

**PS Hyperspectral Imaging of the Leonardian Third Bone Spring Shale,
Whiting Collier 1201 Core, Eastern Delaware Basin:
Application and Results***

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Abstract

The Leonardian Third Bone Spring Shale in the Delaware Basin is an active unconventional exploration target. In this thick calcareous siliceous mudstone, mineralogy and TOC are important parameters needed to define brittleness and high TOC for selecting sweet spots. These parameters can be obtained from hyperspectral imaging (HI) of core. Originally developed for the mining industry, HI uses a combination of short-wave infrared light (SWIR) and long-wave infrared light (LWIR) to create a continuous visual ‘map’ of the minerals in a core that respond to reflectance principles. HI, which requires no special preparation other than that the core is slabbed, clean, and dry, can be applied rapidly and provides mineralogical results related to various energy emitted in wavelength spectrum by either halogen bulb reflectance (short-wave quantification) or heat reflectance spectra (long-wavelength quantification). We collected hyperspectral core imaging data from 300 feet of Leonardian Third Bone Spring Shale core located on the western slope of the Central Basin Platform in the Delaware Basin. We obtained detailed, continuous high-resolution mineralogical and textural information of the cored interval. Digital HI-derived single mineral and TOC curves, calibrated to discrete X-Ray Diffraction (XRD) and TOC measurements respectively, were imported as curves to display mineralogical variations with depth alongside X-Ray Fluorescence (XRF) data and mechanical data. We integrated the hyperspectral data with core description, thin-section, XRF, XRD, and TOC data to determine the mineralogy of different facies and to facilitate property ‘up-scaling’ from SEM and thin-section scales to understand the controls on reservoir quality. Mineralogy at the sub-cm scale was observed. Results were of much higher resolution than was obtained by core description or limited thin-section analysis. The calculated TOC compared favorably to measured RockEval data points, but the HI analysis has the advantage of being continuous. Hyperspectral imaging of cores is a valuable method for obtaining continuous rock-property data that can be integrated with other data to characterize a production interval.

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- Browning D., and T. Kosanke, 2016, Mineral Mapping of core using combined high-resolution SWIR and LWIR sensors: presentation Geological Remote Sensing Group London UK December 2016.
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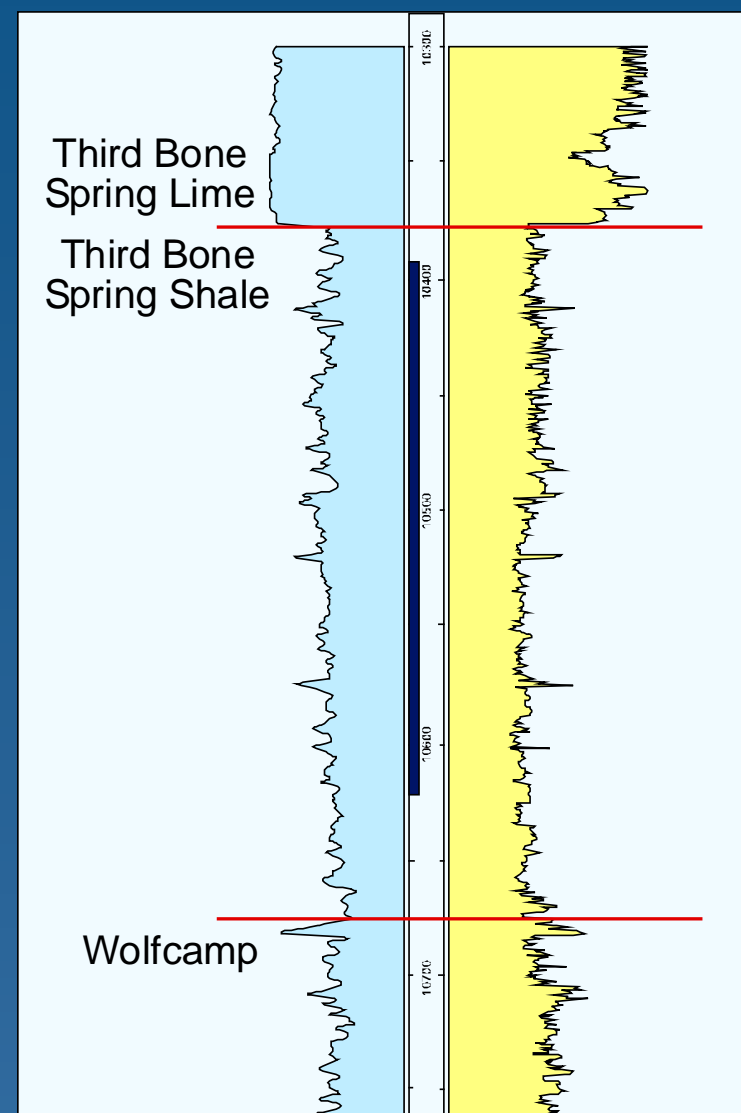
Abstract

The Leonardian Third Bone Spring Shale in the Delaware Basin is an active unconventional exploration target. In this thick calcareous siliceous mudstone, mineralogy and TOC are important parameters needed to define brittleness and high TOC for selecting sweet spots. These parameters can be obtained from hyperspectral imaging (HI) of core. Originally developed for the mining industry, HI uses a combination of short-wave infrared light (SWIR) and long-wave infrared light (LWIR) to create a continuous visual ‘map’ of the minerals in a core that respond to reflectance principles. HI, which requires no special preparation other than that the core is slabbed, clean, and dry, can be applied rapidly and provides mineralogical results related to various energy emitted in wavelength spectrum by either halogen bulb reflectance (short-wave quantification) or heat reflectance spectra (long-wavelength quantification).

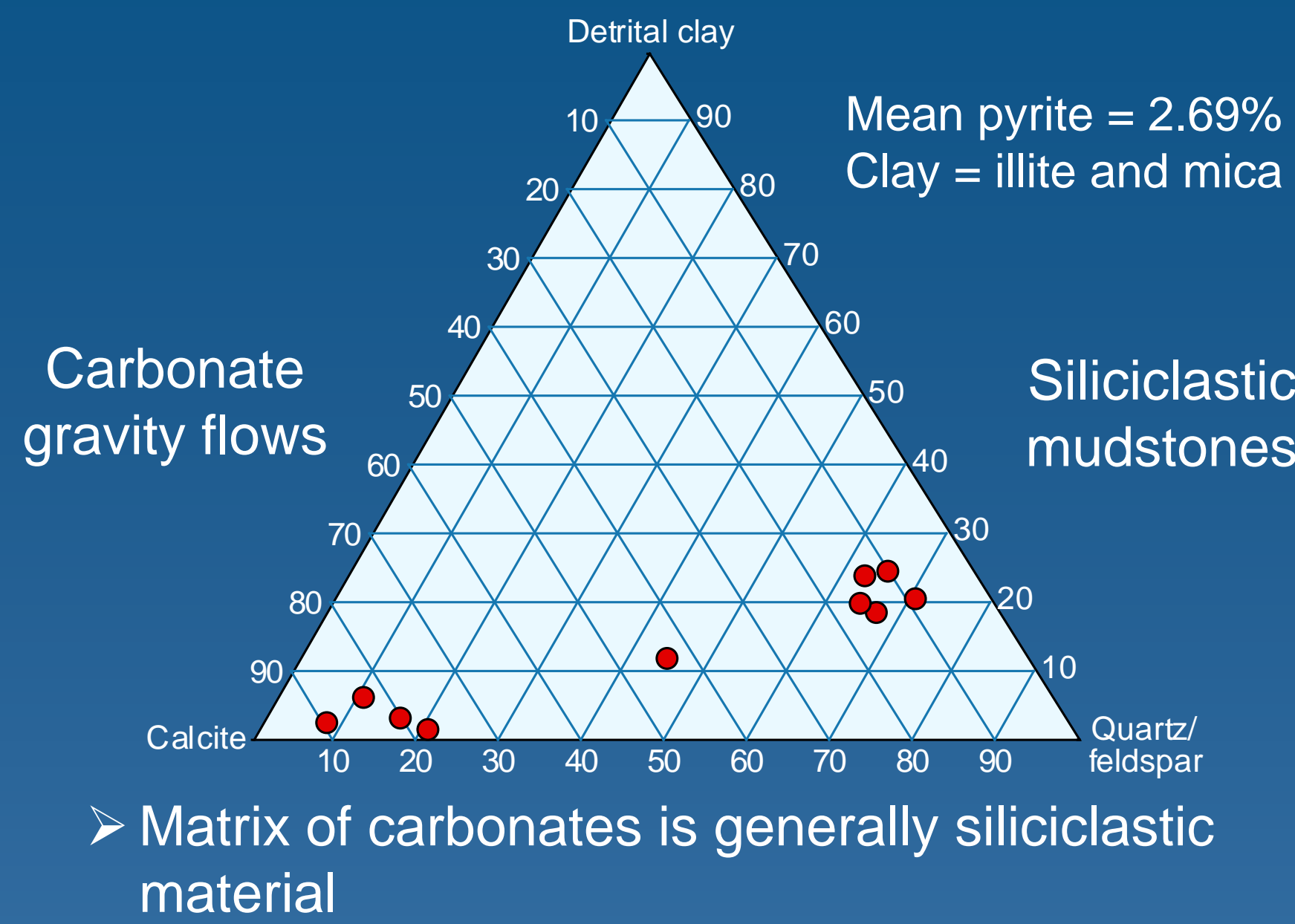
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Stratigraphic Section

Period	Series	Formation
Guadalupe	Delaware Group	Lamar Bell Canyon
		Cherry Canyon
		Brushy Canyon
Leonard		Upper Avalon Shale
		Lower Avalon Shale
		First Bone Spring
		Second Bone Spring
		Third Bone Spring
Wolfcamp		Wolfcamp

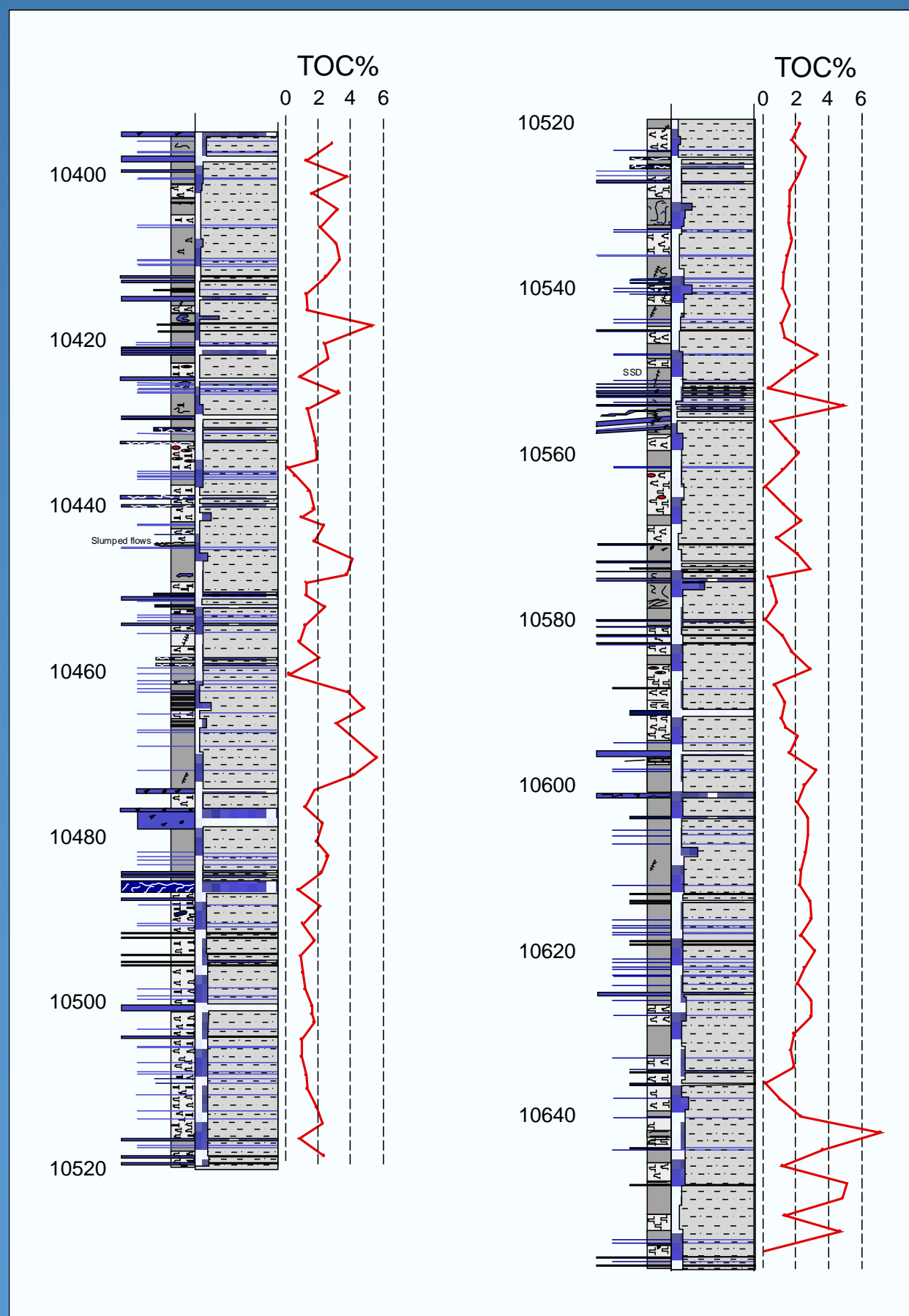


XRD Mineralogy

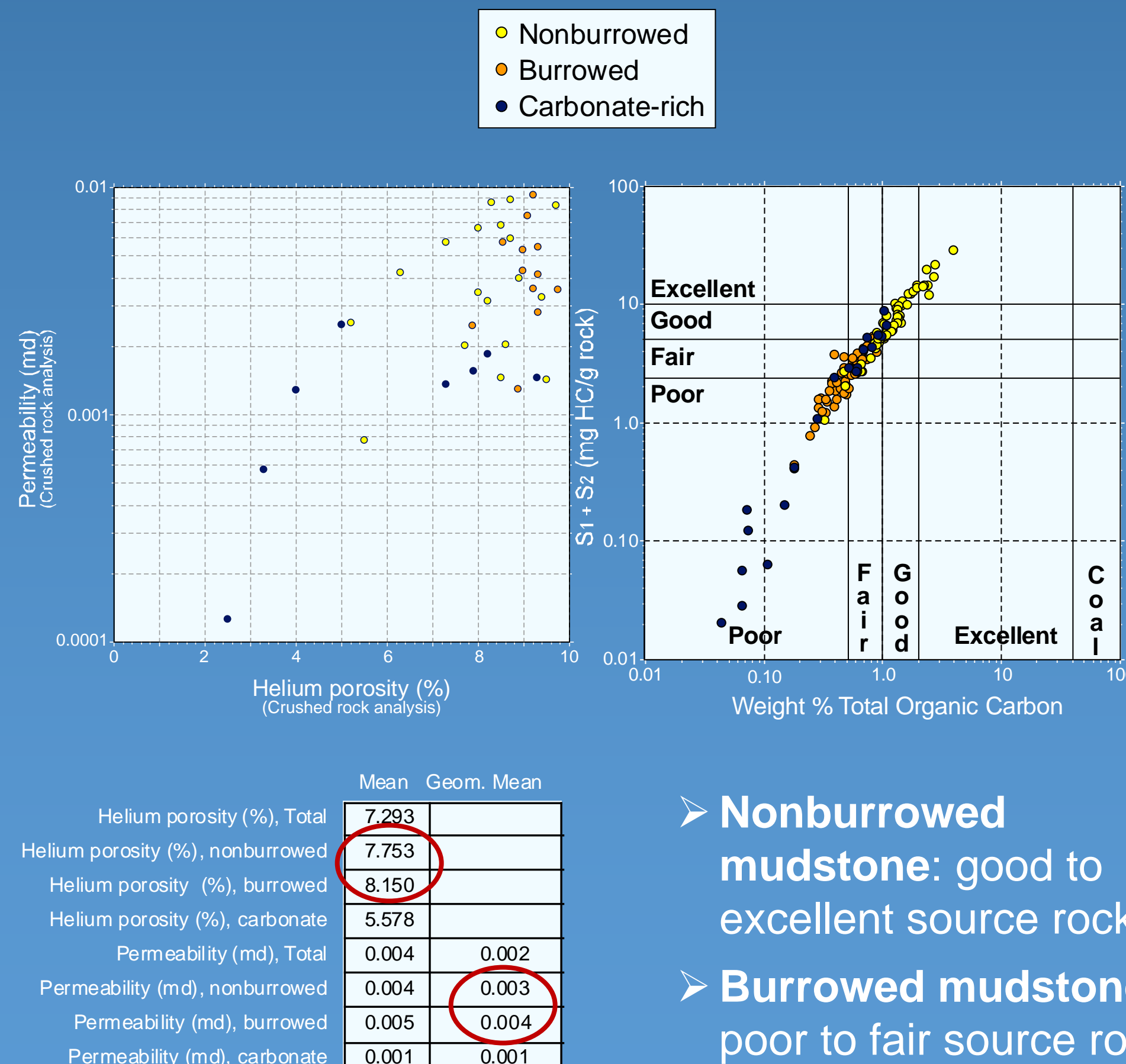


Whiting No. 1201 Collier Core Description and Dominant Lithofacies

- Siliciclastic lithofacies
 - Poorly to well-laminated siliciclastic mudstone
 - Burrowed mudstone
 - Thin-bedded quartz siltstone (minor)
- Carbonate-rich lithofacies
 - Coarse-grained skeletal grainstone (minor)
 - Burrowed mudstone
 - Coarse-grained argillaceous skeletal packstone
 - Fine-grained argillaceous skeletal packstone/grainstone
 - Argillaceous lime mudstone (depositional or diagenetic [concretion])



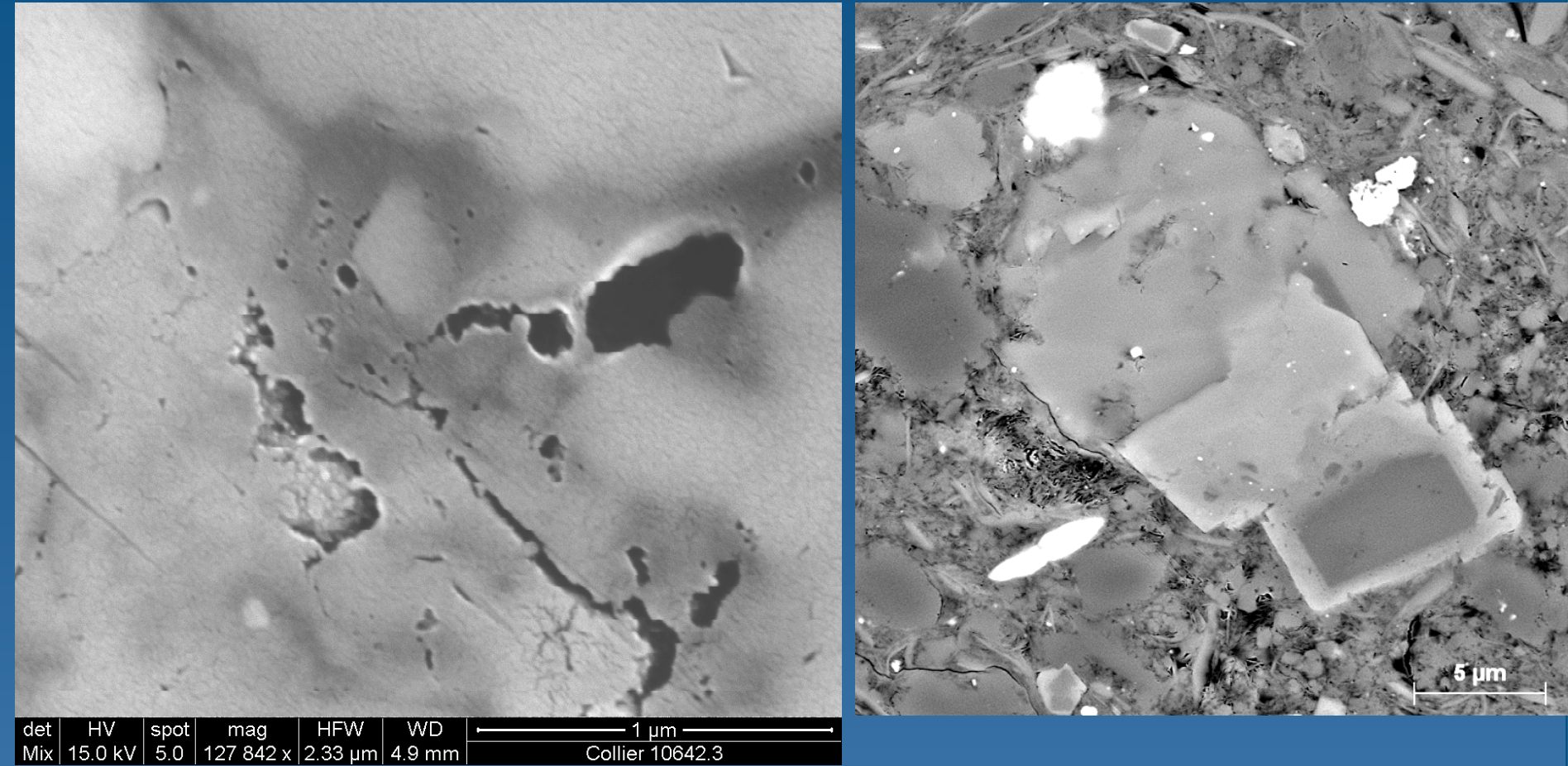
Crushed Rock Porosity and Permeability and Source Rock Quality



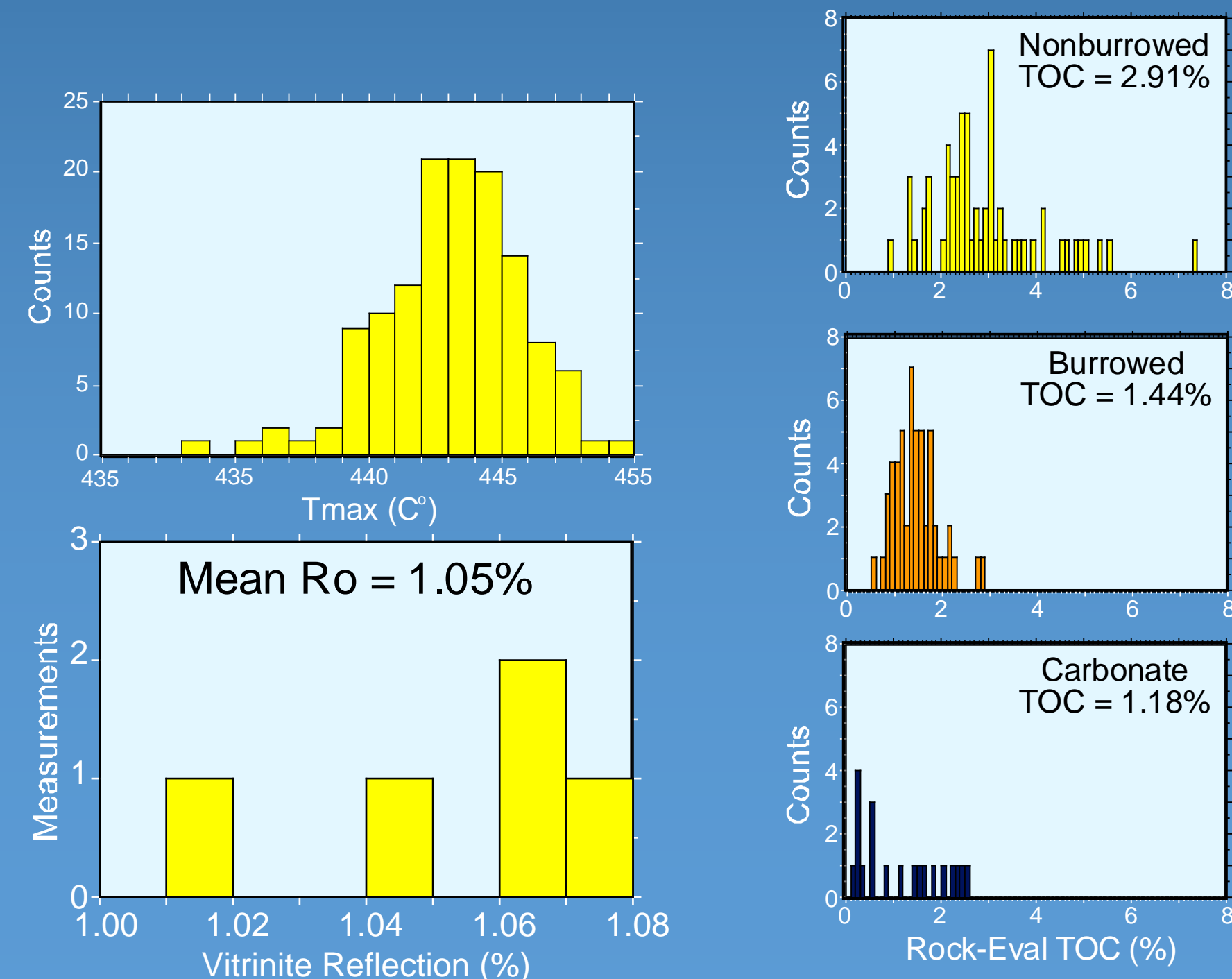
- **Nonburrowed mudstone:** good to excellent source rock
- **Burrowed mudstone:** poor to fair source rock
- **Carbonates:** range in quality as source rocks depending on amount of terrigenous matrix

- Reservoir quality is relatively high for a mudrock (>0.001 md)

Pore Network



T-Max and TOC



Summary

- Reservoir composed of burrowed and nonburrowed siliciclastic mudstone
- TOC ranges between 0.4 and 4%
- Burrowed facies has good TOC and good porosity
- Poorly to well-laminated mudstone is the highest quality source rock (has best TOC and porosity)
- Pore network dominated by OM pores followed by intraparticle pores
- The carbonate gravity flows appear to have little if any affect on the reservoir (has lowest TOC and porosity)

High-Resolution Hyperspectral Imaging (HI) of Core (SWIR and LWIR)

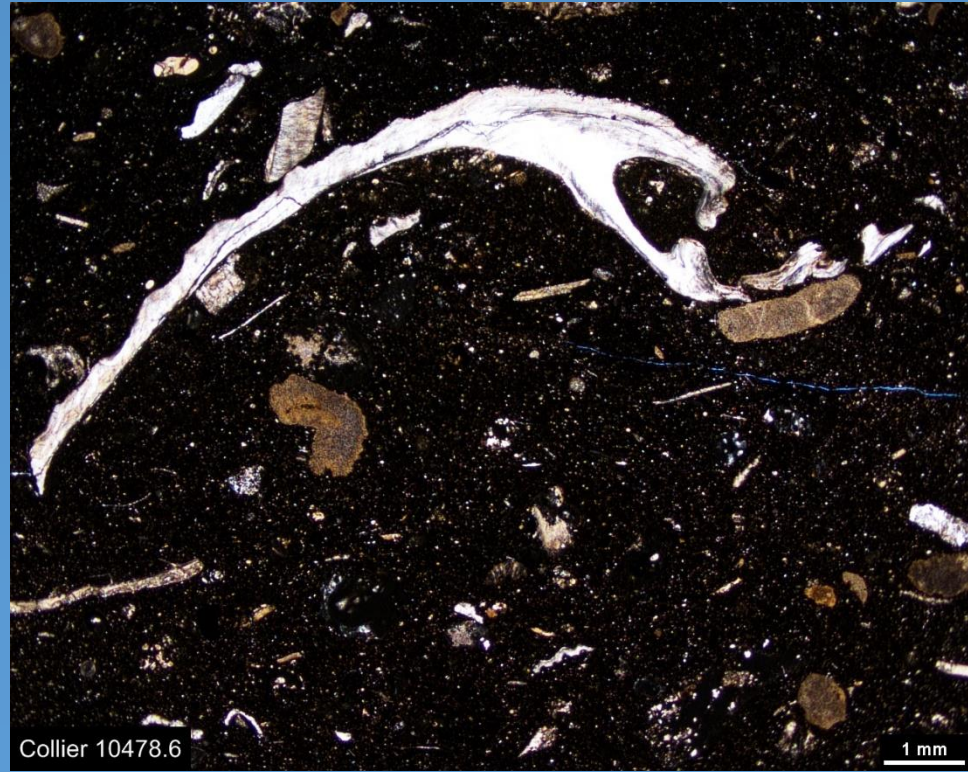
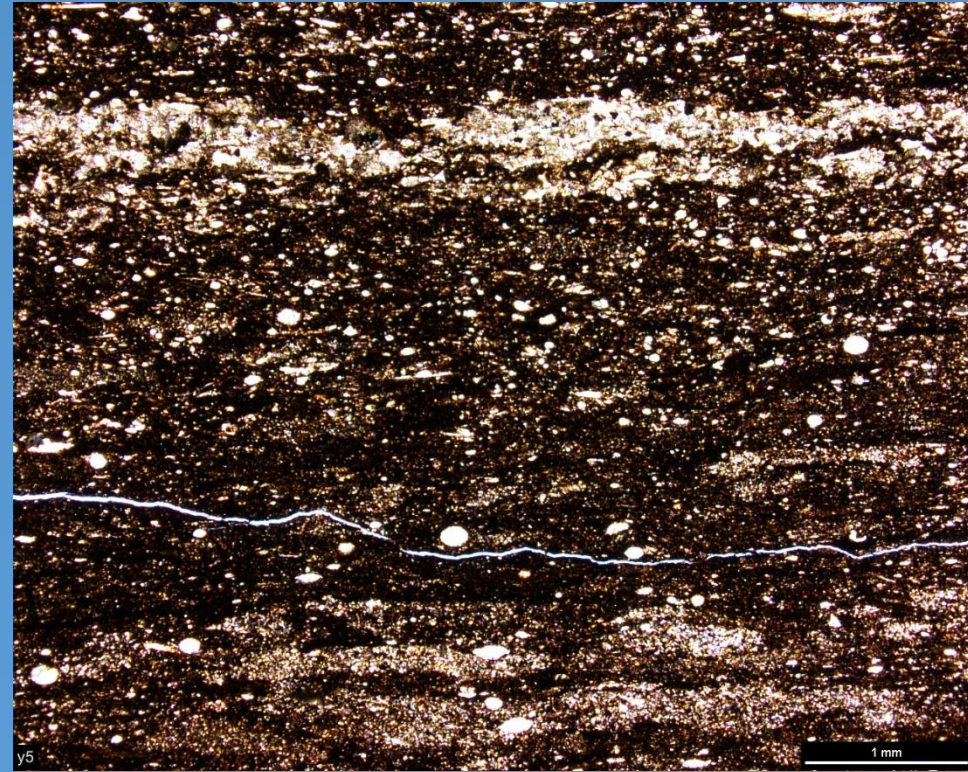
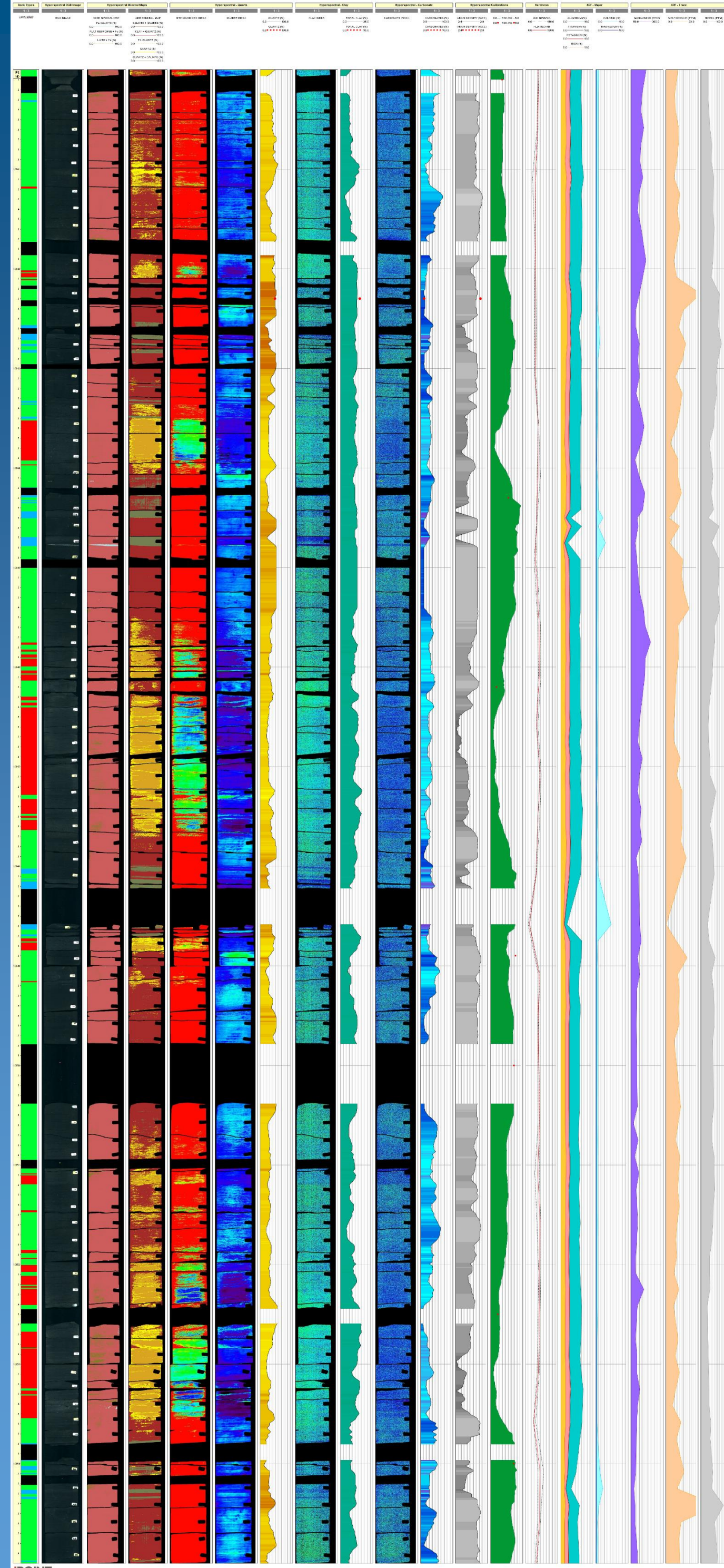
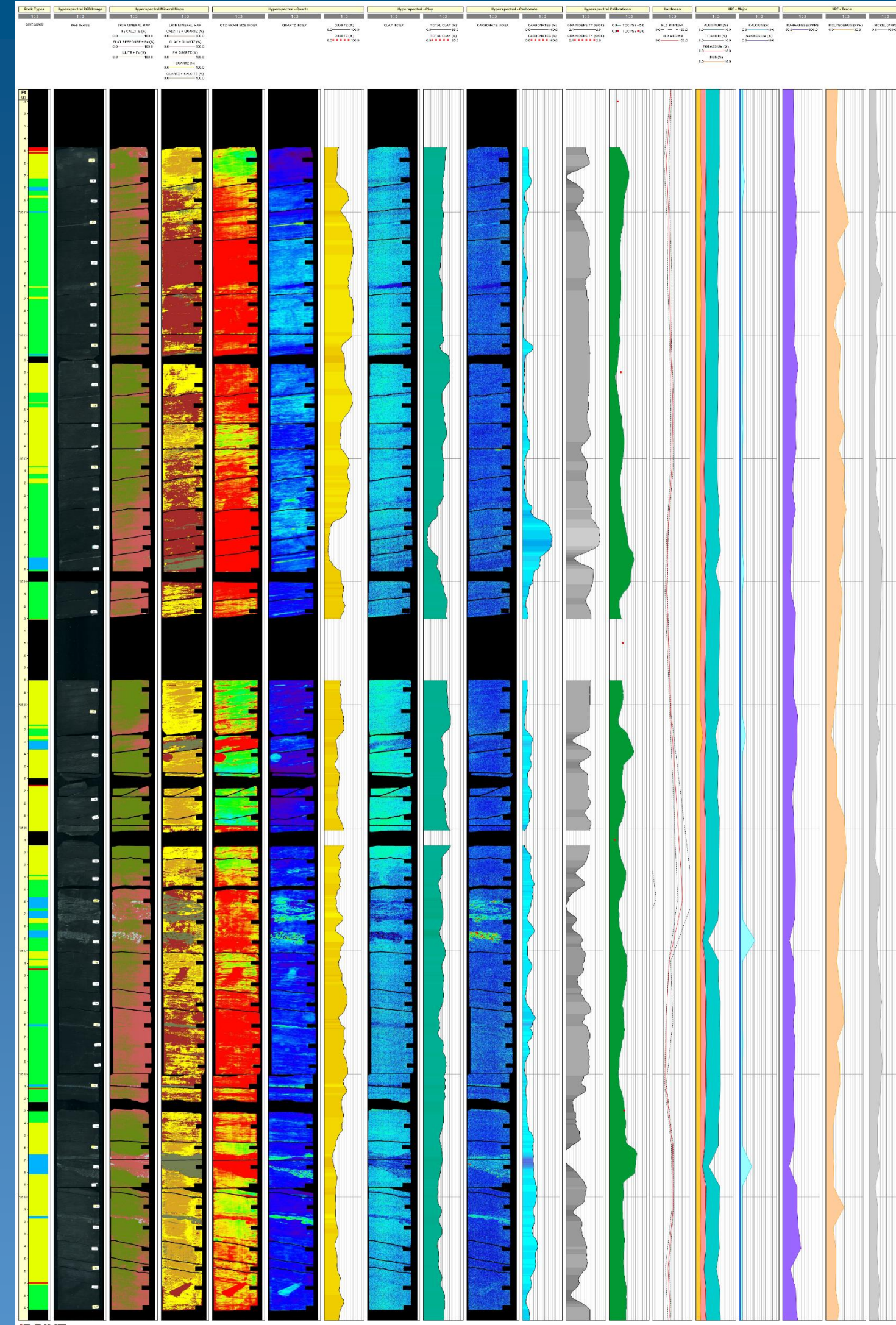
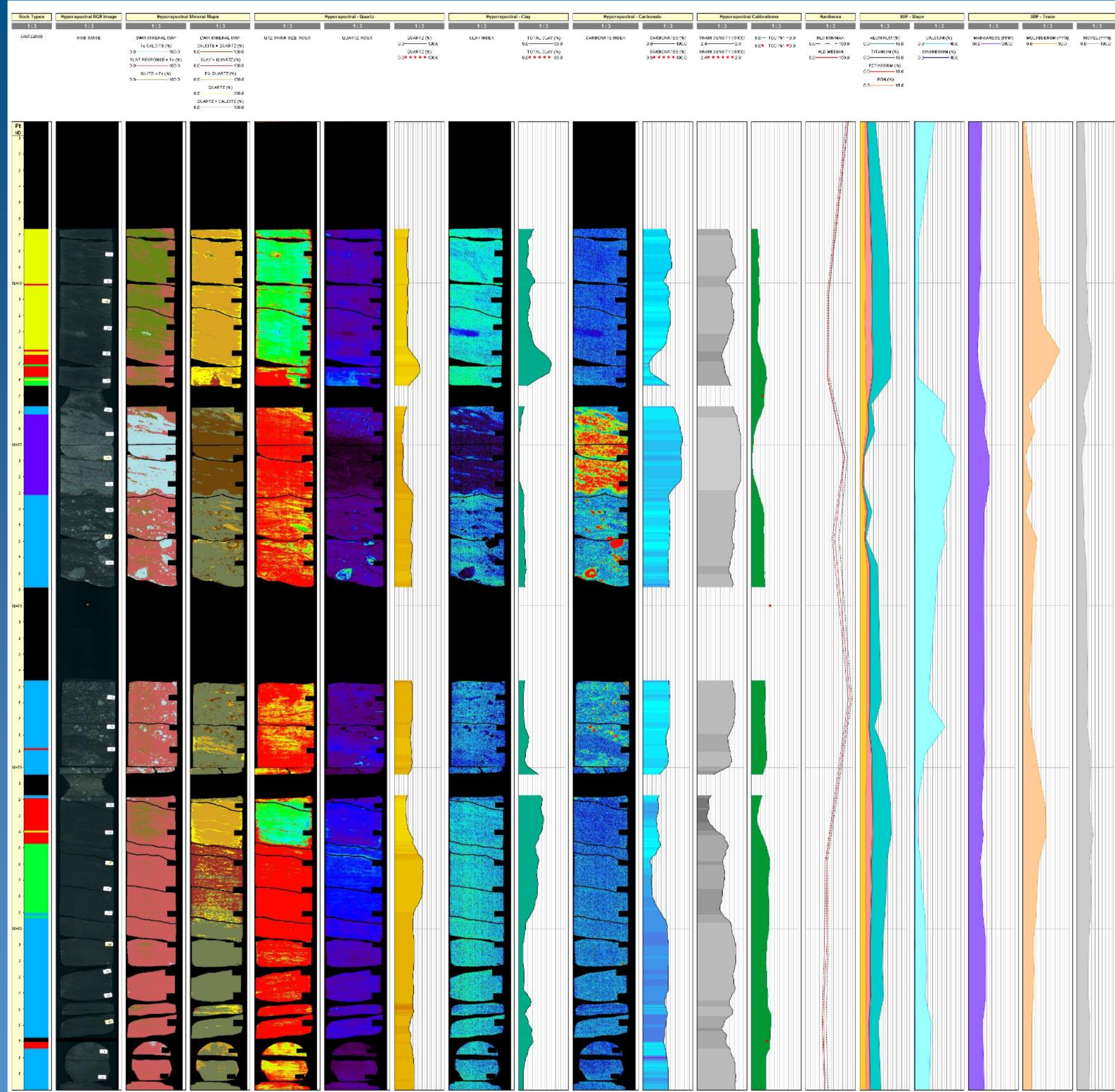
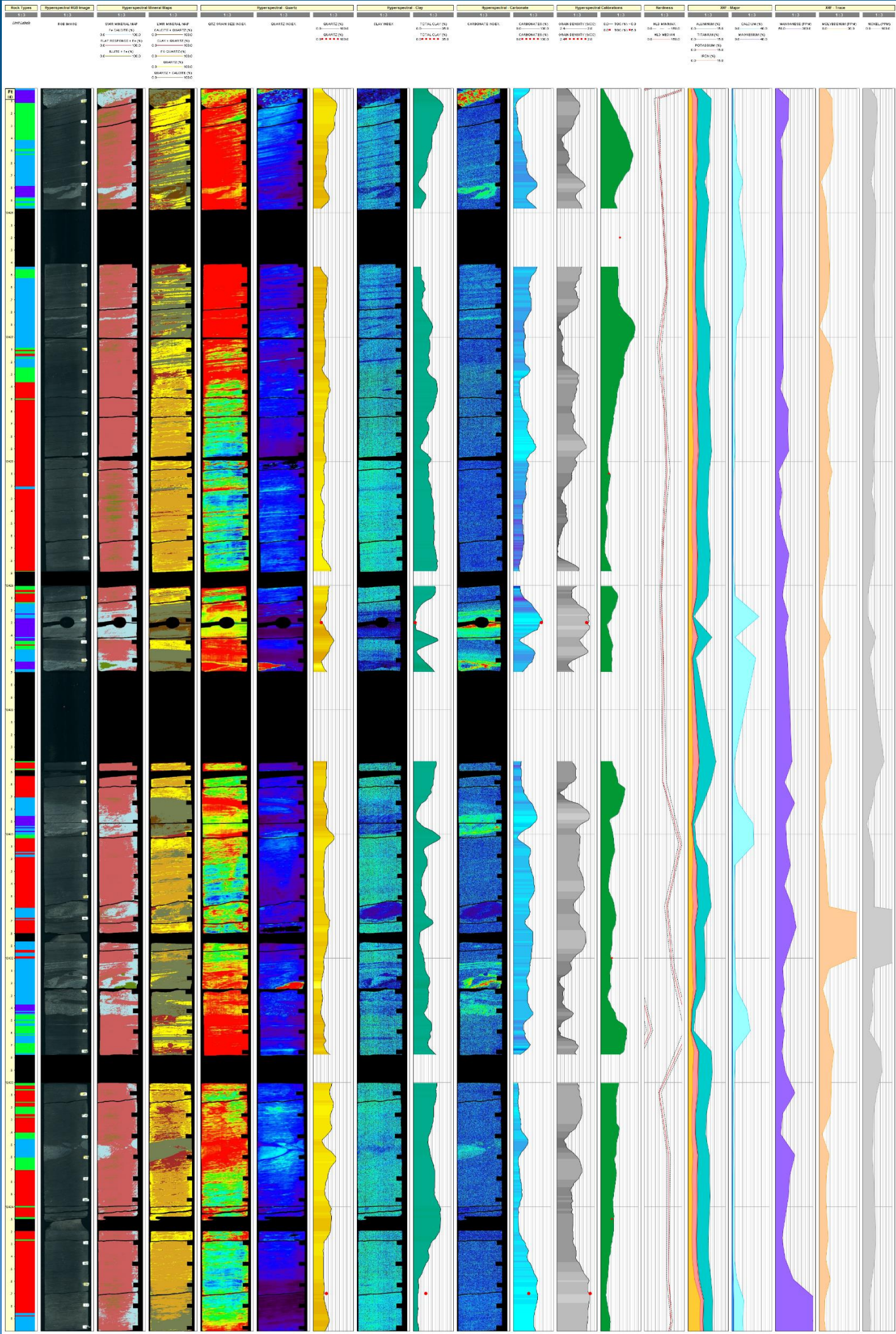
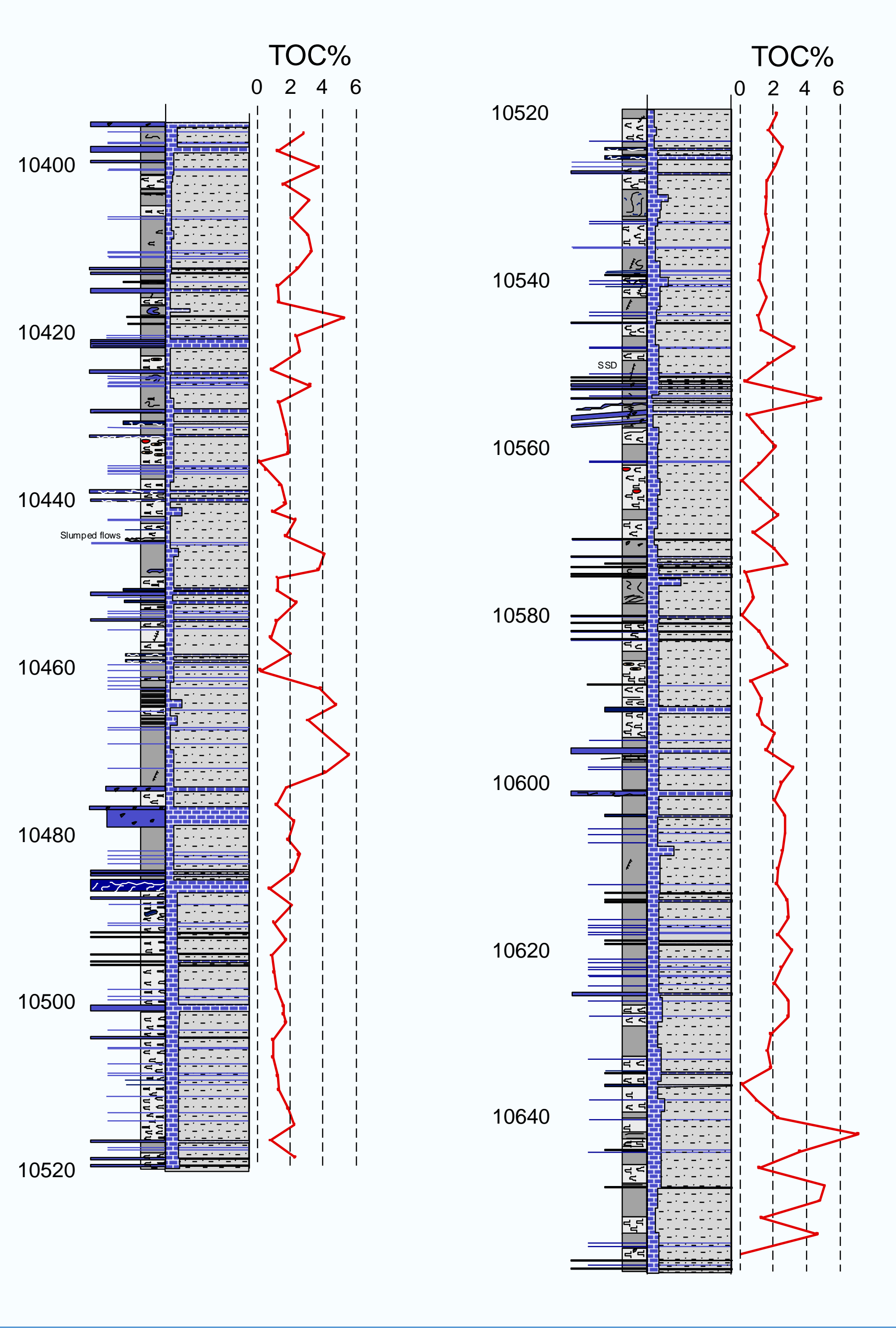
- Continuous high-resolution mineralogy and textural information (mineral maps)
- Digital HI-derived single mineral and TOC curves, calibrated to XRD and TOC imported as curves to display mineralogical variations with depth alongside XRF data and mechanical data

Type	Silicate Structure	Mineral Group	Example	SWIR Response	SWIR Response	LWIR Response
Silicates	Inosilicates	Amphibole	Actinolite	Non-Diagnostic	Good	Moderate
		Pyroxene	Diopside	Good	Moderate	Good
		Cyclosilicates	Tourmaline	Non-Diagnostic	Good	Moderate
		Nesosilicates	Garnet	Moderate	Non-Diagnostic	Good
		Sorosilicates	Forsterite	Good	Non-Diagnostic	Moderate
	Phyllosilicates	Epilite	Epilite	Non-Diagnostic	Good	Moderate
		Mica	Muscovite	Non-Diagnostic	Good	Moderate
		Chlorite	Chlorite	Non-Diagnostic	Good	Moderate
		Clay Minerals	Illite	Non-Diagnostic	Good	Moderate
			Kaolinite	Non-Diagnostic	Moderate	Moderate
Non-Silicates	Tectosilicates	Feldspar	Orthoclase	Non-Diagnostic	Non-Diagnostic	Good
		Albite	Albite	Non-Diagnostic	Non-Diagnostic	Good
		Silica	Quartz	Non-Diagnostic	Non-Diagnostic	Good
		Calcite	Calcite	Non-Diagnostic	Moderate	Good
		Dolomite	Dolomite	Non-Diagnostic	Moderate	Good
	Carbonates	Gibbsite	Gibbsite	Non-Diagnostic	Good	Moderate
		Sulphates	Alunite	Moderate	Good	Moderate
		Gypsum	Gypsum	Non-Diagnostic	Good	Good
		Borates	Borax	Non-Diagnostic	Moderate	?
		Halides	Chlorides	Halite	?	?
Non-Silicates	Phosphates	Apatite	Apatite	Moderate	Non-Diagnostic	Good
		Blumen	Blumen	?	Moderate	?
		Hamate	Hamate	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic
		Oxides	Chromite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic
		Sulphides	Pyrite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic

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Conclusions

- Mineralogy at the sub-cm scale is observed.
- Results are of much higher resolution than was obtained by core description or limited thin-section analysis.
- The calculated TOC compared favorably to measured RockEval data points, but the HI analysis has the advantage of being continuous.
- Hyperspectral imaging provided detailed, high-resolution mineralogical and textural information of a whole core from the Third Bone Springs.
- This technology produces mineral maps of the surface of a core that can be used to refine stratigraphic models and explain petrophysical responses.
- Digital HI-derived single mineral curves calibrated to XRD can be utilized to display mineralogical variations with depth alongside open-hole wireline logs and mechanical data to understand mechanical stratigraphy.
- Hyperspectral imaging of cores is a valuable method for obtaining continuous rock-property data that can be integrated with other data to characterize a production interval and facilitate ‘up-scaling.’
- We conclude that this technique adds a wealth of data that other methods are unable to provide because of time and cost. Future work will include evaluation of the mid-range infrared spectra (MWIR) to identify minerals and hydrocarbons in cores from unconventional resources.

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