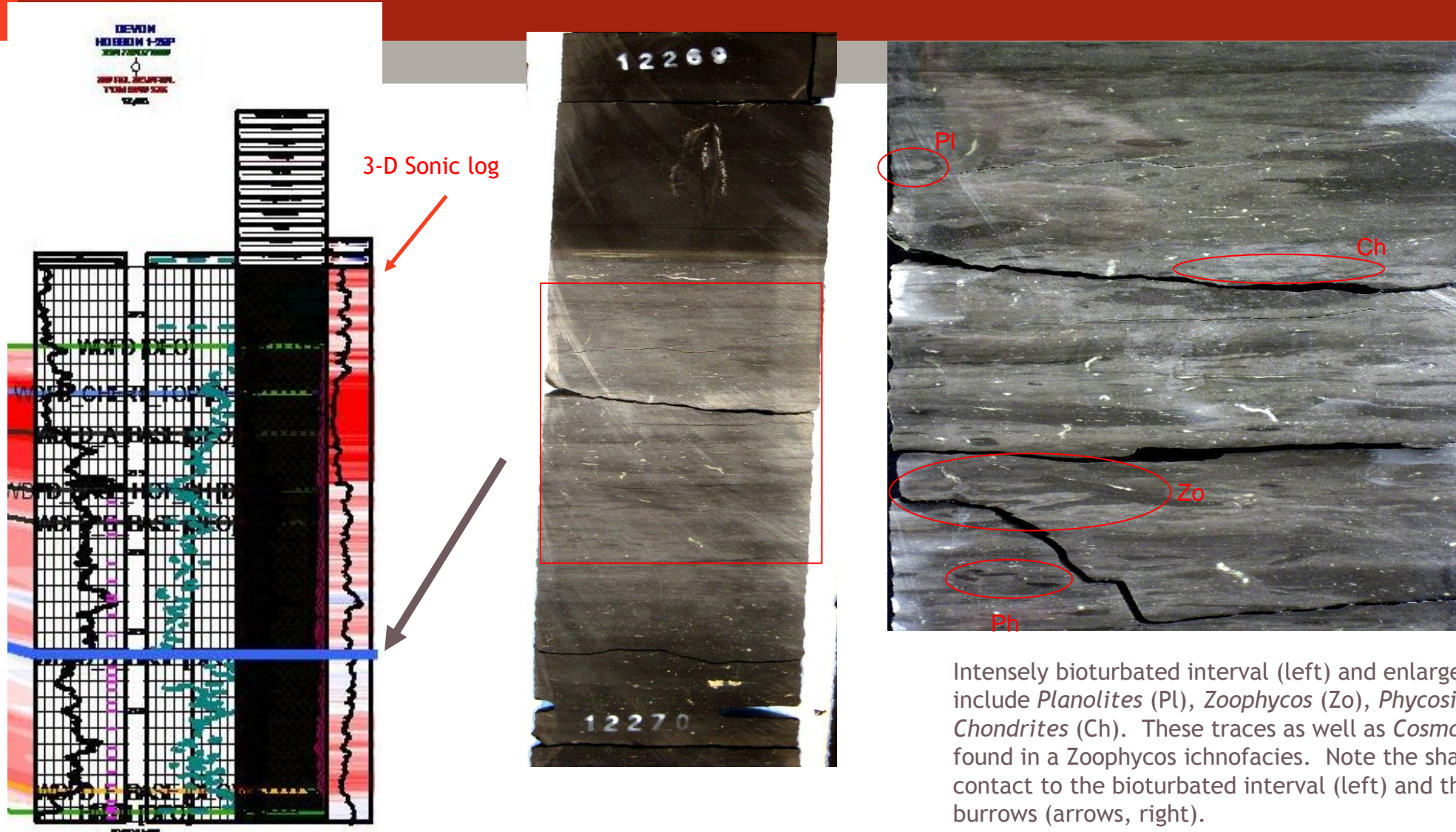


Figure 18. Digitally enhanced image (right) of upper Woodford A showing traces interpreted to be *Schaubcylindrichnus* (circle) and their three-dimensional interpretation (left). Depth is approximately 12,245.5 ft. Scale is in tenths of feet.

Bioturbation and porosity/permeability

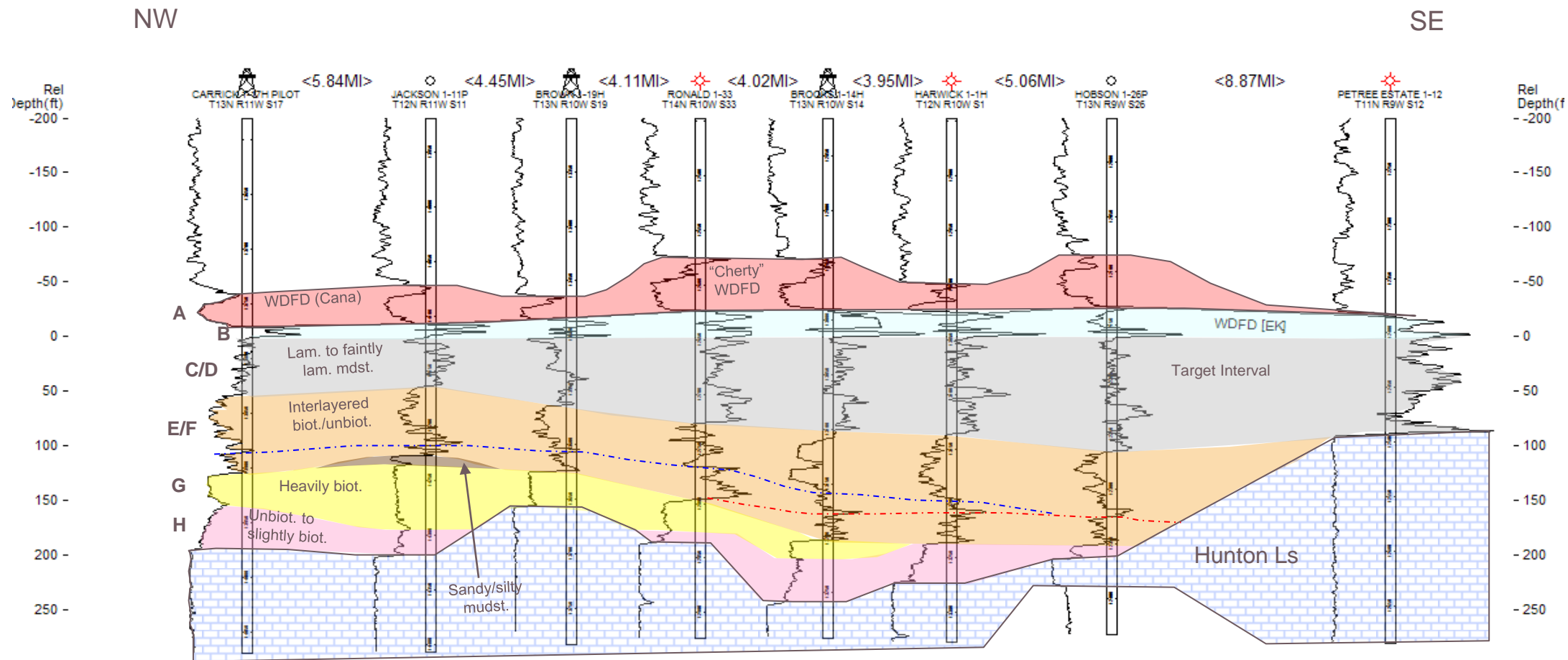


Landing and completion strategies

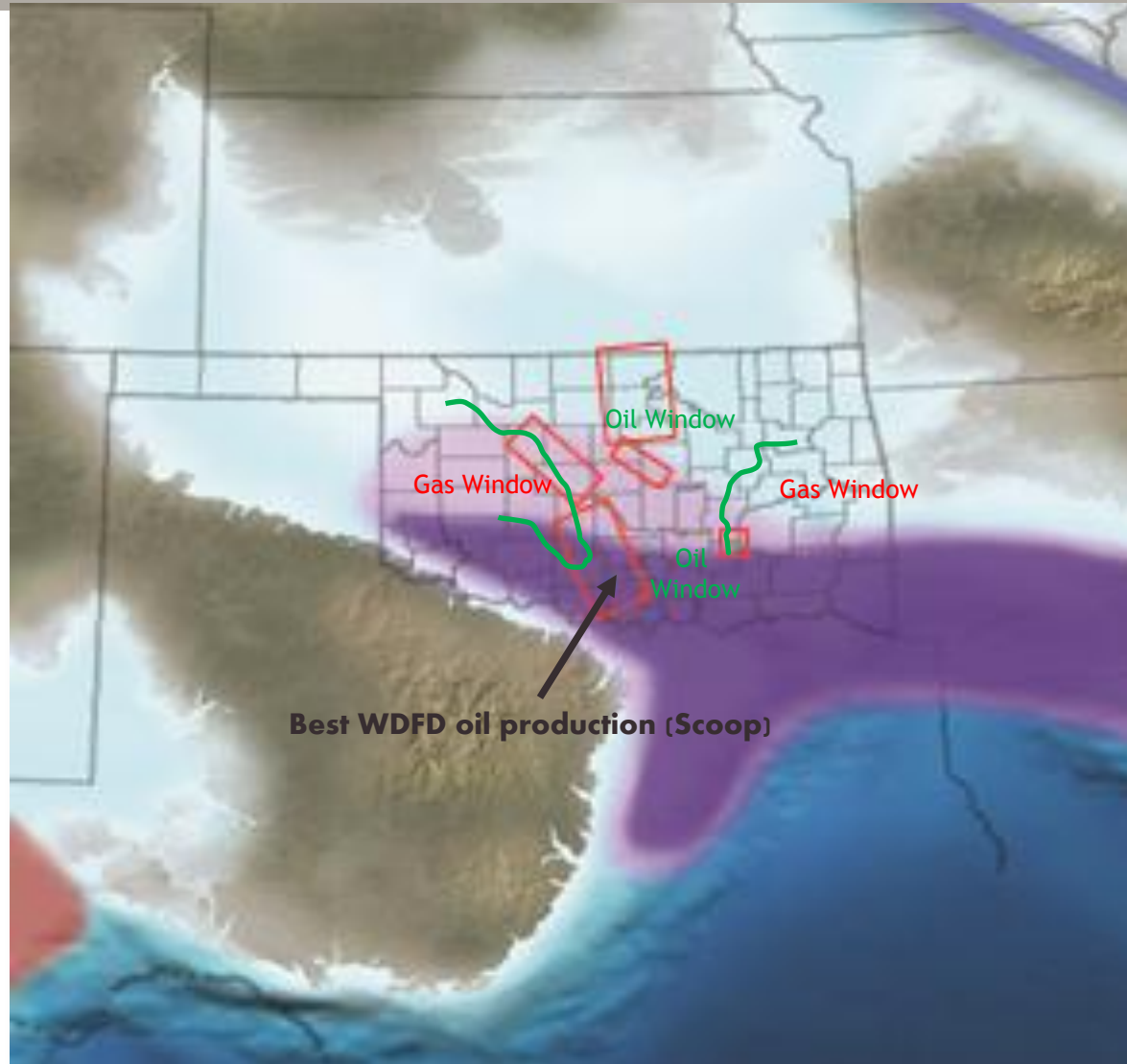


Intensely bioturbated interval (left) and enlargement (right). Traces include *Planolites* (Pl), *Zoophycos* (Zo), *Phycosiphon* (Ph), and *Chondrites* (Ch). These traces as well as *Cosmoraphe* are typically found in a *Zoophycos* ichnofacies. Note the sharp (erosive) upper contact to the bioturbated interval (left) and the pyrite replaced burrows (arrows, right).

Reservoir Characterization - “good” or “better” intervals to target are facies dependent



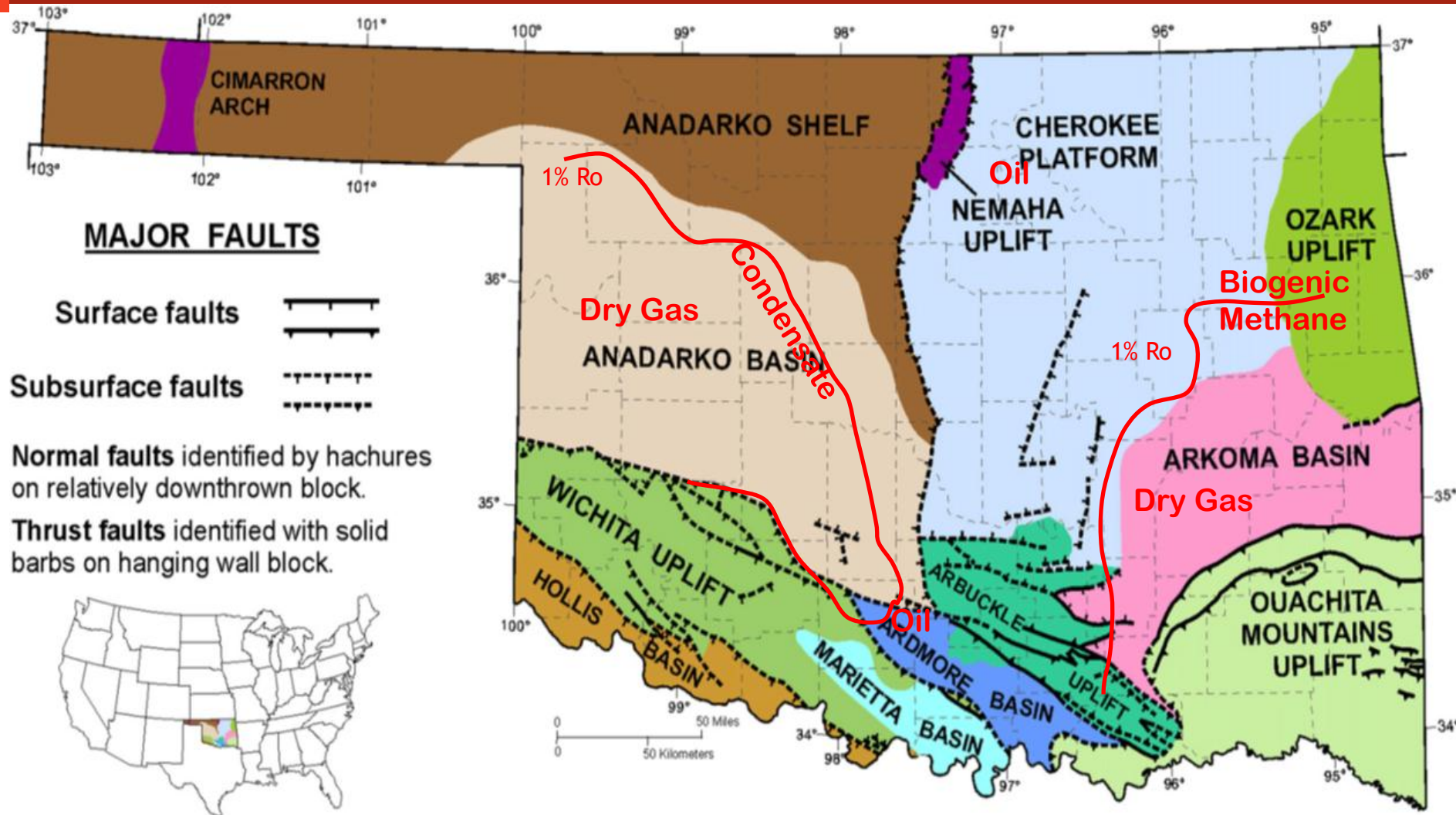
Regional distribution of chert - thins to north and west - best oil production (or potential for) appears to be in chert-rich Woodford in condensate window



Current Woodford play areas

1% Ro

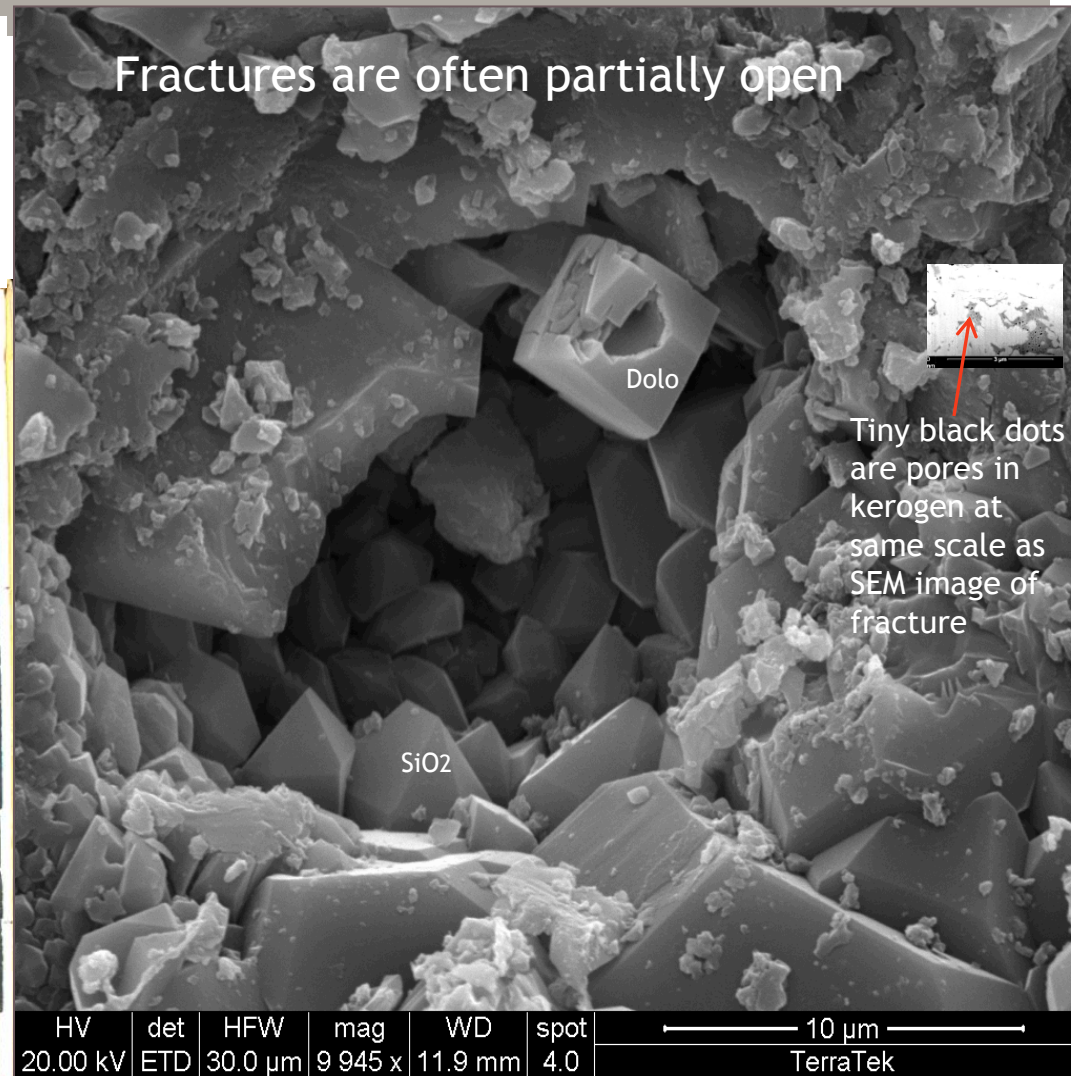
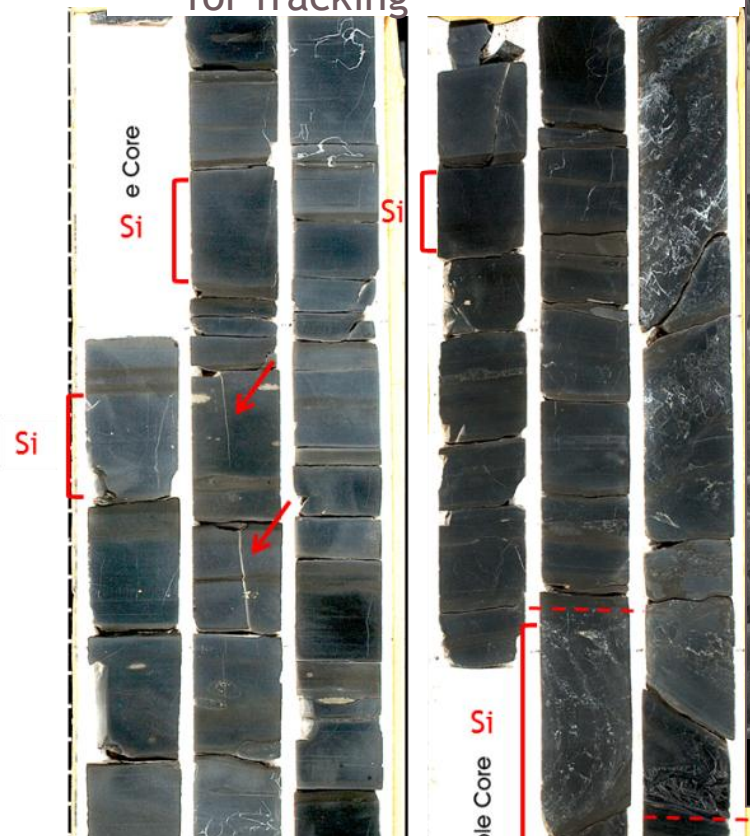
Woodford Shale Plays - But structure-tectonics are also important.



Modified from Cardott, B. J., 2012, Thermal maturity of Woodford Shale gas and oil plays, Oklahoma, USA, International Journal of Coal Geology, v. 103, p. 109-119

Chert beds contain more sub-seismic natural fractures, which are likely conduits for liquids production in the Woodford Sh.

- Increase storability
- Large enough to move oil through
- Vertical paths of weakness for fracking



Tasmanites - algal cysts formed in algal blooms



- *Tasmanites* in some Woodford localities are huge (up to 1mm across) and concentrated
- Given their abundance, *Tasmanites* of all sizes are likely a major contributor to hydrocarbons in the Woodford
- Concentrations of large *Tasmanites* may be a function of paleocurrent sorting or some other paleoecologic factor.

Tasmanites kinetics

J.O. Vigran et al.

Tasmanites algae

- Vigran *et al.* (2008, Polar Research, v. 27, p. 360-371) showed that the hydrocarbon generation kinetics of beds containing concentrations of *Tasmanites* is significantly different than other marine organic-rich beds.
- Tmax values can be 16-19° C higher in *Tasmanites*-enriched beds while at the same time enhancing the hydrocarbon potential for the bed.
- Implication: Woodford beds with abundant *Tasmanites* will enter oil window later than Woodford beds lacking these organics.

Table 1 Total organic carbon content and Rock-Eval pyrolysis results of the samples analysed (mean values).

Sample	TOC wt %	S ₁ mg HC g rock	S ₂ mg HC g rock	S ₃ mg CO ₂ g rock	PI S ₁ S ₁ + S ₂	HI mg HC g TOC	OI mg HC g TOC	T _{max} °C
A	61.4	2.59	553.0	1.2	0.00	901	2	455
B1	8.2	0.42	50.8	0.6	0.01	620	7	446
B2	8.0	0.48	50.0	1.3	0.01	625	16	449
B3	7.1	0.99	41.67	1.0	0.02	587	14	436
C1	13.2	2.47	66.8	1.9	0.04	506	14	430
C2	11.0	2.18	56.9	1.6	0.04	517	15	427

Samples: A, *Tasmanites* concentrate; B1-B3, whole rock with *Tasmanites* (grey, silty, dark shale); C1 and C2, whole rock without *Tasmanites* (dark-grey shale). Sample B3 was analysed in 2007, and the remaining samples were analysed in 1984.

Abbreviations: TOC, total organic carbon; S₁, thermally extracted hydrocarbons; S₂, hydrocarbons formed during pyrolysis; S₃, carbon dioxide formed during pyrolysis at temperatures below 390°C; HI, hydrogen index (100 × S₂/TOC); OI, oxygen index (100 × S₃/TOC); PI, production index (S₁/(S₁ + S₂)); T_{max}, temperature at which the highest pyrolysis yield is obtained.

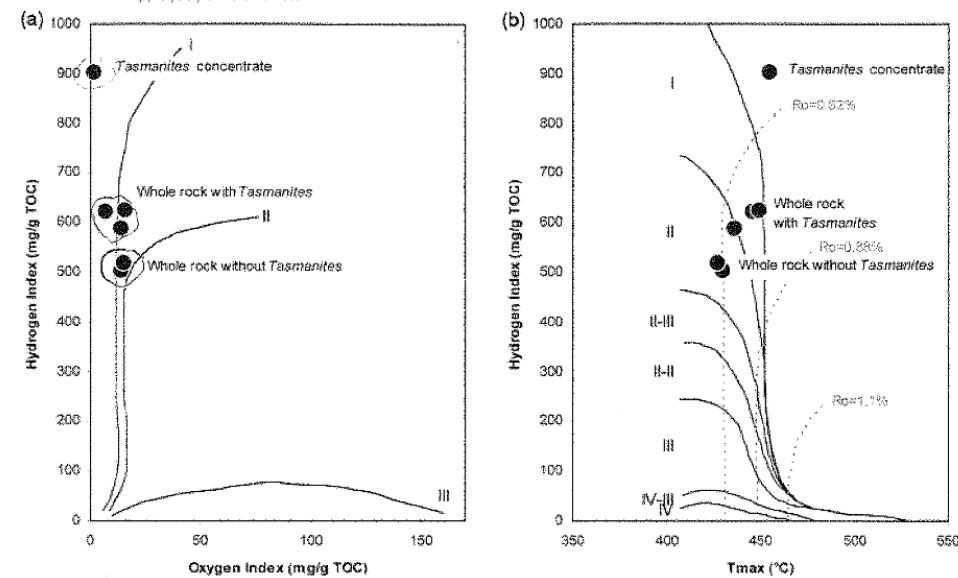


Fig. 7 Differences between Rock-Eval pyrolysis results of *Tasmanites* algae (type I) and matrix kerogen (type II), illustrated in (a) a modified van Krevelen diagram, and (b) a hydrogen index (HI) vs. temperature at which the highest pyrolysis yield is obtained (T_{max}) plot. The latter also illustrates the relatively low maturity of the samples from the Torellneset locality.

Conclusions

The effective exploration and/or exploitation of unconventional resource plays requires an understanding of:

- **Thermal maturity** (e.g. find liquids in Woodford at the appropriate level of thermogenesis)
- **Facies** (e.g. The presence of clay-rich bioturbated facies can impact frac initiation and EUR's. Certain organic types, which are facies related may enhance oil potential but delay on-set of oil generation)
- **Paleoenvironments** and **Paleotopography** (e.g. A good regional model allows Woodford facies trends and thicknesses to be predicted and explained)
- **Structure** and **Regional Tectonics** (e.g. Woodford chert facies are not uniformly distributed and small sub-seismic natural fractures in the chert facies may be the key to Woodford liquids production)

In a “nutshell”, best Woodford oil production will likely be maximized by the following

1. **Thermal maturity** - should be in condensate window
2. **Brittle facies** - should have significant chert component.
3. **Tectonics** - fracture intensity needs to be “significant”
4. **Thickness** - need to have significant “H”