[PS]Preliminary Assessment of the Phosphate and Rare Earth Element Potential in the Upper Woodford Shale on the Lawrence Uplift, Ada, Oklahoma

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Abstract

Apatite-dominated phosphate nodules and phosphorite beds are present in Upper Woodford at the Devonian-Carboniferous boundary over an area of > 19,000mi^2 in central & southern Oklahoma. Phosphate is a key ingredient in fertilizer and REEs, such as neodymium (Nd) and dysprosium (Dy), are critical for manufacturing high-strength magnets. In addition to its world-class source rock and unconventional reservoir attributes, the Woodford Shale of Oklahoma represents a potential resource for elements critical in the drive to decarbonize the global economy.

ICP-MS analyses of 18 Woodford phosphate samples collected along a 150 km dip transect from the Lawrence uplift near Ada to the Criner Hills show that the Lawrence Uplift (LU) is strongly enriched in REEs relative to the other locations: LU phosphates average (n=10) 249ppm Nd and 47ppm Dy. Siy (1988) reported 33 wt.% P_2O_5 in the Woodford nodules. A behind quarry wall core (Wyche -1) at the Wyche Shale Pit establishes U. Woodford has a 60ft/18m interval of ~5% phosphate nodules and thin phosphorite beds. Nodules in the Current-1 core (3mi) north show this interval is an extensive feature on the LU.

The density contrast between the organic rich shale-host (2.4gm/cc) of the phosphates (apatite 3.2gm/cc) points to good recovery (~70-80%) by crushing and gravity separation. Recovery of REE by acid digestion of phosphate commonly exceeds 90%. Assuming total recovery of 70% and average thickness, 5% nodules percentages, average Nd, Dy & P_2O_5 concentrations, and respective current commodity prices we estimate there is around $750,000,000/mi^2 of in-place “value” in the Woodford Shale phosphates on the Lawrence Uplift. Structural relief is low, the overburden is thin, and the Wyche Shale Pit is an active shale mine with phosphate nodules exposed in the quarry walls. This favorable combination of these parameters suggests the need for a more rigorous commercial evaluation of the Woodford Shale’s phosphate and REE potential on the Lawrence Uplift.

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Summary: Apatite-dominated phosphate nodules and phosphorite beds are present in Upper Woodford at the Devonian-Carboniferous boundary over an area of > 19,000mi^2 in central & southern Oklahoma. Phosphate is a key ingredient in fertilizer and REEs, such as neodymium (Nd) and dysprosium (Dy), are critical for manufacturing high-strength magnets. In addition to its world-class source rock and unconventional reservoir attributes, the Woodford Shale of Oklahoma represents a potential resource for elements critical in the drive to decarbonize the global economy.

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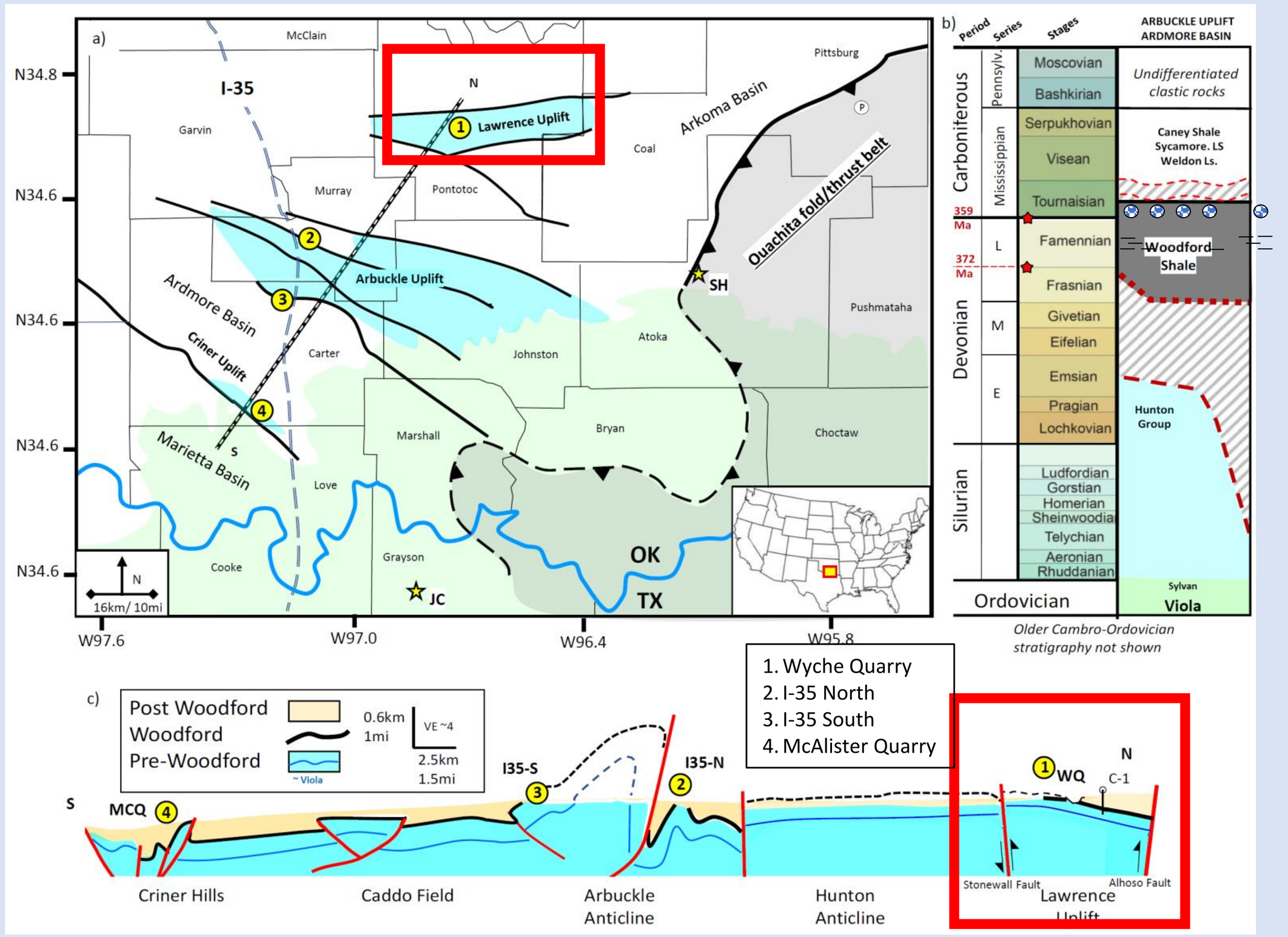
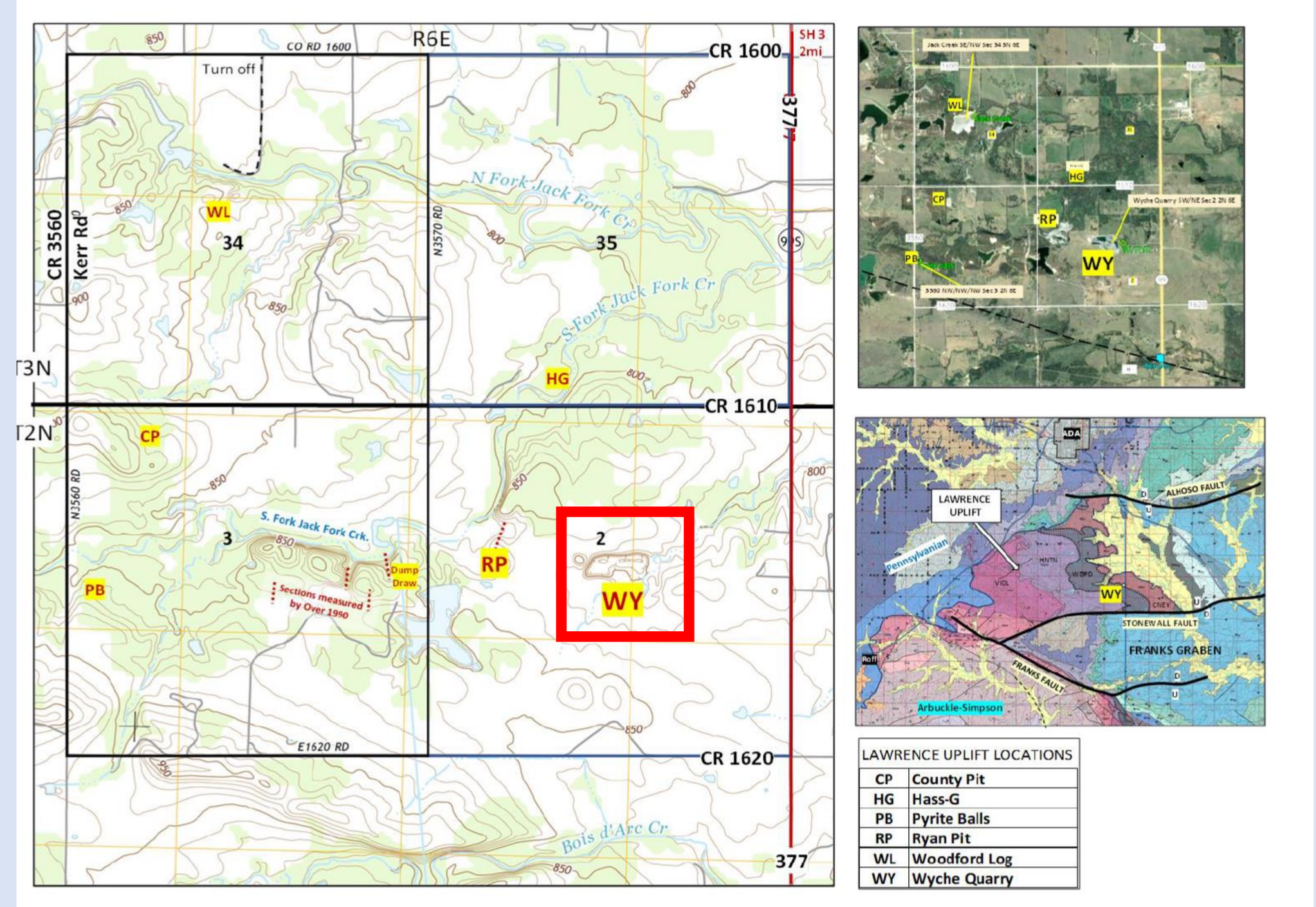
Location and Stratigraphy

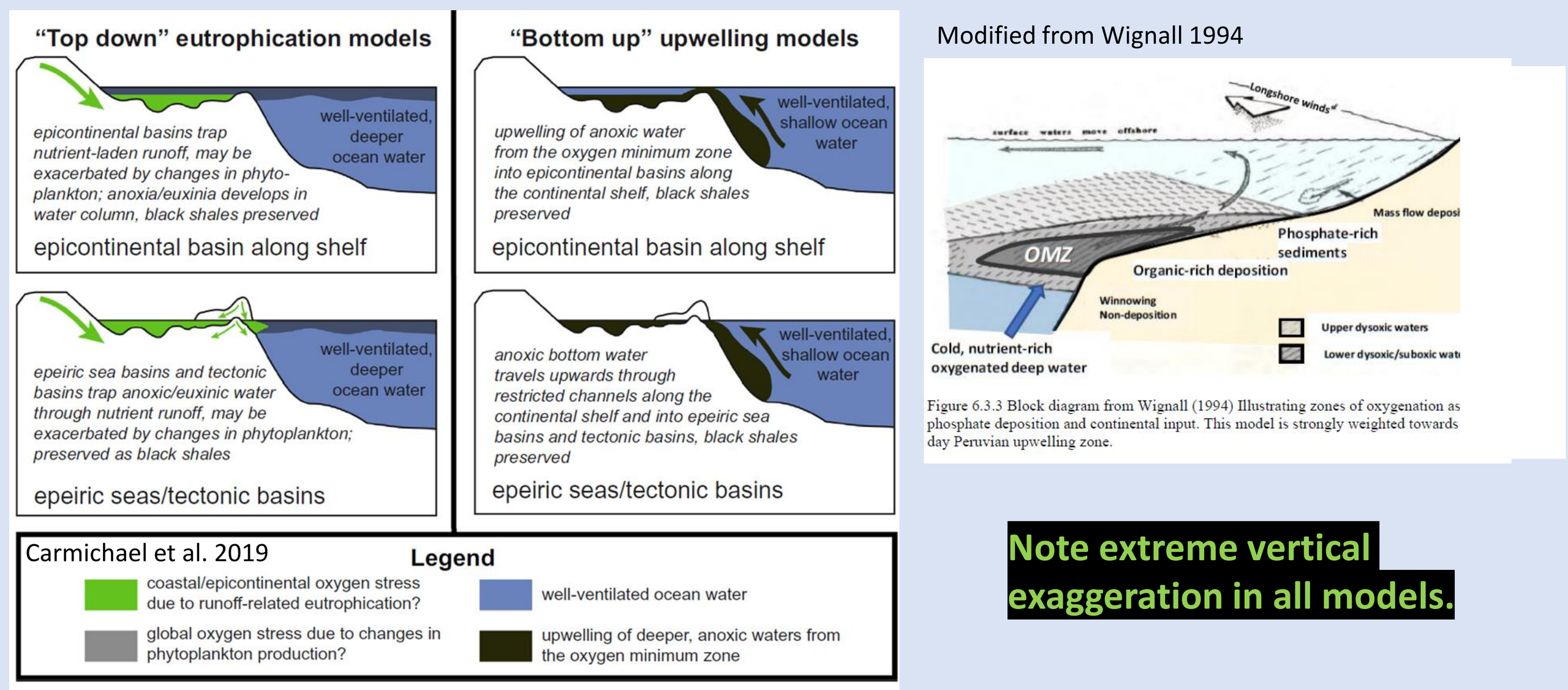


1 a) Southern Oklahoma geological features. Outcrop locations with phosphate nodules. Interstate-35 is in blue dashed double line. A-A' cross section b) Stratigraphic correlation chart. Dashes in Woodford mark clay-rich middle member. Blue patterned circles in Upper Woodford denote phosphate nodules. c) N-S regional schematic structural cross section showing principal Woodford outcrops from the Lawrence uplift to the Ardmore basin.

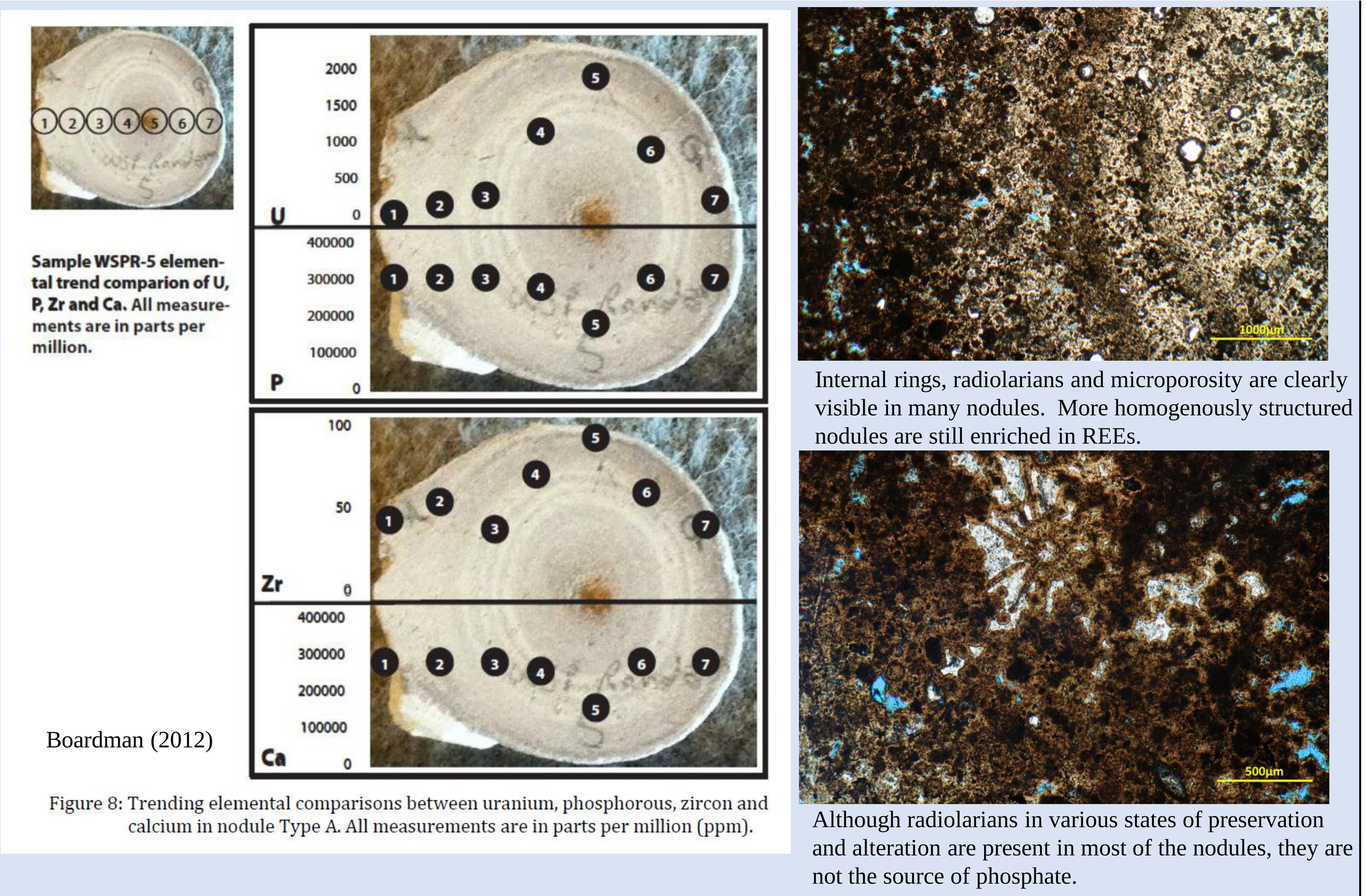


2 Area topo map, geologic map, and satellite photo of the Lawrence Uplift study area. WY (red box) is the primary focus of the dataset but nodules from HG, CP, and RP were also enriched. The nodule bearing strata is not exposed at WL, and PB.

Formation and Enrichment of the Phosphate Nodules

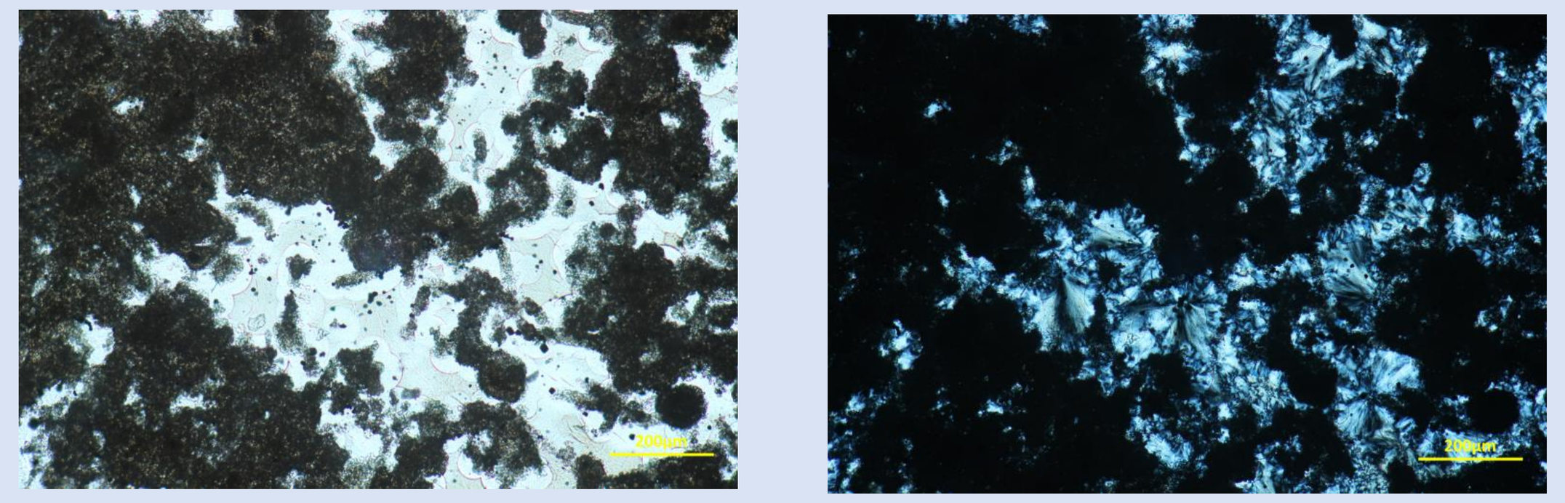


3 Although upwelling (Bottom Up) is the most widely cited model for the formation of phosphate nodules in the Woodford, the influx of terrestrial phosphate (Top Down) could also be a driver especially considering 1) proximity to Devonian-Carboniferous sequence boundary 2) forest fire and log material co-occurring with the phosphate, and 3) REE and trace element enrichment usually attributed to continental erosion.

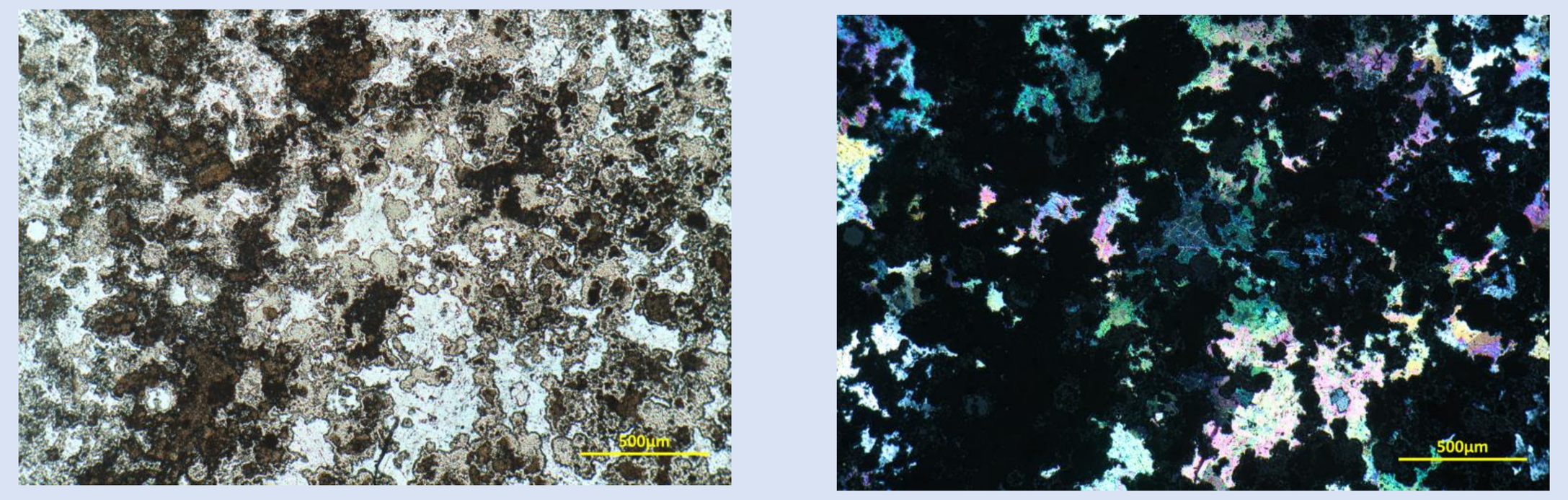


4 Boardman, 2012 and Siy, 1988 documented REE enrichment in the phosphate nodules and noted that darker layers within the phosphate were more enriched than lighter layers. Boardman also note that there were several morphologies of phosphate nodules. Our studies show that the paleogeographic location but not morphology control enrichment.

Diagenetic Differences in the Nodules



Radiolarians are deposited as opal which is often replaced by pyrite and phosphate in the nodules. Chalcedony cement fans and botryoidal textures, evidence of that replacement are clearly visible in PPL and XPL photomicrographs.

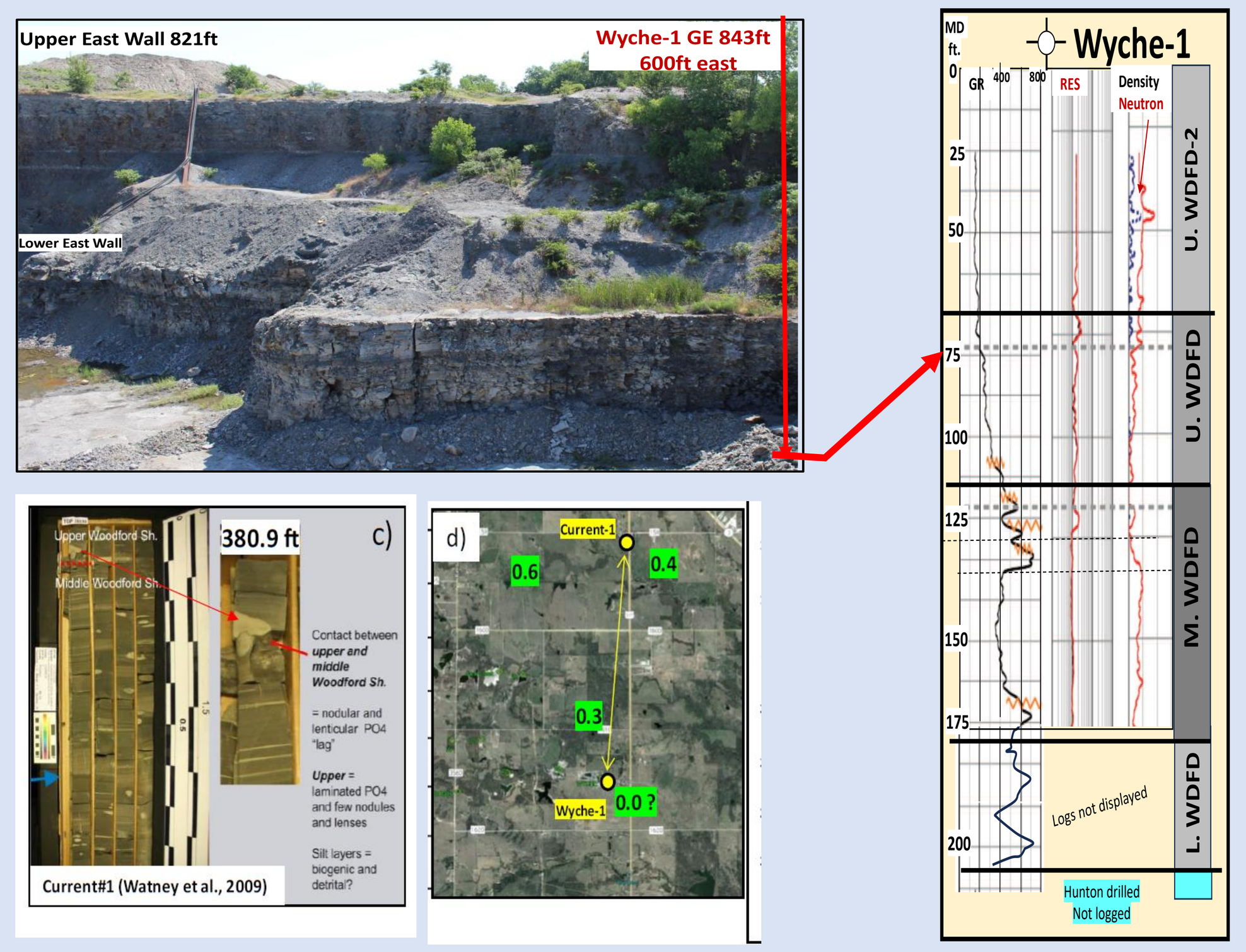


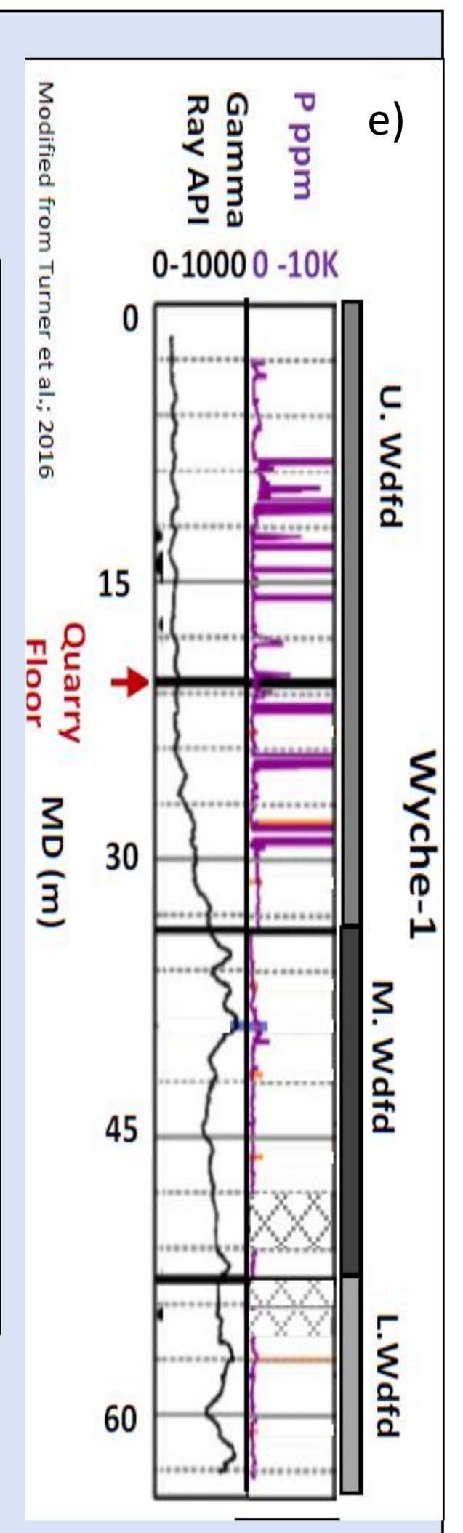
Anhydrite has also been observed in the nodules usually to the excusion of chalcedony and significant pyrite. We have no evidence to indicate that anyhydrite bearing nodules are differentially enriched.

5 In addition to different diagenetic histories the Woodford phosphate have strong morphologic differences, ranging from spherical to elliptical to lenticular phosphoritate beds (see #7). The cause of these differences has not been worked out.

Resource Quantification-Thickness

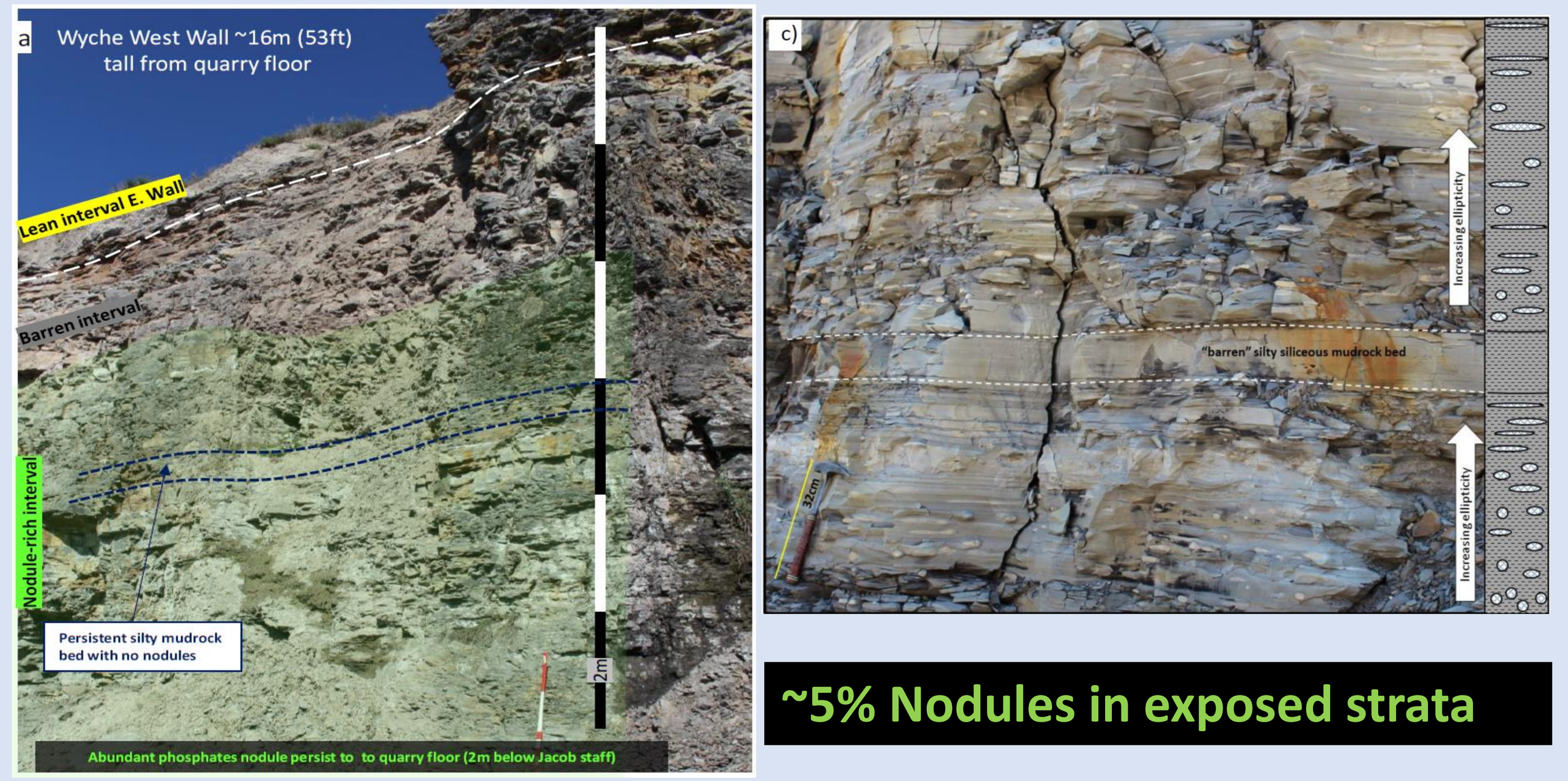
~ 64ft/21m of Po-bearing rock





6 a) Wyche quarry wall with b) Wyche-1 superimposed. c/d) Current-1 core 2.5mi north. e) Gamma Ray Log and XRF Phosphate data from the Wyche #1 core shows phosphatic zone extends 15m below the quarry floor for a total thickness of about 21m.

Local Resource Quantification-Nodule Density



7 a) Western Wall of the Wyche quarry with the nodule rich strata. c) A close up of the quarry wall. This is one of several places where nodules were estimated to be about 5% of the rock. Additionally, nodule morphology stratigraphy is visible.

Resource Valuation

11

Area	acres	sq. cm
	640	25,899,881,088
THICKNESS	ft	cm
	60	1,858
VOLUME		cubic cm
		48,111,619,109,069
Avg. Density		gm/cc
Woodford		2.4
Mass		gm
		115,467,885,861,765
Mass gm		gm
5% Nodules		5,773,394,293,088
Mass oz		oz
5% nodules		206,192,653,325
Nd wt%		oz Nd
0.025%		51,341,971
Recovery		oz
Good Case	42%	21,563,628
Best Case	72%	36,966,219
Nd VALUE	**42%**	**$ 107,818,138**
$5.00/oz	**72%**	**$ 184,831,094**

Dy wt%		oz Dy
0.000048		9897247.36
Recovery		oz
Good Case	42%	4,156,844
Best Case	72%	7,126,018
Dy Value	**42%**	**$ 22,862,641**
$5.50/oz	**72%**	**$ 39,193,100**

P2O5 wt%		tons P2O5
0.33		2126361.737
Recovery		tons P2O5
Good Case	42%	893,072
Best Case	72%	1,530,980
P2O5 Value	**42%**	**$ 308,109,816**
$345.00/ton	**72%**	**$ 528,188,256**

Total Good Case		**$ 438,790,596**
Total Best Case		**$ 752,212,450**

Table 2: Calculation of the value of Phosphates and REE in place under 1 sq mile of the Lawerence Uplift

Resource Pricing and Recovery

Pricing **10**

Commodity	$	Unit
Phosphate	$ 345.00	ton
Neodymium	$ 5.00	oz
Dysprosium	$ 5.50	oz
Road Aggragate*	$ 18.00	ton

*subject to local market saturation

Recovery

Case	Nodule Recovery	Leaching Recovery	Total Recovery
Best Case	80%	90%	72%
Good Case	60%	70%	42%

Table 1: Pricing and recovery factor considerations used for this study dating to early 2023. Recoveries are high due to density differences and the soluble nature of Phosphates (Emsbo et al., 2015).

Other Considerations

Favorable Factors for the Lawerence Uplift

- There is minimal structural and topographic relief. Faulting is minimal. There are multiple active aggregate mines.

Costs

- Overburden, the principal cost, is relatively thin. Because the local road aggregate market is finite, on-site initial separation will be required.
- Rail transport will be needed to transport recovered phosphate for further refinement. Once at a railhead, additional transport cost is marginal.
- A facility for acid digestion and final benefaction needs to be built.

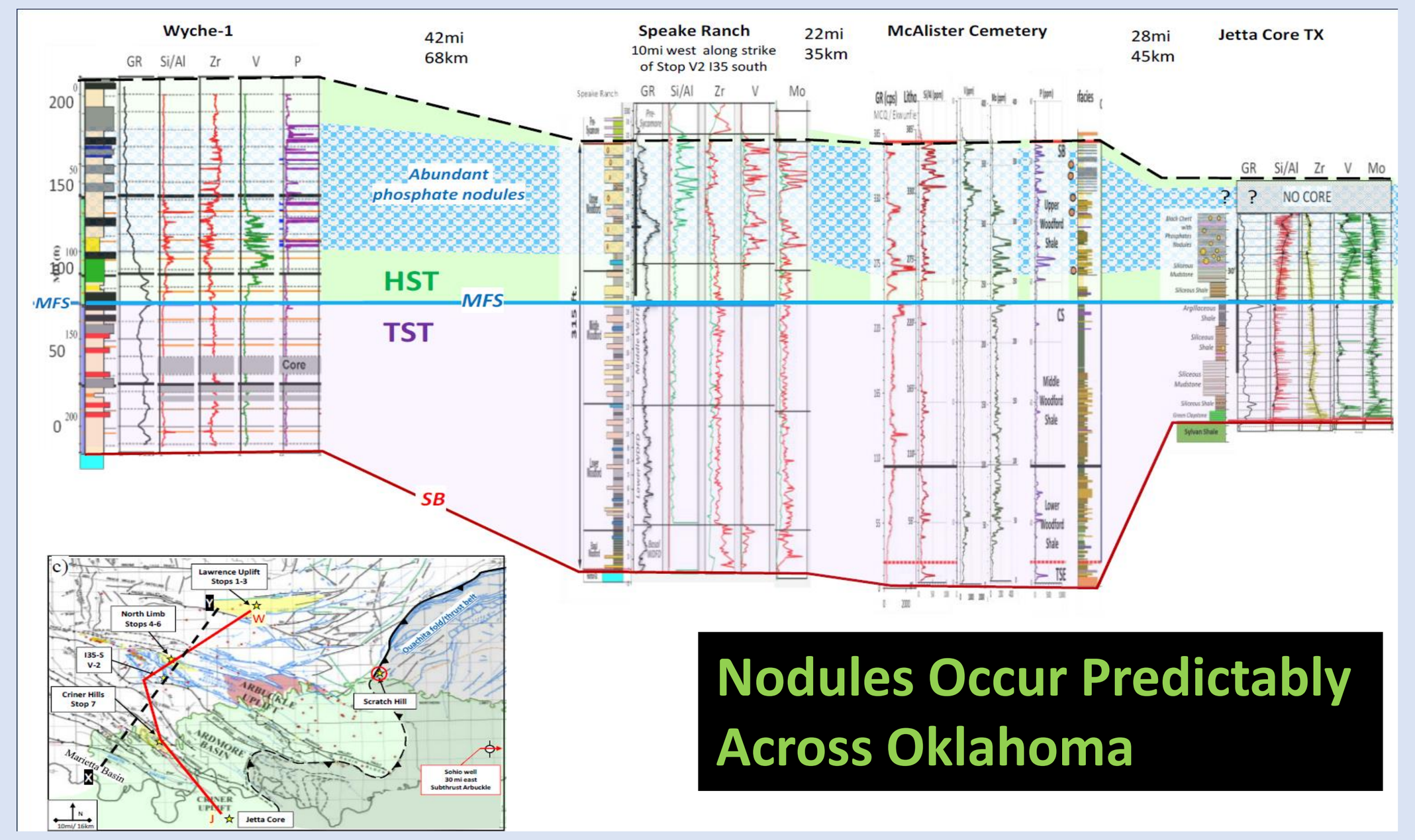
Environmental Impact

- REE and Phosphate mining would likely require larger scale operations than current shale mining and the impact of these has not been assessed.
- Separating the phosphate and concentrating the REEs may produce undesirable bi-products that have to be disposed of. For example, it was not expected to find significant anhydrite in the nodules.

Concluding Thoughts

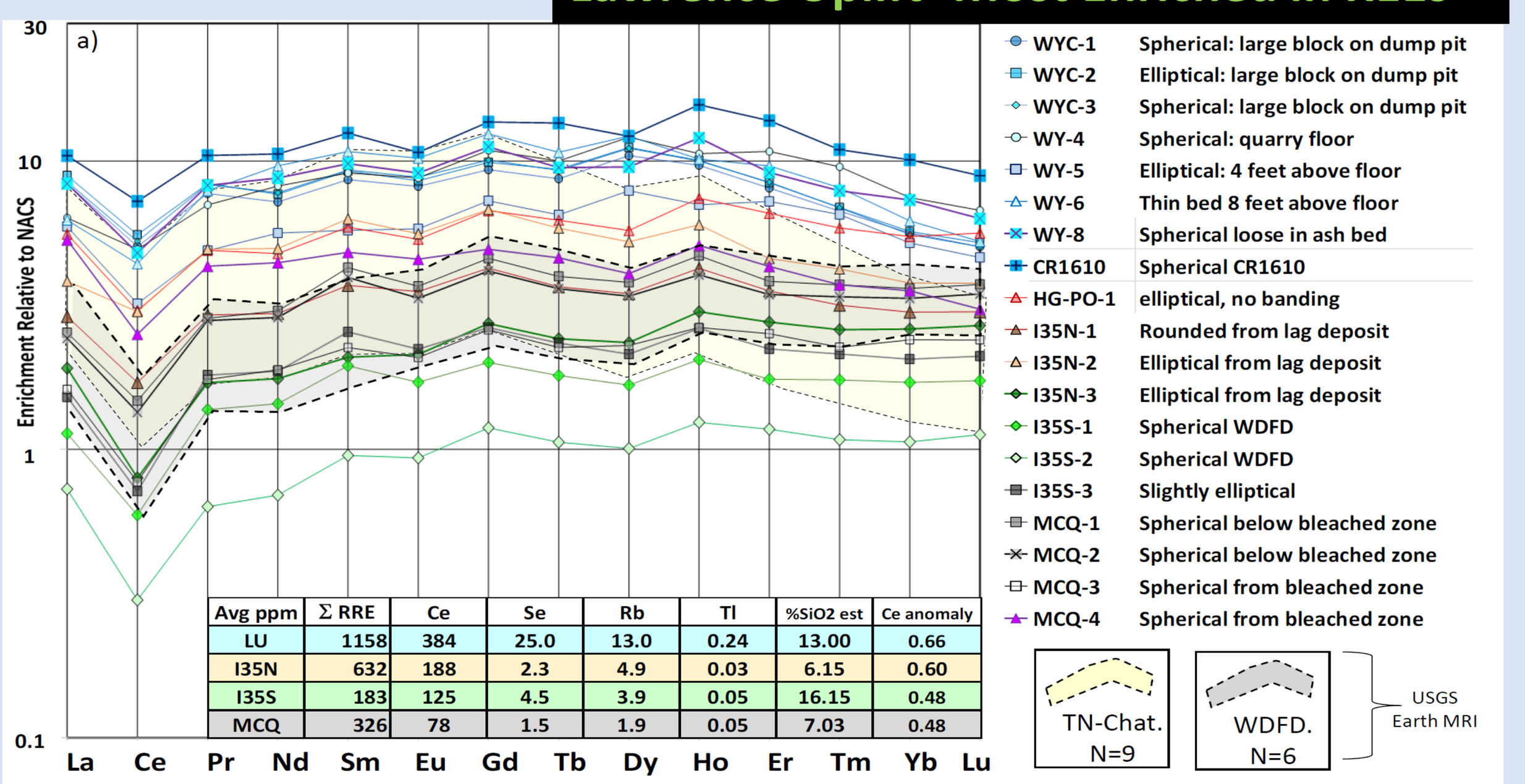
- There is approximately $400-800m/sq mile of REE and Phosphate resource in place in the Upper Woodford of the Lawerence Uplift.
- The nodules appear to be predictably present/ enriched across the Lawerence uplift with 4 localities on the Uplift as well as other localities in Oklahoma analyzed for REE concentration.
- The structure of the Lawerence Uplift and separation and concentration technology appear to be favorable to mining.
- A full cost and environmental accounting has not been undertaken.

REE Enrichment Across Oklahoma



8 The Woodford Phosphate nodules are observed in the Anadarko basin as far north as Kingfisher County and South as Grayson County Texas. Their position in the stratigraphy is biostratigraphically constrained using conodonts. The above cross section documents the occurrence between the Wyche core and north Texas localities.

Lawrence Uplift- Most Enriched in REEs



9 All the nodules analyzed were enriched in REEs relative to the NACS standard. The most landward nodules were consistently most enriched across three subregions of Oklahoma. Paleogeographic position appears to be more important than morphology for controlling enrichment. I-35S samples (green) are silicified/ affected by local diagenesis and are therefore not considered in the interpretation of the trend.

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