Integration of Inorganic/Organic Geochemistry and Geomechanical Stratigraphy to Characterize Permian Shale Plays*

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Abstract

This study presents an integrated inorganic/organic geochemistry and geomechanical stratigraphic methods to characterize Permian organic rich mudstones in the Midland Basin, to understand controls on organic carbon richness, such as primary productivity, depositional environments, sediment supply, and bottom water preservation conditions, and its implications on petroleum generation/charge and on shale oil development. A high frequency sampling of core samples from a thick sequence (~1000 ft) of argillaceous mudstones, organic-rich mudstones, siliceous mudstones, and carbonate mudstones in the Midland basin were characterized for elemental concentrations and source rock geochemistry, and for high resolution gas chromatography and biomarkers on extracts. The small maturity differences from the top to the bottom of this 1000 ft section and limited migration of hydrocarbons into the rock pore space due to low permeability and high capillary entry pressure allows us to interpret the extract geochemistry fingerprints to compositions of the source rock kerogen and its in-situ generated bitumen. Geologic, petrophysical, and elemental analysis have divided the section into many depositional packages (chemozones) with distinct signatures. This has suggested cycles of para-sequences with varied sediment (clastic vs carbonate) supply, a likely shift in detrital sediment source and organic matter input, and also changes in bottom water oxygen conditions during the deposition of these organic rich mudstone units. Source rock characters respond to these depositional environmental variations with changes in total organic carbon contents and HI/OI values. Depositional environment dependent biomarker parameters (Pr/Ph, DBT/Phen, etc.) from core extracts also show systematic changes reflecting variations in source rock facies

and preservation conditions. Geomechanical properties of these shale formations, such as unconfined compressive strength (UCS) from rebound hammer analysis, also correspond to para-sequence changes in depositional environments and associated lithological variations. Forward geocellular modeling based on XRF-defined mineral compositions and burial history, when calibrated with petrophysical properties, allows us to extend well- based geomechanical stratigraphy to include all rock volumes from heel to toe. This integrated approach greatly enhances our description of Permian age resource play stratigraphy and petroleum systems, which in turn helps with sweet spot mapping and lateral landing zone definition.

INTEGRATION OF INORGANIC/ORGANIC GEOCHEMISTRY AND GEOMECHANICAL STRATIGRAPHY TO CHARACTERIZE PERMIAN SHALE PLAYS

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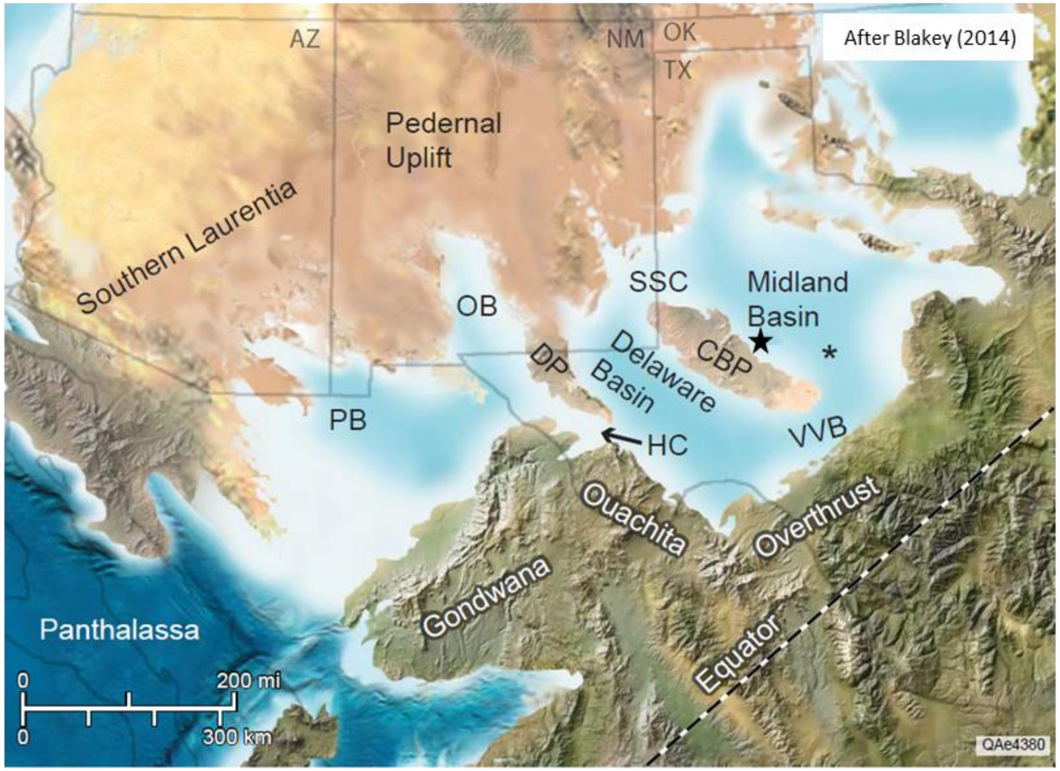
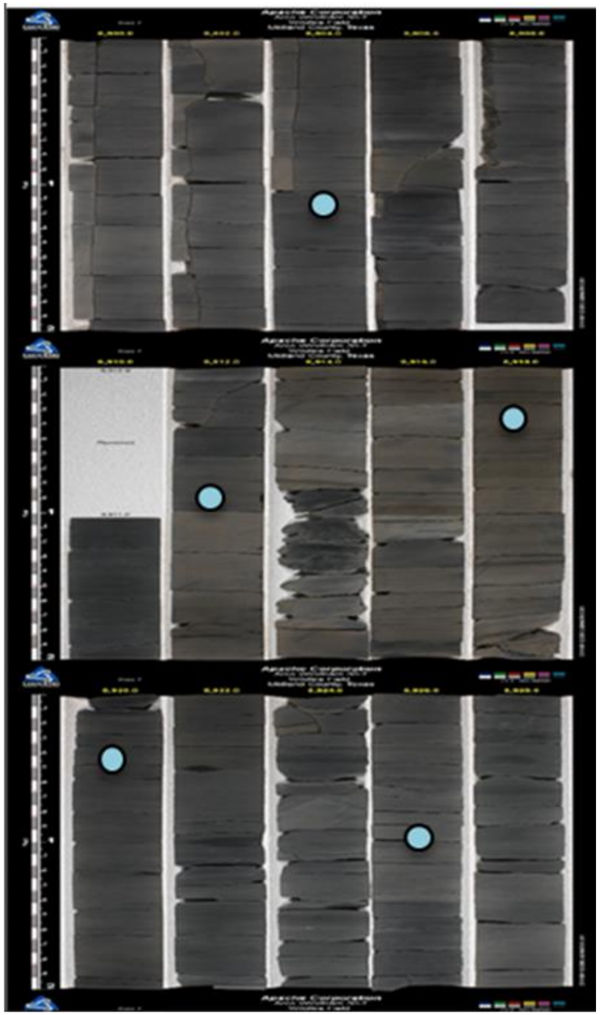
PRESENTATION OUTLINES

- Geologic background and approach
- XRF elements and chemo-stratigraphy
- Integration with geomechanic properties
- Source rock potentials and relationship to chemozones
- Depositional environments from elemental data and core plug extract geochemical fingerprinting
- Summary and acknowledgement

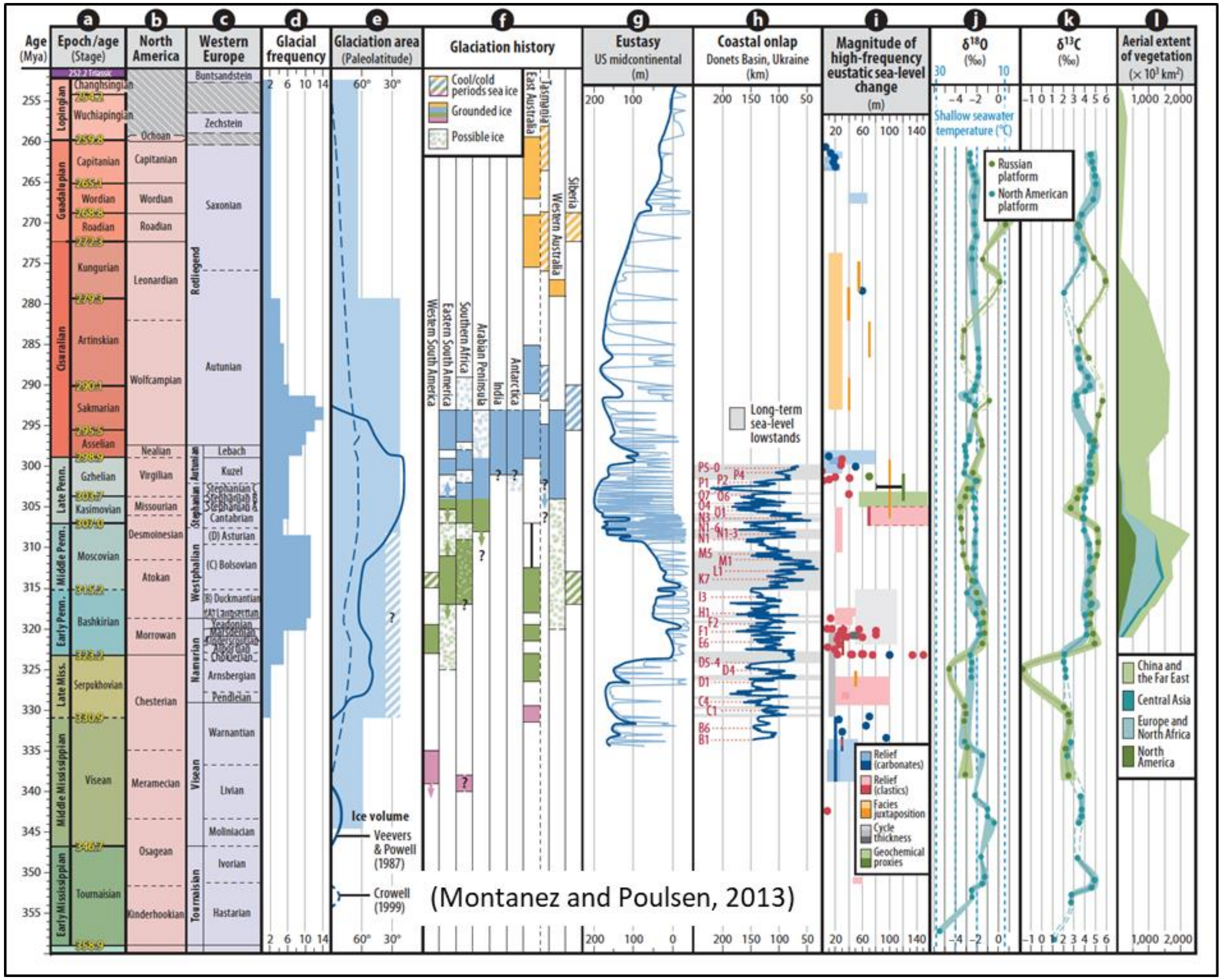
GEOLOGIC BACKGROUND AND APPROACH





- Core plug samples of lower Permian age formations from a Midland basin well
- Integration of core petrophysics, descriptions, XRF, rebound hammer UCS
- Rock geochemistry and core extract geochemistry
- Understanding of depositional environments and controls on organic matter accumulation

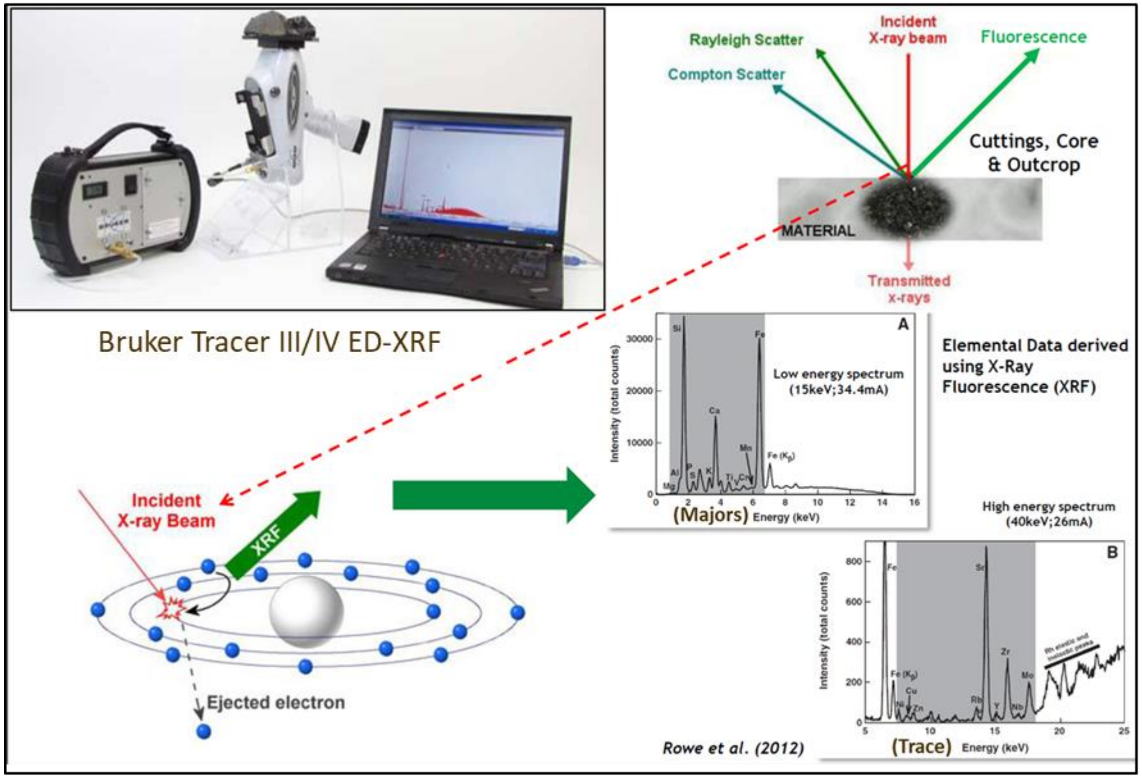
LATE PALEOZOIC GLACIAL EVENTS



(Montanez and Poulsen, 2013)

- Late Pz ice age (LPIA) likely peaked in Early Permian (the Asselian and early Sakmarian)
- Major landscape changes driven by supercontinental (Gondwana) reconfiguration with lowest atmospheric CO_2 and highest O_2
- High glacial frequency and ice coverage extended down to 30° latitude
- Eustatic sea level changes and ^{18}O and ^{13}C isotope excursions in Brachipods

APACHE XRF AND UCS DATA COLLECTION



Unconfined Compressive Strength (UCS)

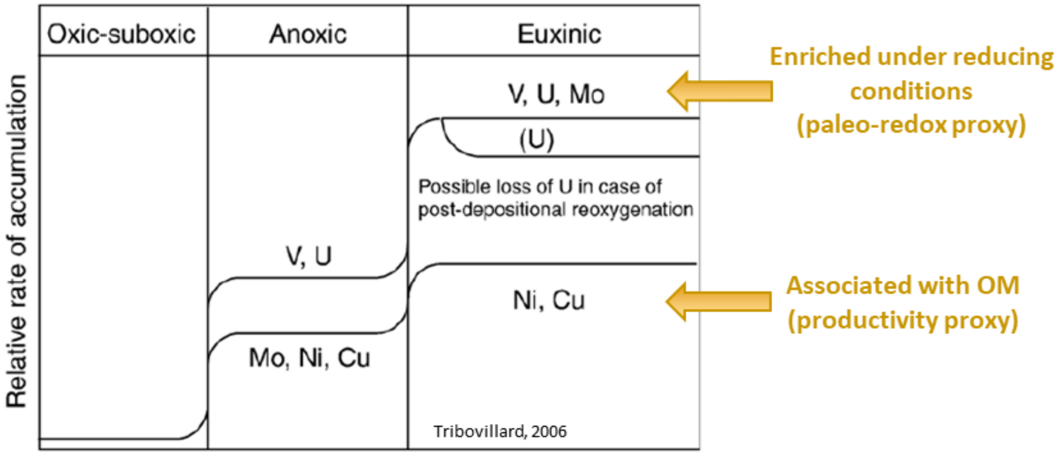
$$HL = \frac{Vr}{Vi} \cdot 1000$$

UCS (MPa) = $0.000000683\, x^{2.9}$

UCS (MPa) = $2.1454 * e^{(0.0058*x)}$

- Hand-held units, cheap and portable
- Easily deployed in many wells across Midland basin
- Semi-quantitative data for major and trace elements
- Calibration with lab XRF/XRD/ICPMS and tri-axial tests
- Continuous semi-quantitative mechanical property log

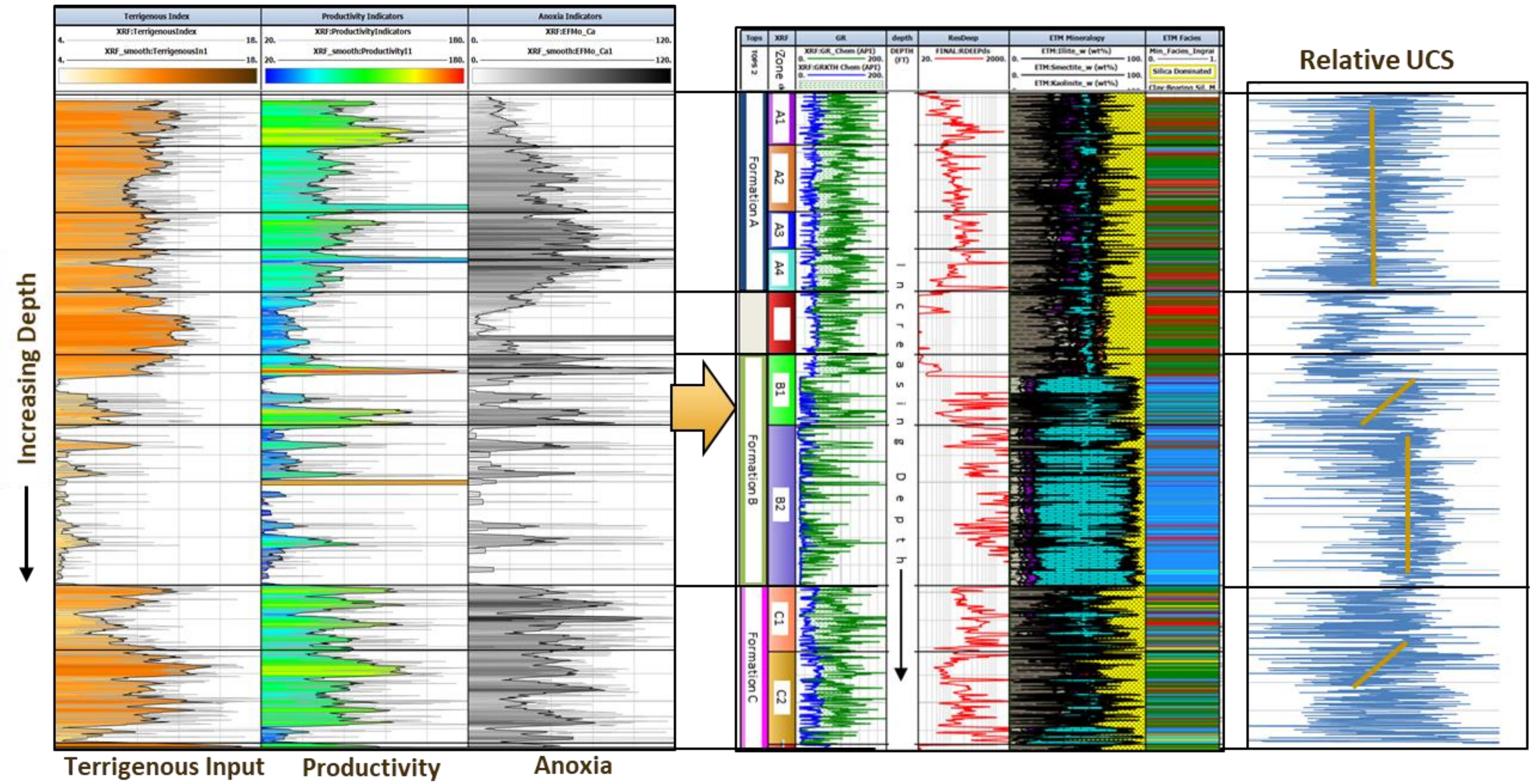
COMMONLY USED ELEMENTS



- Elements reflecting detrital sediment inputs, such as Al, Ti, etc.
- Elements indicative of carbonate input, such as Ca and Mg
- Redox-sensitive elements U, V, Mo are commonly associated with bottom water anoxia, and can be indicative of preservation conditions
- Ni and Cu, also P, Zn, and Cd, are micronutrients to primary production, indicative of water column productivity

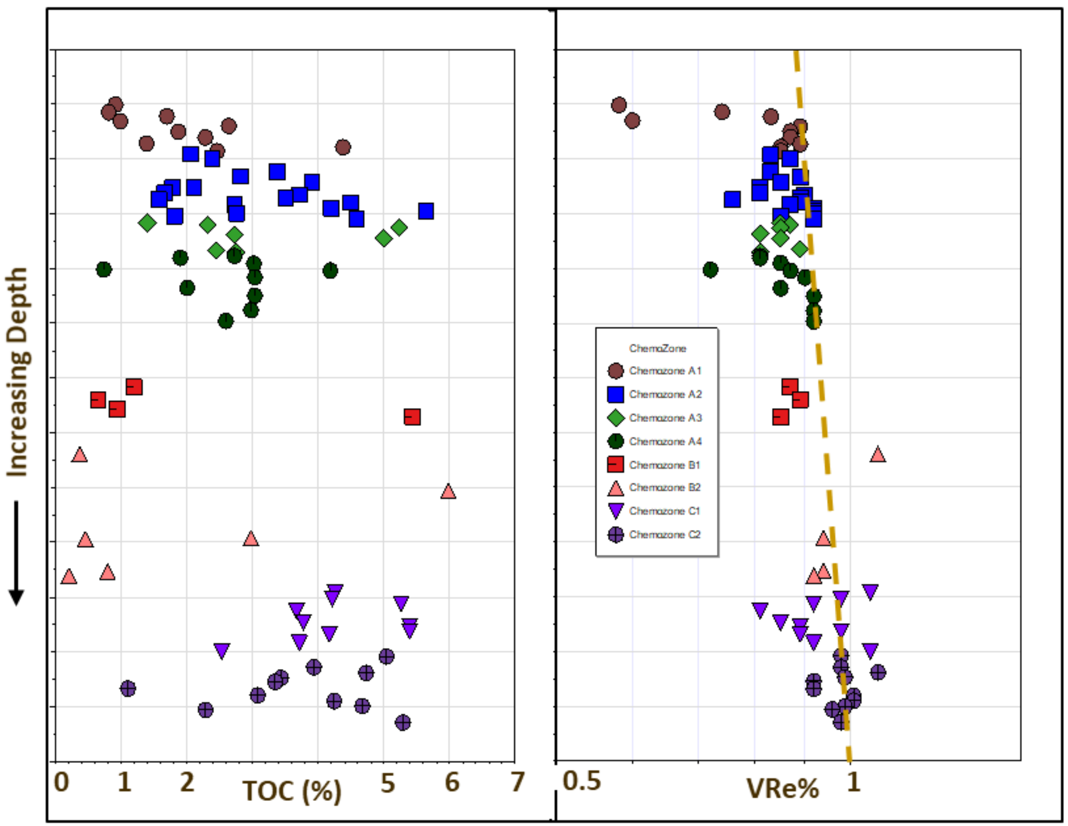
- Mineralogy/lithology
- Determination of depositional environment
- Used to construct a sequence stratigraphic framework
- Interpretation for organic matter accumulation parameters: production, dilution, and preservation
- Proxies for total organic carbon content (TOC), an important parameter for resource play evaluation

CHEMOZONES AND GEOMECHANIC STRATIGRAPHY

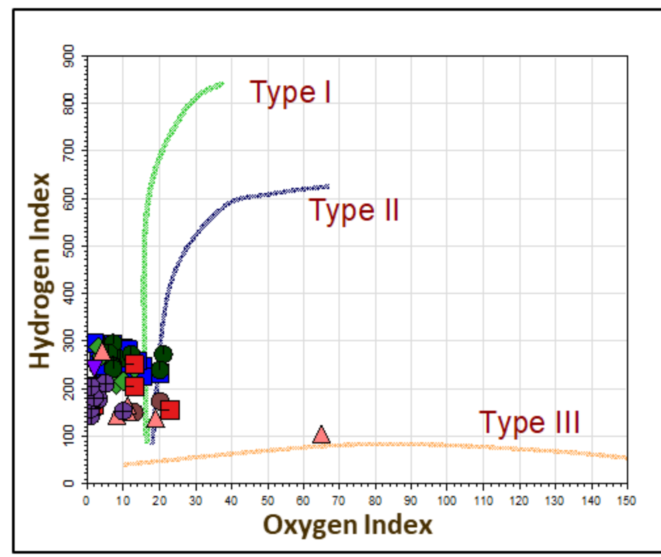


- Internally developed elemental proxies for terrigenous input, water column productivity, and sedimentary oxygen conditions
- Integrated with physical description of the core and under sequence stratigraphic framework
- Relative UCS values correspond to minerology/lithology defined from elemental analysis
- Consistent chemo and mechanical stratigraphy definition in these shale units

SOURCE ROCK CHARACTERS AND MATURITY

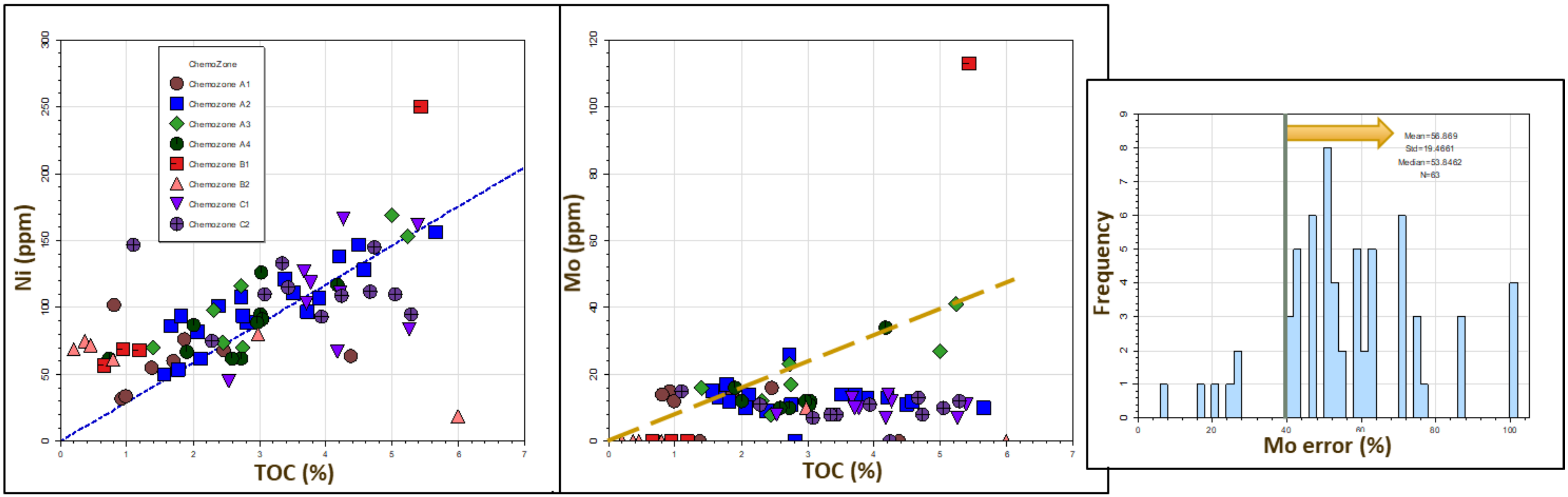


- Variable TOC at peak oil maturity window
- Well preserved organic matter
- Organofacies B kerogen composition
- Formation B mostly low TOC with interbedded organic rich zones

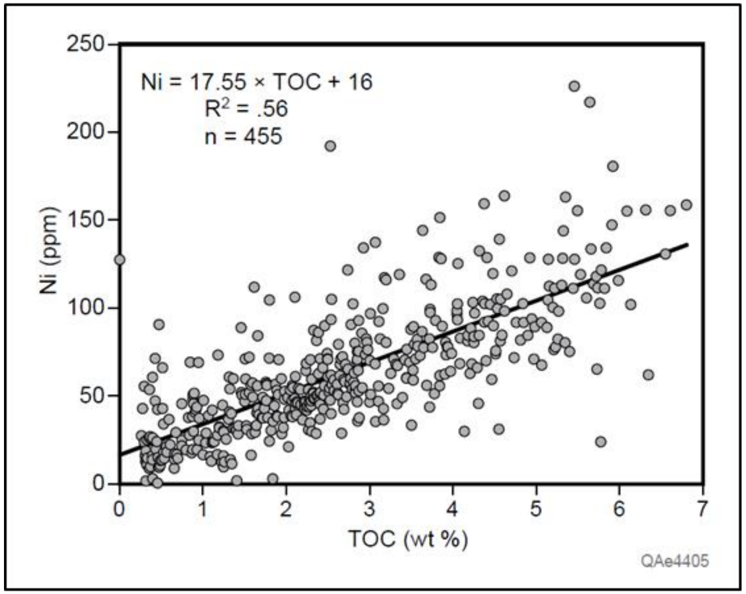


CORRELATION BETWEEN INORGANIC AND ORGANIC GEOCHEMISTRY DATA

- Elemental data can be very useful to define redox, productivity, terrigenous input, depositional facies
- The best proxy among the elements for organic richness is productivity indicator Ni concentration
- Redox sensitive element Mo has significant analytical errors for majority of the samples



RESULTS FROM OTHER STUDIES



Cross plot of Ni and TOC values for Midland Basin Reagan County O. L. Greer 1 and R. Ricker 1 wells (Baumgardner et al., 2016), 40 miles SE of the studied well

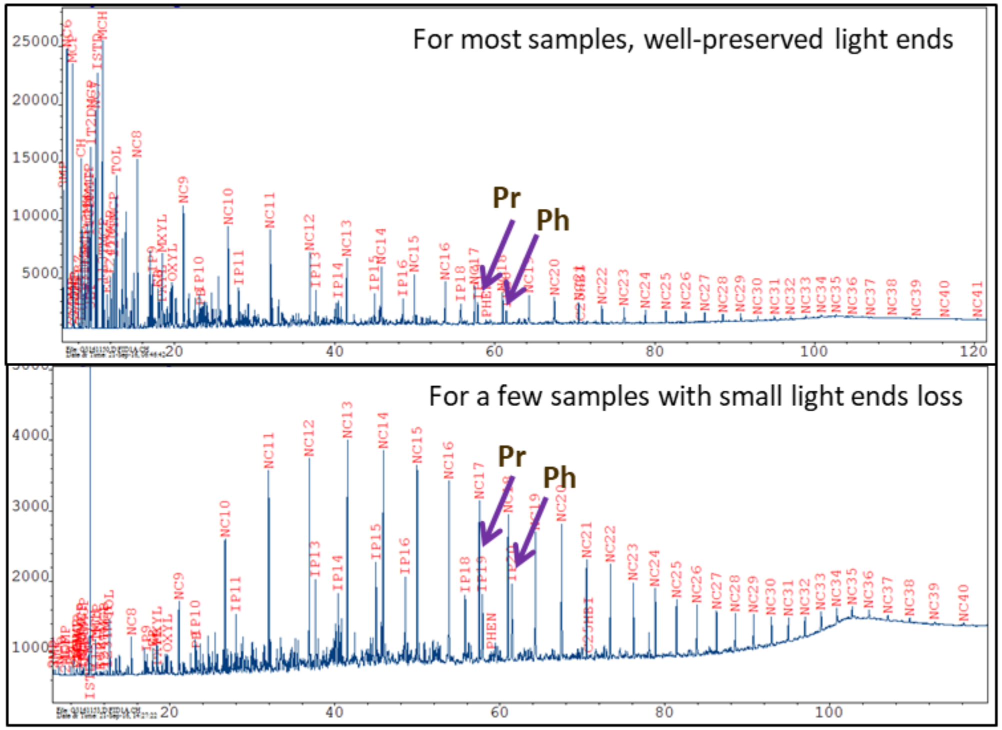
Element	R2
As	0.51
Co	0.25
Cr	0.14
Cu	0.70
Fe	0.28
Mo	0.17
Ni	0.67
S	0.33
Se	0.73
U	0.52
V	0.34
Zn	0.12

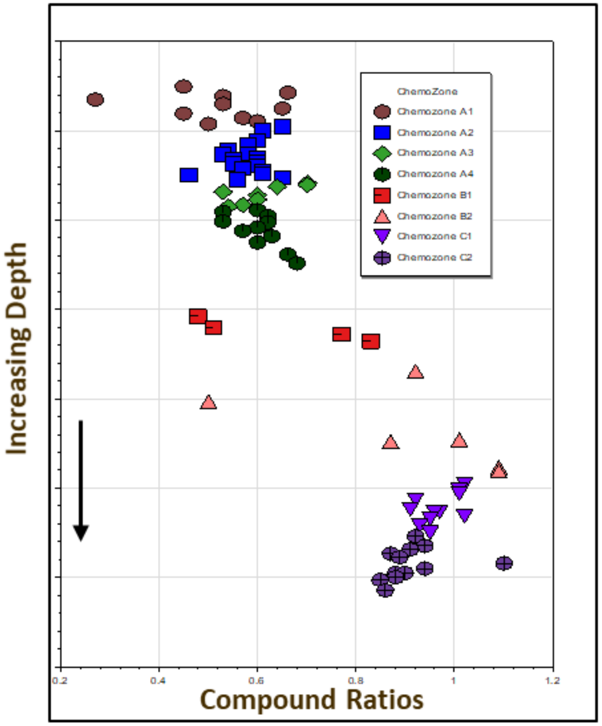
R^2 values from regressions of LECO TOC and selected XRF elements (Driskill et al., 2018)

- Driskill et al. (2018) documented correlations between XRF-derived metal contents and TOC, and found similarly good Ni-TOC relationship in a Delaware basin well Bone Spring and upper Wolfcamp sections.
- In addition Cu and Se, both of them are micronutrients, have even better correlation with TOC.
- Redox sensitive elements, Mo, V and U, show much less correlation with TOC.

CORE PLUG EXTRACT AND GEOCHEMICAL FINGERPRINTING

- Core chips were extracted with organic solvent and have good preservation of light ends for tight shale samples
- High porosity carbonate samples show light-end loss in extracts
- Limited vertical migration in the section and small maturity differences from top to bottom
- Geochemical parameters related to sedimentary organic matter characters

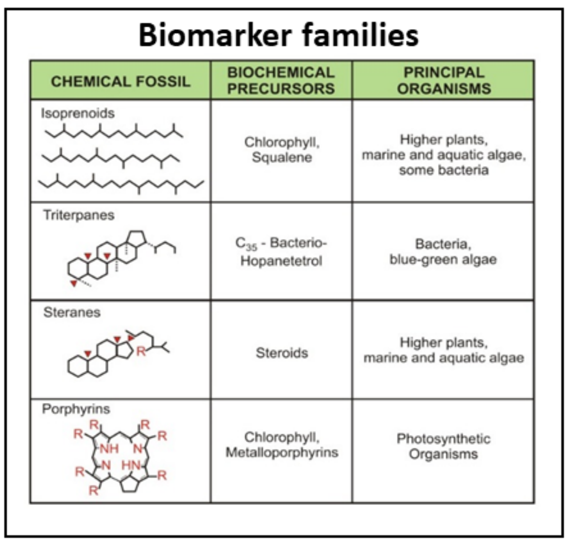




INTRODUCTION TO BIOMARKER DATA

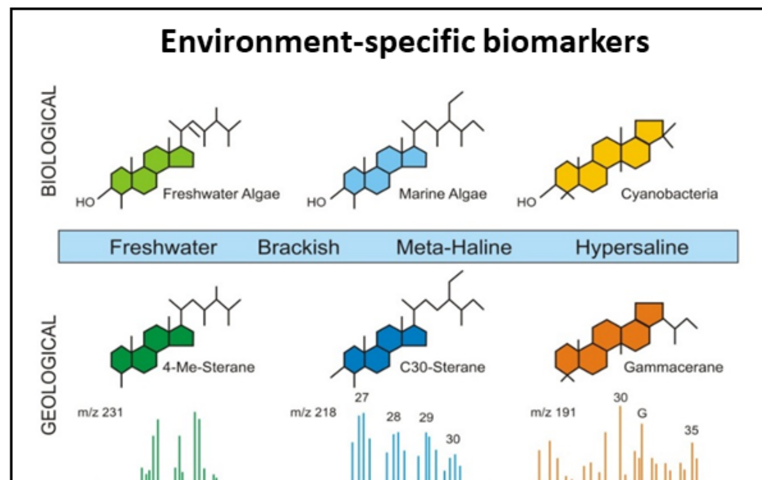
"Chemical compounds contained in rocks and petroleum whose basic molecular structure can be linked to a known biological precursor" (Peters & Moldowan, 1993).

- Different depositional environments are characterized by different assemblages of organisms, resulting in different organic facies and therefore molecular compositions.
- Biological markers or 'biomarkers' are effectively molecular fossils.
- They may be acyclic, or contain 1-5 (or more) linked carbon rings.
- There are also compounds that can be associated with specific diagenetic and alteration processes.



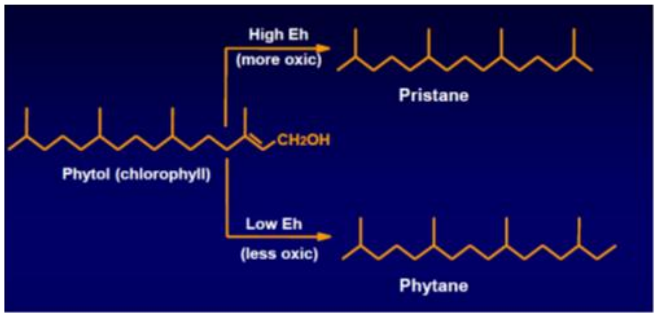
Biomarker families

CHEMICAL FOSSIL	BIOCHEMICAL PRECURSORS	PRINCIPAL ORGANISMS
Isoprenoids	Chlorophyll, Squalene	Higher plants, marine and aquatic algae, some bacteria
Triterpanes	C_{35} - Bacterio-Hopanetetrol	Bacteria, blue-green algae
Steranes	Steroids	Higher plants, marine and aquatic algae
Porphyrins	Chlorophyll, Metalloporphyrins	Photosynthetic Organisms



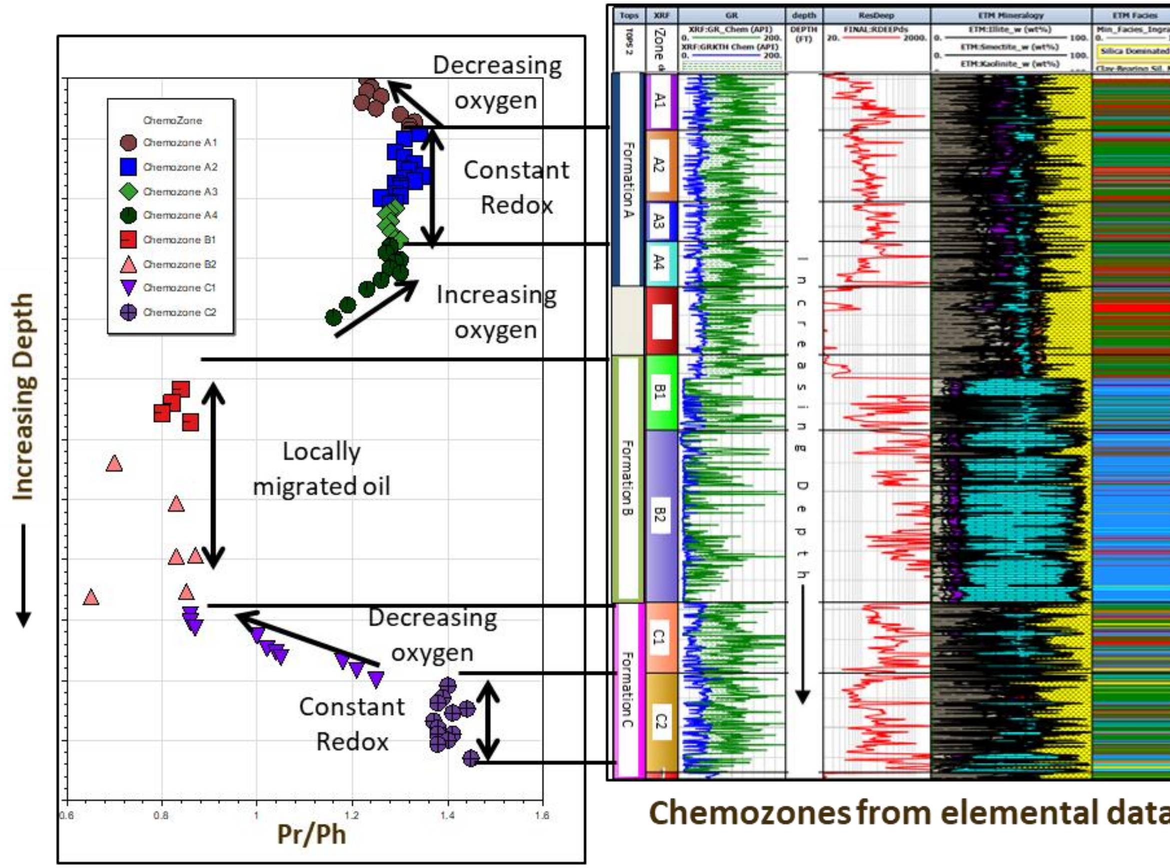
(Peters et al., 2005)

PR/PH RATIOS REFLECTING DEPOSITIONAL/PRESERVATION CONDITIONS



- Pristane and phytane are good markers for preservation oxygen conditions: more oxic favors Pr and more anoxic Ph

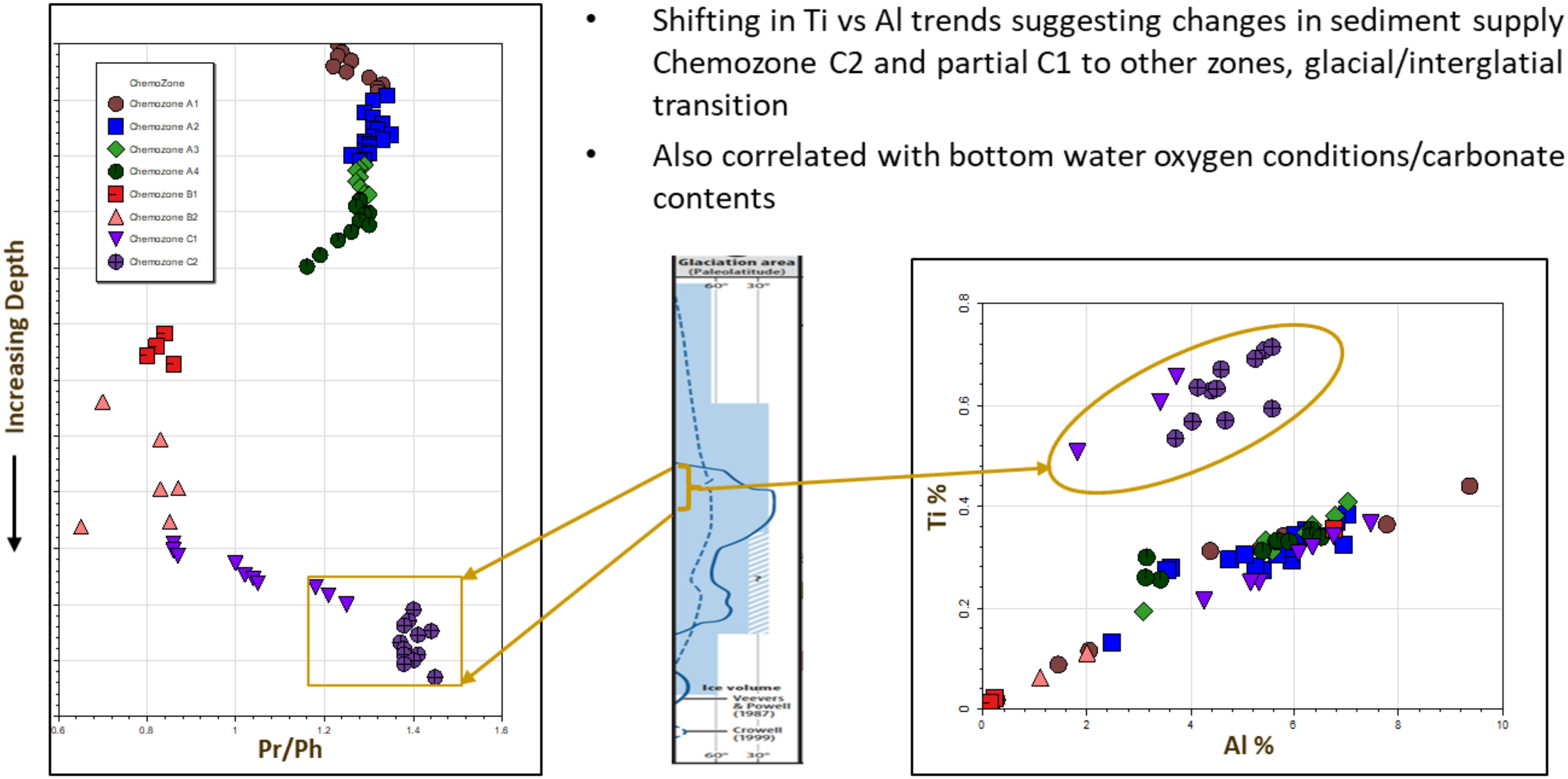
- Distinct and step changes in Pr/Ph trends correspond to chemozones from elemental data reflecting cycles of bottom water environment changes



Chemozones from elemental data

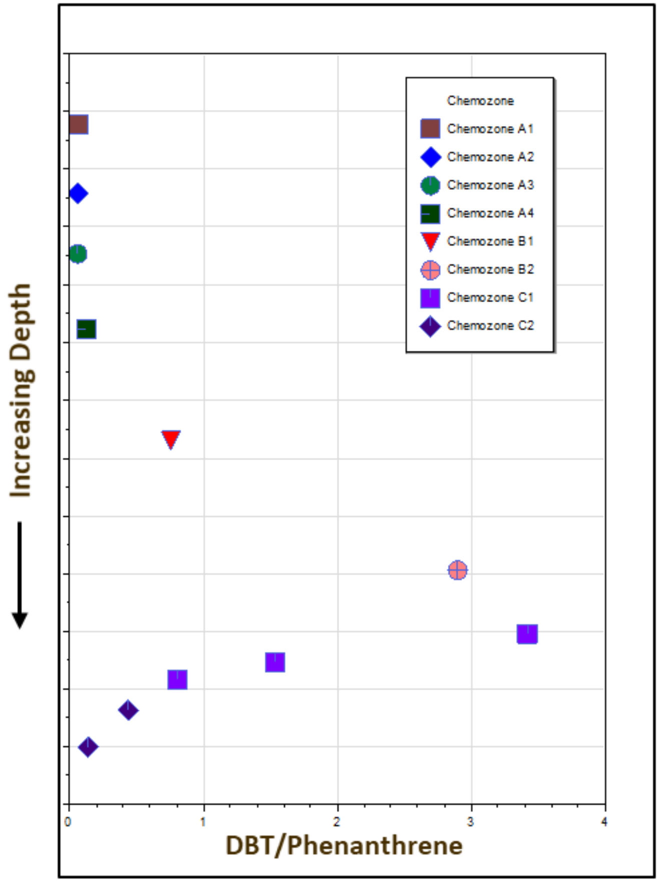
SEDIMENT SUPPLY AND PRESERVATION CONDITIONS

- The ratio of Ti to Al generally indicator for source of detrital sediments
- Shifting in Ti vs Al trends suggesting changes in sediment supply from Chemozone C2 and partial C1 to other zones, glacial/interglatial transition
- Also correlated with bottom water oxygen conditions/carbonate contents



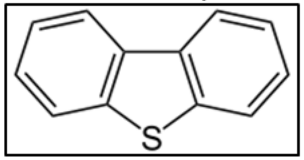
(Montanez and Poulsen, 2013)

DEPOSITIONAL ENVIRONMENTS/FACIES FROM BIOMARKERS

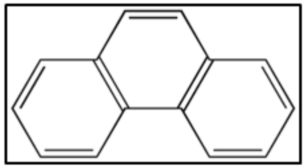


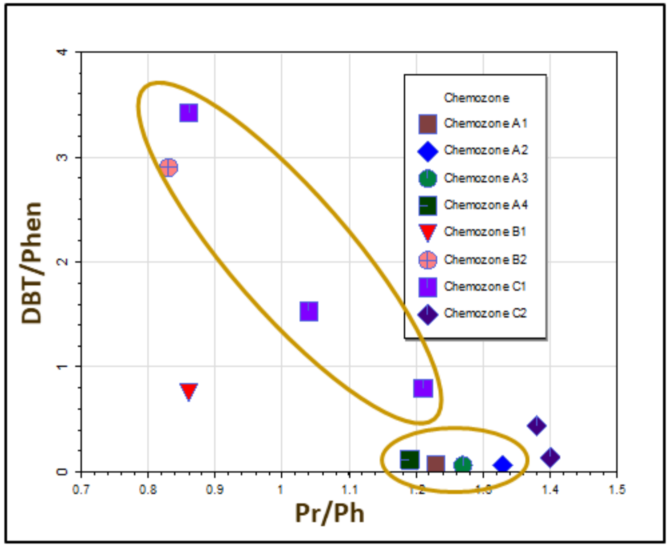
- The abundance of sulfur containing compound dibenzothiophene (DBT) is generally related to restricted/anoxic bottom water sedimentary conditions
- Increase in DBT/Phen ratios suggests increasingly more restricted depositional environment with more carbonate input from Formation C C2 to C1 chemozones
- Consistent with Pr/Ph interpretation

Dibenzothiophene

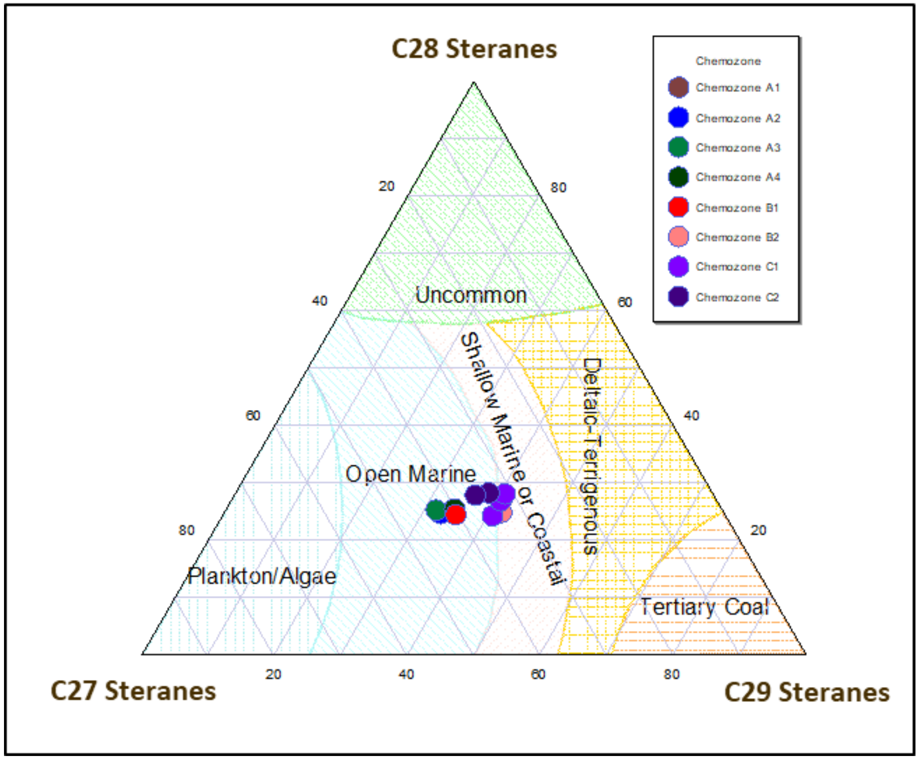


Phenanthrene



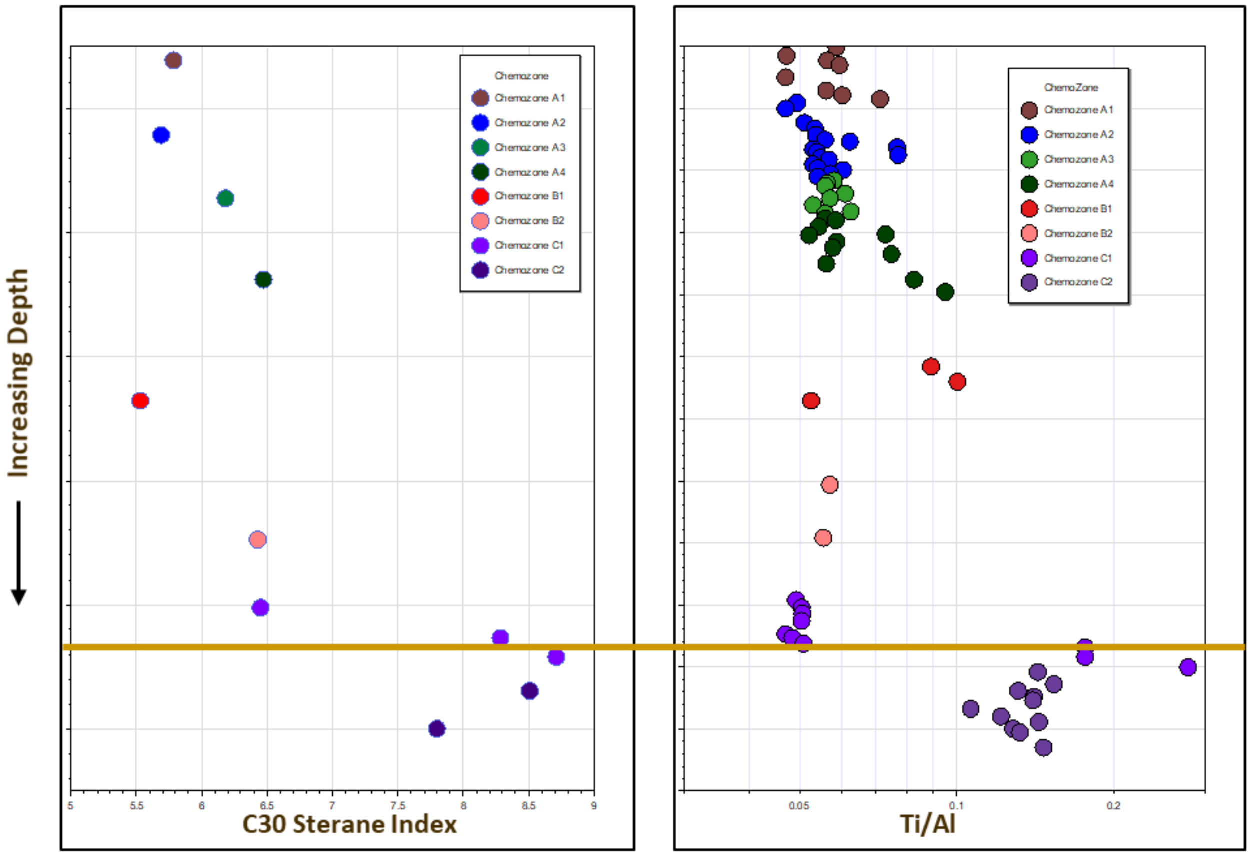


DEPOSITIONAL ENVIRONMENTS FROM BIOMARKERS



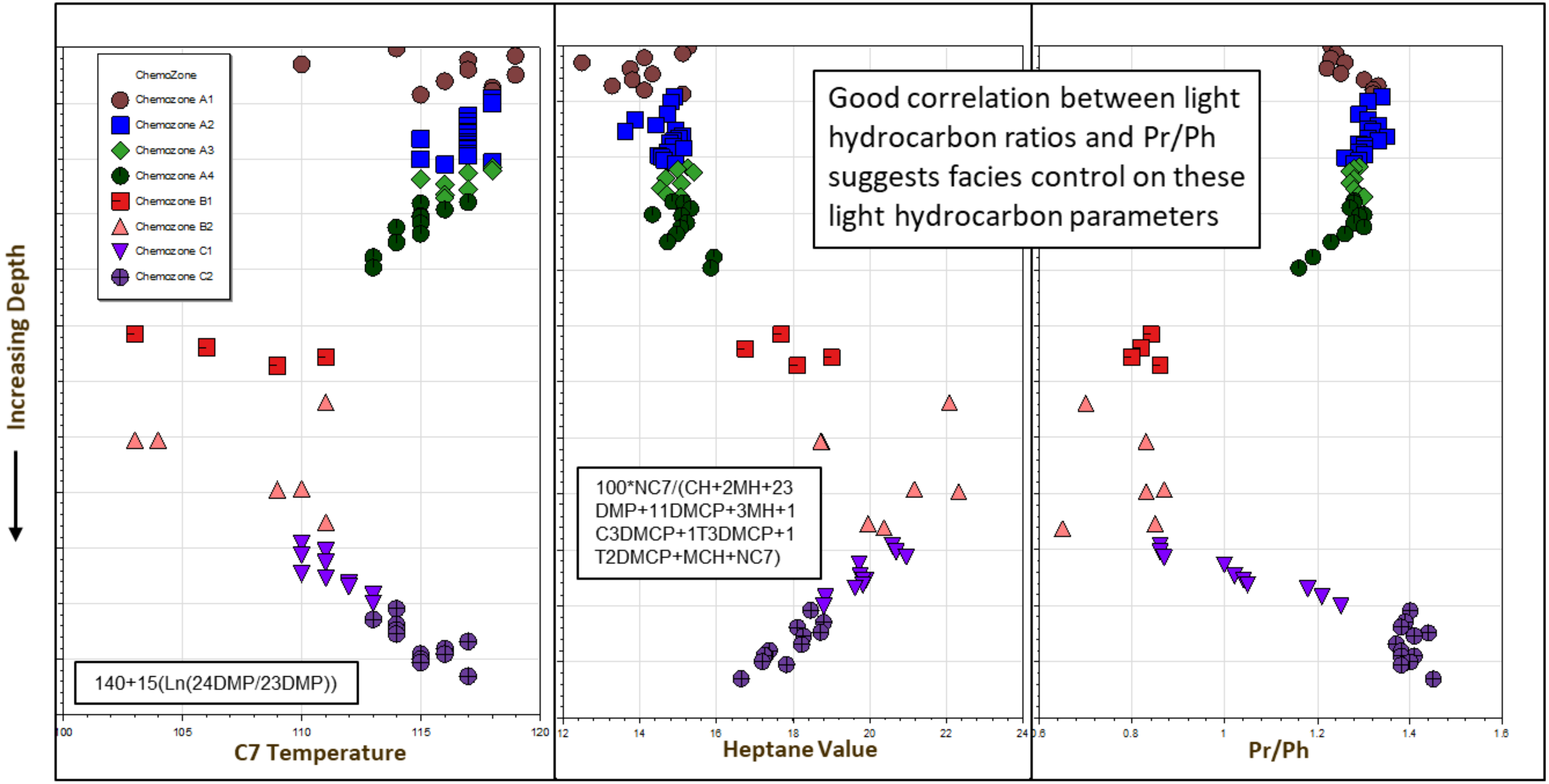
- Percentages of C27, C28, and C29 steranes are commonly associated with contribution of different portion of marine and terrigenous organic material.
- Deposition of Leonardian and Wolfcampian source rock is mostly shallow marine to open marine.
- Relative portions of C27, C28, C29 steranes suggest that there is a slight shift of organic source material from shallow marine-coastal in Formation C to more open marine deposition in Formation A.

SEDIMENT PROVENANCE IMPACTING ORGANIC MATTER PRODUCTIVITY



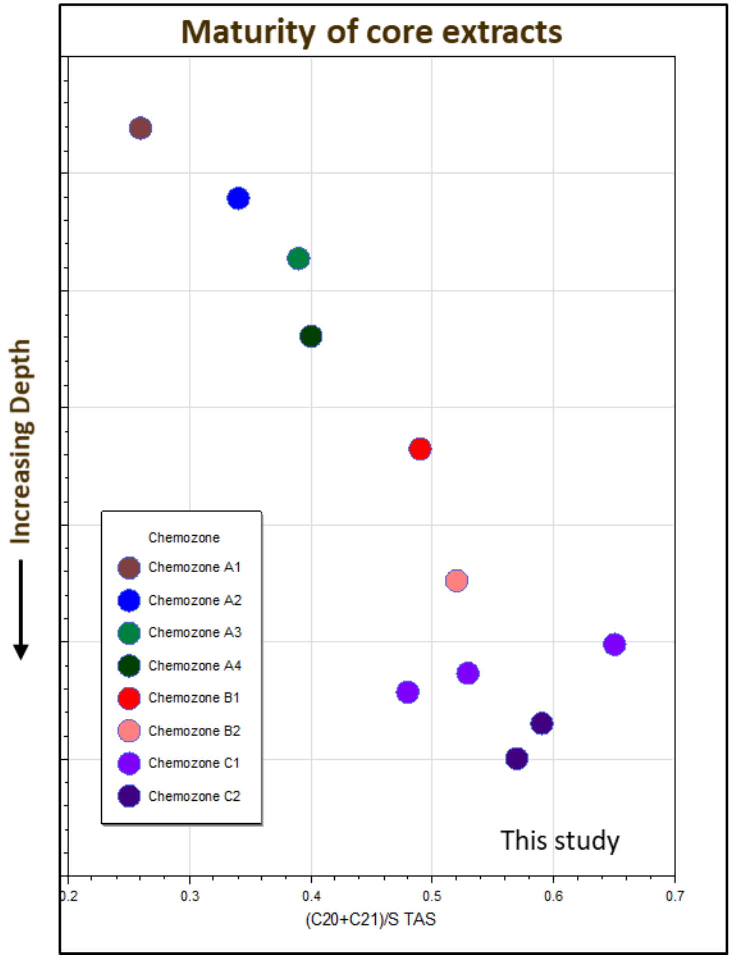
- Proportion of C30 steranes generally increases with marine organic matter inputs versus terrigenous organic matter input to the source rock.
- Much higher values in Chemozone C2 and partial C1 corresponding to higher Ti/Al ratios, a parameter for detrital sediment supply/provenance
- Also an interval with relatively less anoxic sedimentary conditions
- Less land-derived organic matter due to a drier climatic condition or glacial/interglacial transition

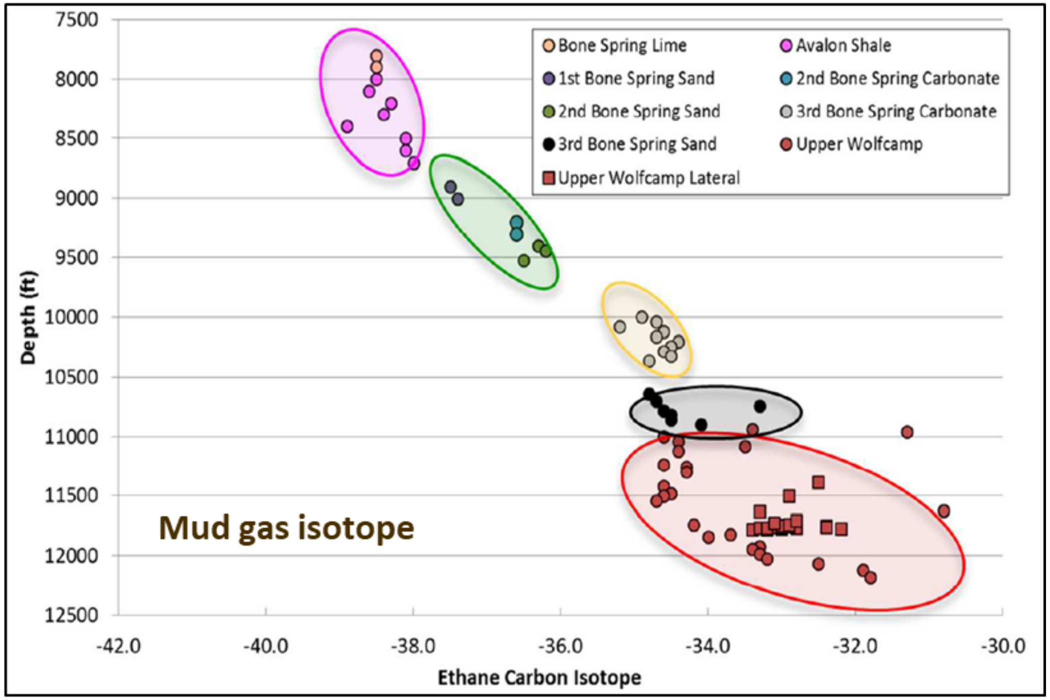
UTILITIES OF LIGHT HYDROCARBON COMPOUNDS



FLUID MATURITY FROM MOLECULAR AND ISOTOPE DATA

- Many cases of consistent maturity depth trends on both liquid and gas fractions suggest limited vertical migration in tight shale systems





(Goldsmith et al., 2016)

SUMMARY AND ACKNOWLEDGEMENT

- Organic rich black shale sequences in this Midland basin mid-Leonardian and Wolfcampian formations can be divided into multiple depositional chemozones/facies/parasequences/ geomechanic units, reflecting changes in sediment supply, primary productivity, and preservation conditions.

- The inorganic and organic geochemistry data, combined with detailed sediment fabric description, have indicated a likely shift in detrital sediment source and organic matter input, and also changes in bottom water redox conditions.

- It appears that water column productivity played a dominant role in accumulation of high TOC rocks, together with possibly enhanced preservation conditions.

- Depositional environments may also impact light hydrocarbon parameters that were "commonly" used for temperature and maturity interpretations.

- Many geochemistry parameters show consistent maturity depth trends on both liquid and gas fractions, suggesting limited vertical migration in tight shale systems.

- Apache Corporation is acknowledged for permission to publish and to present this study.