PS Detailed Characterization of a Complete, New Woodford Shale Section in the Ardmore Basin of Oklahoma: The Case for a New Type Section?*

Henry A. Galvis-Portilla[1], Daniela M. Becerra-Rondon[1], and Roger Slatt[1]

Search and Discovery Article #11045 (2018)**
Posted January 29, 2018

*Adapted from poster presentation given at the 2017 AAPG Annual Convention & Exhibition, Houston, Texas, April 2-5, 2017

[1] University of Oklahoma, Norman, Oklahoma (henry.galvis@ou.edu)

Abstract

To date very few outcrops in the Ardmore Basin and Arbuckles area of Oklahoma preserve a complete stratigraphic section of the Woodford Shale. In this study, we present the results of an unpublished and recently discovered Woodford outcrop in southern Oklahoma. Characterization techniques such as XRF, XRD, SEM, TOC, and petrography, tied with subsurface well-log responses provide significant contributions towards a better understanding of the shale heterogeneities at different scales. The exposed section comprises the entire Woodford Shale (320 ft), and partially its under- and overlying units, the Hunton Group and Sycamore Limestone respectively. The lower contact is sharp and characterized by the presence of a Pre-Woodford coarse sandstone (Misener Sandstone?) interbedded with non-organic greenish and brown shales. The upper contact with the Sycamore Limestone is transitionally represented by interbeddings of chert, and black and greenish mudstones.

Twelve lithofacies were recognized, and distributed into 3 major compositional domains (siliceous, argillaceous and calcareous) and honoring sedimentological features such as texture, structure, mineral assemblages and bioturbation. Vertical stacking of these lithofacies, tied with hand-held Gamma Ray profiles and chemostratigraphic proxies reveal a cyclical pattern interpreted as fourth-order transgressive (TST) and regressive (HST) cycles superimposed onto a major third-order stratigraphic sequence. Also, a Maximum Flooding Surface (MFS) was recognized near the transition between the middle and upper members of the Woodford Shale. Reservoir quality of this section was assessed via mineralogical composition, organic richness, porosity and the vertical arrangement of lithofacies; where potential target zones are interpreted to be composed of high-frequency interbeddings of organic-rich beds (acting as source) and brittle beds (acting as more fracturable or fractured rocks). According to this model, and relating our high frequency sequence stratigraphic framework, the best horizontal drilling zones are interpreted within the HST right above the MFS. Finally, but not least with this work, we propose this outcrop as a renovated type locality for the Woodford shale in Oklahoma, since this preserves the entire Woodford thickness and its boundaries very well exposed, we think this could be an exceptional opportunity for operators to calibrate subsurface correlations and stratigraphic models of this, and other resource shales.

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Detailed Characterization of a Complete, New Woodford Shale Section in The Ardmore Basin of Oklahoma: The Case for a New Type Section?

GALVIS-PORTILLA, Henry - henry.galvis@ou.edu - BECERRA-RONDON, Daniela and SLATT, Roger. The University of Oklahoma, Institute of Reservoir Characterization

100 AAPG ANNIVERSARY ACE 2017 ANNUAL CONVENTION & EXHIBITION
2-5 April 2017 • Houston, TX • George R. Brown Convention Center

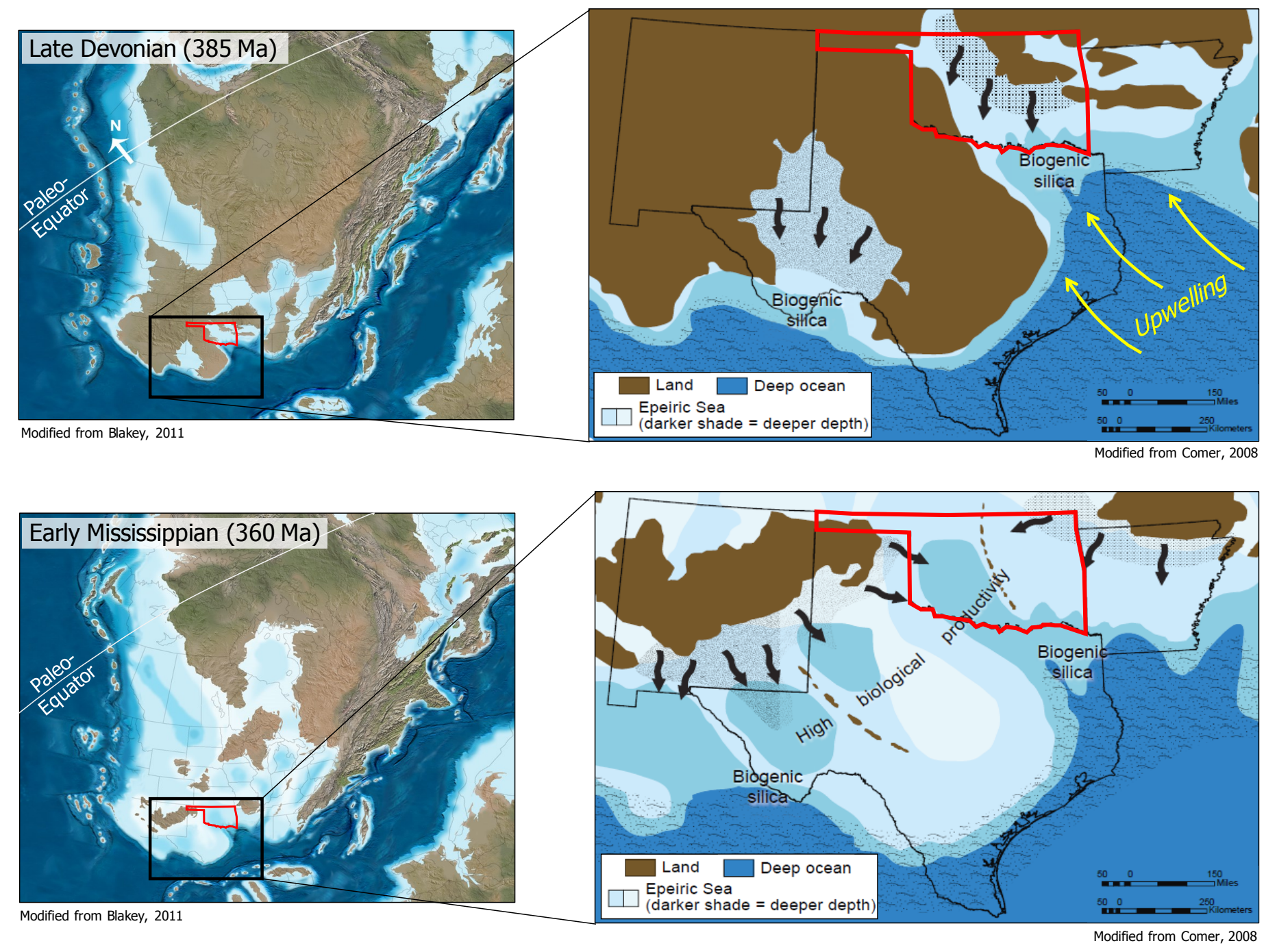
ABSTRACT

To date very few outcrops in the Ardmore Basin and Arbuckles area of Oklahoma preserve a complete stratigraphic section of the Woodford Shale. In this study, we present the results of an unpublished and recently discovered Woodford outcrop in southern Oklahoma. The exposed section comprises the entire Woodford Shale (320ft), and partially its under- and overlying units, Hunton Group and Sycamore Limestone respectively. The lower contact is sharp and characterized by the presence of a Pre-Woodford coarse sandstone (Misener Sandstone?) interbedded with non-organic greenish and brown shales. The upper contact with the Sycamore Limestone is transitionally represented by interbeddings of non-organic cherts and greenish mudstones/siltstones.

Internally, at the bed scale, the Woodford is represented by two highly contrasting rock types that were featured from a broader set of lab techniques (XRD, XRF, TOC, Petrography, SEM, and Hardness). Soft beds appear fissile, clay-rich, with high TOC, low Si/Al ratios, high Ti, Zr, K, Al, and with low hardness values. Whereas hard beds are massive, quartz-rich, with lower TOC, low Ti, Zr, K, Al and much higher hardness values. From this scale, statistically we found that almost regardless of their stratigraphic position, either a hard or soft bed will maintain such unique lithological properties throughout the section.

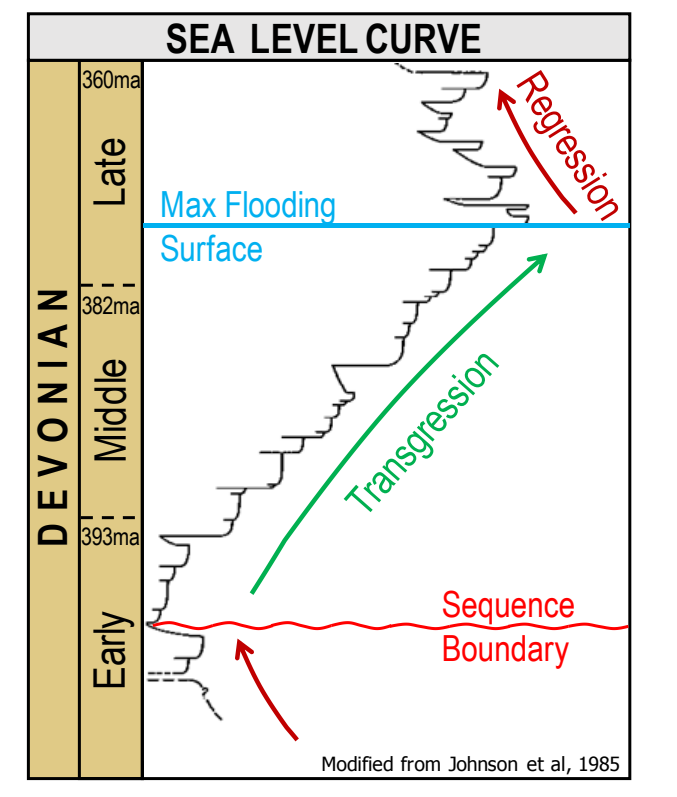
Vertical stacking of lithofacies, tied with hand-held Gamma Ray profiles and chemostratigraphic proxies reveal a cyclical pattern interpreted as fourth-order para-sequences superimposed onto a major third-order stratigraphic sequence. Also, a Maximum Flooding Surface (MFS) was recognized near the transition between the middle and upper member of the Woodford Shale. Reservoir quality of this section was assessed analyzing the vertical arrangement of lithofacies; where potential target zones are interpreted to be composed by high-frequency interbeddings of organic-rich beds (acting as source) and brittle beds (acting as more frackable or fractured rocks). According to this model, and relating our high frequency sequence stratigraphic framework, the best horizontal drilling zones are interpreted to be within the upper half of the middle Woodford member

GOING BACK TO THE LATE DEVONIAN - EARLY MISSISSIPPIAN



Modified from Blakey, 2011

Modified from Comer, 2008



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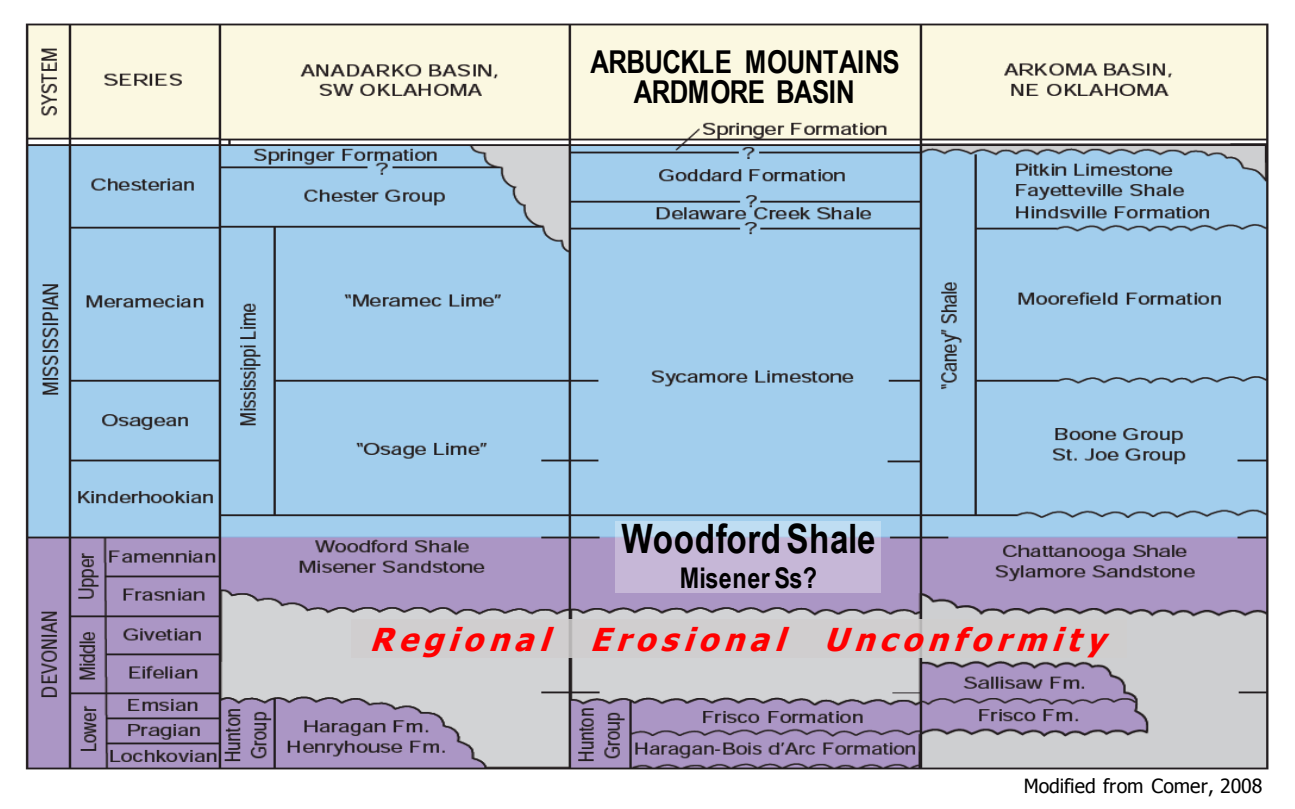

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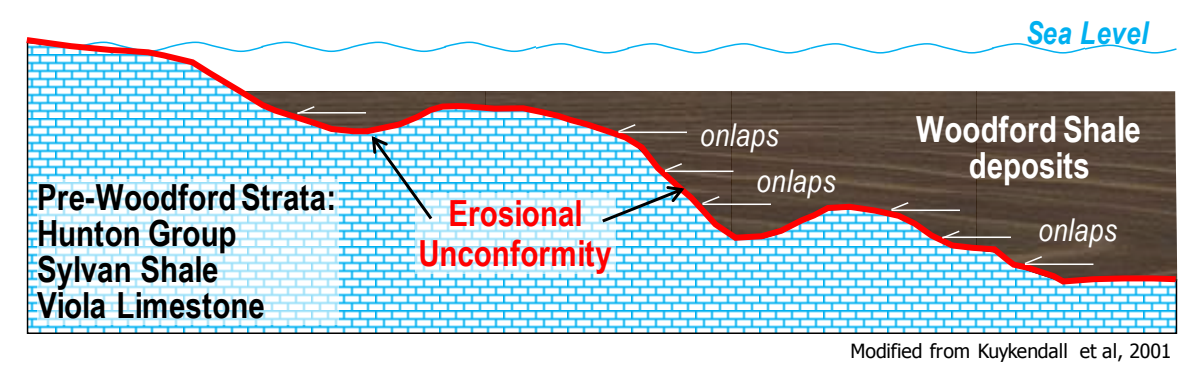
Major conditions during Woodford Shale Deposition

- ✓ Semi-restricted to open marine
- ✓ Global sea level rise, transgression
- ✓ Near equatorial latitudes and high organic productivity
- ✓ Poorly oxygenated waters, Anoxia



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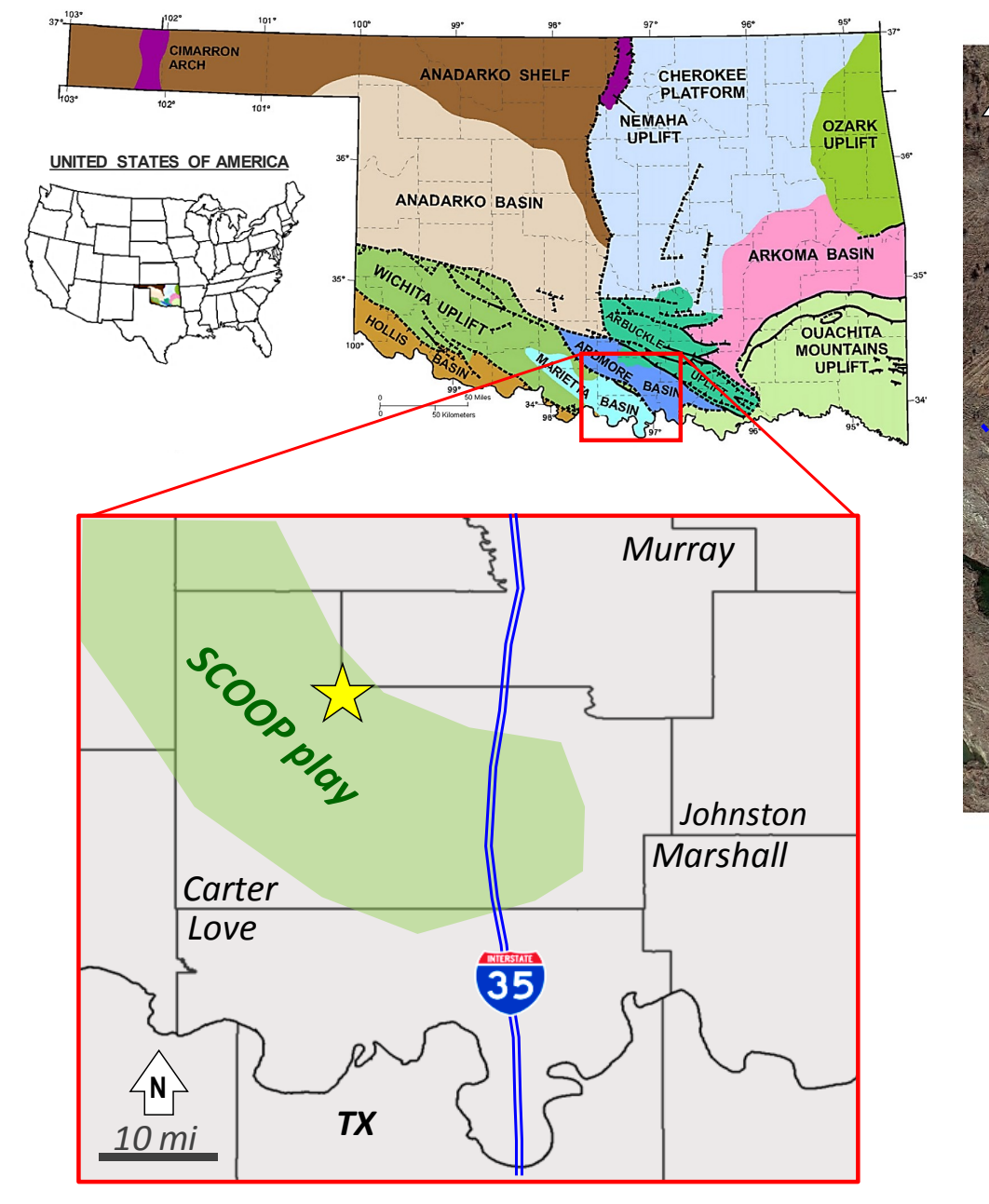
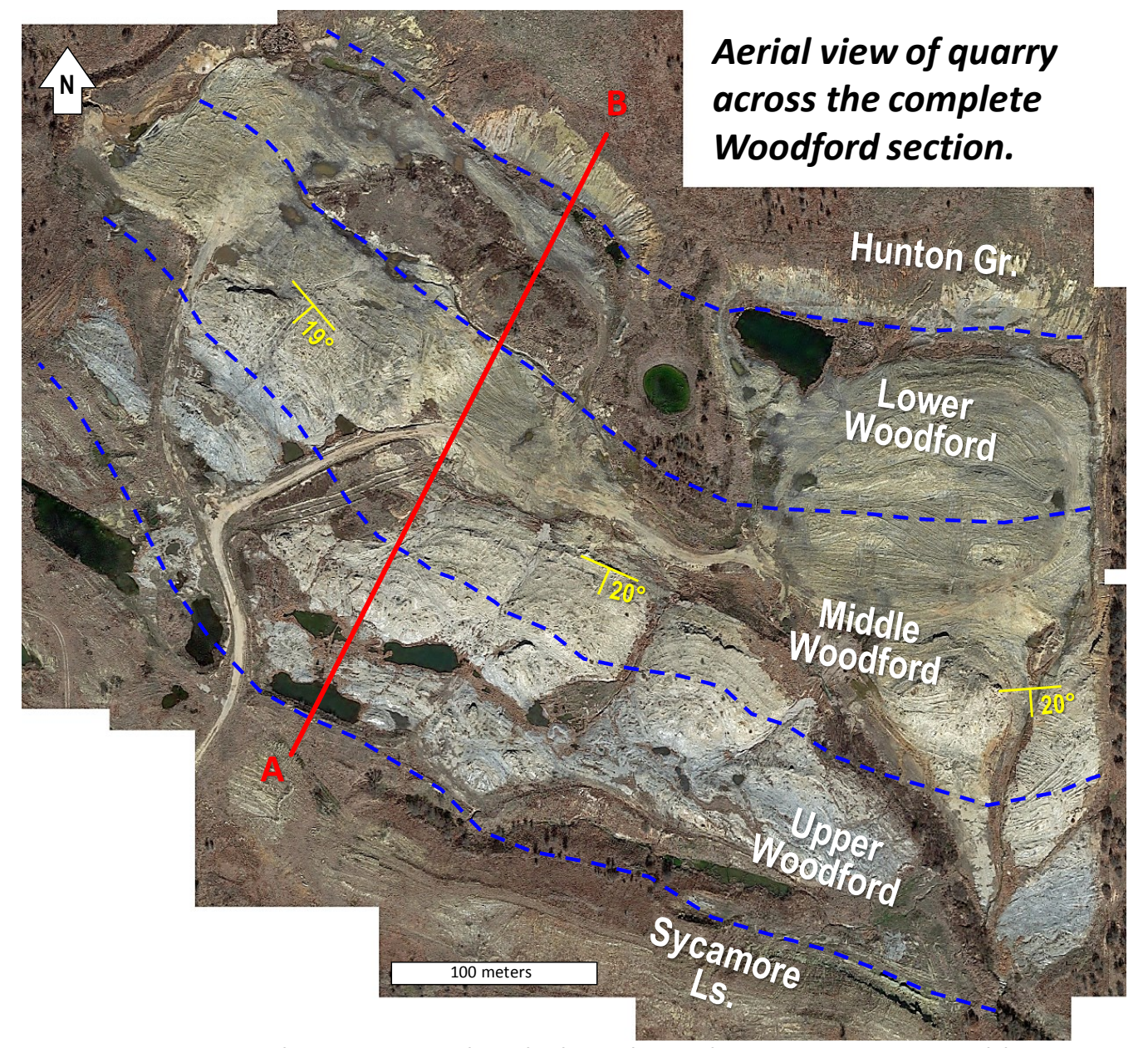
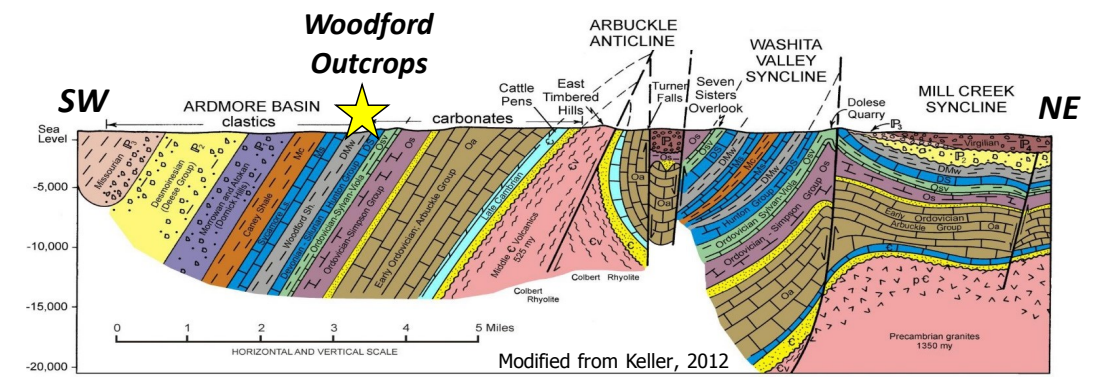
THE OUTCROP IN THE ARDMORE BASIN, SOUTH CENTRAL OKLAHOMA





Aerial view of quarry across the complete Woodford section.

Contacts with its over- and underlying bounding units are mappable over 100's of meters in the area. Hunton and Sycamore limestones are more competent units compared with the Woodford shale.



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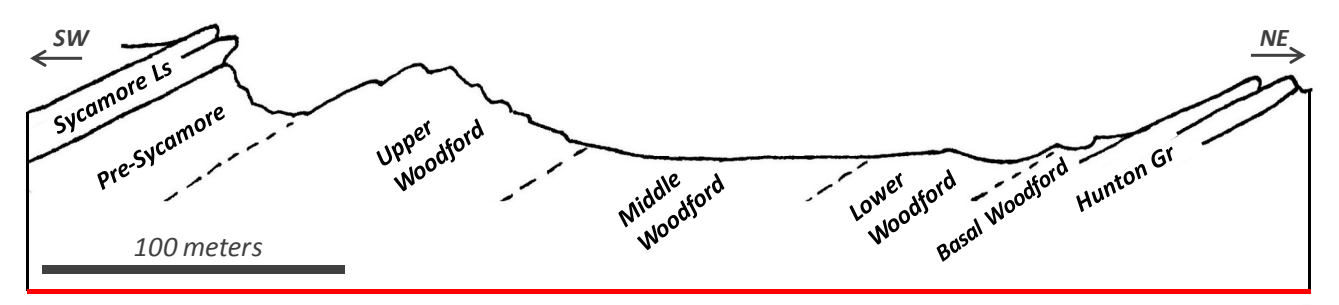
Woodford strata deepening towards the SW into the Ardmore Basin



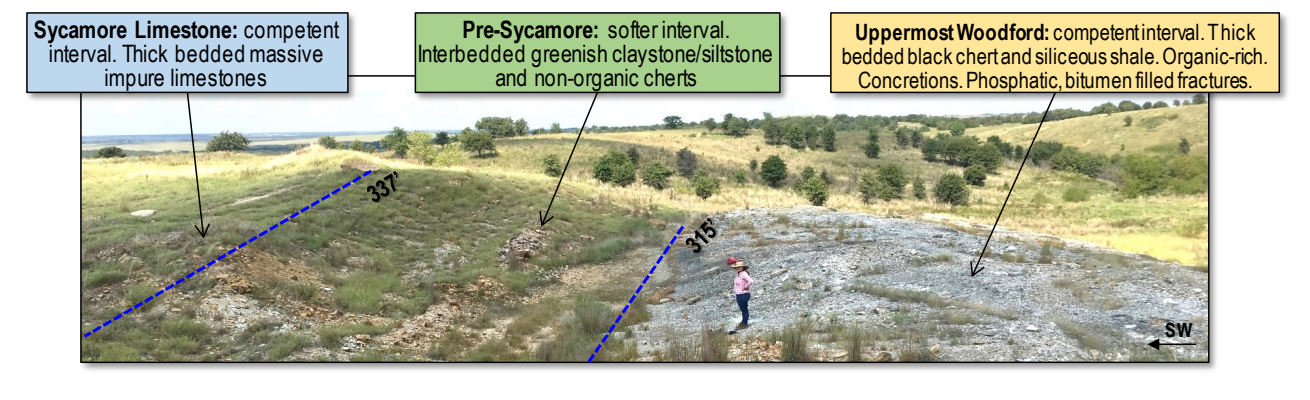
Outcrop measured section and surface topography

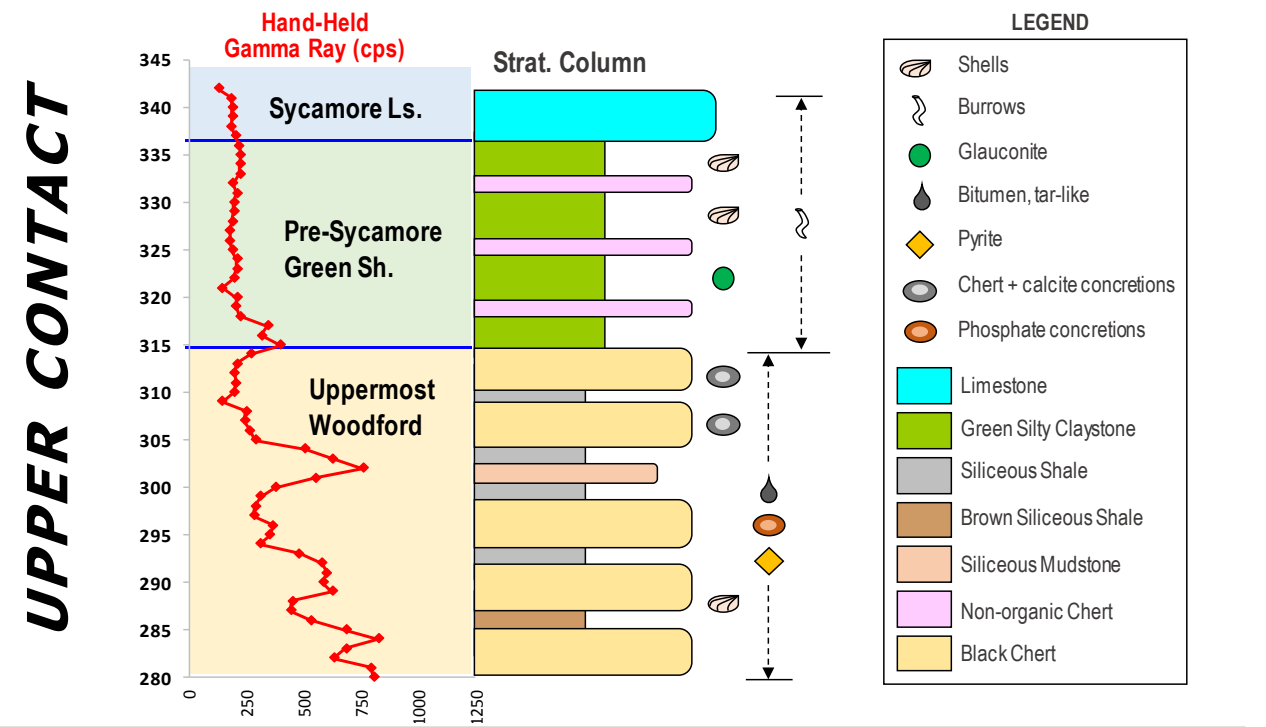
NATURE OF THE FORMATIONAL CONTACTS

Sycamore Limestone: competent interval. Thick bedded massive impure limestones

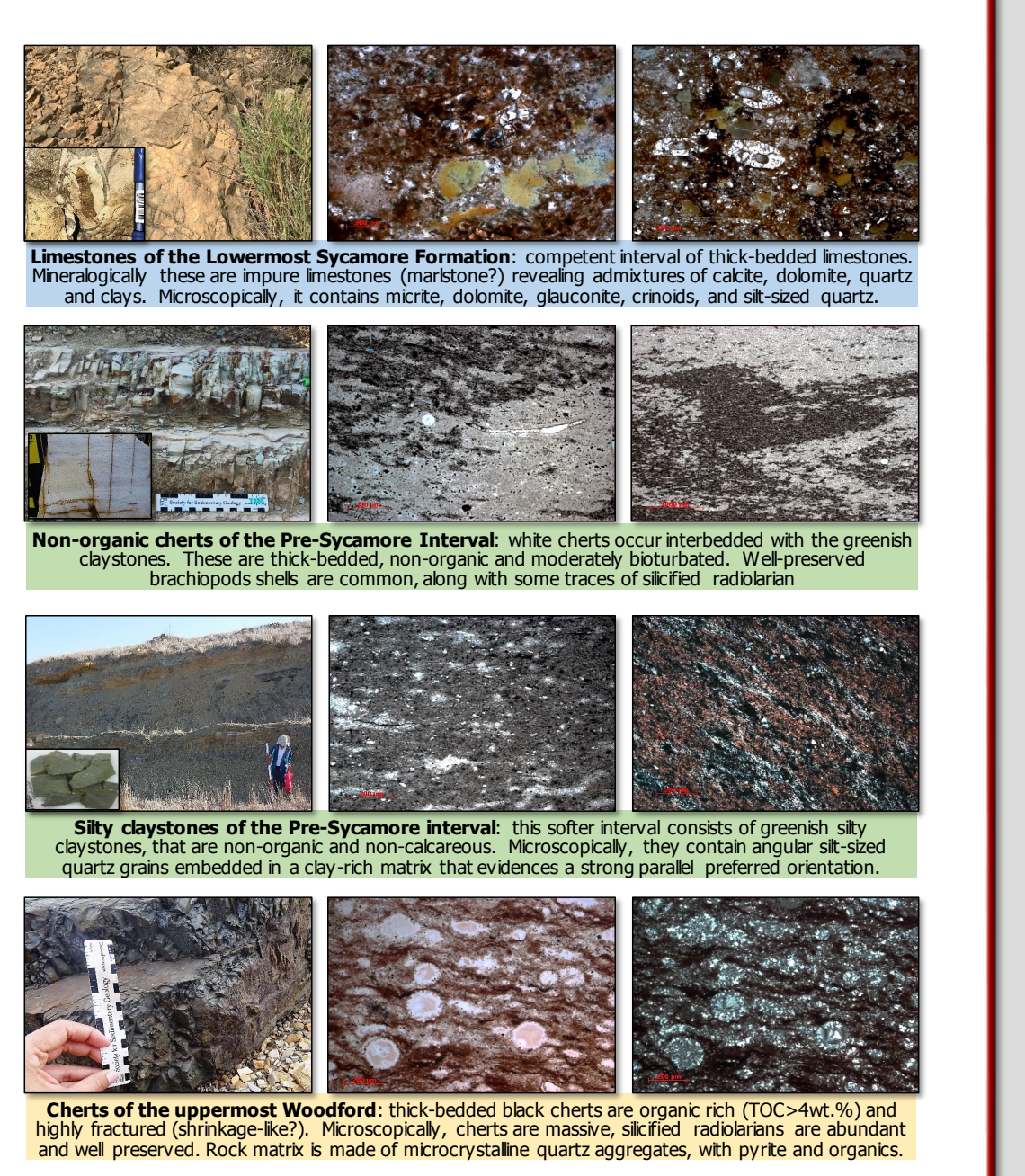
Pre-Sycamore: softer interval. Interbedded greenish claystone/siltstone and non-organic cherts

Uppermost Woodford: competent interval. Thick bedded black chert and siliceous shale. Organic-rich. Concretions. Phosphatic, bitumen filled fractures.





Interpretation: This upper contact occur transitional with its overlying Sycamore limestone. A 20 feet transitional interval records very late stages of a highstand system tract, where the biogenic input of the woodford decreases, while the detrital and carbonate (with allochems) increases upward, suggesting more oxygenated bottoms along with a reduction in the rate of sea level rise influenced by more continental input.



Limestones of the Lowermost Sycamore Formation: competent interval of thick-bedded limestones. Mineralogically these are impure limestones (marlstone?) revealing admixtures of calcite, dolomite, quartz and clays. Microscopically, it contains micrite, dolomite, glauconite, crinoids, and silt-sized quartz.

Non-organic cherts of the Pre-Sycamore Interval: white cherts occur interbedded with the greenish claystones. These are thick-bedded, non-organic and moderately bioturbated. Well-preserved brachiopods shells are common, along with some traces of silicified radiolarian

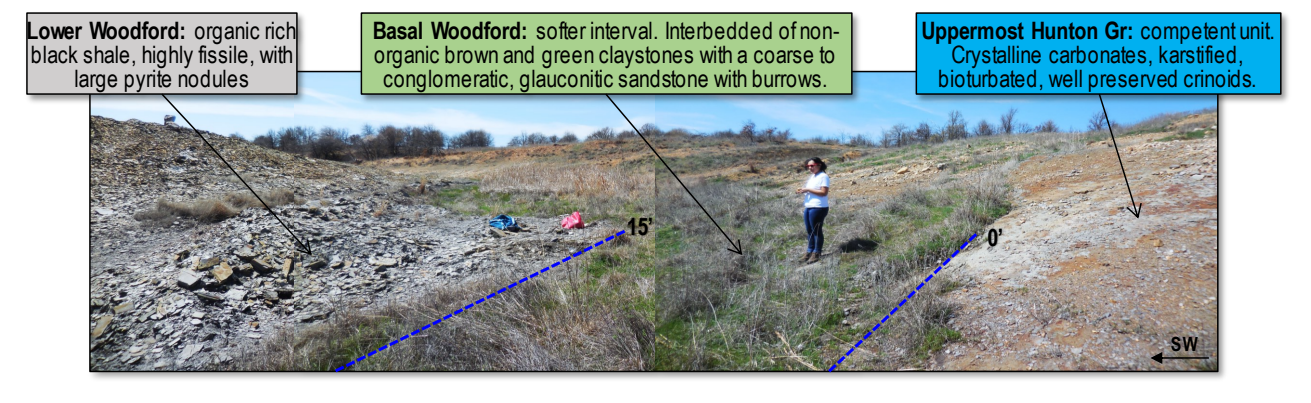
Silty claystones of the Pre-Sycamore interval: this softer interval consists of greenish silty claystones, that are non-organic and non-calcareous. Microscopically, they contain angular silt-sized quartz grains embedded in a clay-rich matrix that evidences a strong parallel preferred orientation.

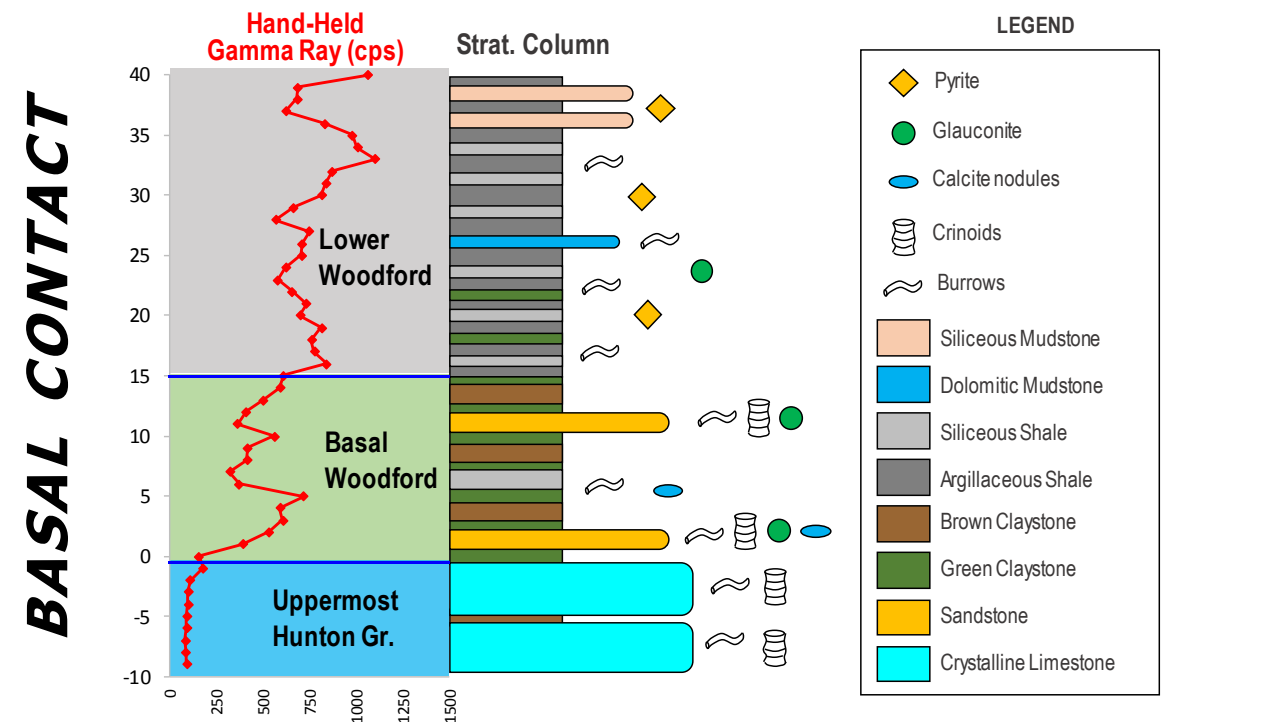
Cherts of the uppermost Woodford: thick-bedded black cherts are organic rich (TOC>4wt.%) and highly fractured (shrinkage-like?). Microscopically, cherts are massive, silicified radiolarians are abundant and well preserved. Rock matrix is made of microcrystalline quartz aggregates, with pyrite and organics.

Lower Woodford: organic rich black shale, highly fissile, with large pyrite nodules

Basal Woodford: softer interval. Interbedded of non-organic brown and green claystones with a coarse to conglomeratic, glauconitic sandstone with burrows.

Uppermost Hunton Gr: competent unit. Crystalline carbonates, karstified, bioturbated, well preserved crinoids.





Interpretation: This lower contact records the unconformable nature between the Hunton and Woodford. The uppermost Hunton deposits evidences sub-areal exposure related with a sea level drop, then rising in the sea level and the onset of transgression allows the depositons of shallower deposits (sandstones and siltstones), that gradually shifts into organic-rich black shales.

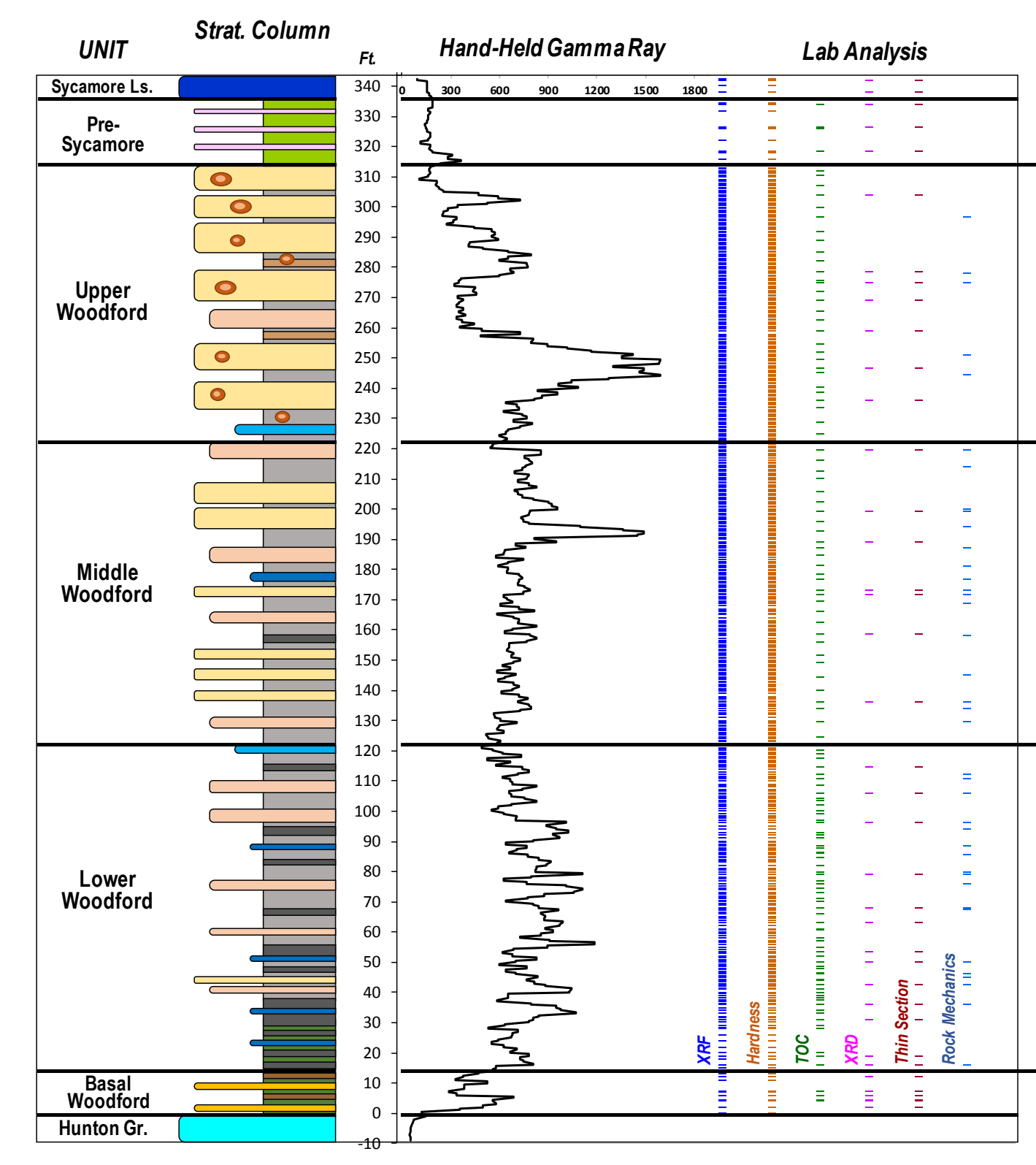
Lower Woodford: black shales dominates and are interbedded with few thin beds of greenish claystones. Black shales are silty and organic rich (TOC>4wt.%), highly fissile, with pyrite, marcasite, glauconite and silt-sized detrital quartz. Palynomorphs (tasmanites) are common and appear flattened.

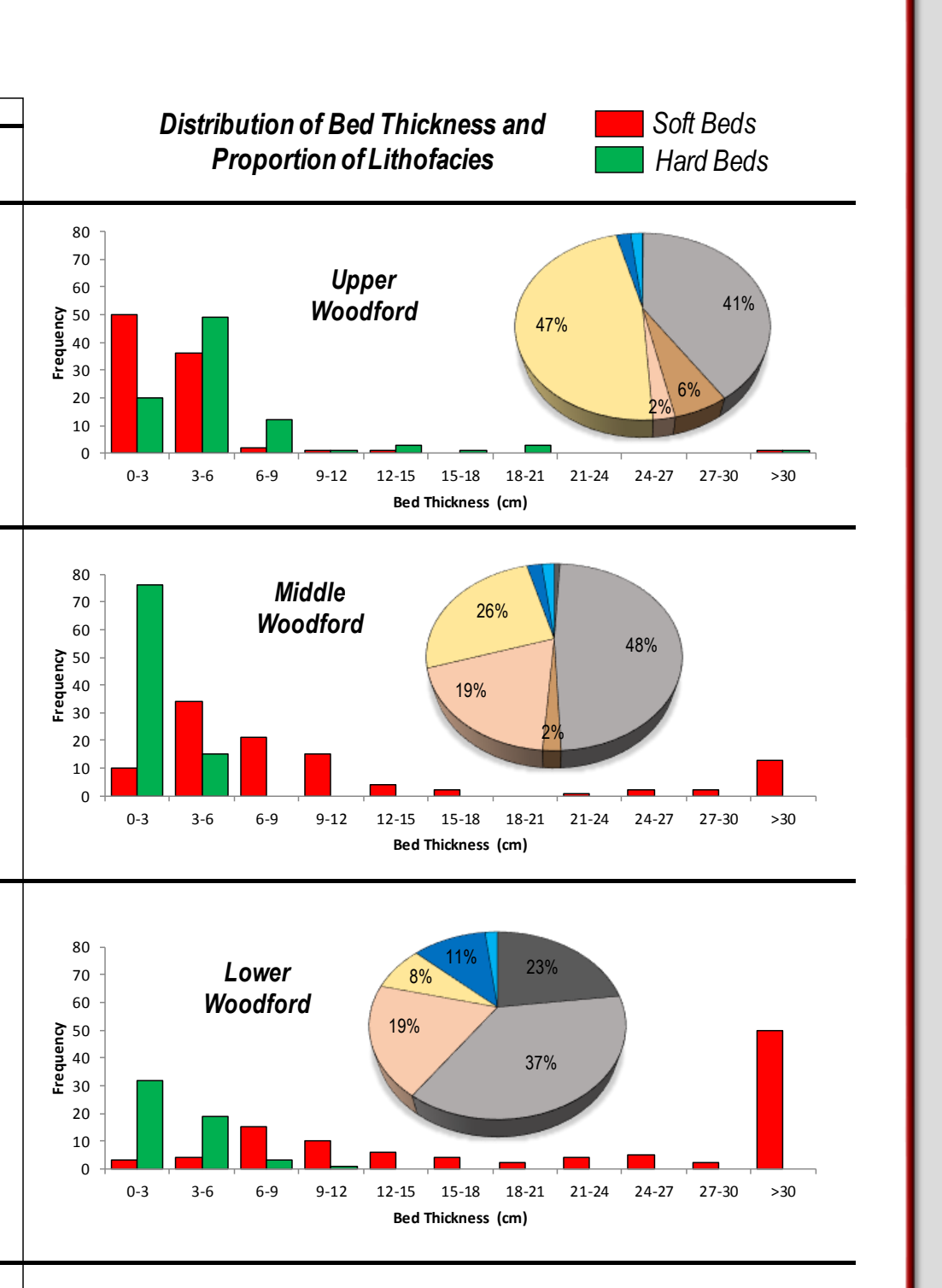
Sandstones of the Basal Woodford: Sandstones bodies are coarse grained to conglomeratic, thick-bedded and displays macroscopic burrows networks along the bed planes. Microscopically, sandstones are poorly sorted, contain glauconite, phosphatic pelloids, fossil fragments and slightly cemented with calcite

Greenish claystones of the Basal Woodford: medium interbeddings of non-organic brown and green claystones. Clay contents are greater than 70% (illite+kaolinite). Silt-sized angular quartz scattered within the clay matrix. Burrowing is common along with cm-sized calcareous nodules (hard grounds?)

Limestones of the uppermost Hunton Gr: intense macroscopic and recrystallized bioturbation, dissolution along bed planes and fractures. Microscopically it shows massive mosaics of sparry calcite, from finely to very coarse crystalline. Well preserved and recrystallized crinoids and brachiopods.

WOODFORD GENERAL STRATIGRAPHY





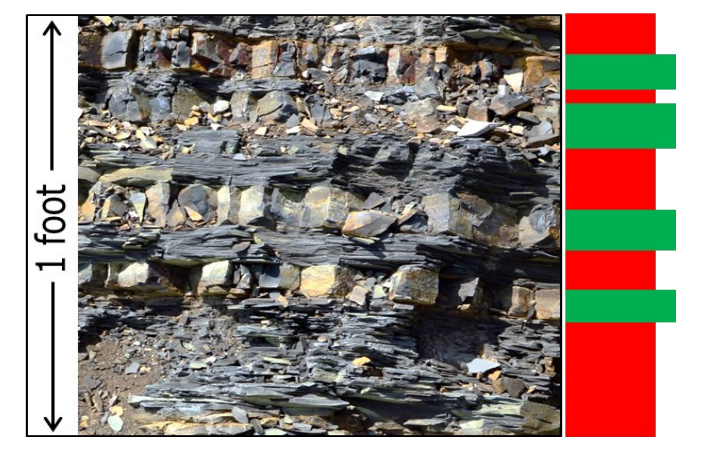
The Lower Woodford is 105 ft. thick and usually generates topographic lows. Radioactivity readings are very high, from 600 to 1300 cps (avg. 800 cps). The 'soft' component is mostly represented by Argillaceous, siliceous and Dolomitic shales. Distribution of average bed thicknesses is very contrasting, showing that soft beds are much thicker (>30cm) than hard beds (1-6cm). The contact between the Lower and middle Woodford is represented by a major turnaround point in the radioactivity profile, which coincides with a calcareous-rich and bioturbated zone.

The Middle Woodford is 104 ft thick. And evidences a gradual upward increase in the content of hard beds. Radioactivity readings are more homogeneous, ranging from 650 to 900 cps. Average bed thickness between soft and hard beds is less contrasting, varying from 1-12 cm and 1-6 cm respectively, which implies the occurrence of high-frequency alternations between soft and hard beds. Lithofacies within this Middle Woodford are mostly represented by Siliceous Shales, Cherts and Siliceous mudstones, suggesting that the argillaceous and calcareous content have decreased upward from its underlying lower member. The contact between the Middle and Upper Woodford is marked by the first occurrence of phosphate nodules/concretions of variable diameter (2-5cm) at about 222', as well as by a trough in radioactivity.

The Upper Woodford is 92 ft thick, and generally more competent than its preceding members. Radioactivity responses are highly variable, ranging from 400 cps to 800 cps, with outliers greater than 1300 cps. Distributions of bed thickness reveal a dominance of thicker hard beds (5-20cm) compared to the soft ones (<6cm). Cherts and Siliceous Shales are the most abundant lithofacies. Other field-scale features to highlight about this Upper Woodford, include the abundant occurrence of phosphate nodules/concretions of variable diameter (1-25cm), the nodular bedded geometry of the hard beds, the bitumen (tar-like?) microfractures and cm-sized balls, and the strong HC's odor.

LITHOFACIES

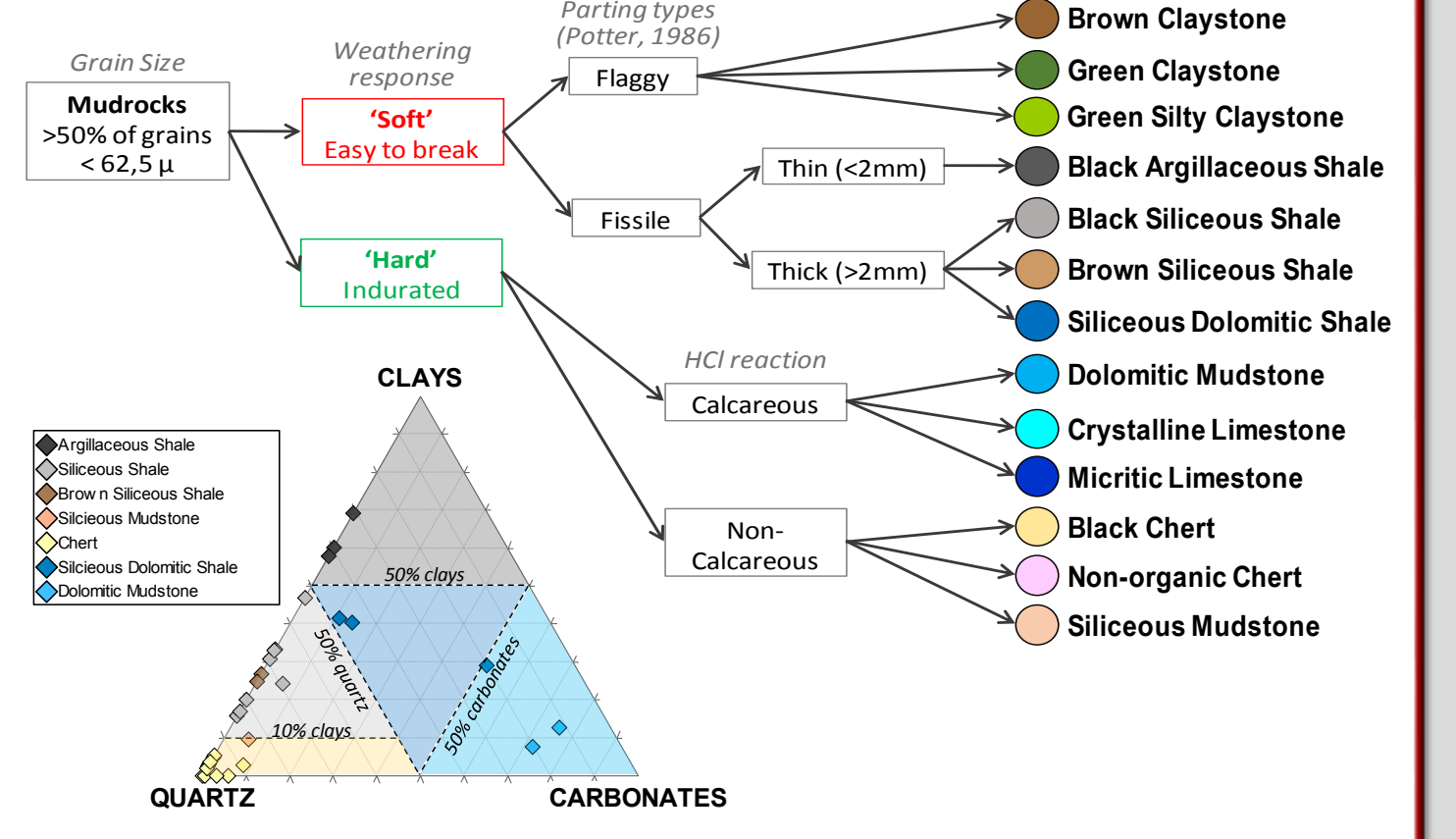
Typical cyclical heterogeneity between soft and hard beds

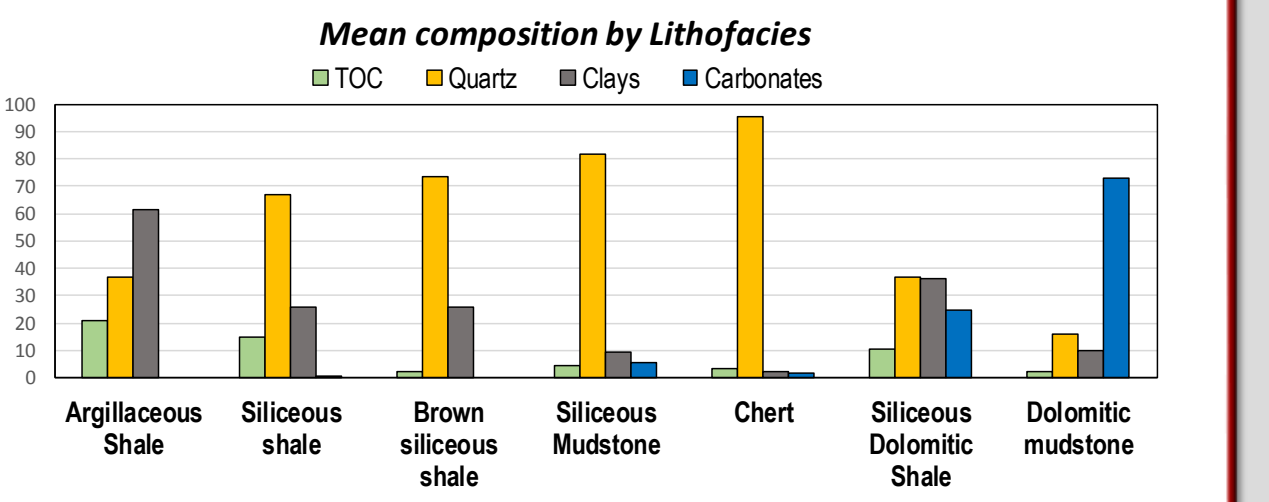


$$Soft{:}Hard\ Ratio = Soft\ beds : Hard\ beds$$

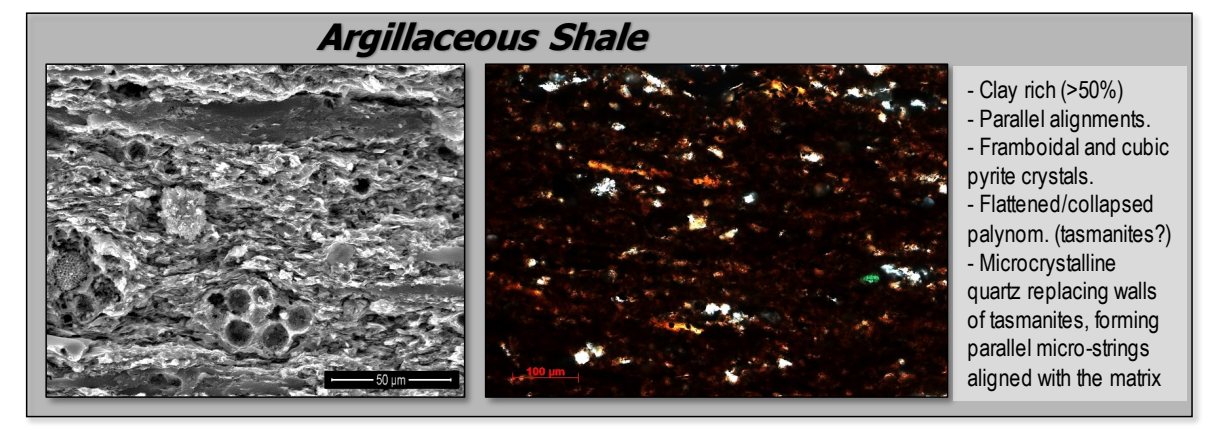
$$Soft\ \% = \frac{Avg\ thick.Soft * 100}{Avg\ thick.Hard + Avg\ thick.Soft}$$

$$Hard\ \% = \frac{Avg\ thick.Hard * 100}{Avg\ thick.Hard + Avg\ thick.Soft}$$



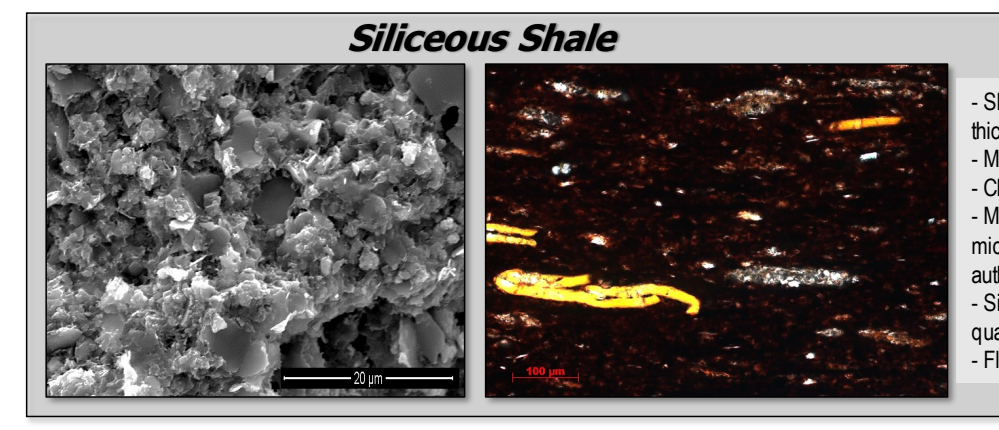


Argillaceous Shale

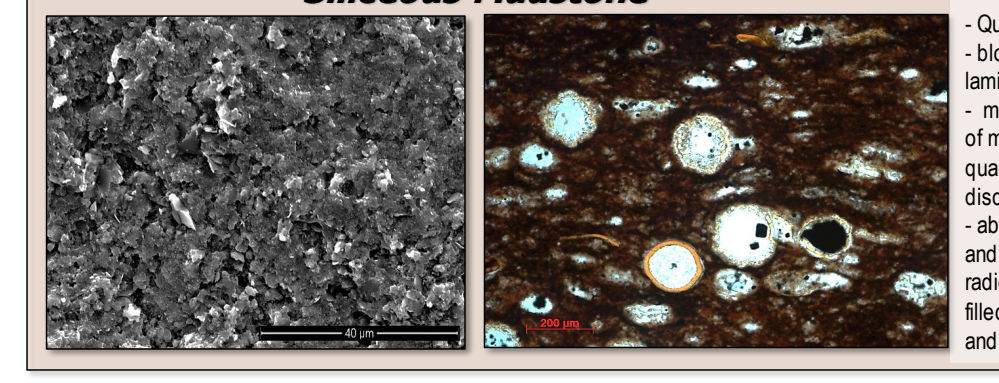


- Clay rich (>50%)
- Parallel alignments.
- Framboidal and cubic pyrite crystals.
- Flattened/collapsed palynom. (tasmanites?)
- Microcrystalline quartz replacing walls of tasmanites

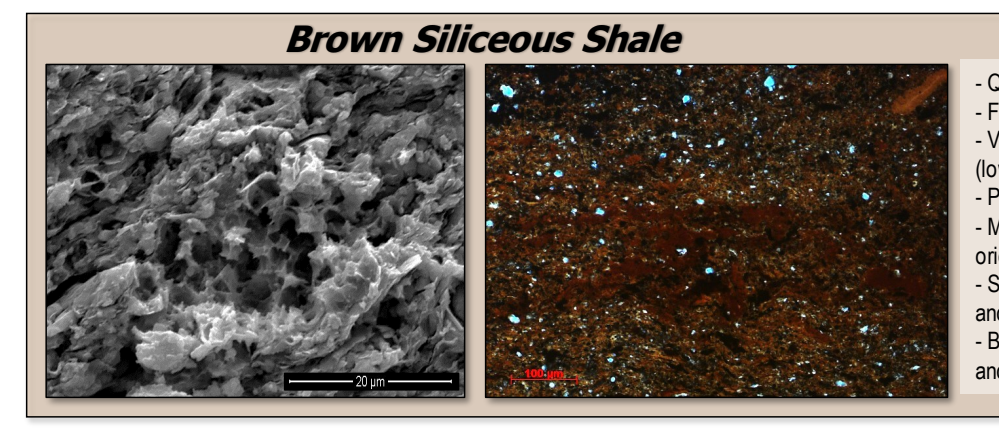
Siliceous Shale



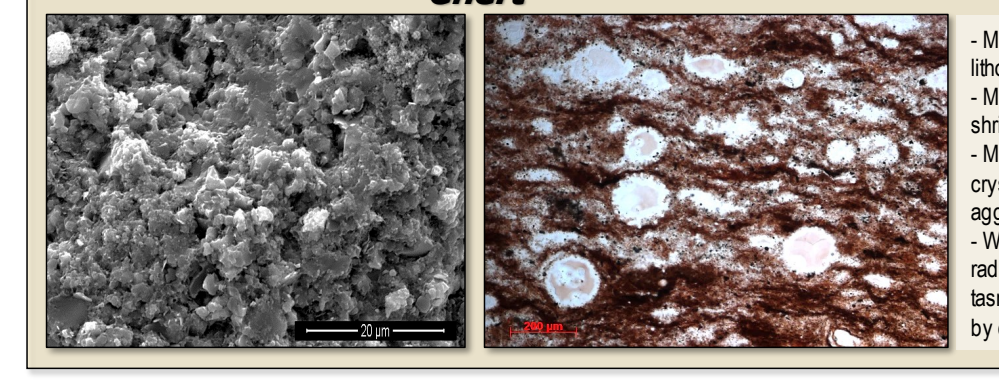
Siliceous Mudstone



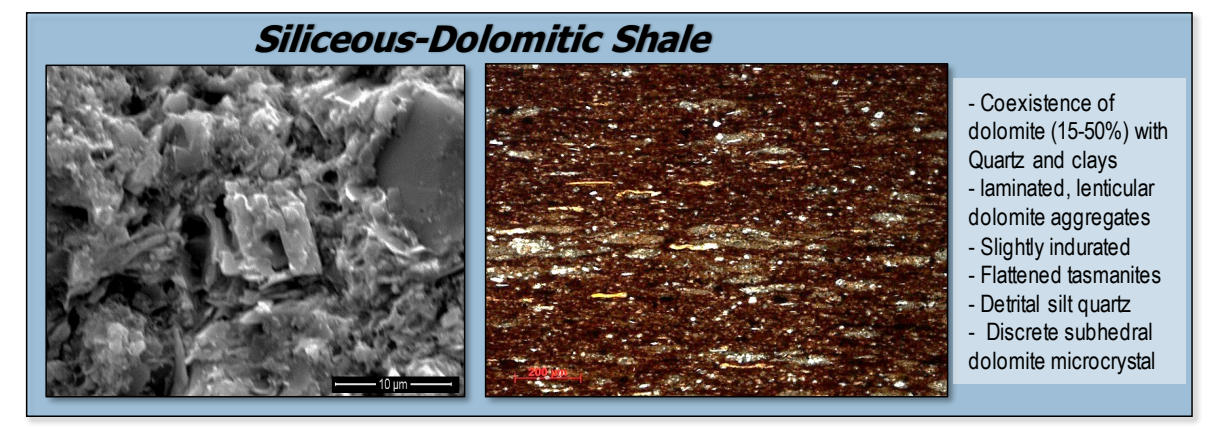
Brown Siliceous Shale



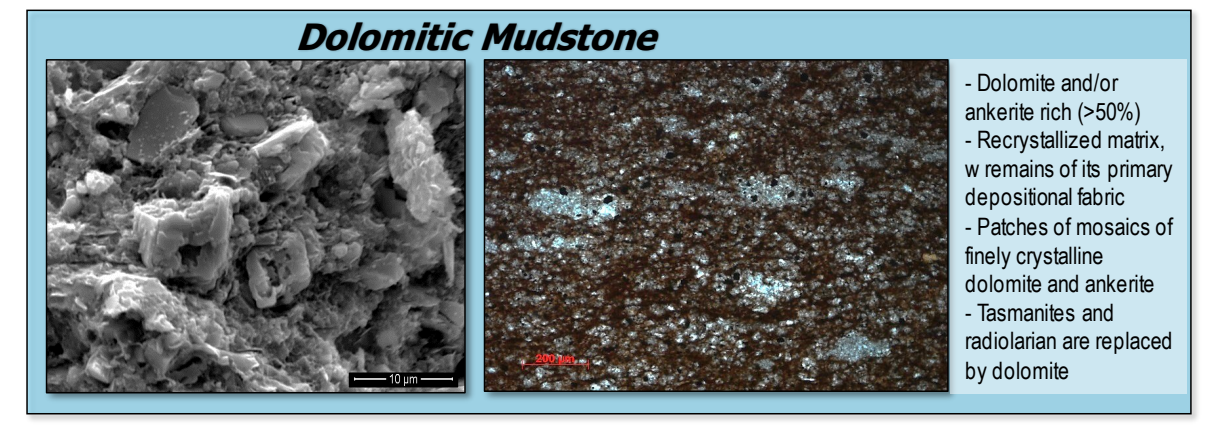
Chert



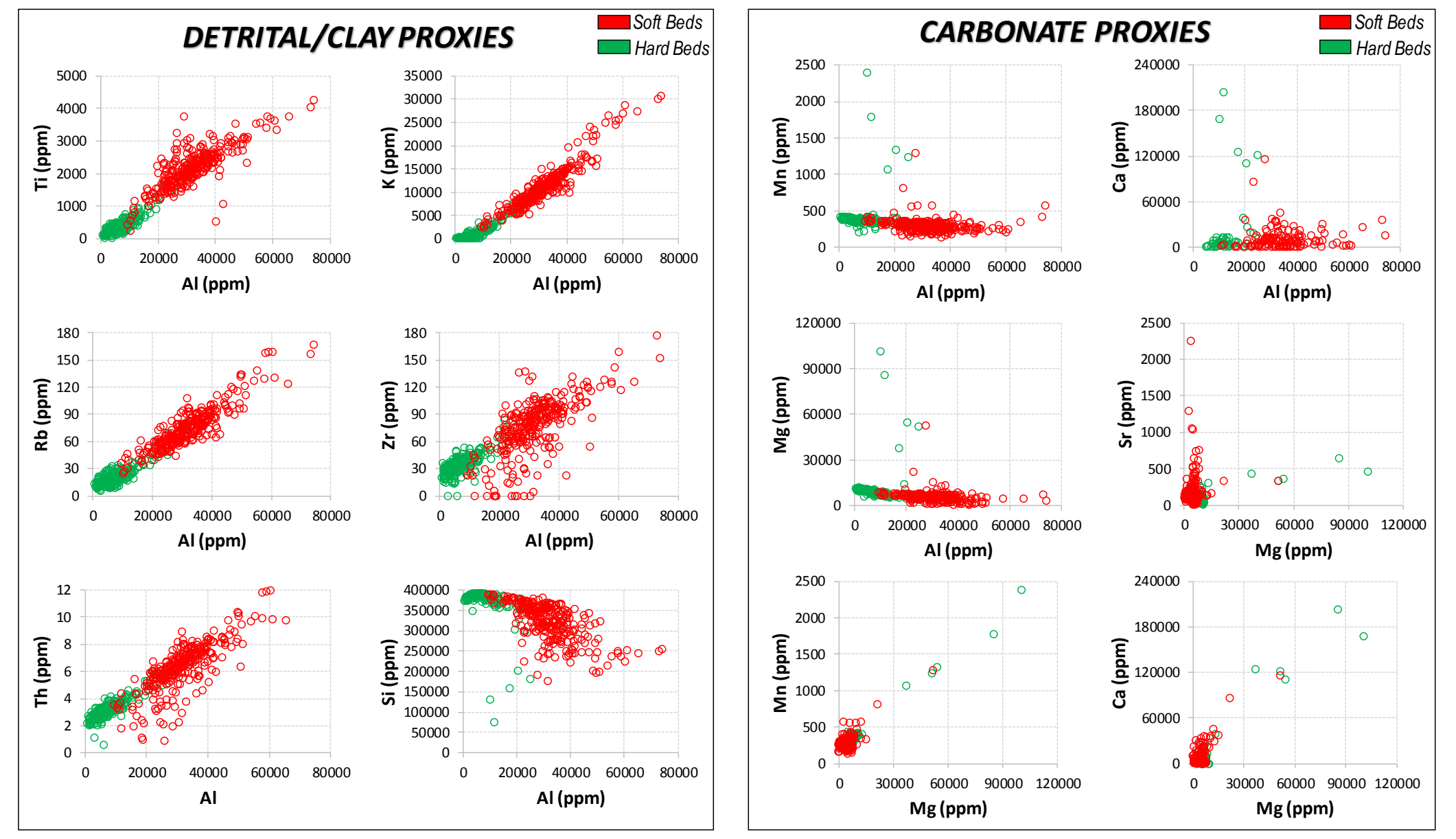
Siliceous-Dolomitic Shale



Dolomitic Mudstone

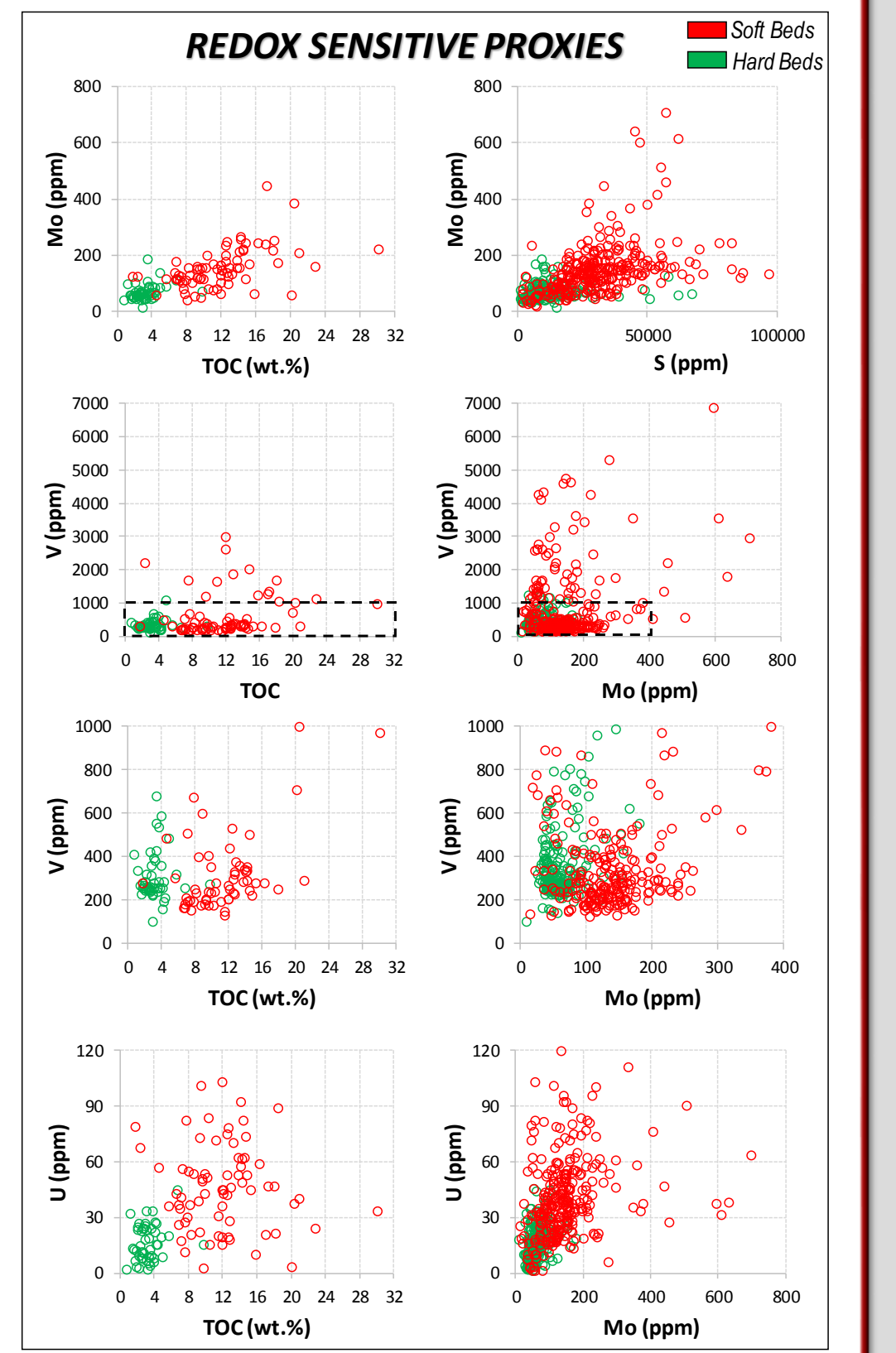


CHEMOSTRATIGRAPHY



A remarkable observation is the well-defined segregation between Hard and Soft samples all over the elemental proxies. **Hard** samples are characterized by low concentrations of detrital-sensitive elements (Al, Ti, K, Rb, Zr, Th) along with an excess of Si over Al, which together suggest that Hard beds within the Woodford Shale are more of biogenic/authigenic affinity. **Soft** samples on the other hand, present higher concentrations of Al, Ti, K, Rb, Zr, Th and moderate to low Si concentrations, which suggest that Soft beds within the Woodford are more of detrital origin. Petrographic results, confirm that the higher contents of biogenic particles (radiolarian and sponge spicules) are more evident within cherts and siliceous mudstones, whereas the occurrence of detritus (silt-sized quartz) is mostly restricted to the Argillaceous and siliceous shales.

Carbonate-sensitive elements reveal a good but negative covariance between Ca, Mg, Mn with Al. Since, Aluminum rich beds are regarded as mostly of detrital affinity, thus the negative correlation between Al with Ca, Mg, Mn, might discard the detrital origin of carbonates within the Woodford Shale. Rather, petrographic observations reveal euhedral dolomite rhombs forming micro-mosaics with some relicts of the precursor mudrock, implying a diagenetic or authigenic origin instead of detrital. Within the Woodford shale, most of the carbonates are enriched in Mg and Mn together, confirming the significant proportion of dolomite/ankerite.



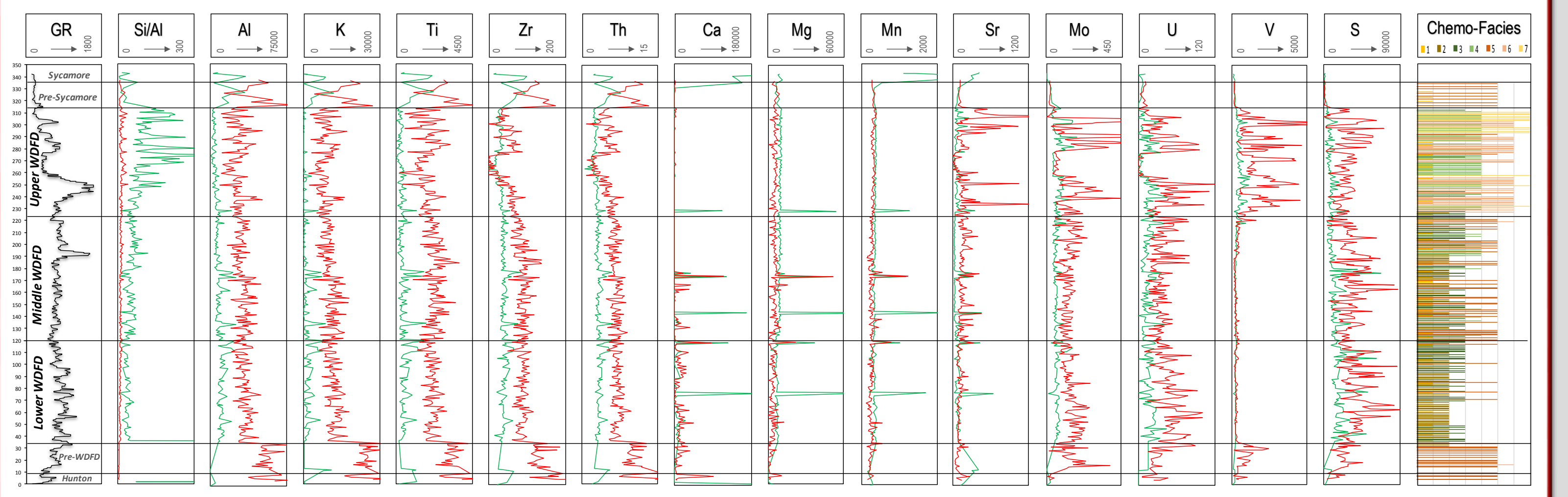
Cross plots between Mo vs TOC and S, reveal a good positive covariance, suggesting a generalized anoxic-euxinic deposition accompanied by high levels of sulfur. Also, it is noticed that generally Soft beds (shales) are interpreted to be relatively more anoxic-euxinic than Hard beds (cherts), which tend to present lesser concentrations of Mo, S and TOC.

Cross plots of V versus TOC and Mo, reveal good positive correlations mostly defined by the population of Soft beds, thus confirming the strong linkage of soft beds with more anoxic conditions comparatively with the hard beds.

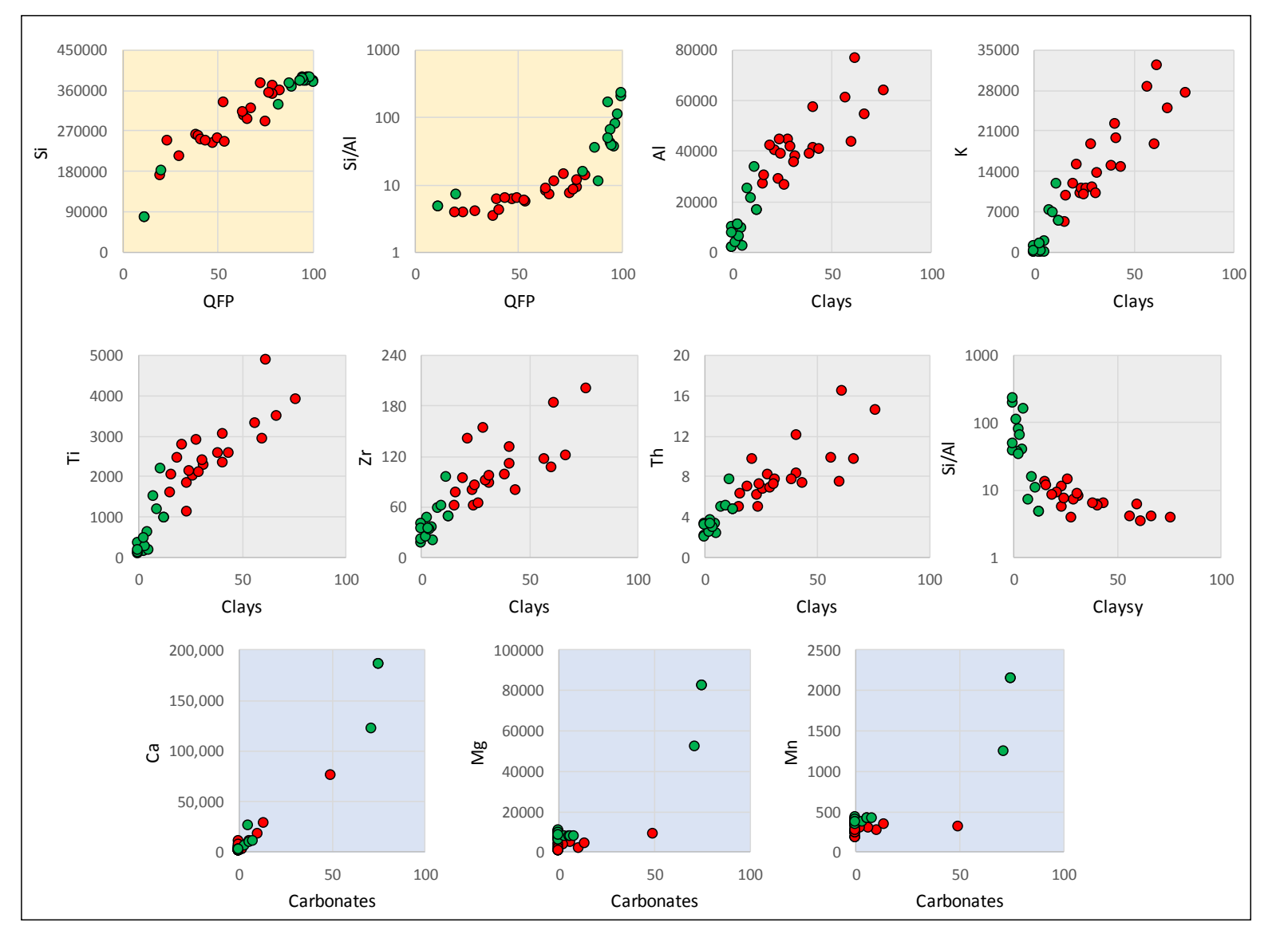
Anomalously in this study, cross plots of U with TOC and Mo, do not show clear positive correlations. Particularly, U enrichments of the upper Woodford might be due to the contribution of phosphates plus organic matter, whereas the U enrichments of the middle and lower Woodford are mostly due to organic matter, so in part this would explain the numerous outliers points with elevated U and moderate or low TOC and Mo. Thus, in general for the Woodford shale, U does not resulted as a reliable indicator of anoxia-dysoxia.

ENRICHMENT RATIOS AND IDENTIFICATION OF CHEMOFACIES

Cluster #	Chemofacies	Interpretation	Si/Al	Al	K	Ti	Zr	Th	Ca	Mg	Mn	Sr	Mo	U	V	P	S
Cluster 1	High Si/Al, Mg, Mn Low K, Ca	Biogenic input and dolomites	1.140	0.471	0.254	0.384	0.601	0.655	0.267	1.111	1.051	0.457	0.586	0.524	0.703	0.768	0.649
Cluster 2	Low Si/Al, V, P High Mo, S, U	High organics with detrital input and clays	0.234	1.512	1.642	1.534	1.426	1.355	1.612	1.320	1.025	1.142	1.689	1.771	0.460	0.751	2.070
Cluster 3	Low Si/Al High Ti, K, Al, S, Mo	Detrital input, clay-rich, with organics	0.335	1.254	1.271	1.335	1.229	1.173	0.622	0.654	0.868	1.231	1.240	1.198	0.605	0.695	1.319
Cluster 4	High Si/Al Low K, Al, Ti, Ca	Biogenic input, moderate organics	3.208	0.178	0.012	0.167	0.455	0.517	0.000	1.402	1.147	0.428	0.792	0.375	0.745	0.978	0.323
Cluster 5	Low Si/Al High Al, K, Ti, Zr, Th	Clay-rich, Detrital input, low organics	0.211	1.978	2.454	2.045	1.908	1.716	1.059	0.506	0.867	1.048	0.867	1.175	0.799	0.487	0.767
Cluster 6	Low Si/Al, Ca High V, Mo, Al, Ti, S	Detrital input, moderate clays, with organics	0.329	1.325	1.335	1.420	0.810	0.964	0.084	0.677	0.912	1.252	2.347	1.608	4.360	1.265	1.348
Cluster 7	Moderate Si/Al High P, Sr	Biogenic input with Phosphates	2.437	1.194	1.236	0.943	0.678	0.983	0.194	0.816	1.095	6.660	0.534	1.269	2.275	8.968	0.814



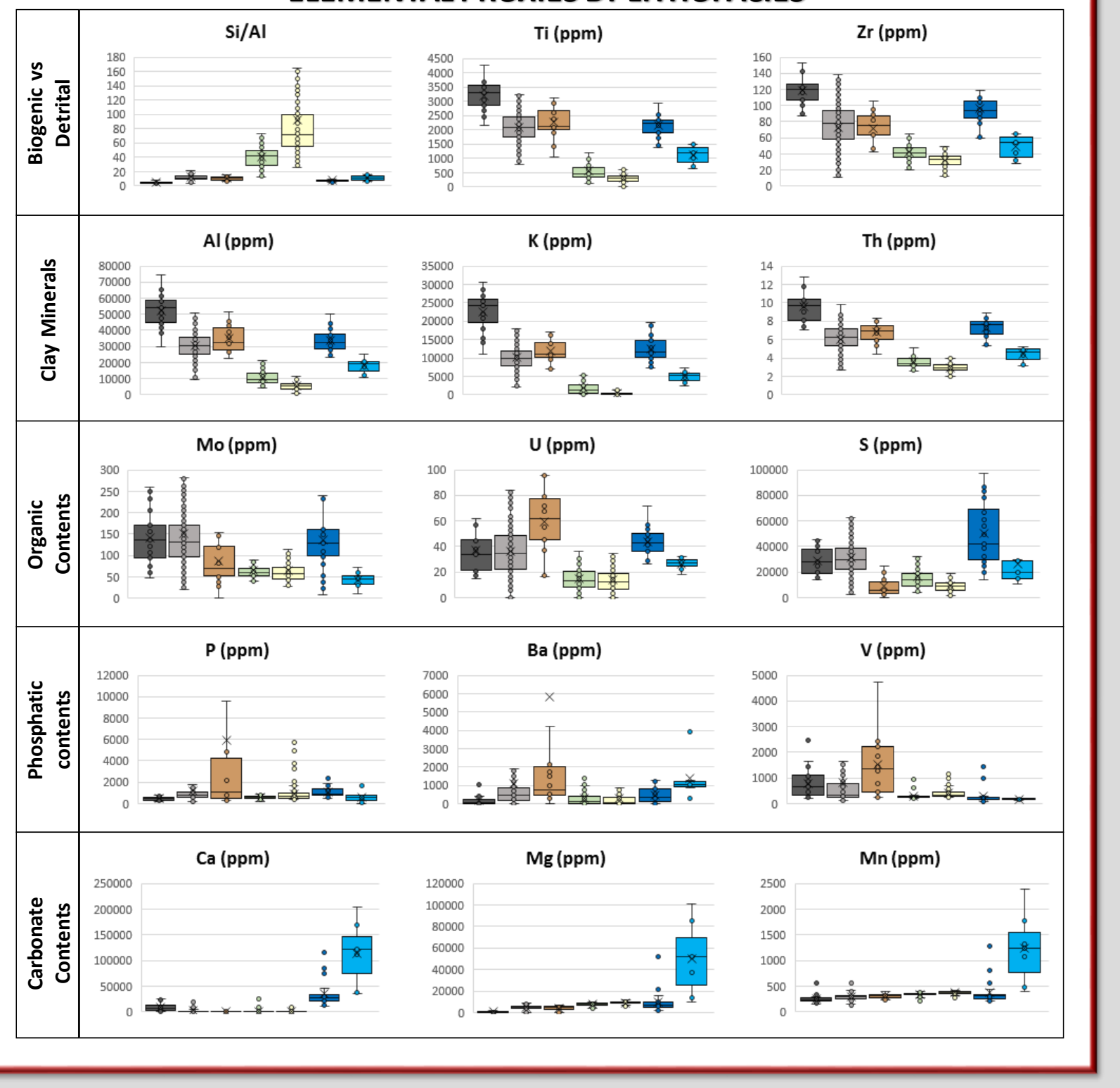
ELEMENTAL CONCENTRATIONS AND MINERALOGICAL COMPOSITION



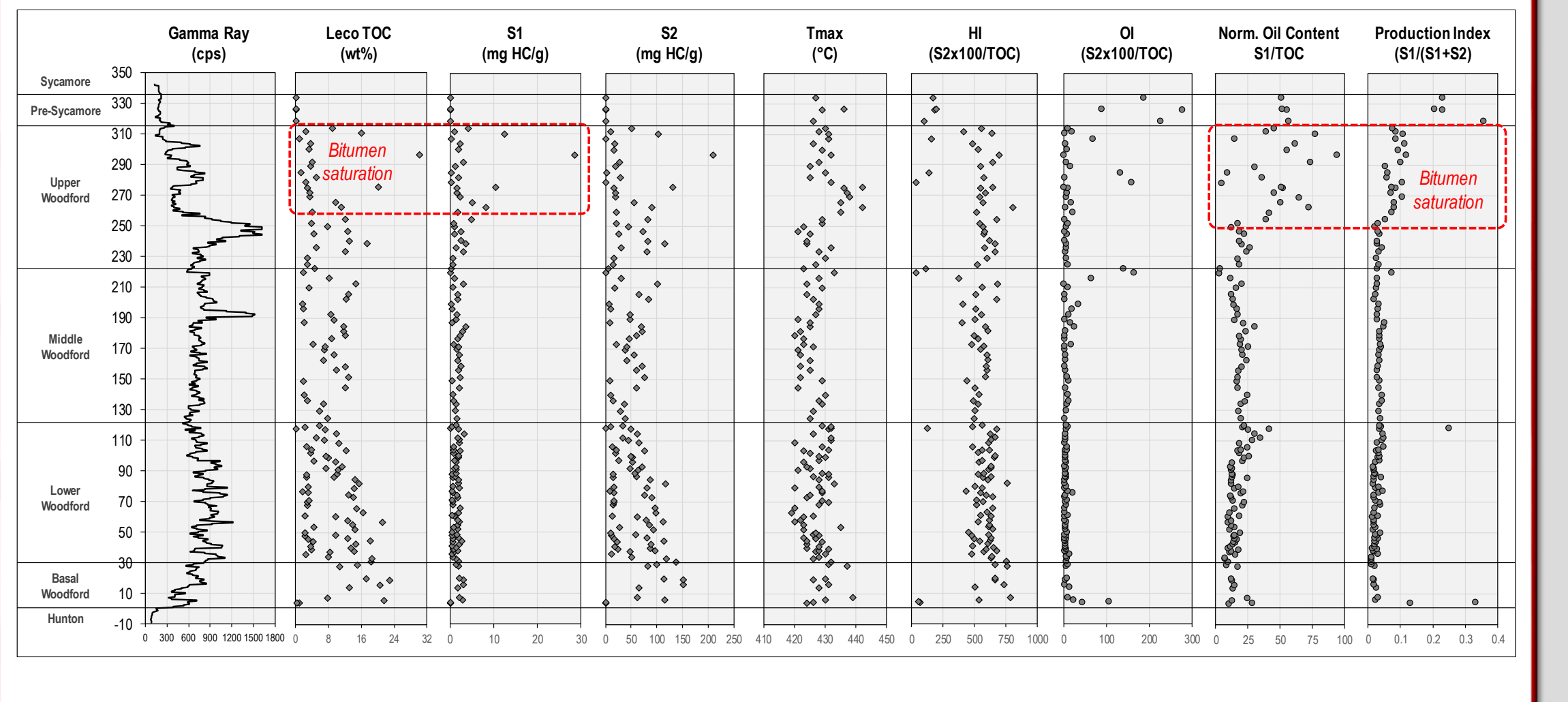
Quartz contents positively correlate with Si and Si/Al. Elements presenting negative correlations with quartz are Al, K, Ti, Zr, and Th, from which can be seen that the quartz component in hard beds tend not to host any detrital-related element. For clay-rich soft samples (clays>15%), elements that show strong positive correlation with clay minerals are Al, K, Ti, Zr and Th. For carbonate minerals can be noted that, overall elemental contents of Ca, Mg, and Mn, are matching positively as the carbonate content increases.

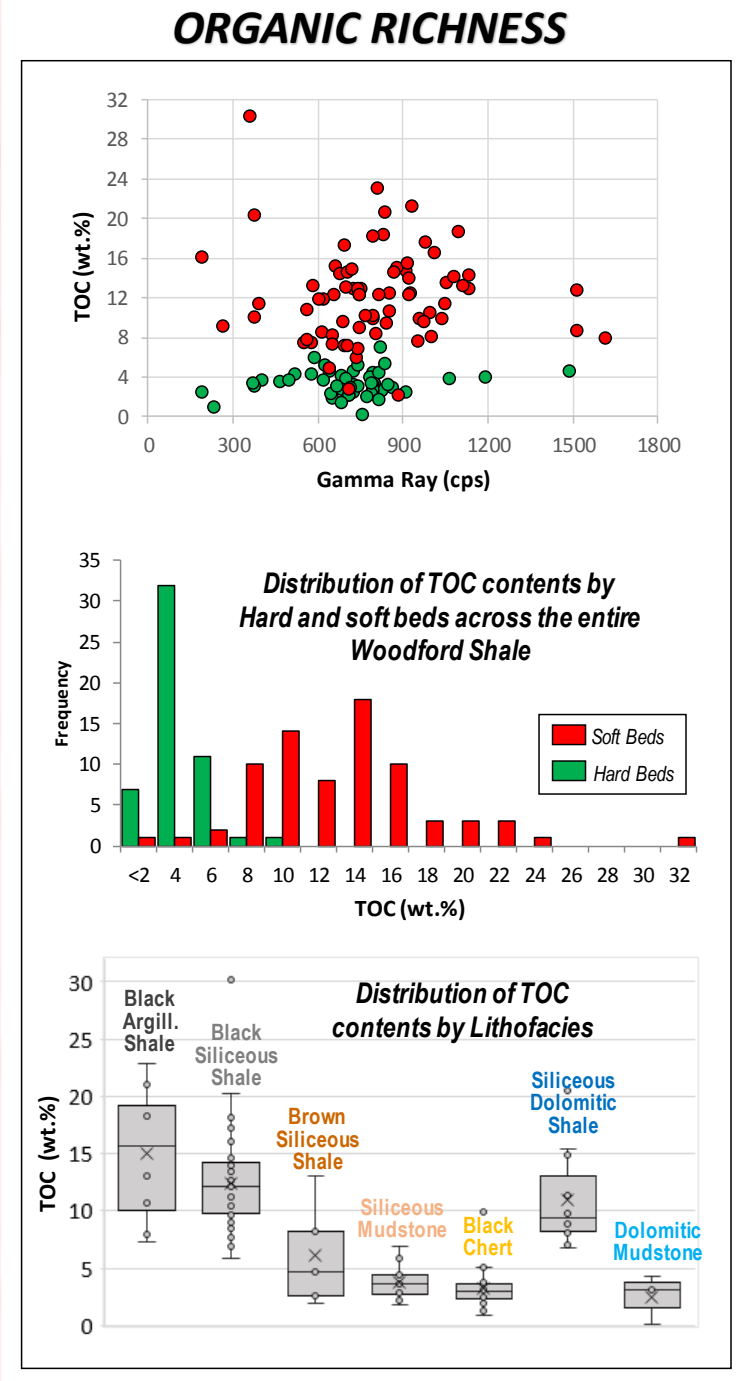
It was noticed throughout the elemental vertical profiles and cross-plots, that two populations of rock types are very well clustered, thus helping to highlight compositional and elemental heterogeneities. Also, qualitatively, when compared with elemental concentrations, lithofacies proved the ability to be grouped based on their elemental similarities.

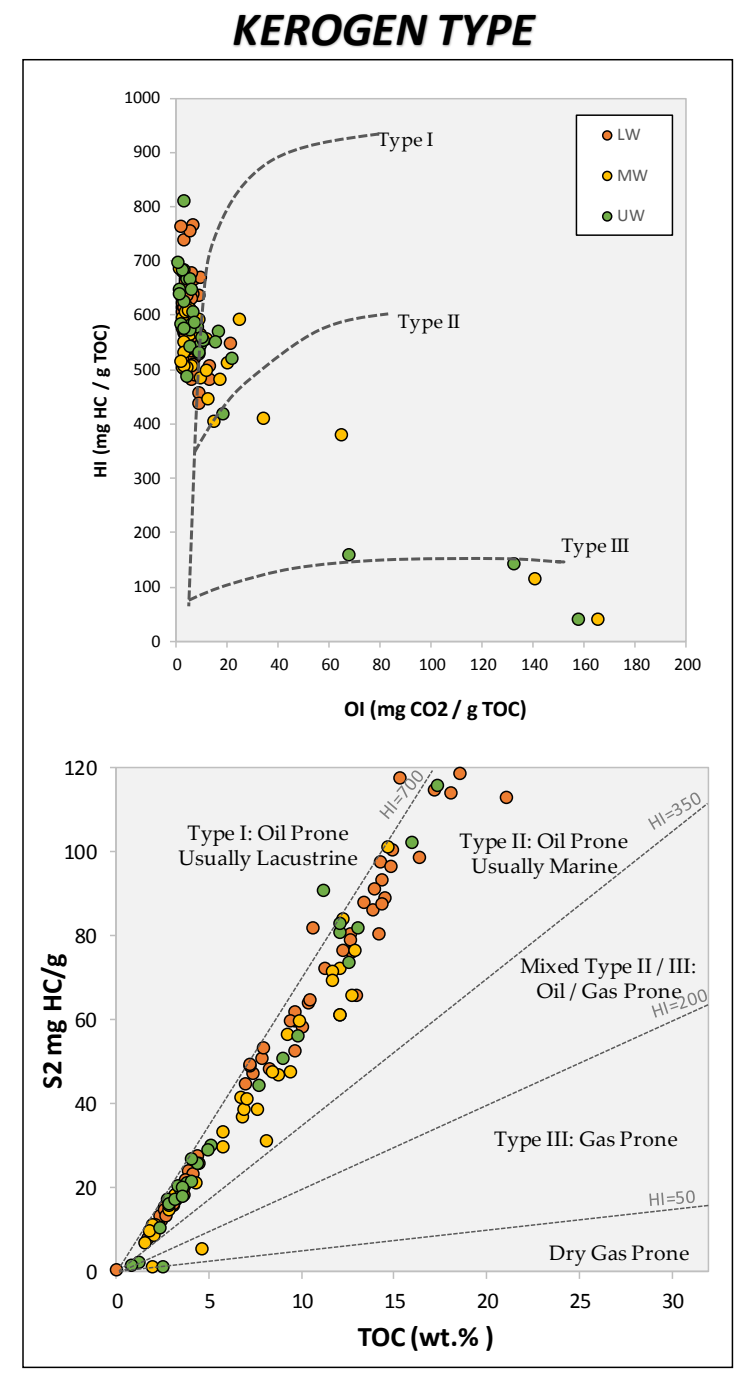
ELEMENTAL PROXIES BY LITHOFACIES

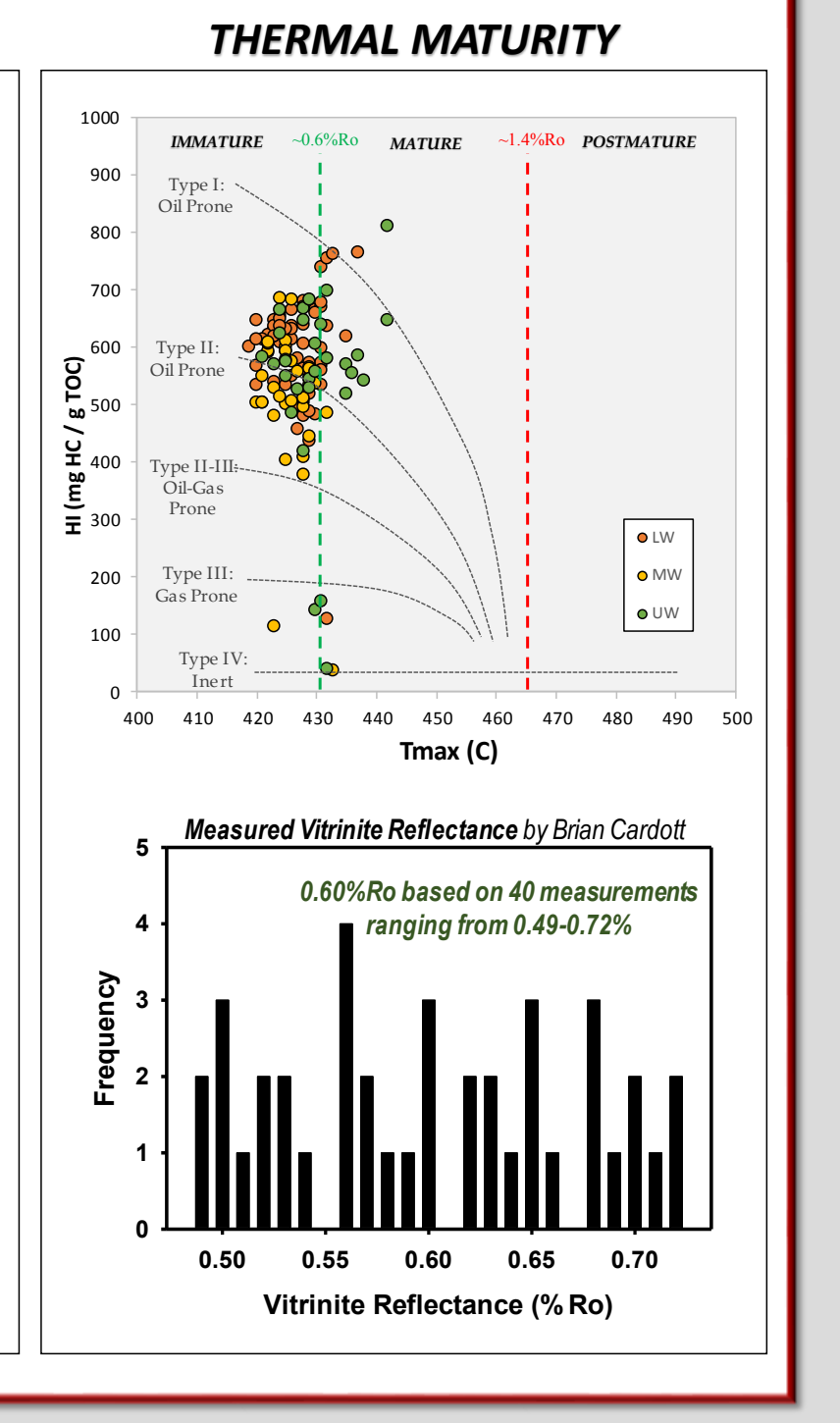


ORGANIC GEOCHEMISTRY







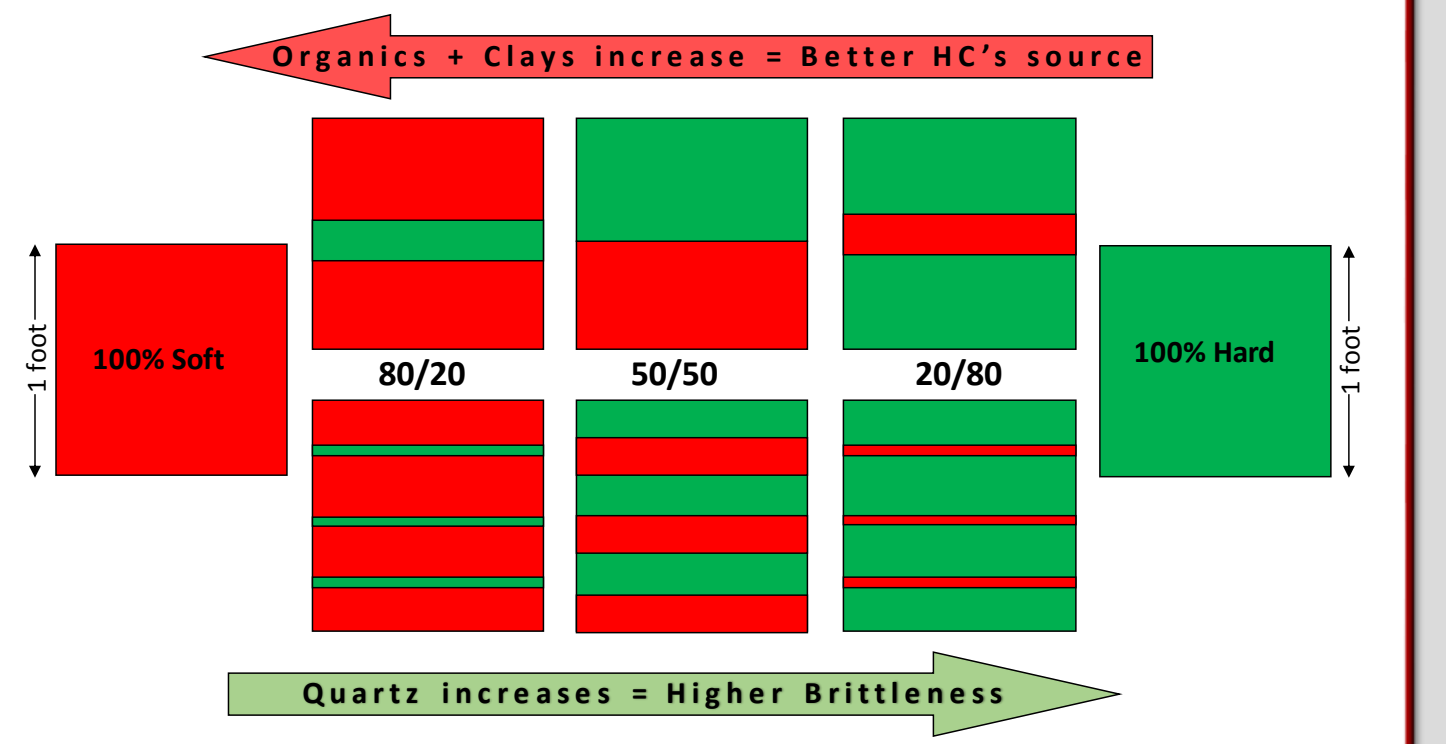


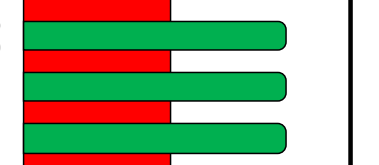
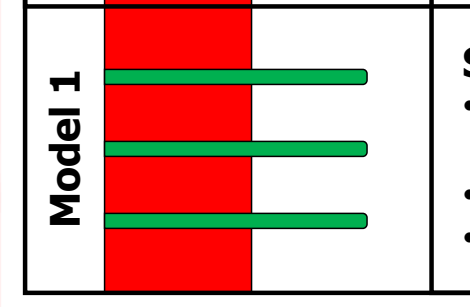
RESERVOIR IMPLICATIONS

A balance between Reservoir Quality and Completion Quality yield better Well performance

Reservoir Quality = high TOC + porosity
Provide HC's and storage capacity in the shale matrix as in the organic pores

Completion Quality = high quartz + low clays/organics + high freqcuency interbedding
Provide brittle rocks able to hold open fractures,



Model 3		**Hard >>> Soft** • Interbedding of thick chert beds (8-12 cm) with very thin shale beds (<2cm) • Moderate to poor organic content (<4%) • Moderate lo low fractures density	• Low potential as a hydrocarbon source interval • Poor primary porosity and low natural fractures, low reservoir quality • High brittleness, good completion quality (fracable and no proppant embedment)
Model 2		**Soft ≈ Hard** • Homogeneous interbedding of chert and shale beds, medium bed thickness (3 cm) • Very organic rich shale beds and moderate richness in cherts • High frequency interbeddings	• Moderate potential as a hydrocarbons source interval, and excellent storage capacity in fractures as in primary porosity • Good source-reservoir connectivity from the rock matrix through natural fractures and hydraulic fractures (good completion quality)
Model 1		**Soft >>> Hard** • Thick shale beds (>10cm) interbedded with very thin and scattered chert beds (<2cm) • Excellent organic content (8-15%) • Very low density of natural fractures	• High potential as a hydrocarbon source interval • High ductility, Low fracability • Poor completion quality (proppant embedment)

ACKNOWLEDGEMENTS