Sequence Stratigraphy and its Bearing on Reservoir Characteristics of Shale Successions – Examples from the Appalachian Basin*

Gary G. Lash[1] and Randy Blood[2]

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[1]Dept. of Geosciences, SUNY Fredonia, Fredonia, NY 14063 (Lash@fredonia.edu)
[2]Randy Blood, EQT Production, Pittsburgh, PA 15222 (RBlood@eqt.com)

Abstract

Variations of gas reservoir properties, many of which reflect the physical and chemical nature of the depositional environments of the reservoir rocks, can be linked to base level fluctuations. The resulting sequence stratigraphic framework, then, can be extrapolated into regions of minimal data control. Our sequence stratigraphic paradigm is based on the transgressive-regressive (T-R) sequence concept. A single T-R sequence comprises transgressive systems tract (TST) deposits overlain by a regressive systems tract (RST) succession, the contact being a maximum flooding surface (MFS), and is bounded on top and bottom by maximum regressive surfaces. Ongoing studies of the Devonian shale succession of the Appalachian Basin reveal that such parameters as mineralogy and microfabric vary predictably within the T-R sequence stratigraphic framework. A general increase in silica, much of which is diagenetic, and reduction of clay upward through the TST reflects the rapid landward migration of the shoreline. Early precipitation of silica cement preserves porosity and inhibits the development of a planar clay grain microfabric. TST deposits are commonly pyritiferous and organic-rich; indeed, TOC and pyrite content are maximum close to the MFS. Increasing thermal maturity of these deposits is accompanied by increasing porosity (principally nanoporosity) as a consequence of the transformation of kerogen. Under some conditions, bacterial reworking of organic-rich sediment deposited during transgression, especially proximal to the base level maximum, results in suppression of vitrinite reflectance. Accumulation of RST deposits is marked by increasing terrigenous sediment flux (clay and detrital quartz) and concomitant dilution of the organic contribution. This favors the more widespread development of a strongly planar clay-grain microfabric disrupted only by discrete laminae of detrital quartz or isolated grains. The base level minimum is defined by minimal TOC and local carbonate horizons. The predictive capabilities inherent to sequence stratigraphy make it especially applicable to exploration programs of seemingly homogenous shale successions.

References

Embry, A., E. Johannessen, D. Owen, B. Beauchamp, and P. Gianolla, 2007, Sequence stratigraphy as a "concrete" discipline: Report of the ISSC task group on sequence stratigraphy, 104 p, Web accessed 3 March 2011, http://strata.geol.sc.edu/SeqStratForm.html.

Loucks, R.G., R.M. Reed, S.C. Ruppel, and D.M. Jarvie, 2009, Morphology, genesis, and distribution of nanometer-scale pores in siliceous mudstones of the Mississippian Barnett Shale: JSR, v. 79/12, p. 848-861.

Macquaker, J.H.S. and C.R. Jones, 2002, A sequence-stratigraphic study of mudstone heterogeneity; a combined petrographic/wireline log investigation of Upper Jurassic mudstones from the North Sea (U.K.), *in* M. Lovell and N. Parkinson, (eds.), Geological applications of well logs: AAPG Methods in Exploration Series, v. 13, p. 123-141.

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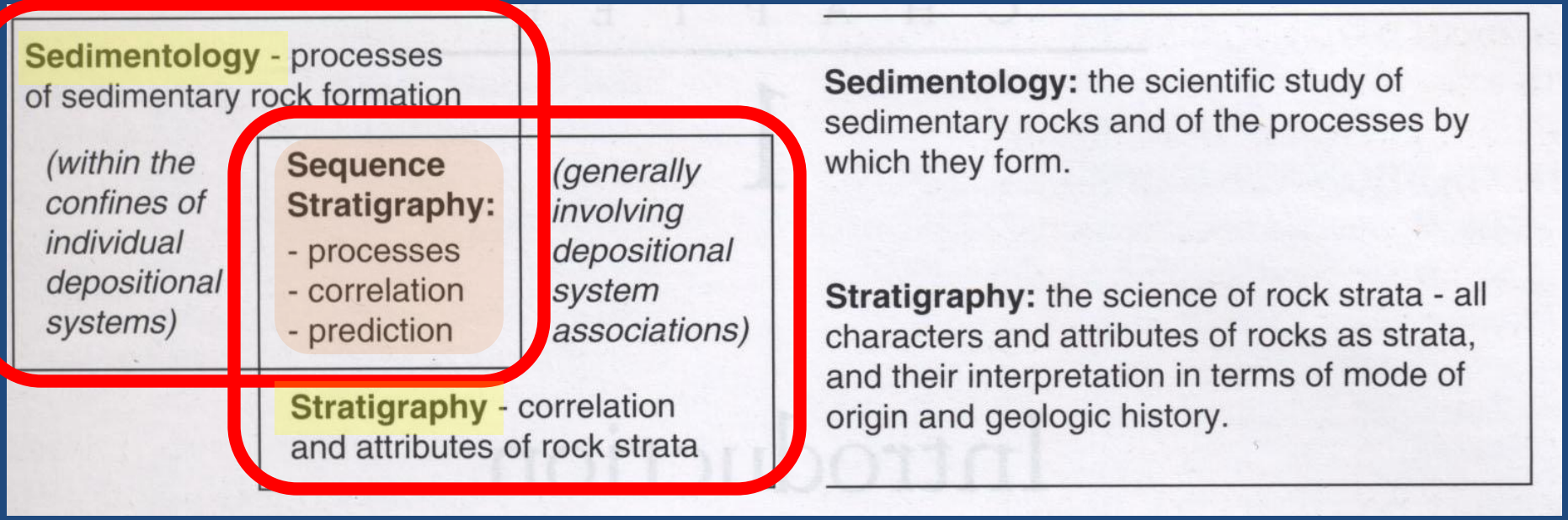
Gary G. Lash,
Dept. of Geosciences,
SUNY Fredonia,
Fredonia, NY, 14063

Randy Blood,
EQT Production,
Pittsburgh, PA 15222

sequence stratigraphy and reservoir properties…

…stresses processes, correlation and prediction…

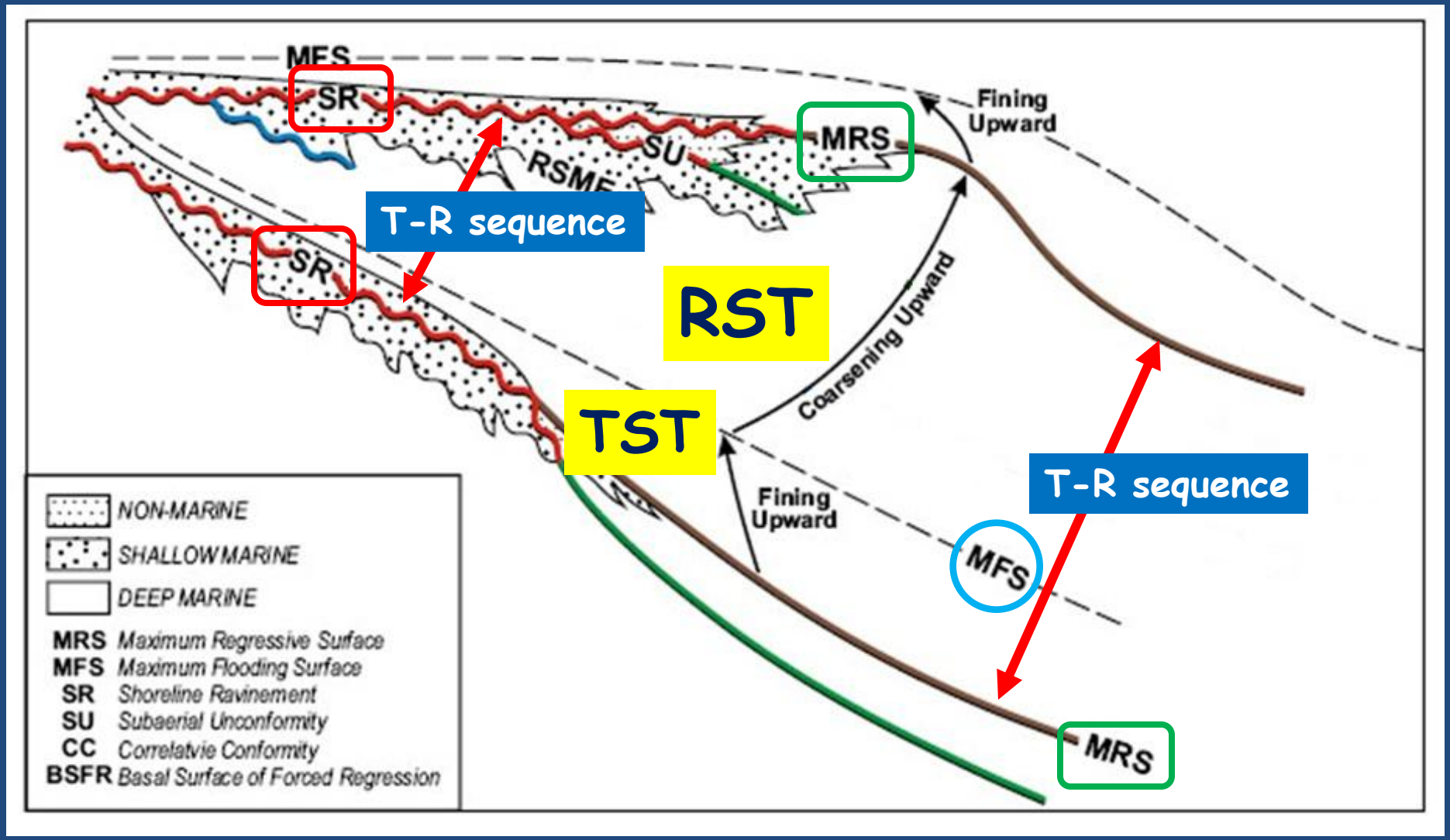


from Catuneau, 2006

…reservoir architecture and characteristics are driven largely by relative rates of sedimentation and subsidence and consequent base-level fluctuation…

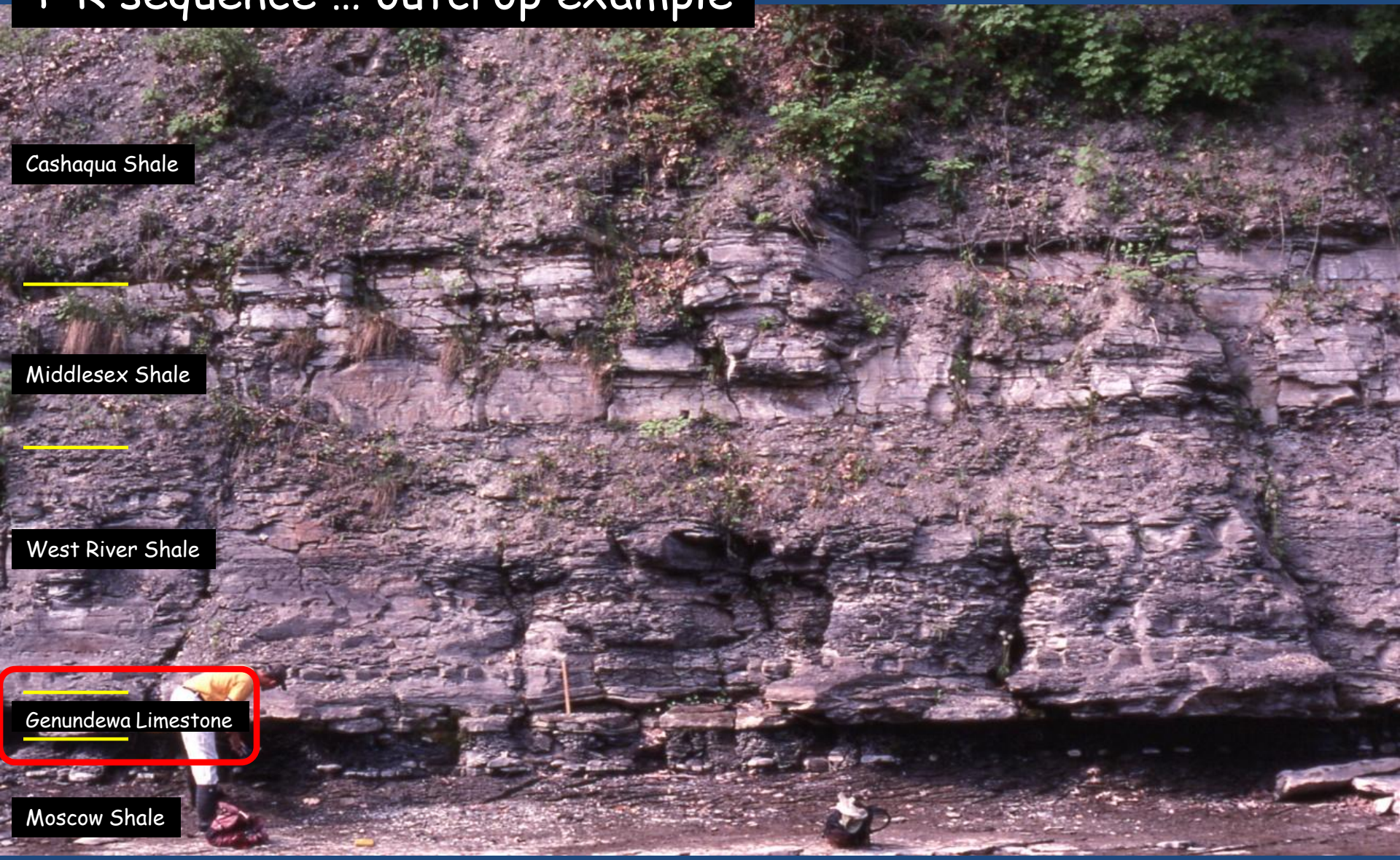
…unique sedimentologic/stratigraphic attributes related to base level fluctuations that reflect their respective depositional histories, include a variety of parameters critical to reservoir properties that would be important to exploration and production strategies…

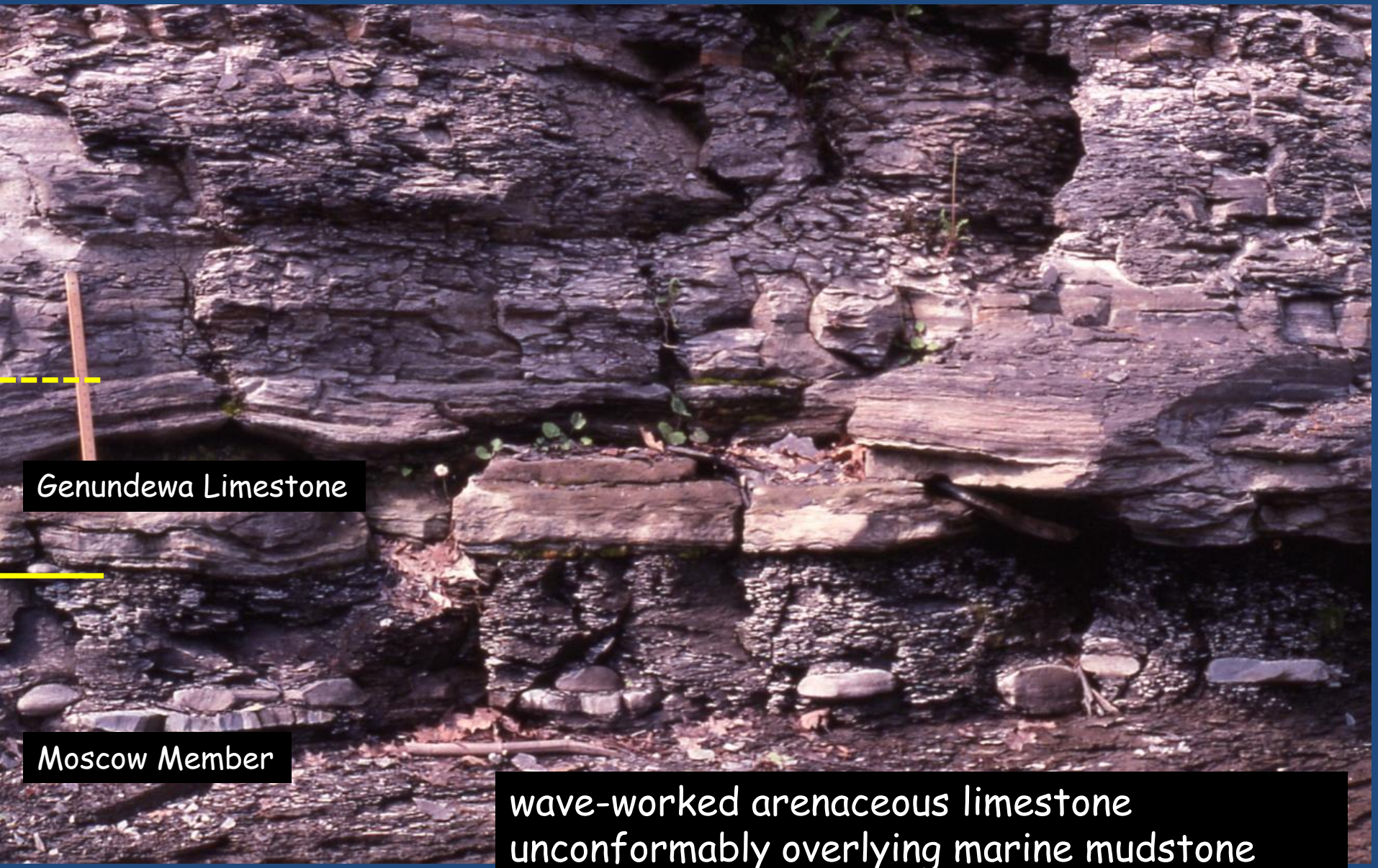
… transgressive-regressive sequence …



modified after Embry et al., 2007

T-R sequence … outcrop example

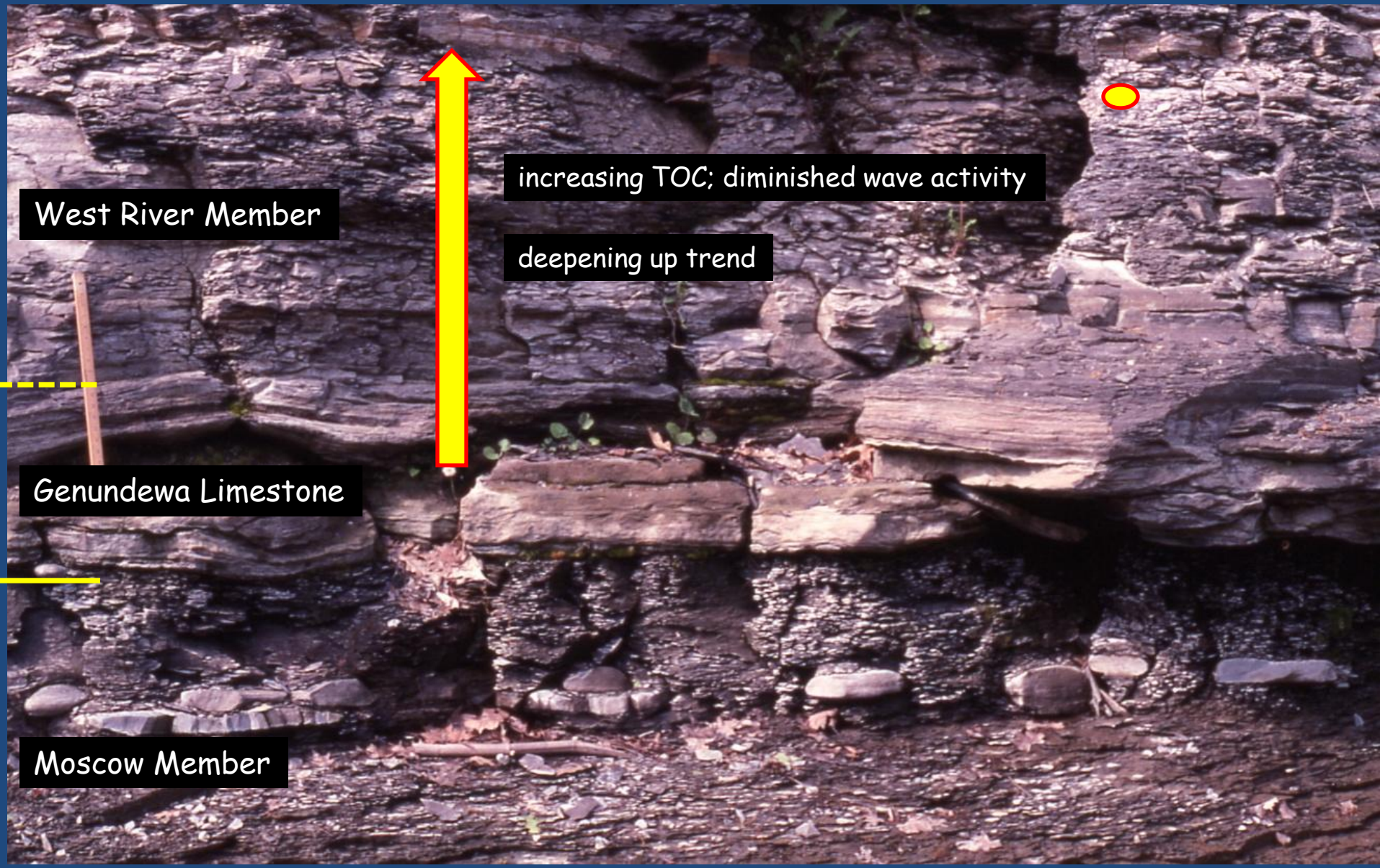


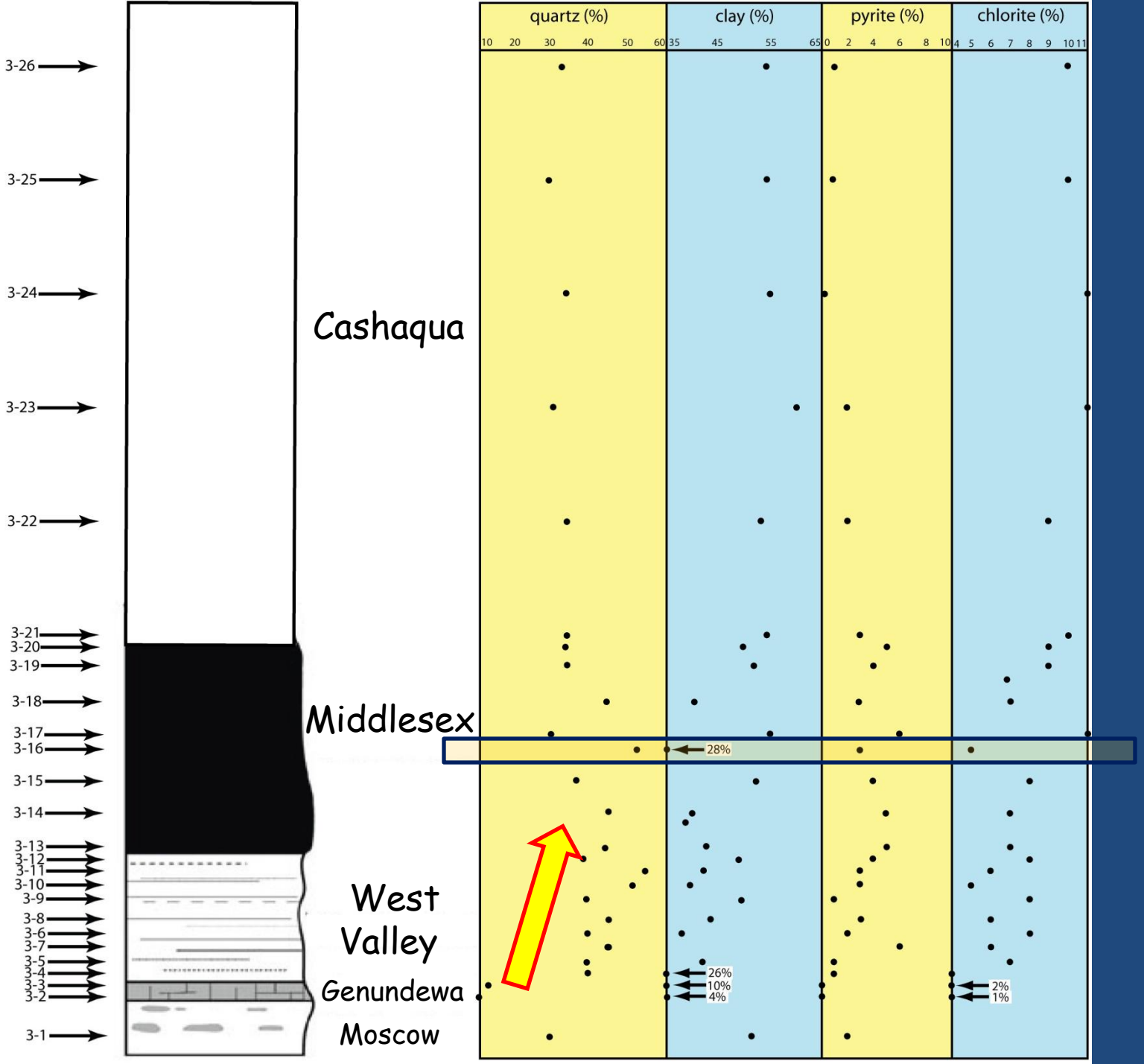


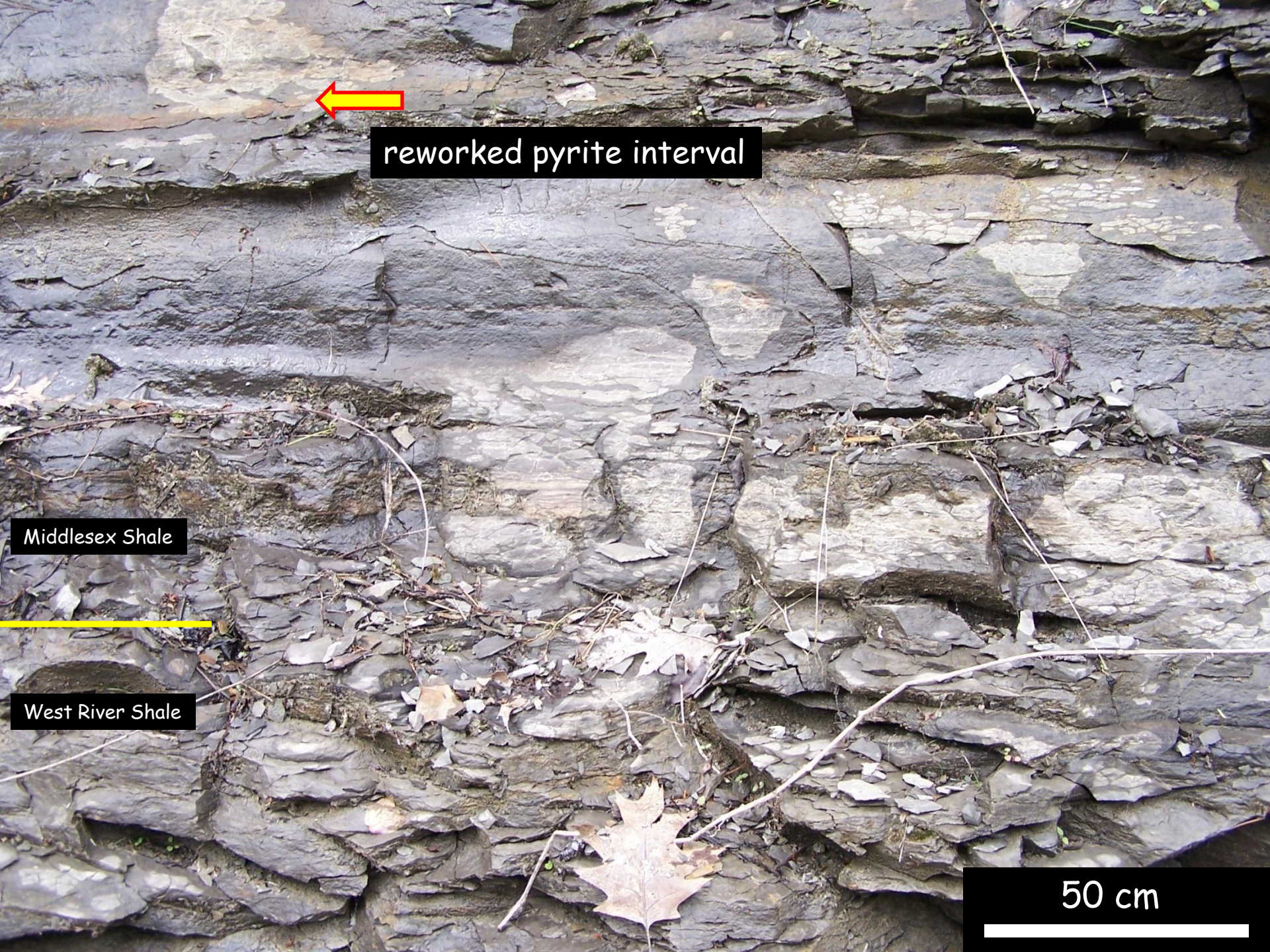
wave-worked arenaceous limestone unconformably overlying marine mudstone (Moscow Member) …


Genundewa Limestone
Moscow Member

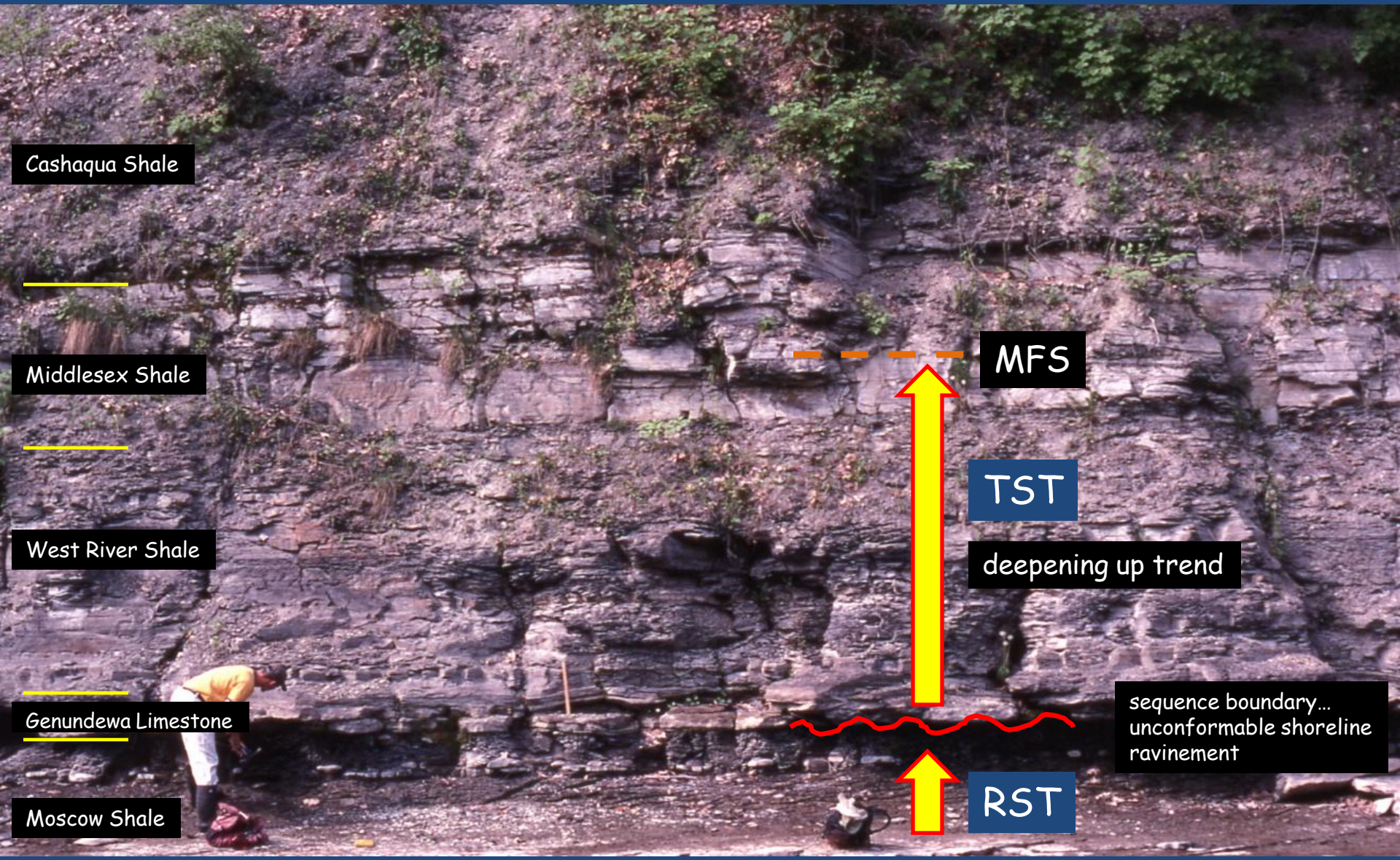

clay draps

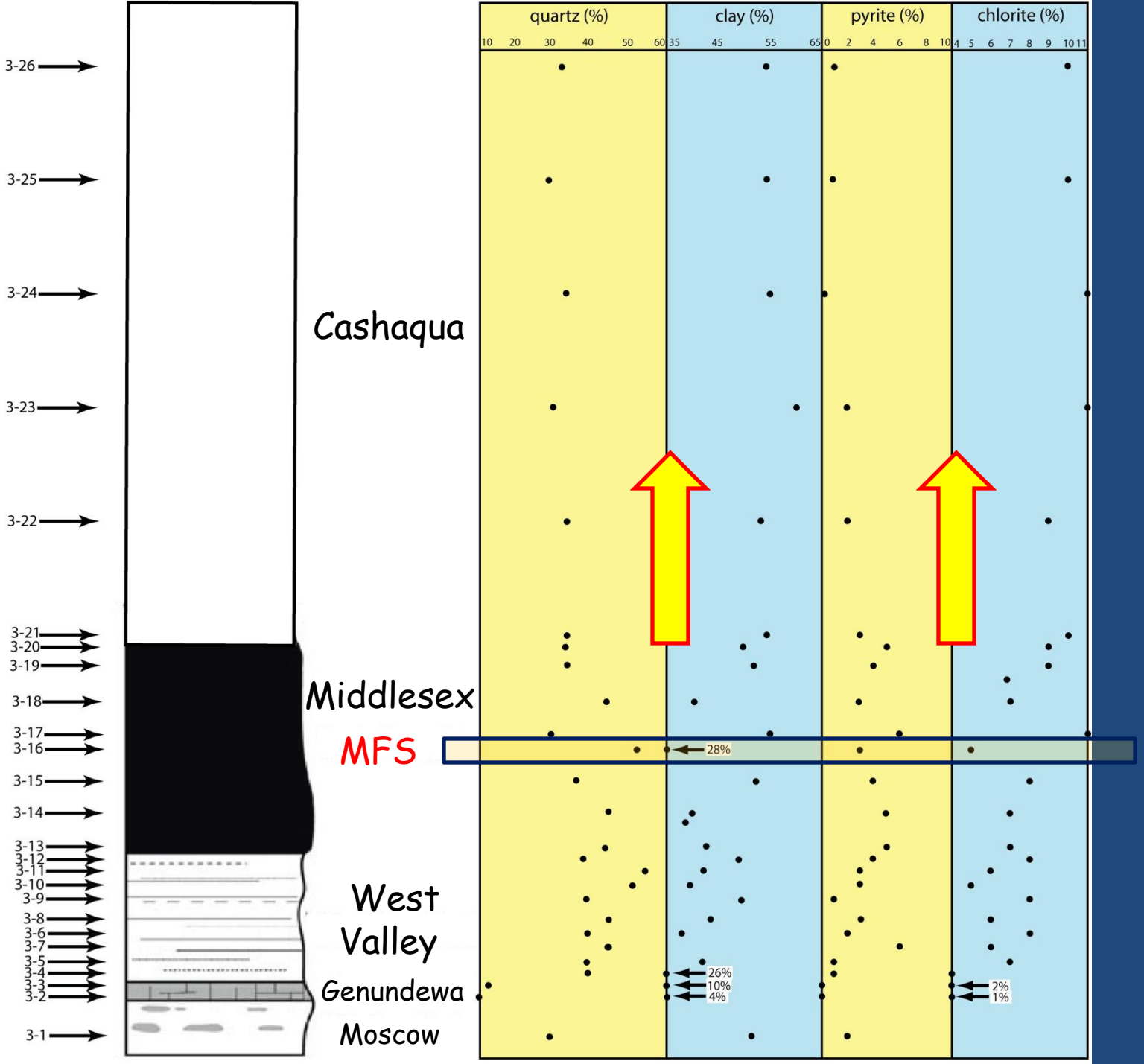

increasing TOC; diminished wave activity
West River Member
deepening up trend
Genundewa Limestone
Moscow Member

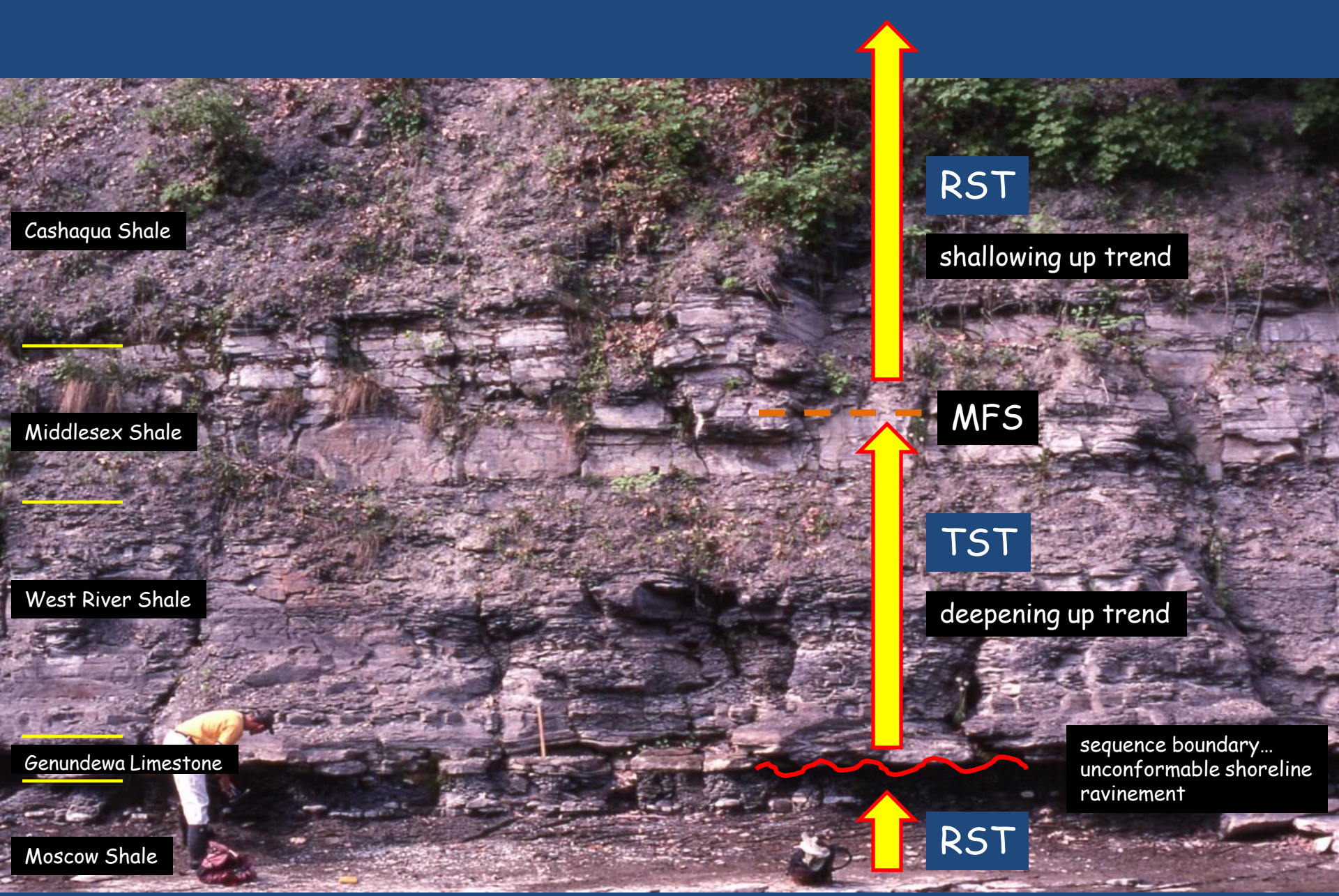

quartz (%)
clay (%)
pyrite (%)
chlorite (%)
10 20 30 40 50 60
35 45 55 65
0 2 4 6 8 10
4 5 6 7 8 9 10 11
3-26
3-25
3-24
3-23
3-22
3-21
3-20
3-19
3-18
3-17
3-16
3-15
3-14
3-13
3-12
3-11
3-10
3-9
3-8
3-6
3-7
3-5
3-4
3-3
3-2
3-1
Cashaqua
Middlesex
West Valley
Genundewa
Moscow
28%
26%
10%
4%
2%
1%

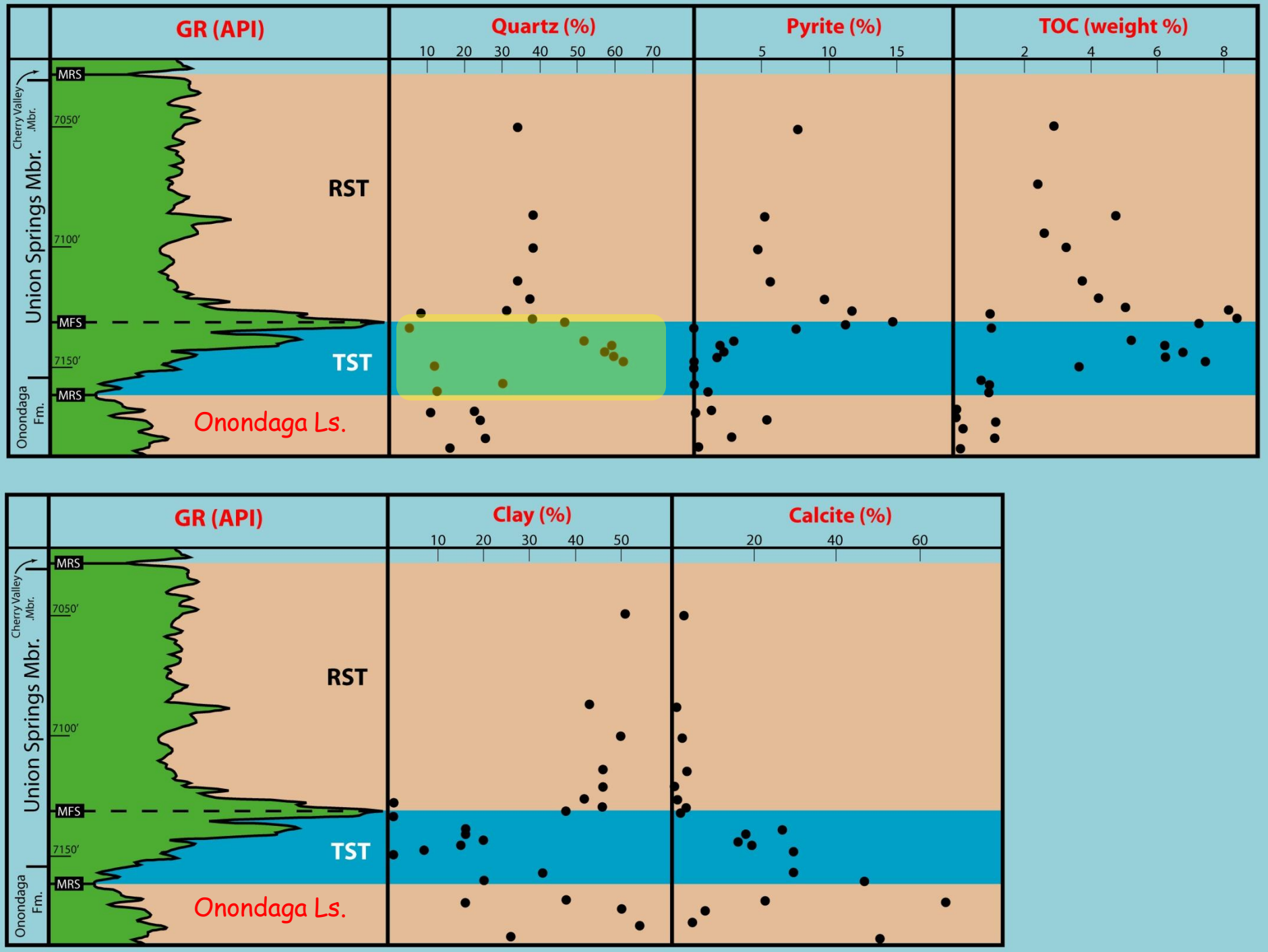

reworked pyrite interval
Middlesex Shale
West River Shale
50 cm

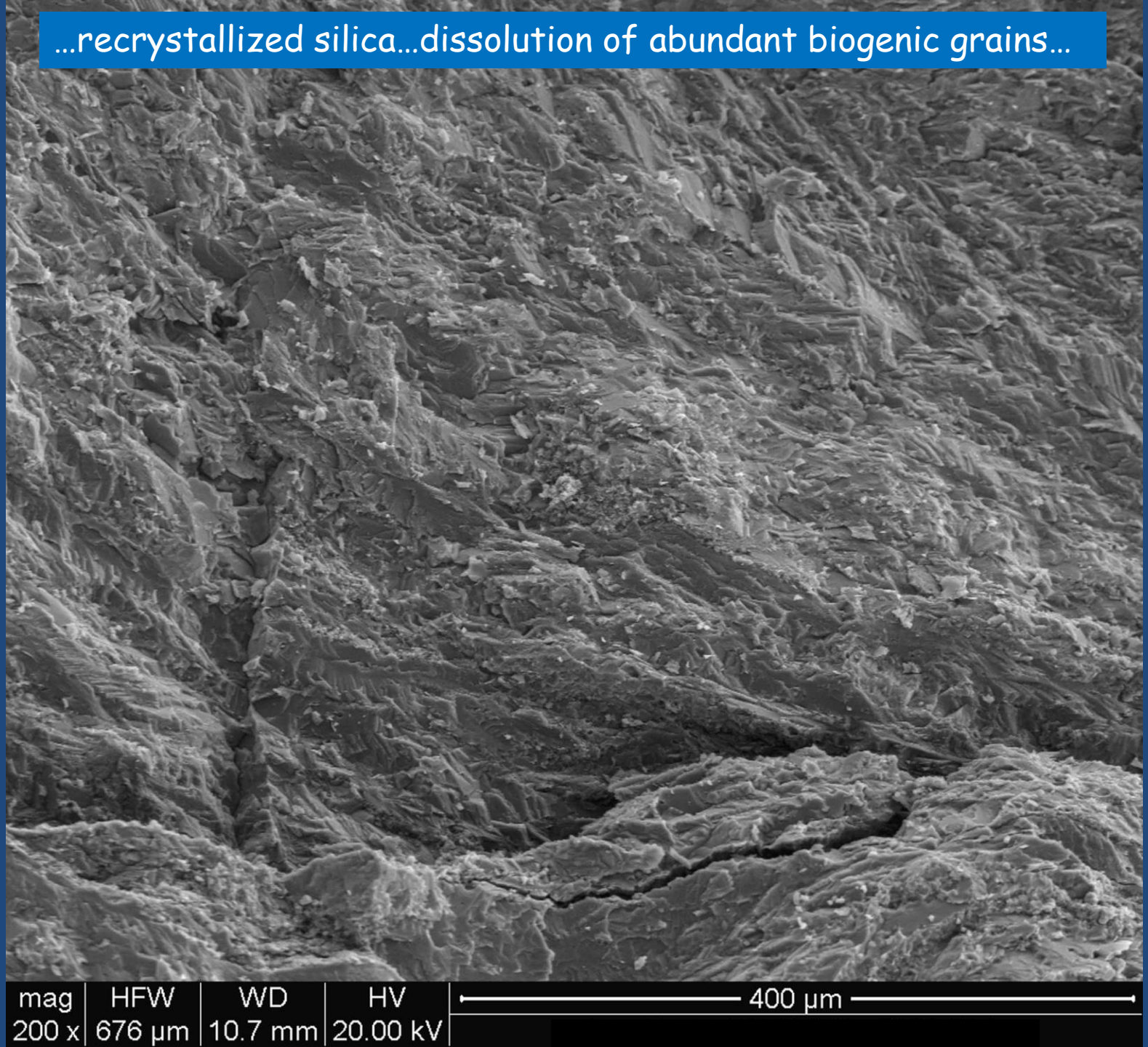
reworked pyrite interval

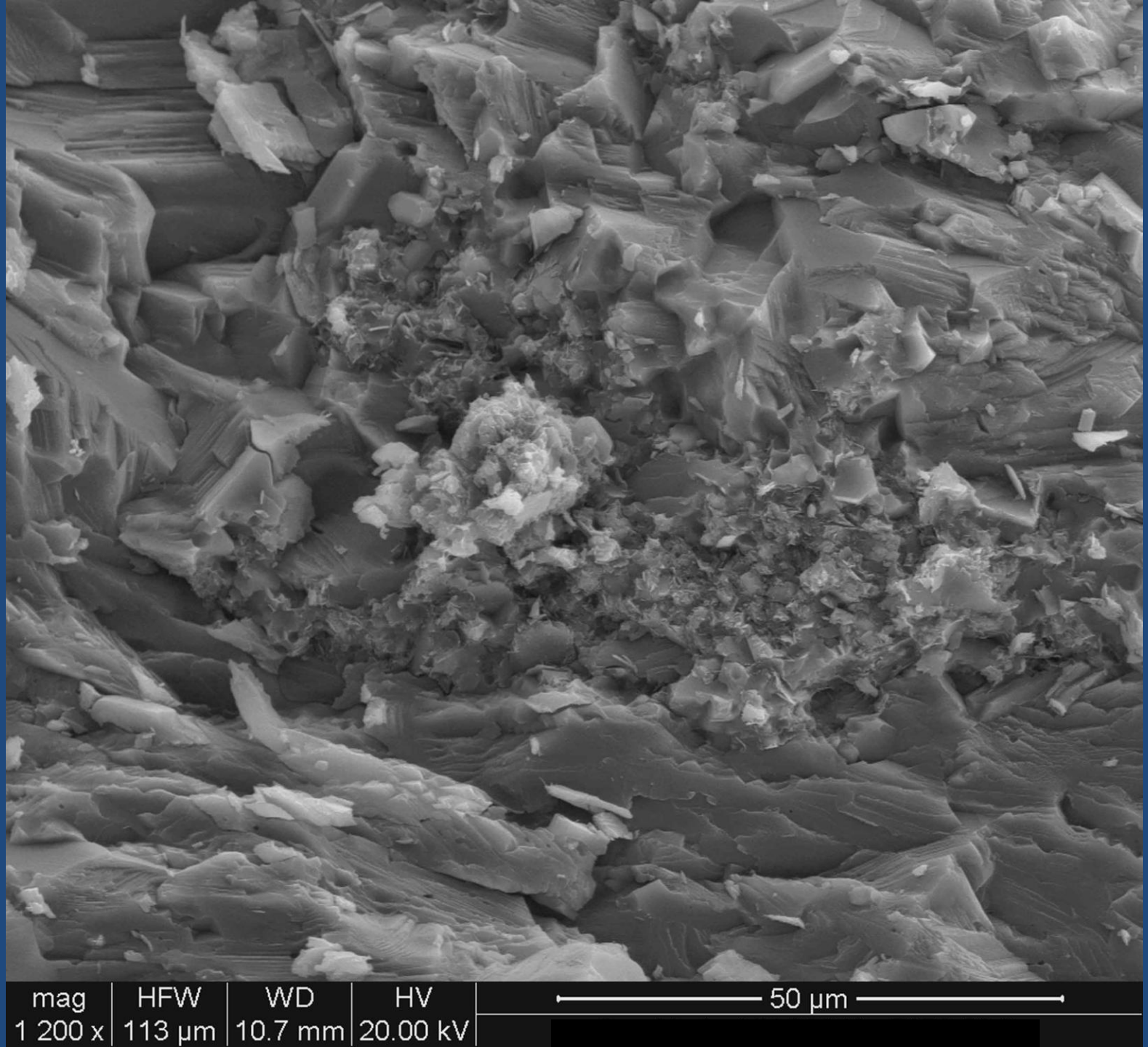

Cashaqua Shale
Middlesex Shale
West River Shale
Genundewa Limestone
Moscow Shale
MFS
TST
deepening up trend
sequence boundary…
unconformable shoreline
ravinement
RST

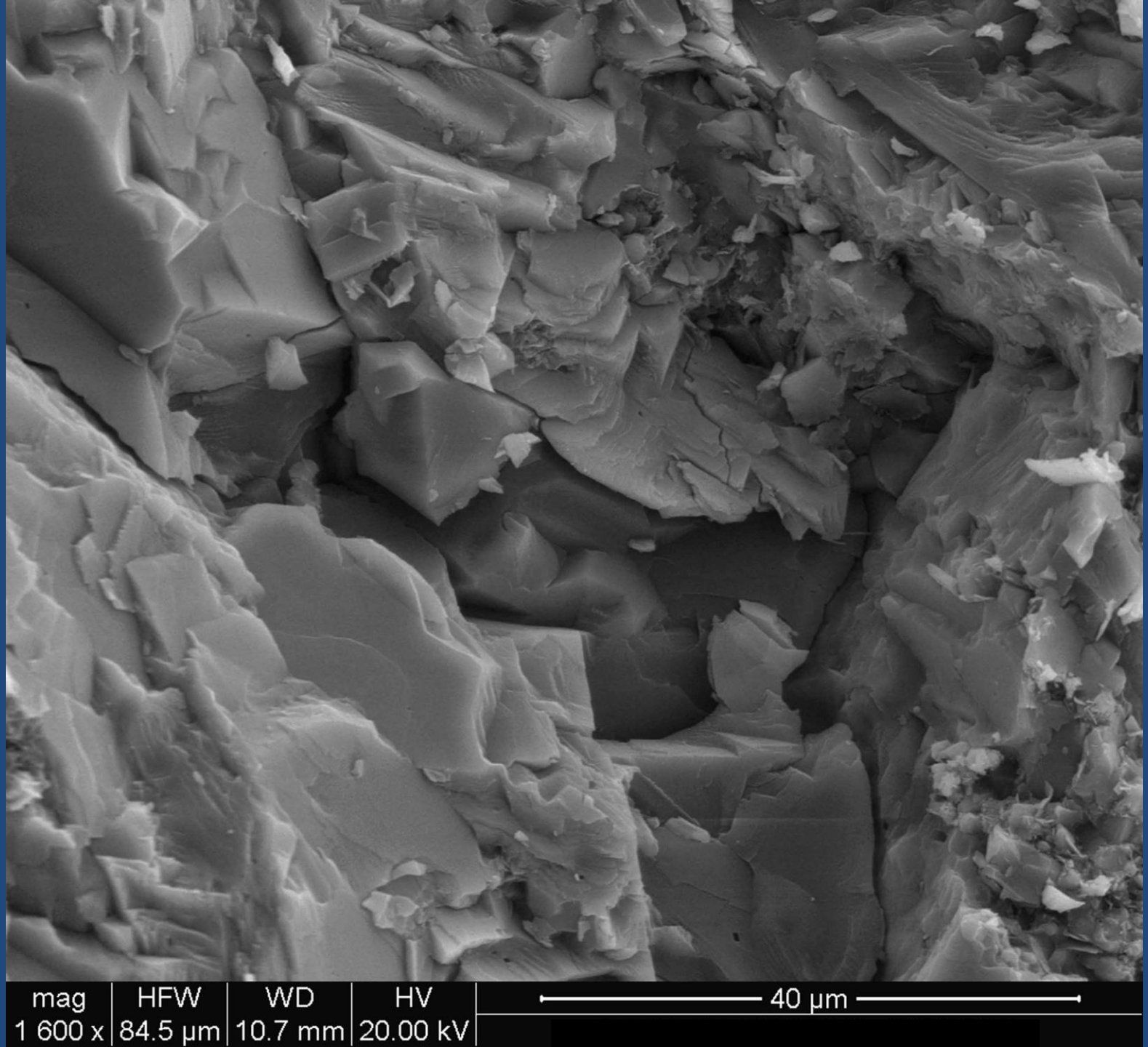

quartz (%)
clay (%)
pyrite (%)
chlorite (%)
10 20 30 40 50 60
35 45 55 65
0 2 4 6 8 10
4 5 6 7 8 9 10 11
3-26
3-25
3-24
3-23
3-22
3-21
3-20
3-19
3-18
3-17
3-16
3-15
3-14
3-13
3-12
3-11
3-10
3-9
3-8
3-6
3-7
3-5
3-4
3-3
3-2
3-1
Cashaqua
Middlesex
MFS
West Valley
Genundewa
Moscow
28%
26%
10%
4%
2%
1%

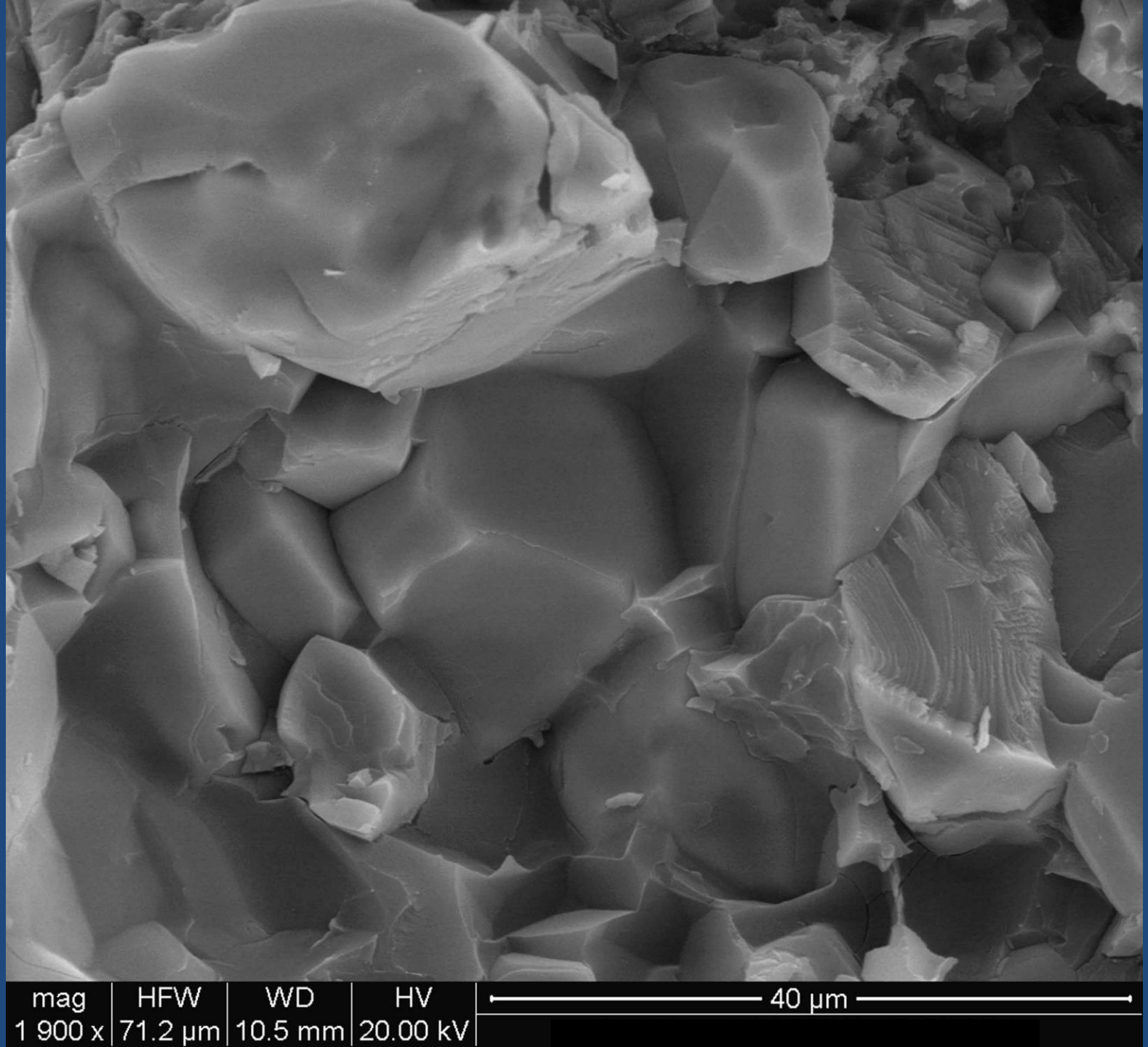

RST
shallowing up trend
Cashaqua Shale
Middlesex Shale
MFS
TST
deepening up trend
West River Shale
Genundewa Limestone
sequence boundary...
unconformable shoreline
ravinement
RST
Moscow Shale

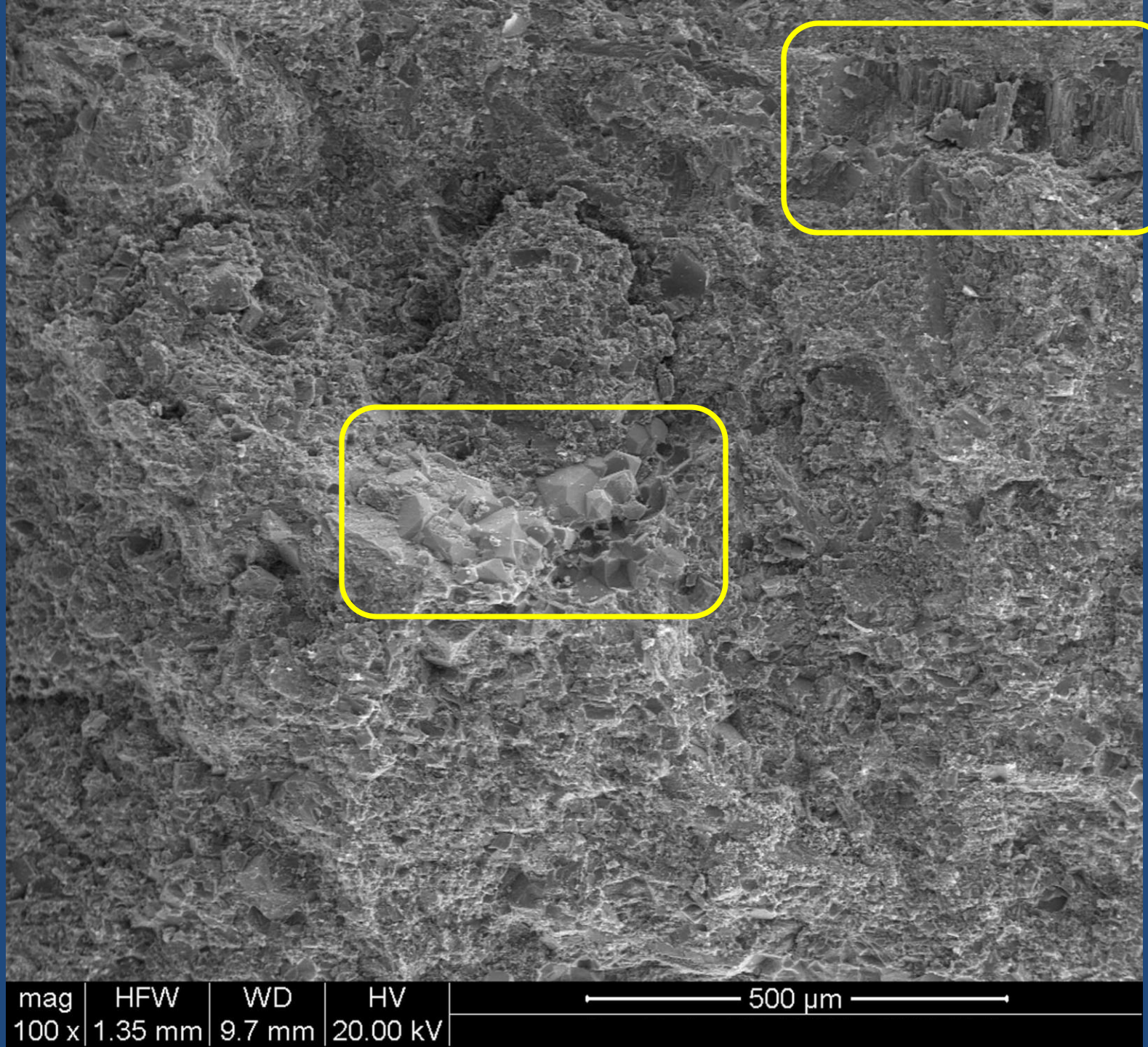

GR (API)
Quartz (%)
10 20 30 40 50 60 70
Pyrite (%)
5 10 15
TOC (weight %)
2 4 6 8
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.
GR (API)
Clay (%)
10 20 30 40 50
Calcite (%)
20 40 60
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.

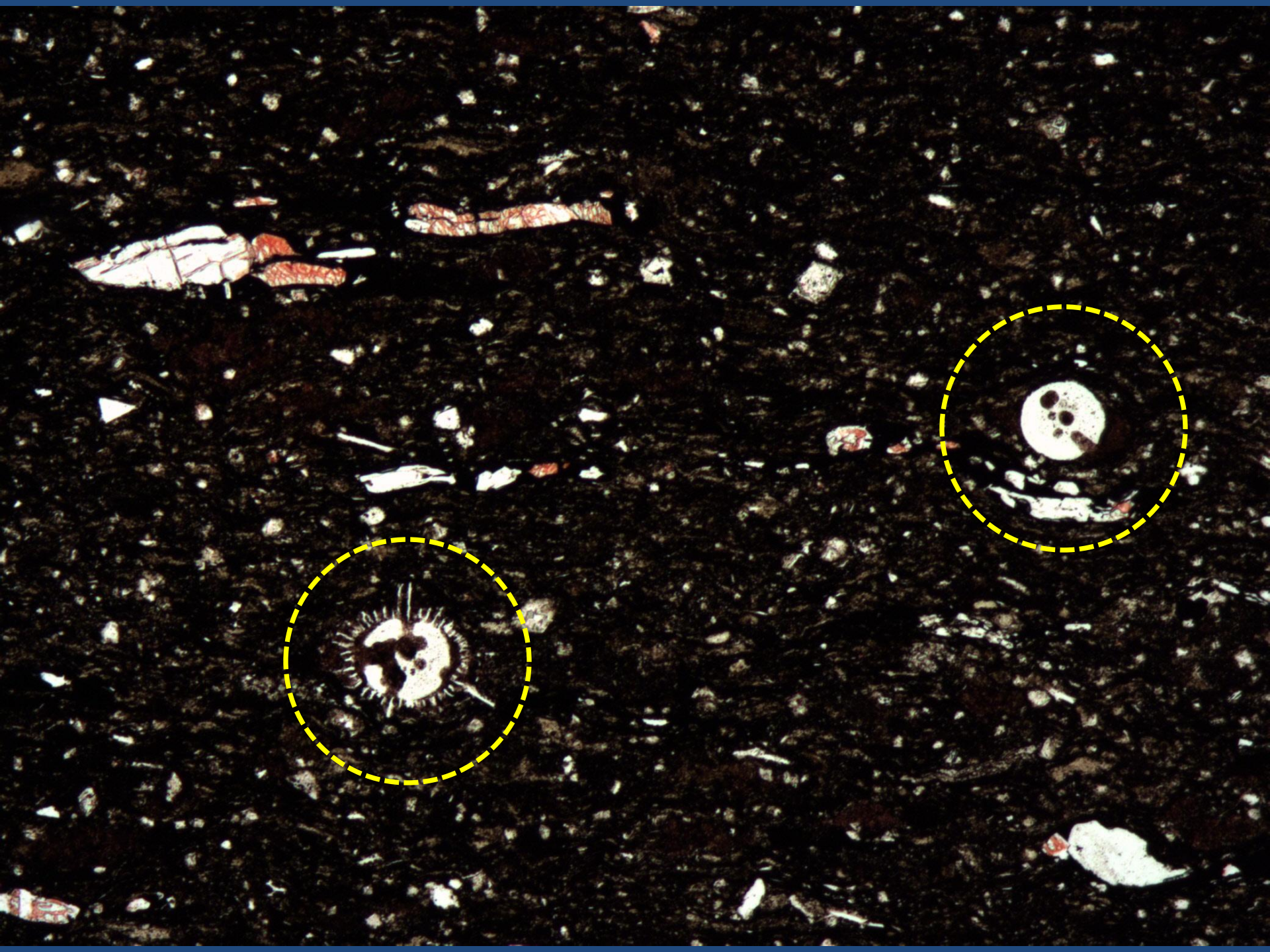

…recrystallized silica…dissolution of abundant biogenic grains…
mag
200 x
HFW
676 µm
WD
10.7 mm
HV
20.00 kV
400 µm

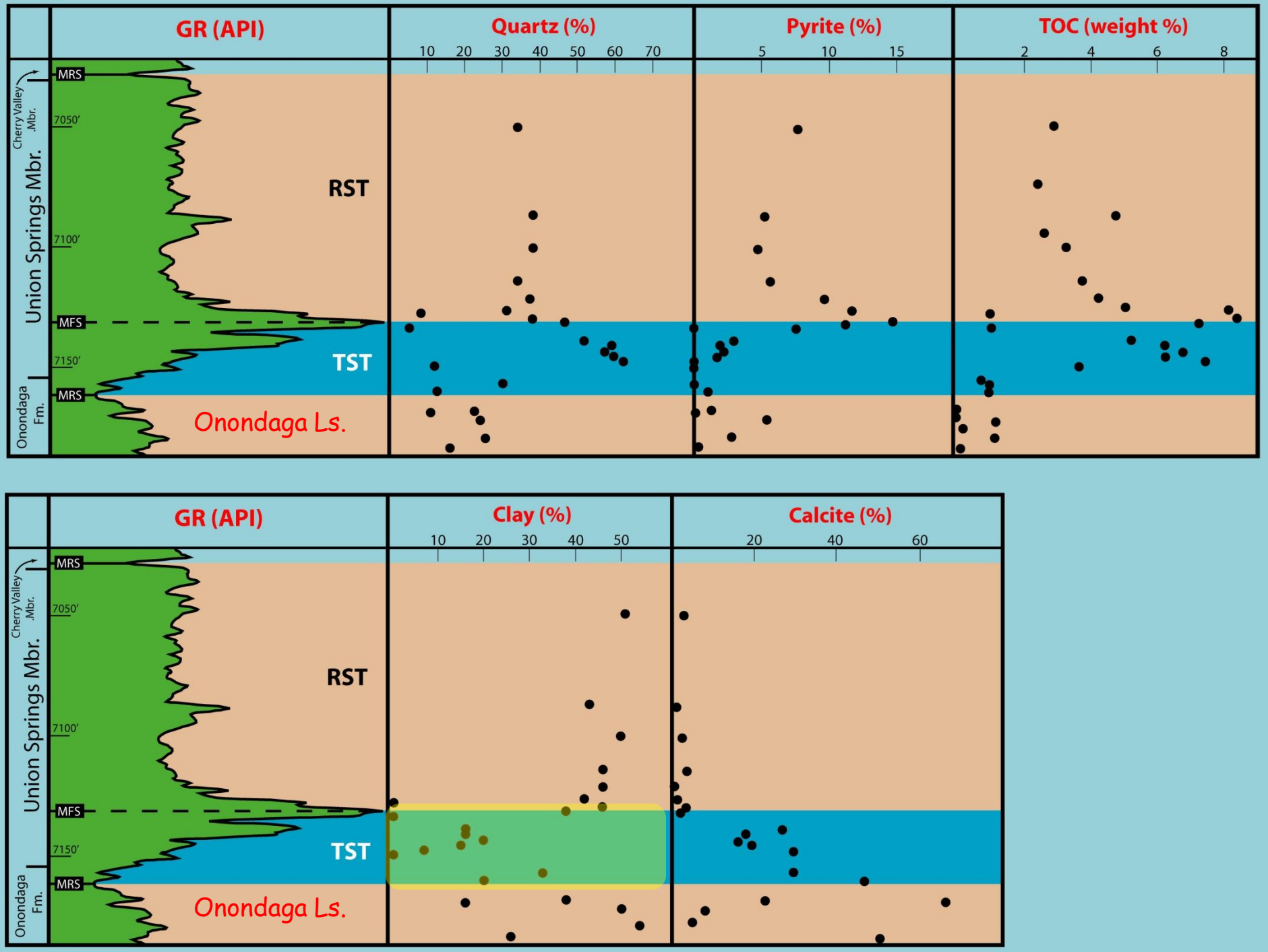

mag
1 200 x
HFW
113 µm
WD
10.7 mm
HV
20.00 kV
50 µm

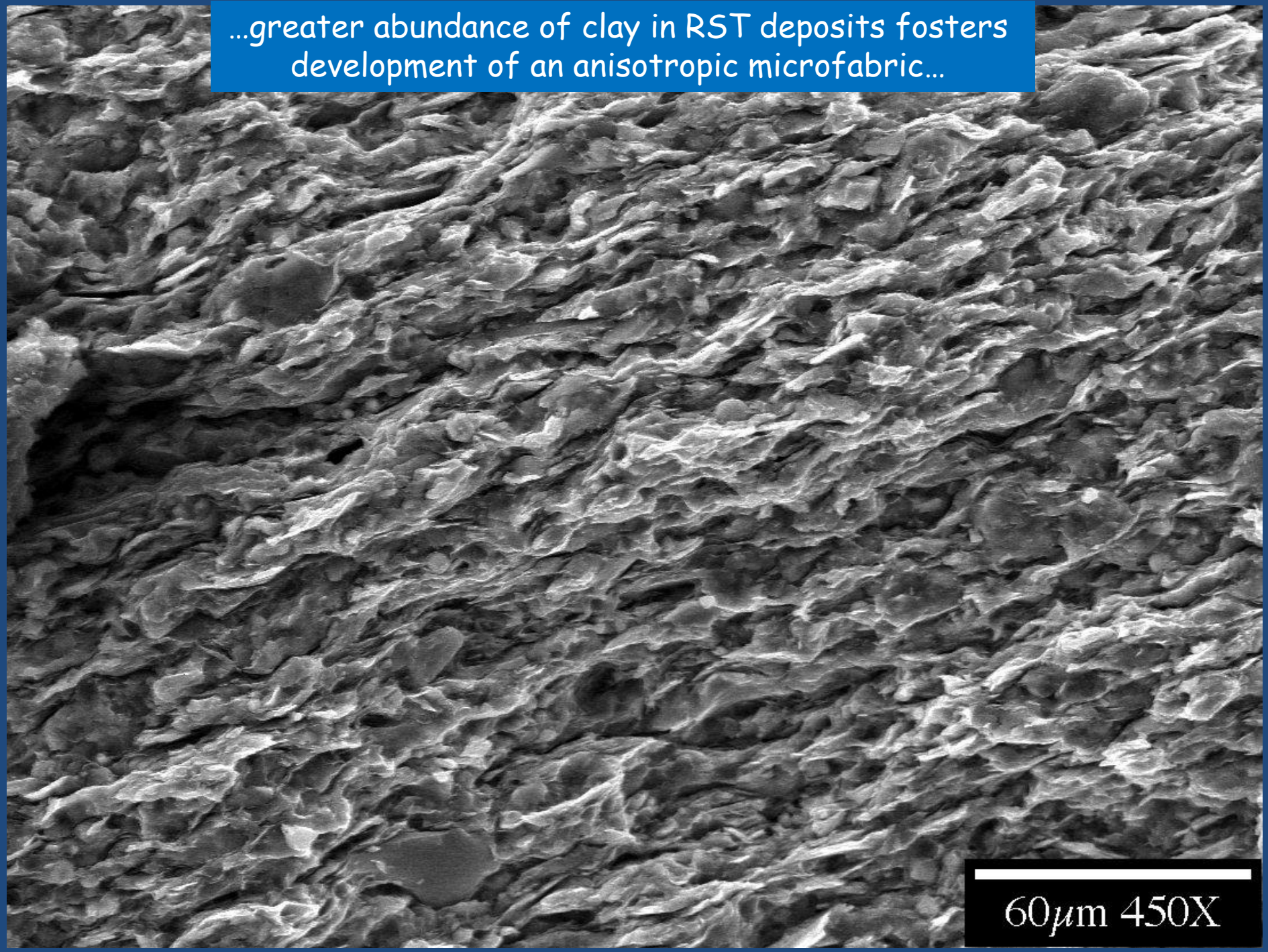

mag
1 600 x
HFW
84.5 µm
WD
10.7 mm
HV
20.00 kV
40 µm

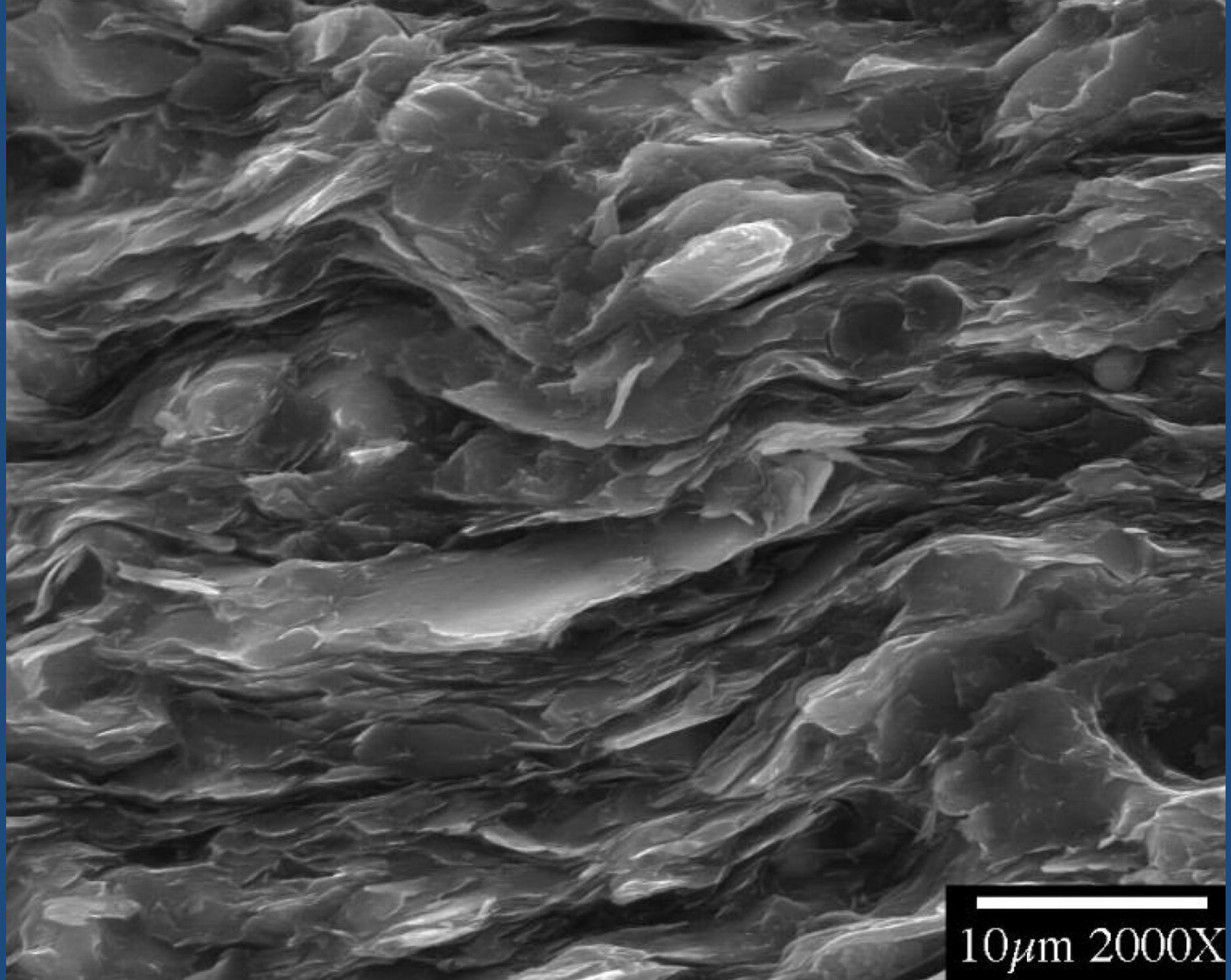

mag
1 900 x
HFW
71.2 µm
WD
10.5 mm
HV
20.00 kV
40 µm

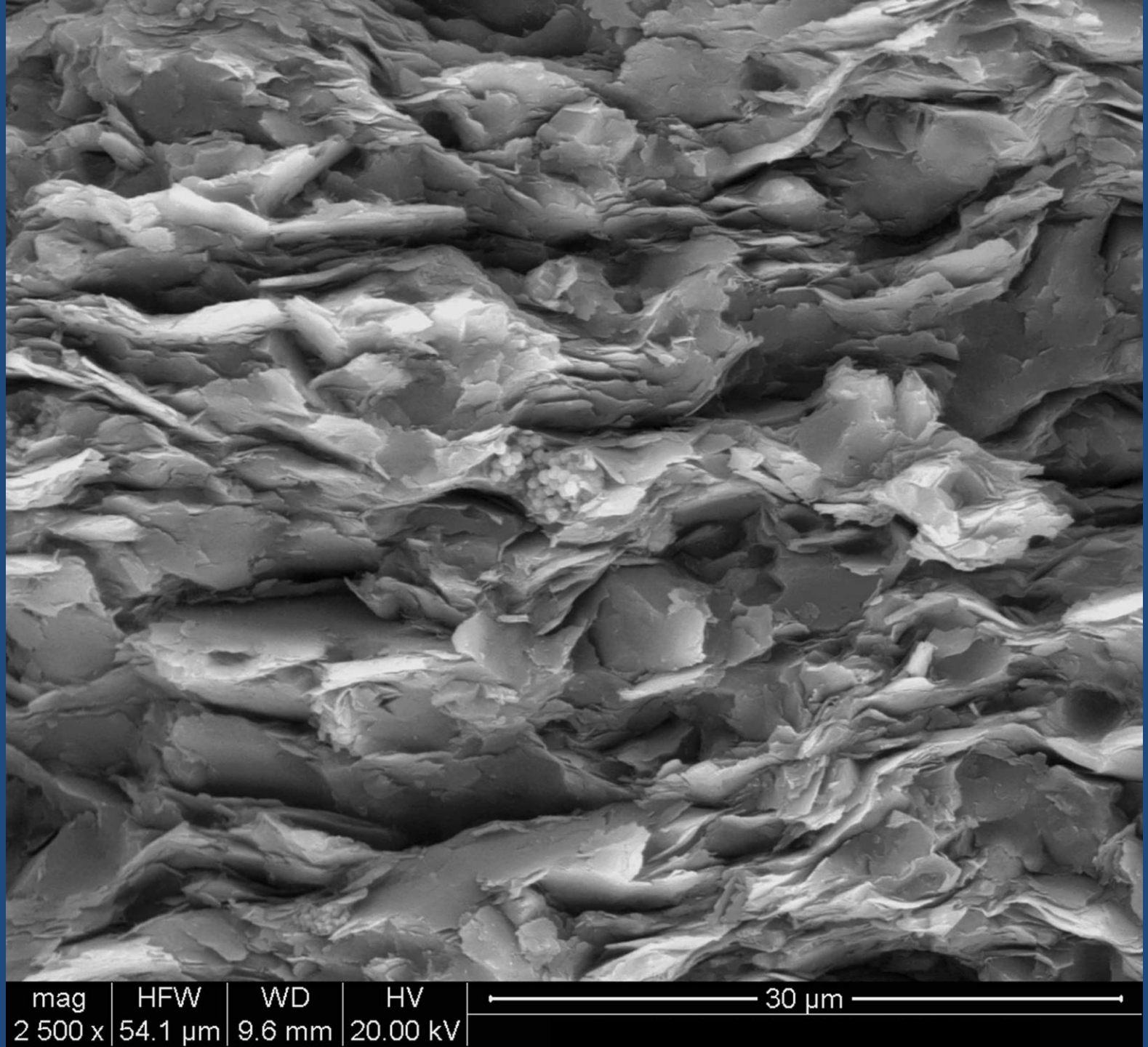

mag
100 x
HFW
1.35 mm
WD
9.7 mm
HV
20.00 kV
500 µm

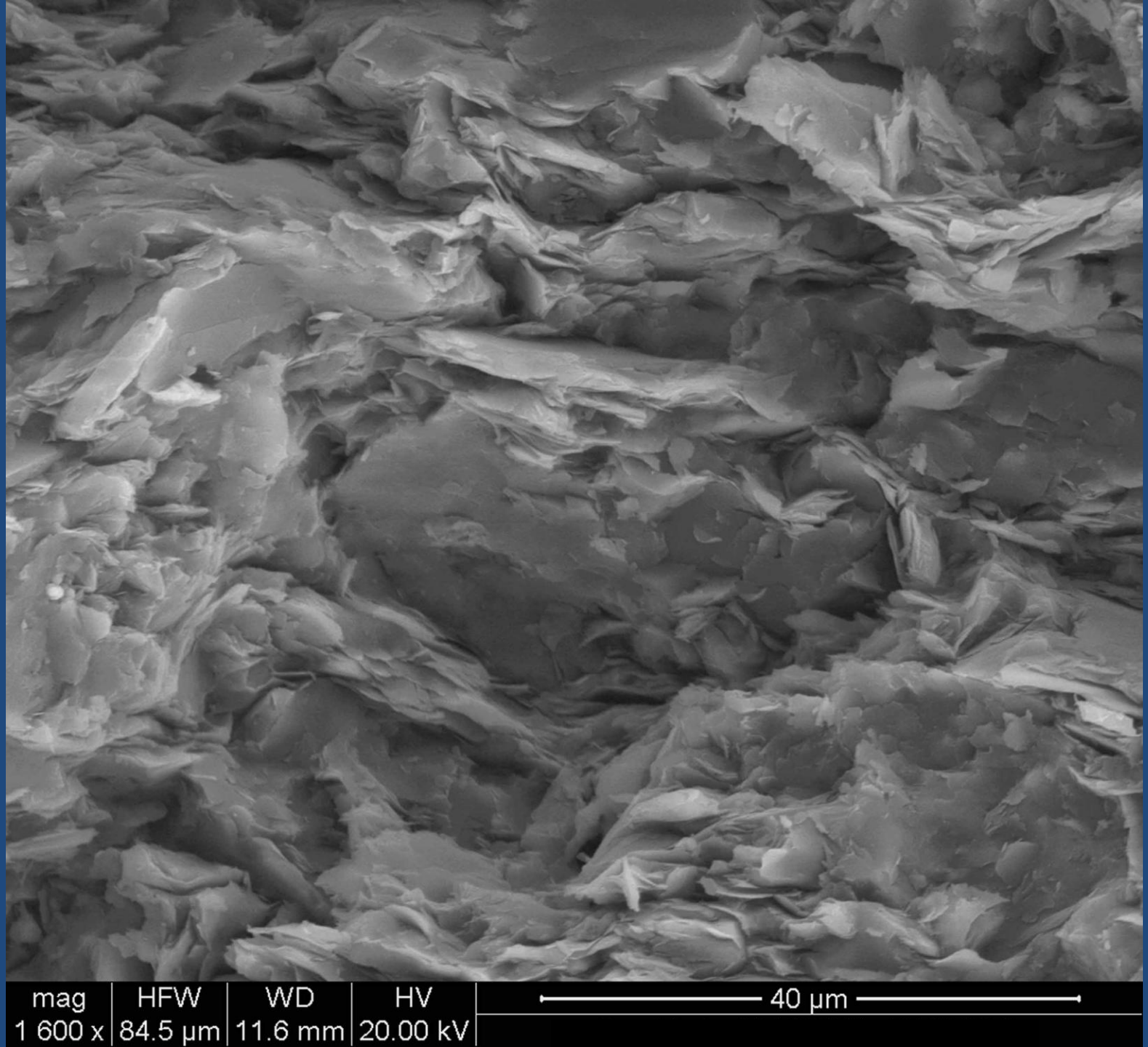


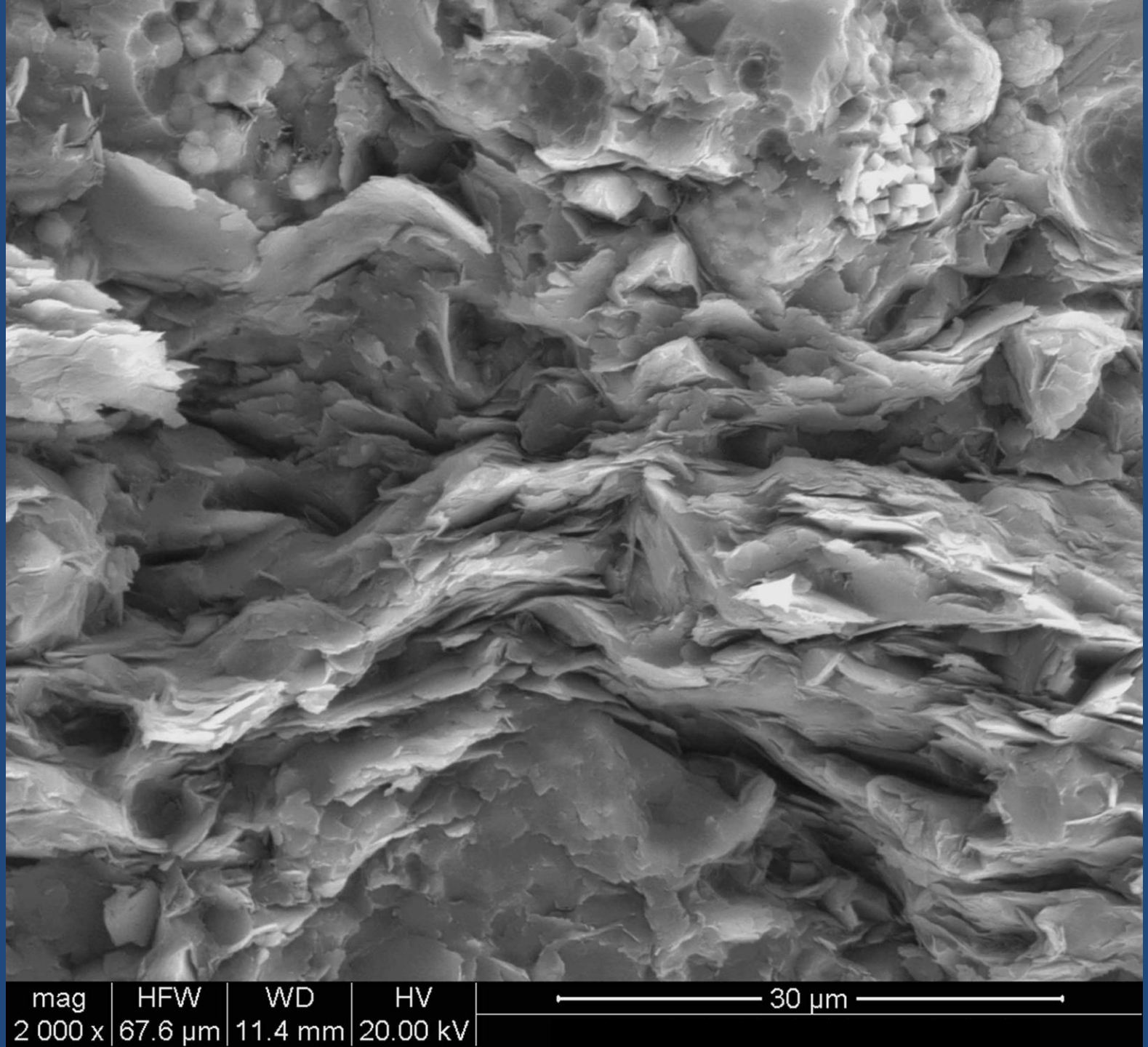

GR (API)
Quartz (%)
10 20 30 40 50 60 70
Pyrite (%)
5 10 15
TOC (weight %)
2 4 6 8
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.
GR (API)
Clay (%)
10 20 30 40 50
Calcite (%)
20 40 60
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.

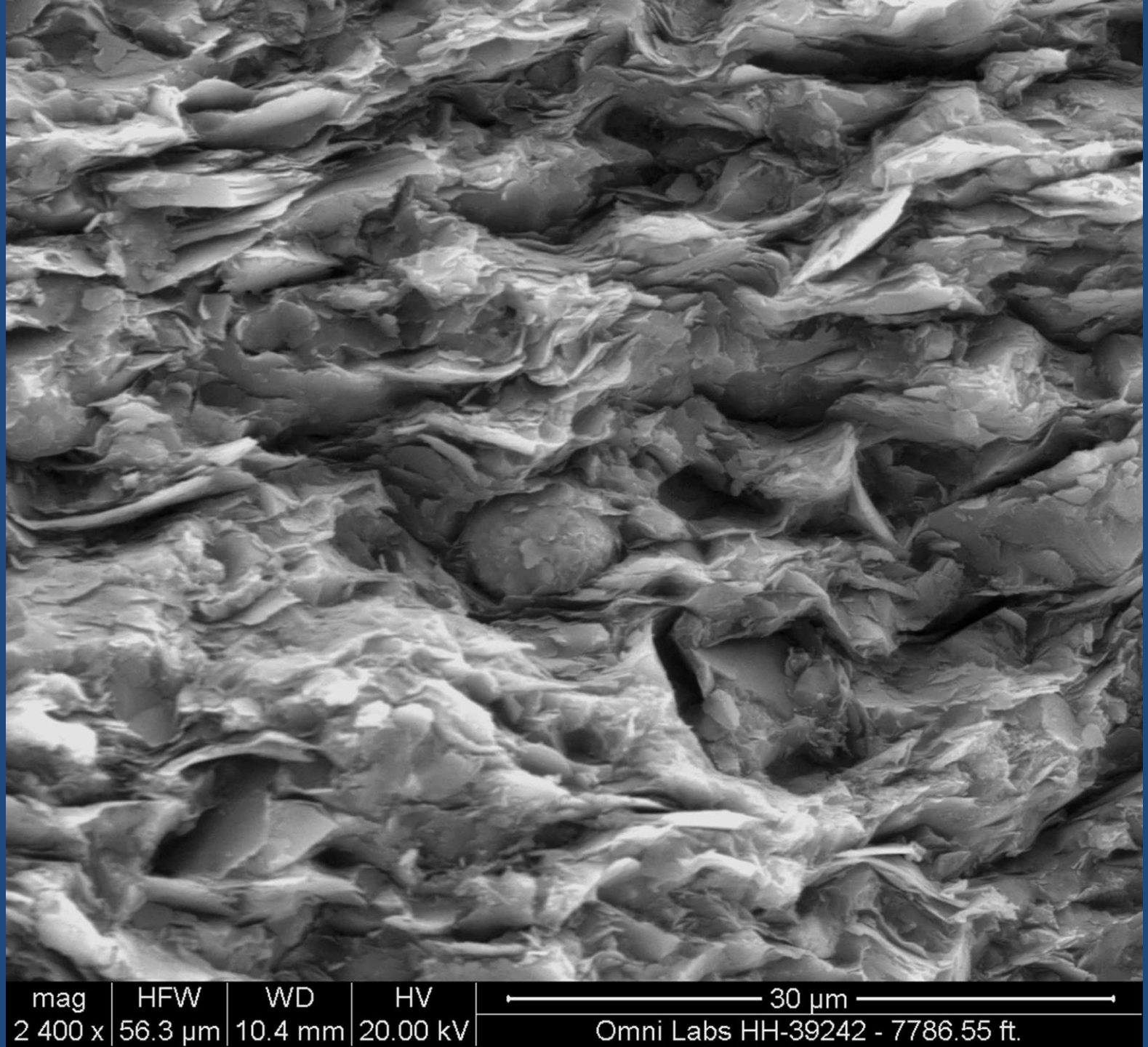

…greater abundance of clay in RST deposits fosters development of an anisotropic microfabric…
60μm 450X


10μm 2000X


mag
2 500 x
HFW
54.1 µm
WD
9.6 mm
HV
20.00 kV
30 µm

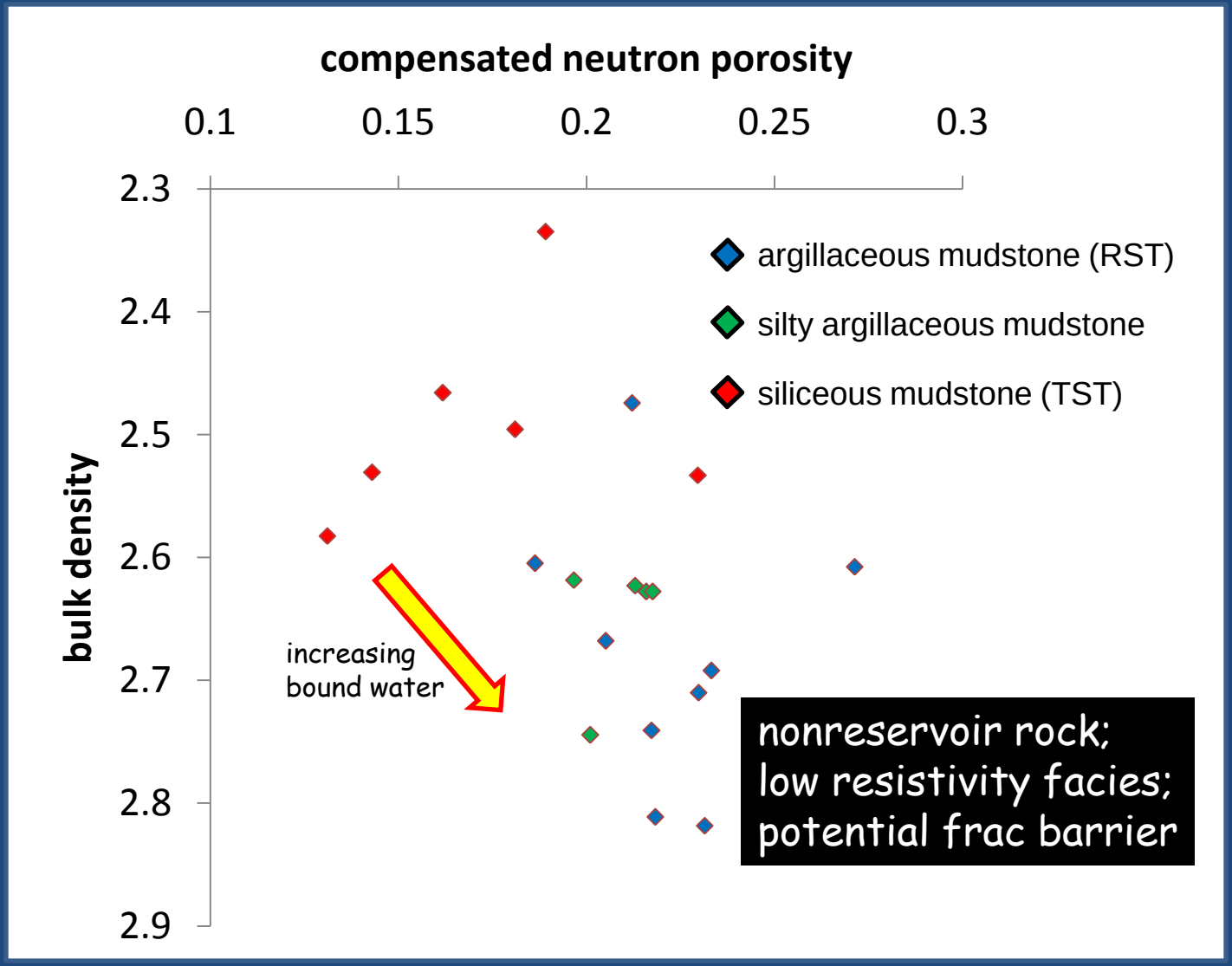

mag
1 600 x
HFW
84.5 µm
WD
11.6 mm
HV
20.00 kV
40 µm

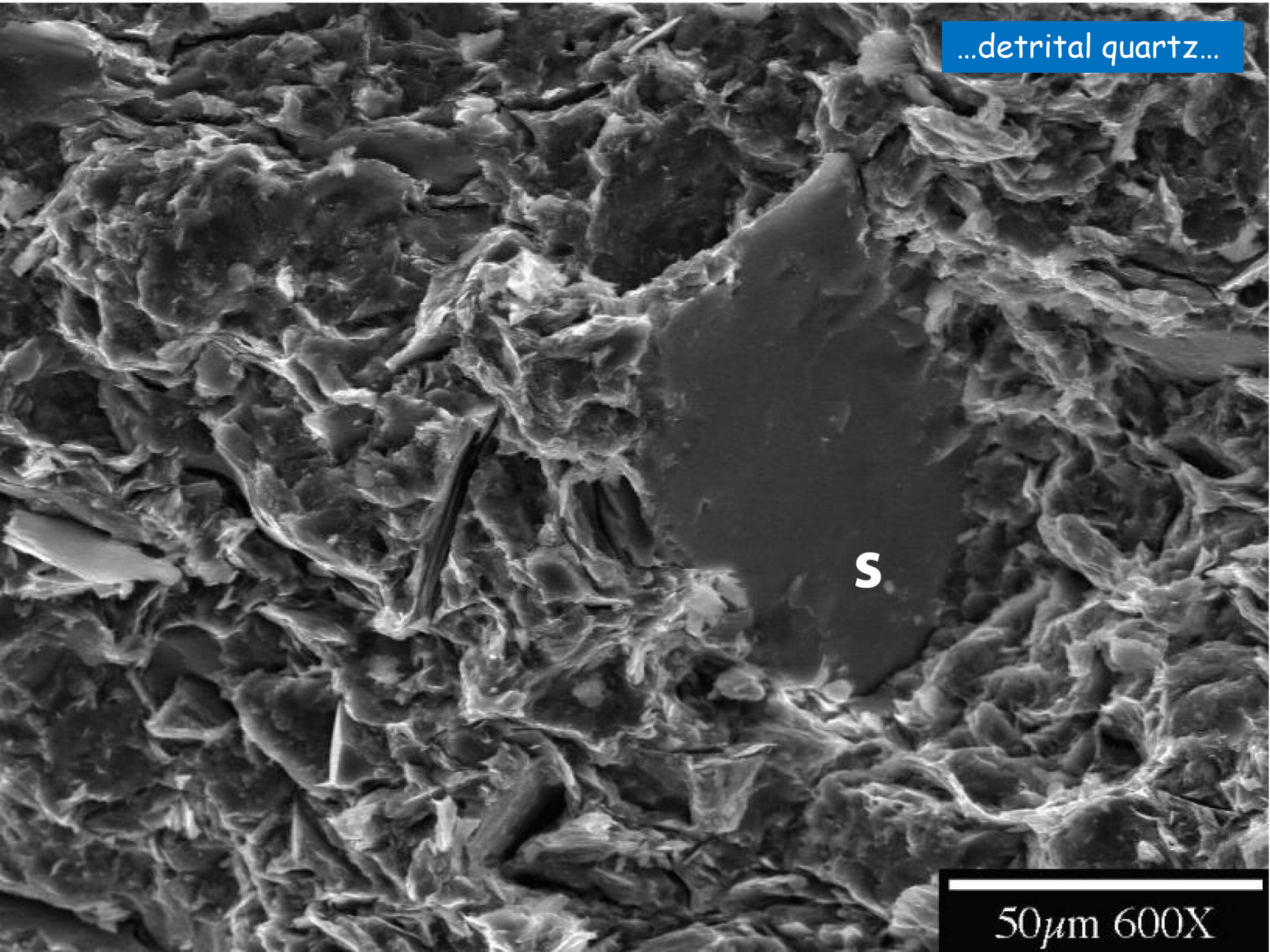

mag
2 000 x
HFW
67.6 µm
WD
11.4 mm
HV
20.00 kV
30 µm

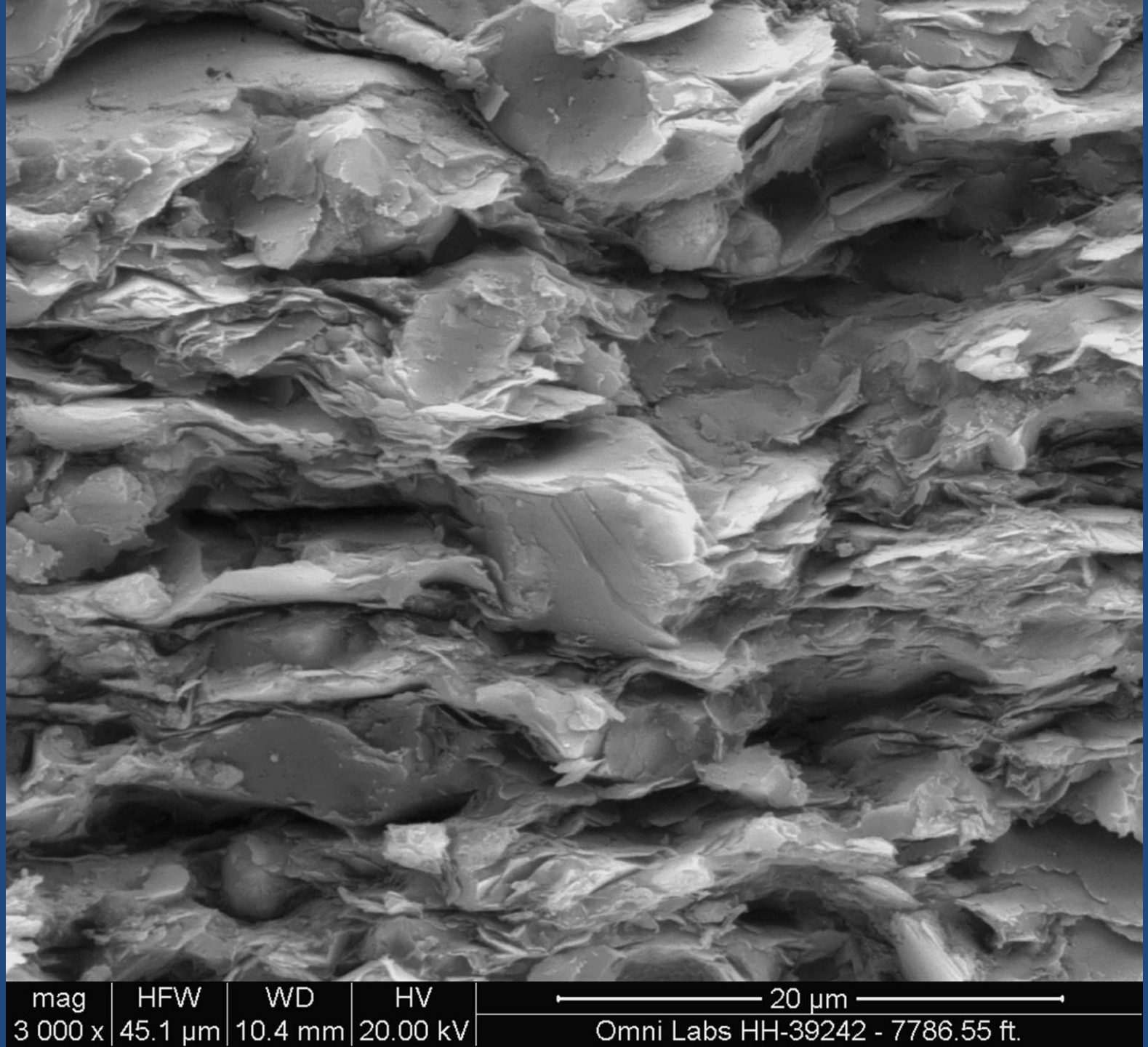

mag
2 400 x
HFW
56.3 µm
WD
10.4 mm
HV
20.00 kV
30 µm
Omni Labs HH-39242 - 7786.55 ft.

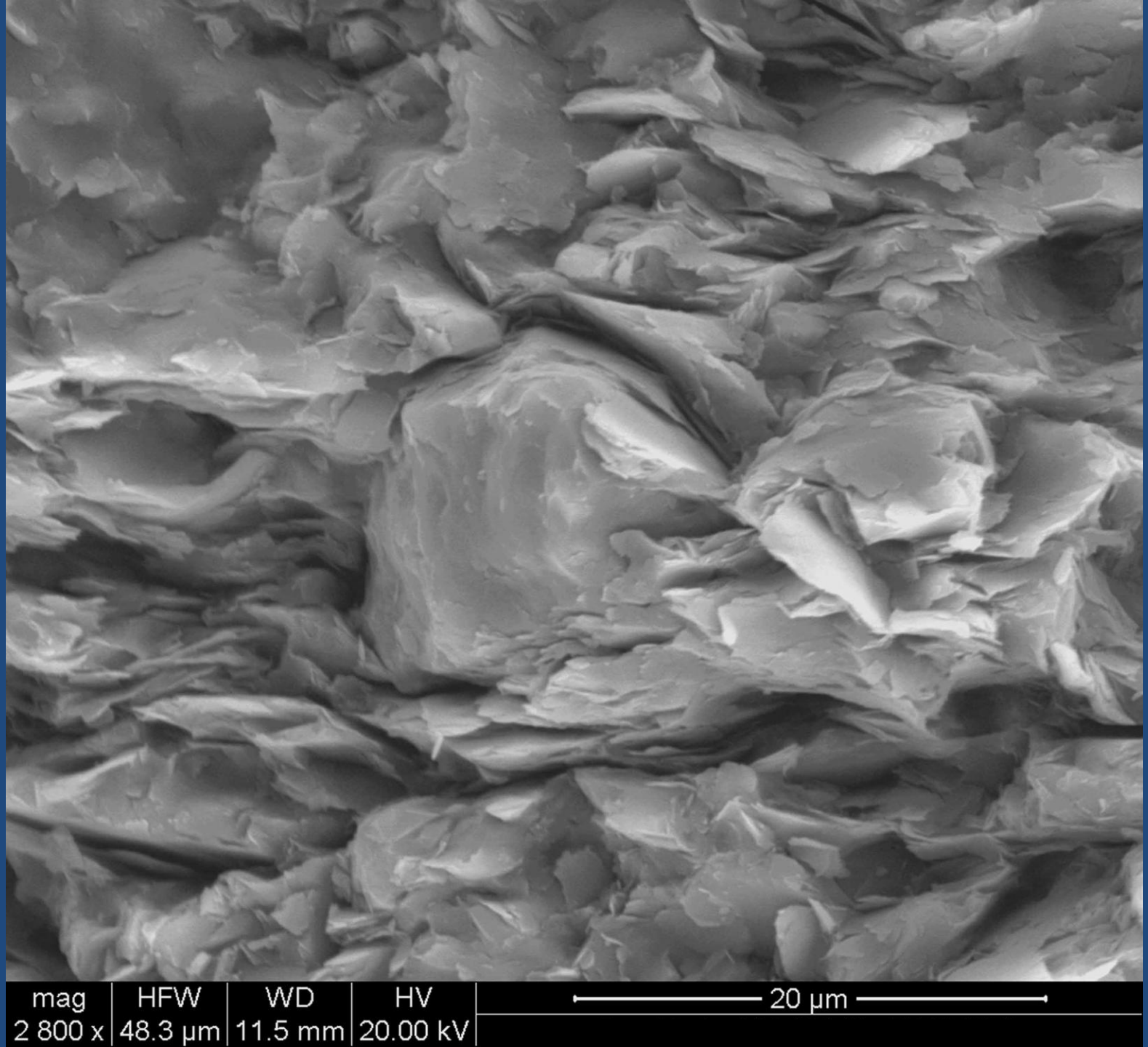
mudstone heterogeneity revealed by electrofacies analysis…

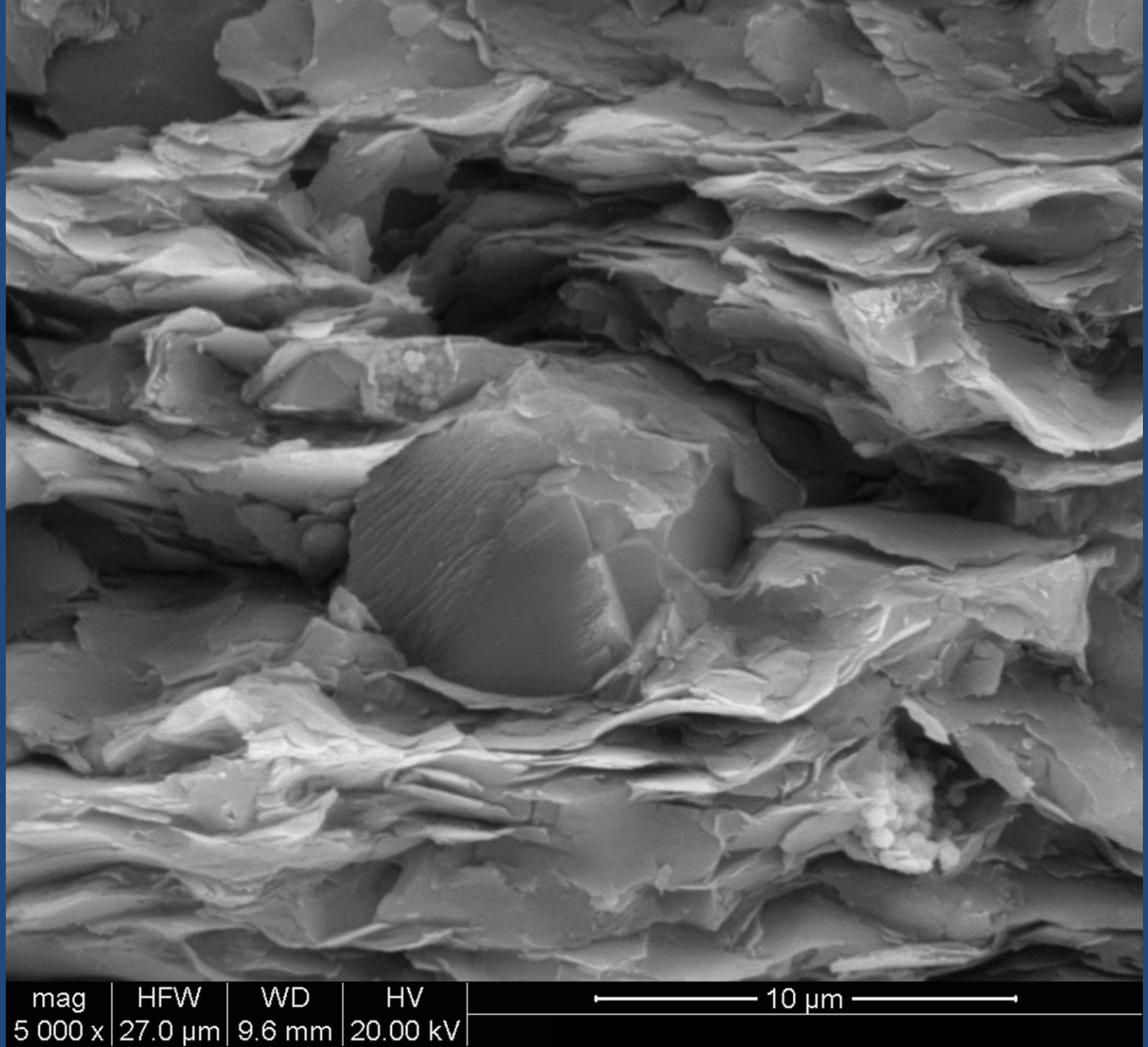
Macquaker and Jones, 2002

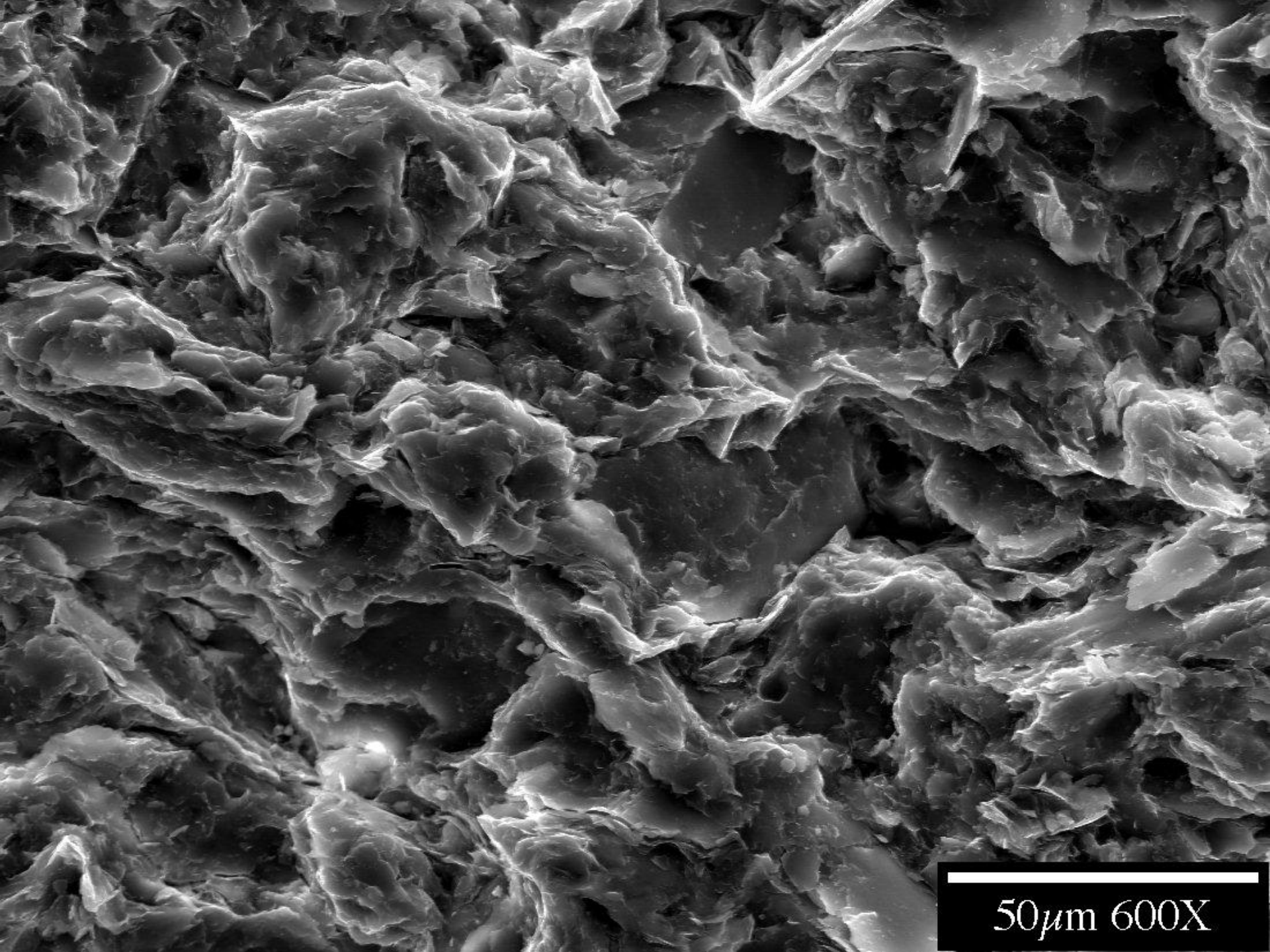



…detrital quartz…
S
50μm 600X

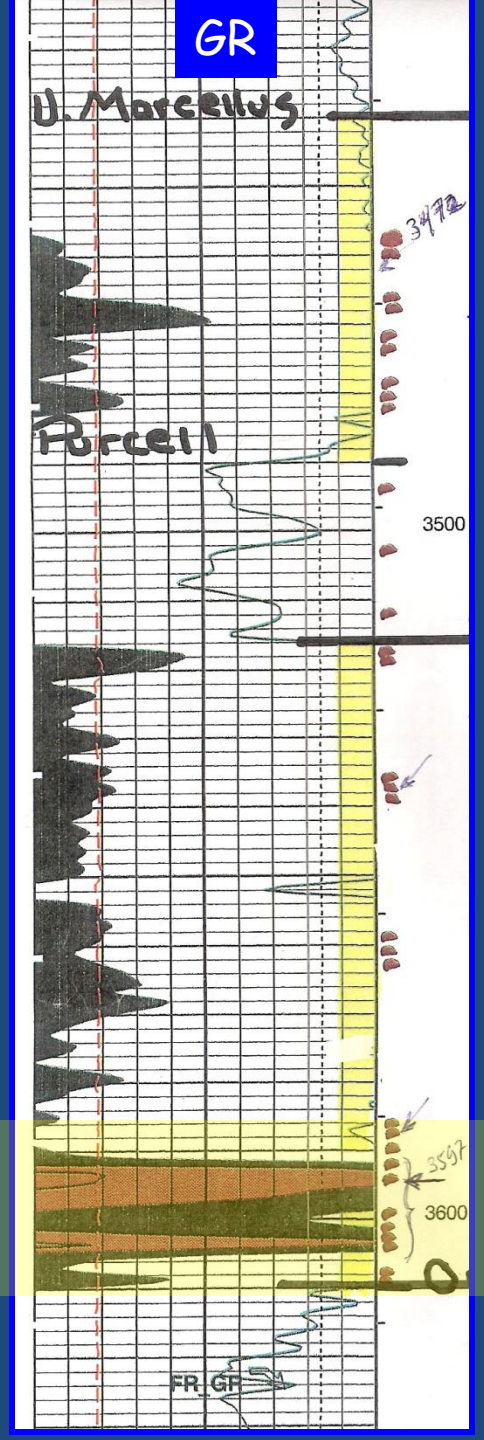

mag
3 000 x
HFW
45.1 µm
WD
10.4 mm
HV
20.00 kV
20 µm
Omni Labs HH-39242 - 7786.55 ft.


mag
2 800 x
HFW
48.3 µm
WD
11.5 mm
HV
20.00 kV
20 µm


mag
5 000 x
HFW
27.0 µm
WD
9.6 mm
HV
20.00 kV
10 µm


50μm 600X

Marcellus Shale



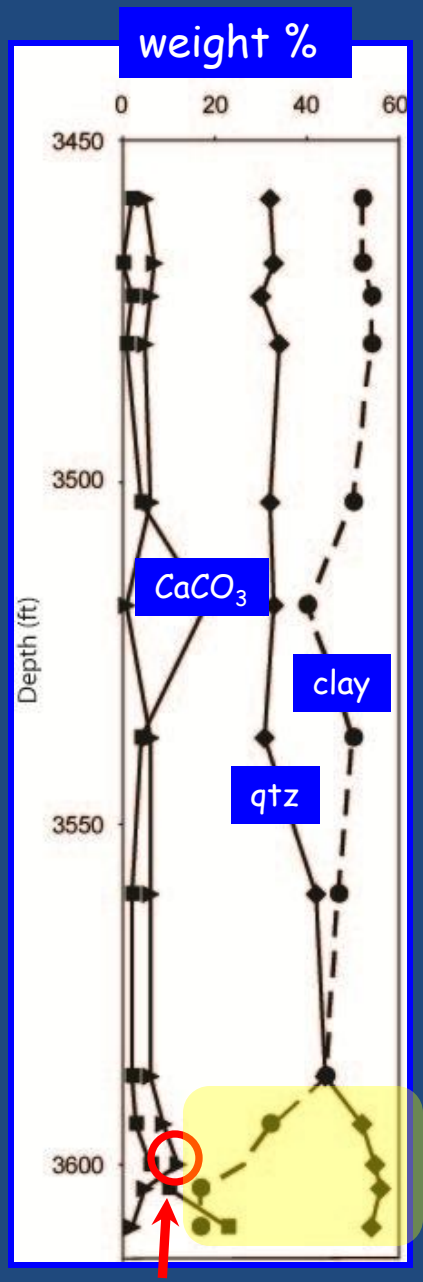
Stafford Limestone

Oatka Creek Shale

Purcell Limestone

Union Springs Shale

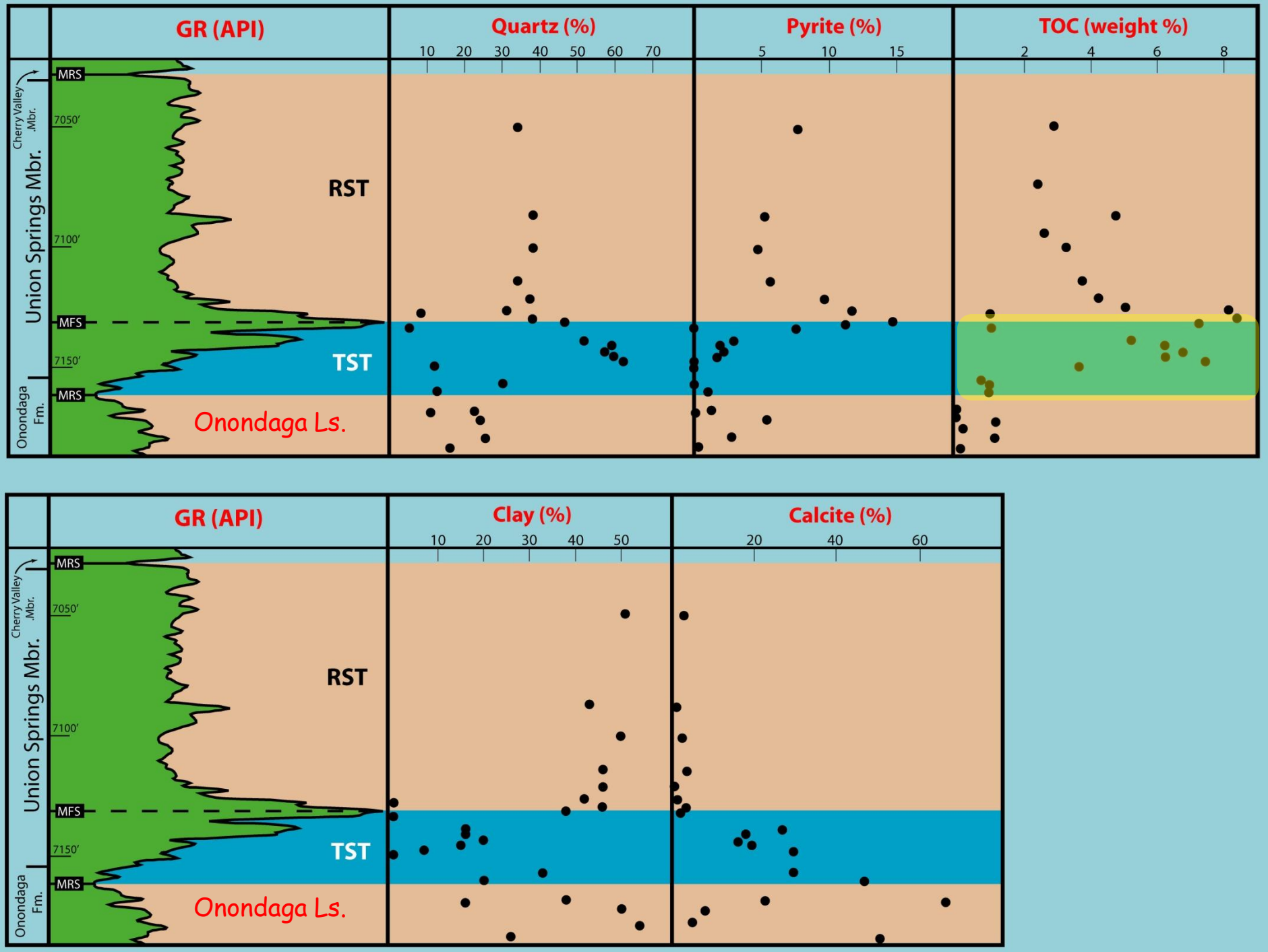
Onondaga Limestone



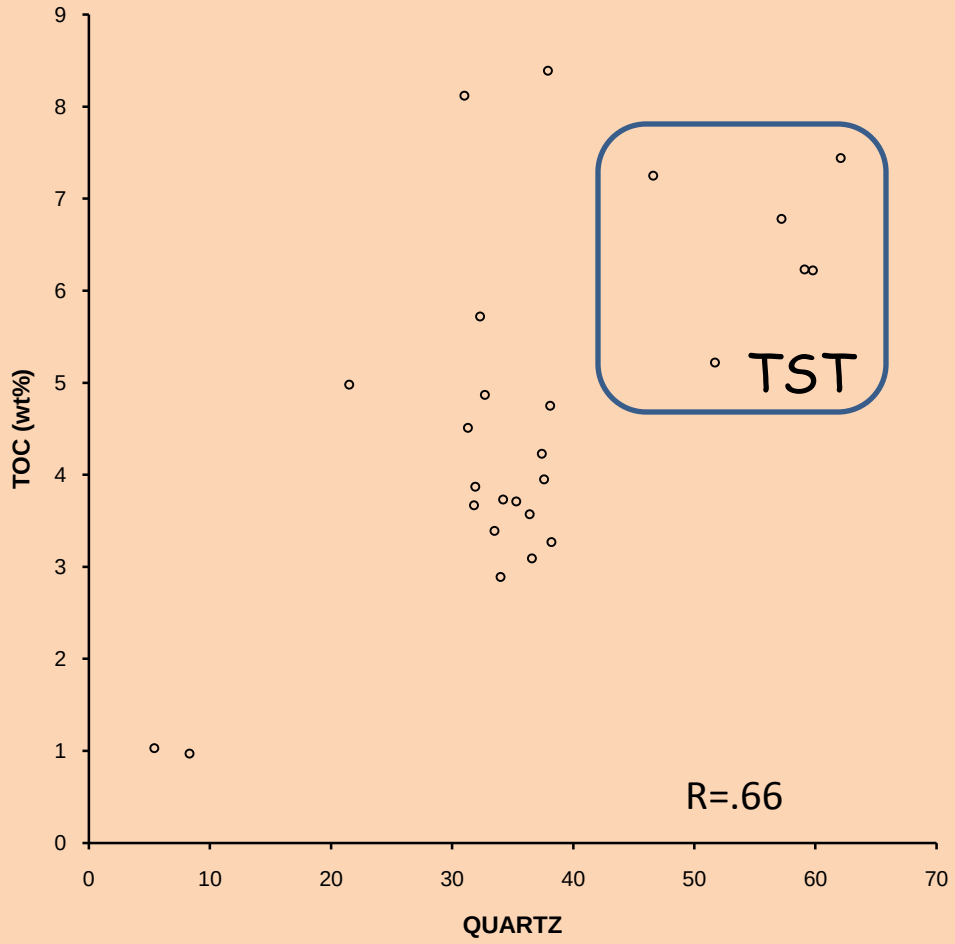
11% pyrite

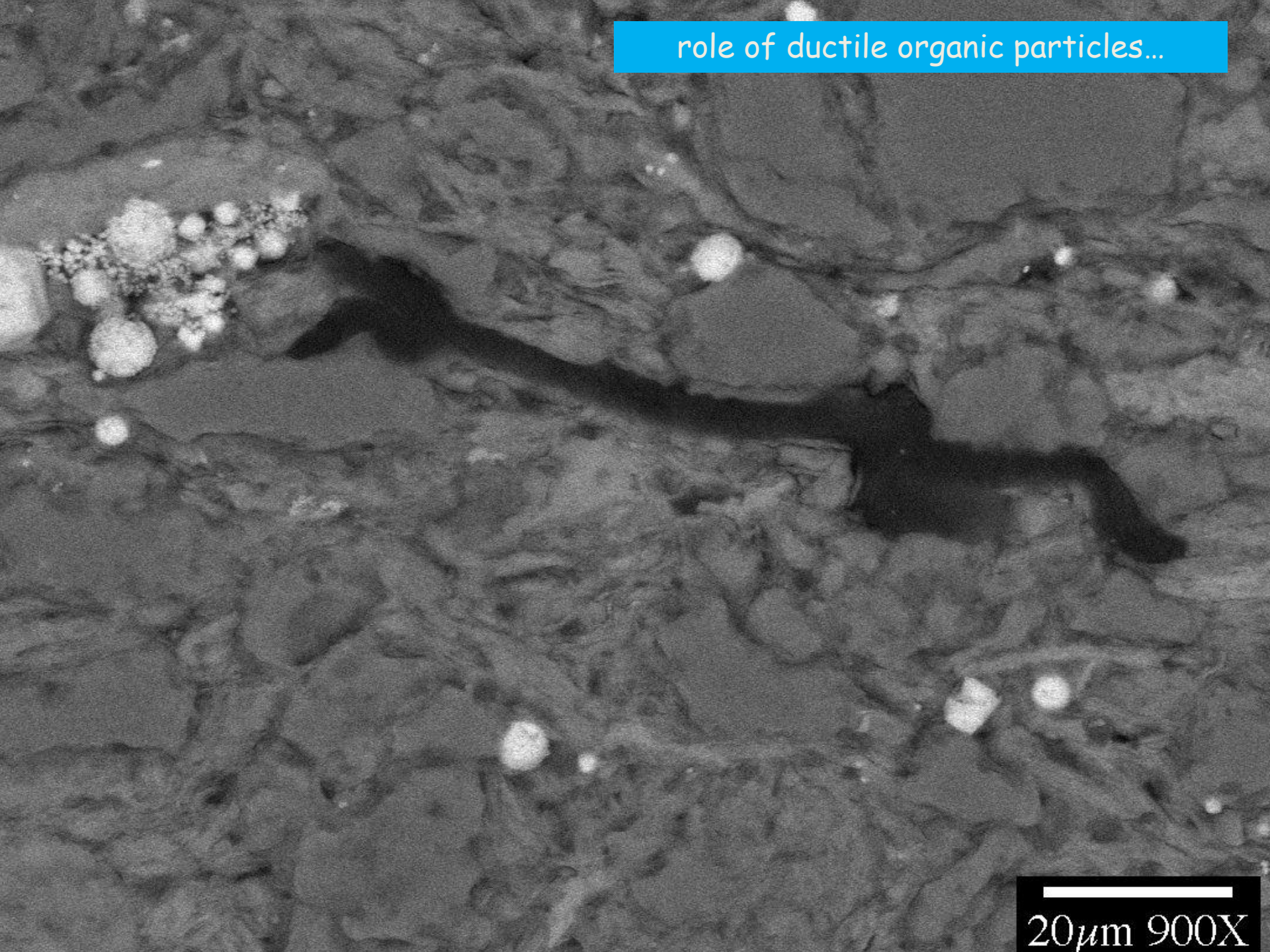
…TST… increasing base level and related landward shift of depositional environments leads to 1) reduced clastic flux (clay and detrital quartz) and 2) increased abundance of bioclastic particles…

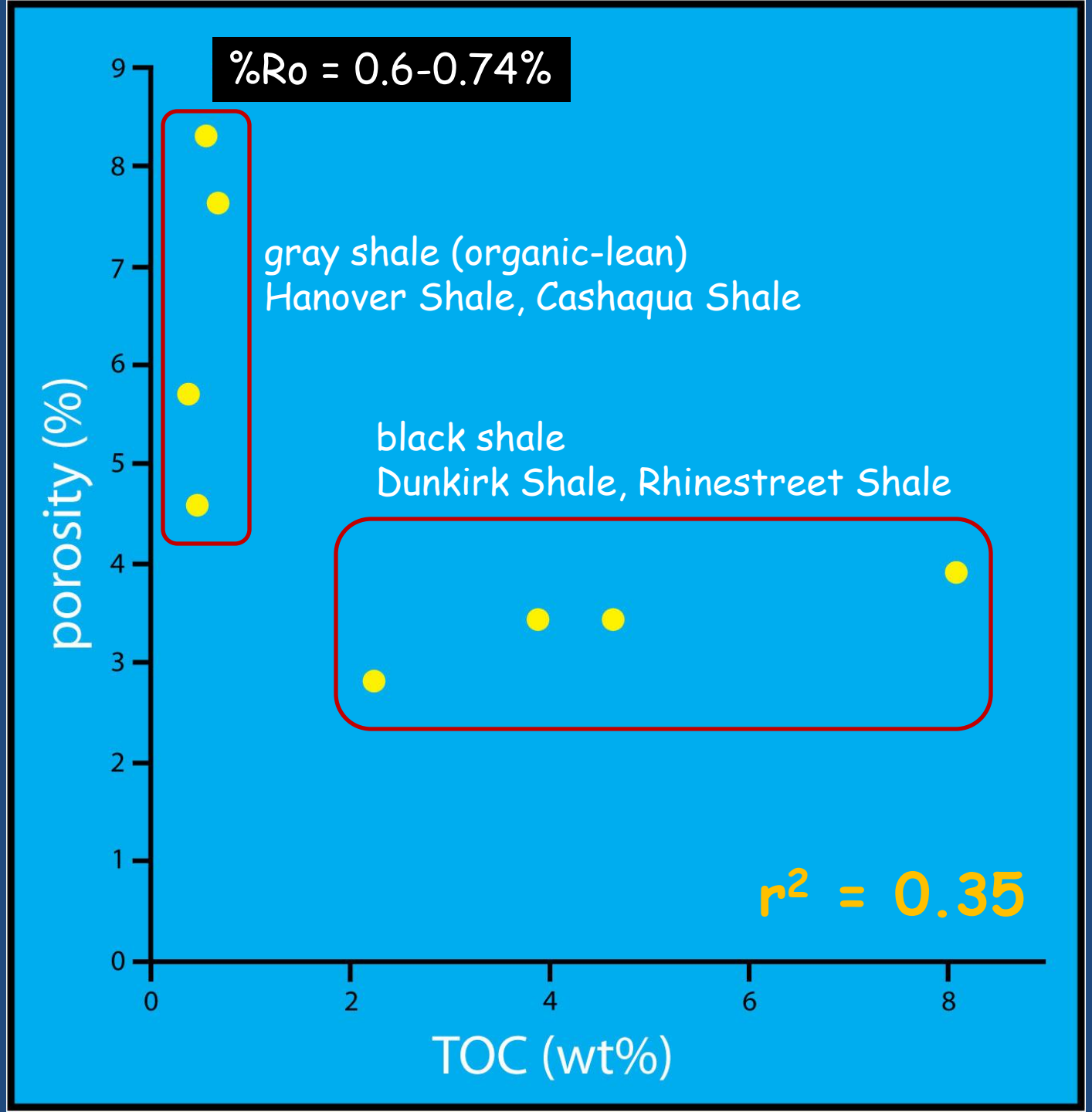
…elevated (diagenetic) quartz and reduced clay
>>>> enhanced brittleness…

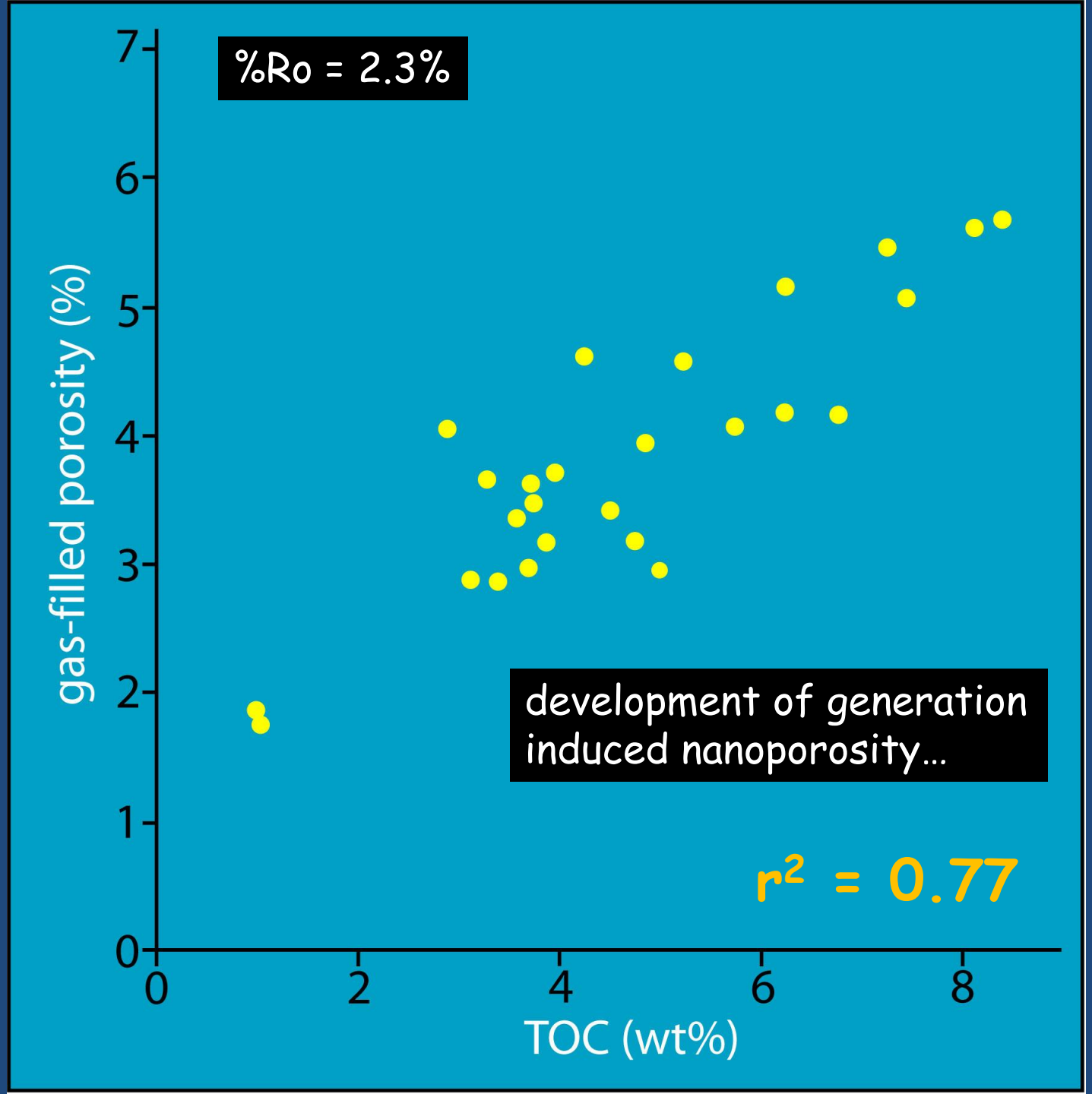

GR (API)
Quartz (%)
10 20 30 40 50 60 70
Pyrite (%)
5 10 15
TOC (weight %)
2 4 6 8
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.
GR (API)
Clay (%)
10 20 30 40 50
Calcite (%)
20 40 60
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.

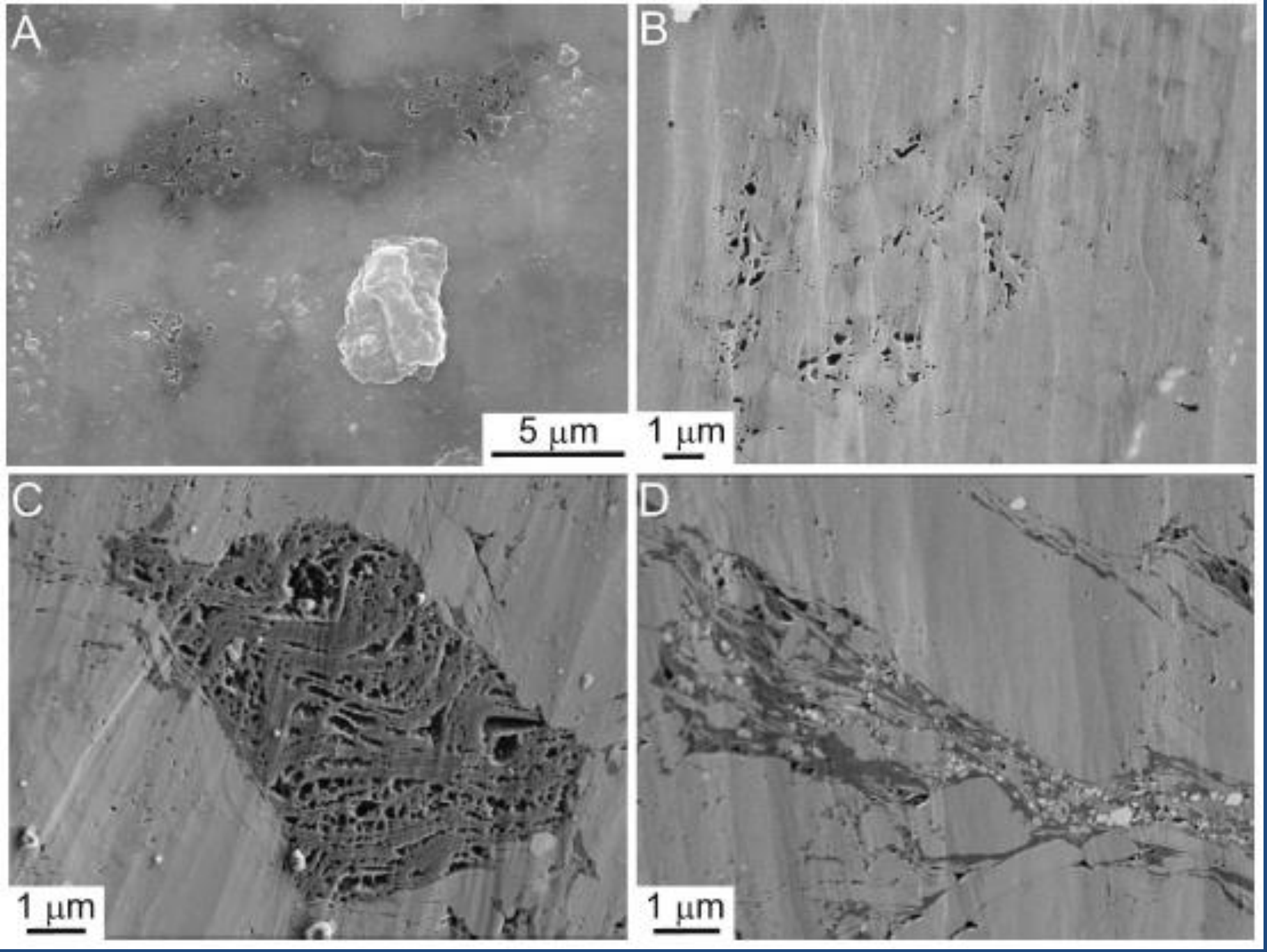
TOC vs. quartz



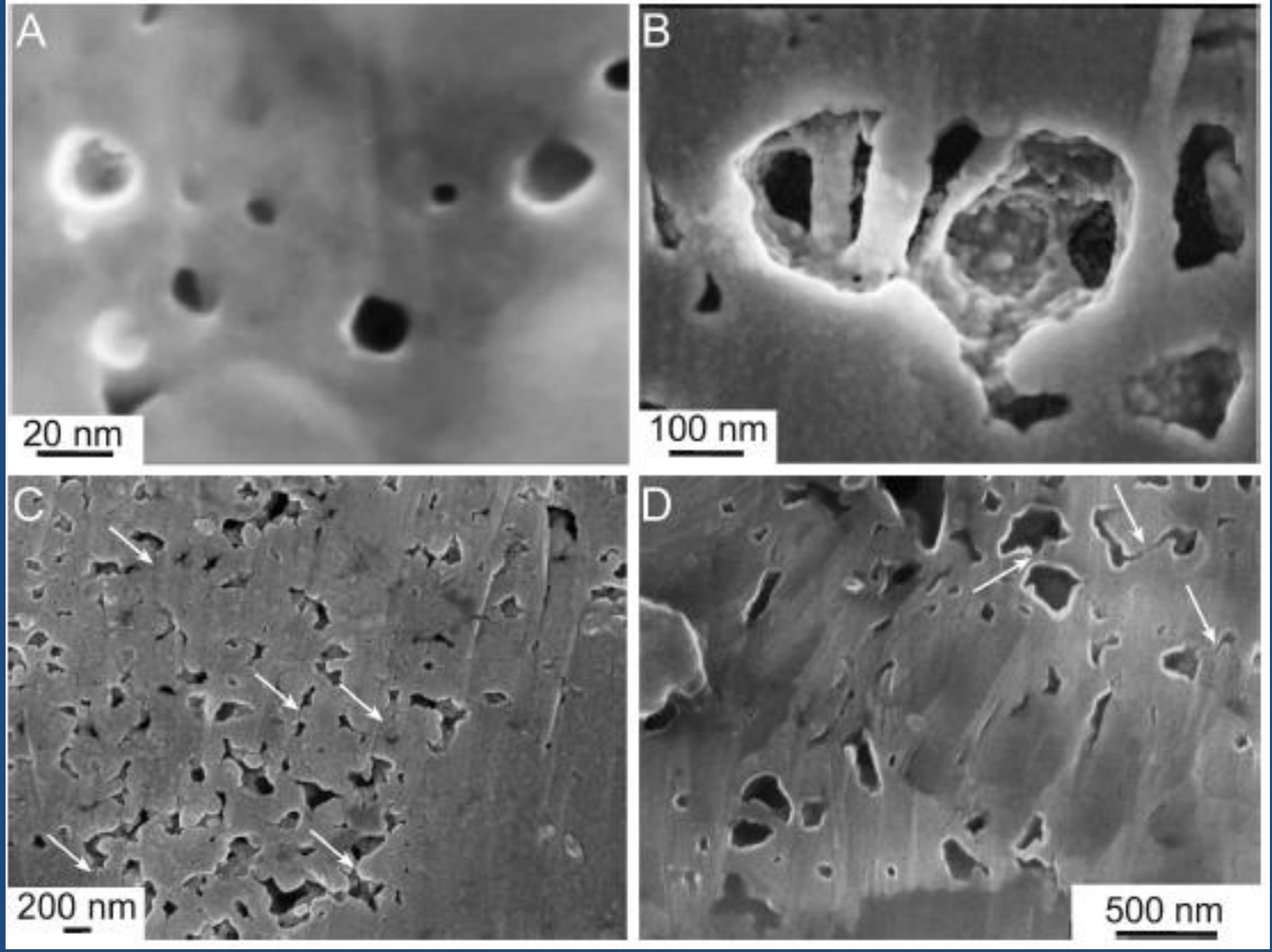

role of ductile organic particles…
20μm 900X


%Ro = 0.6-0.74%
gray shale (organic-lean)
Hanover Shale, Cashaqua Shale
black shale
Dunkirk Shale, Rhinestreet Shale
r² = 0.35
porosity (%)
TOC (wt%)
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8

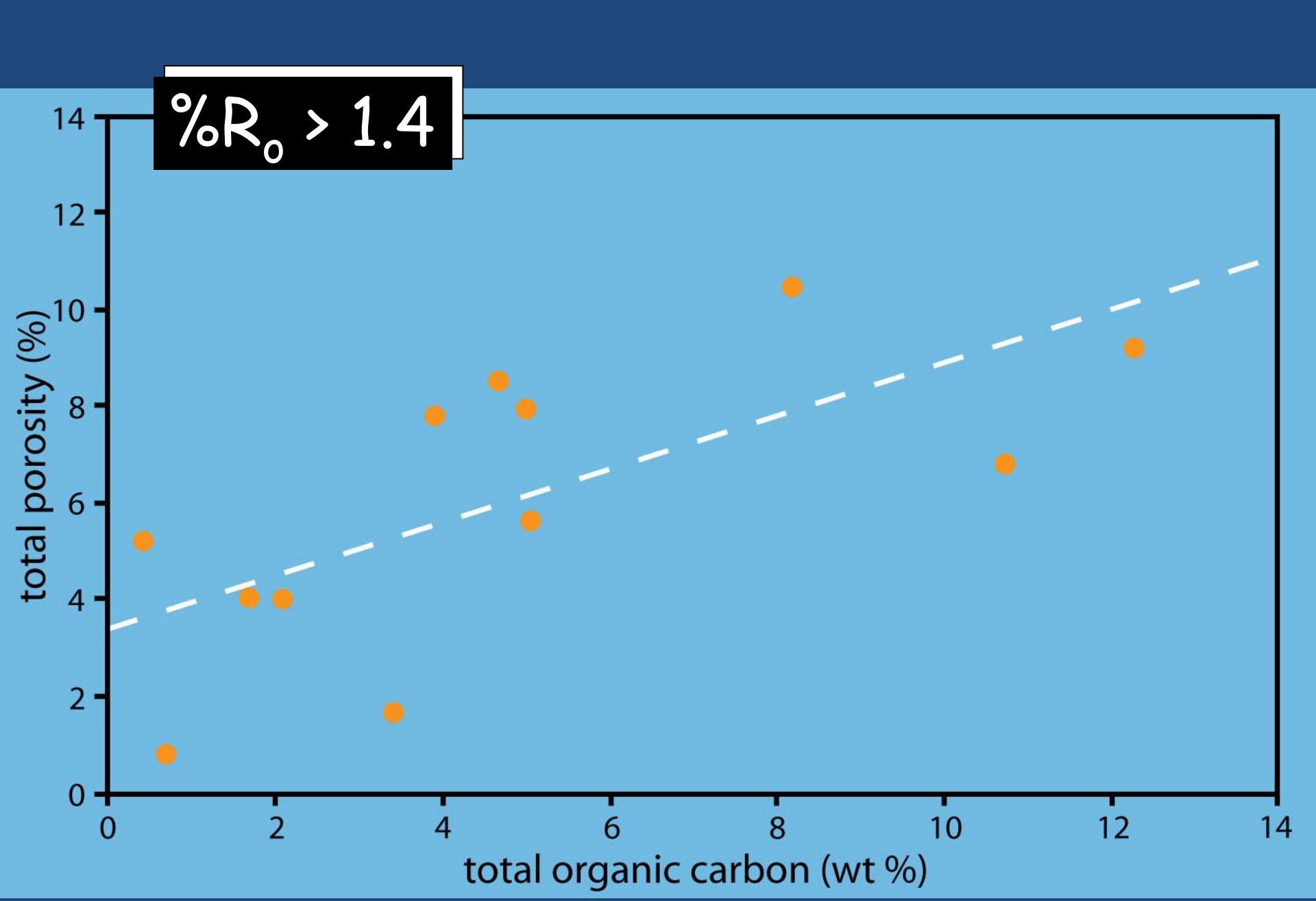

%Ro = 2.3%
gas-filled porosity (%)
0
1
2
3
4
5
6
7
0
2
4
6
8
TOC (wt%)
development of generation induced nanoporosity...
r2 = 0.77

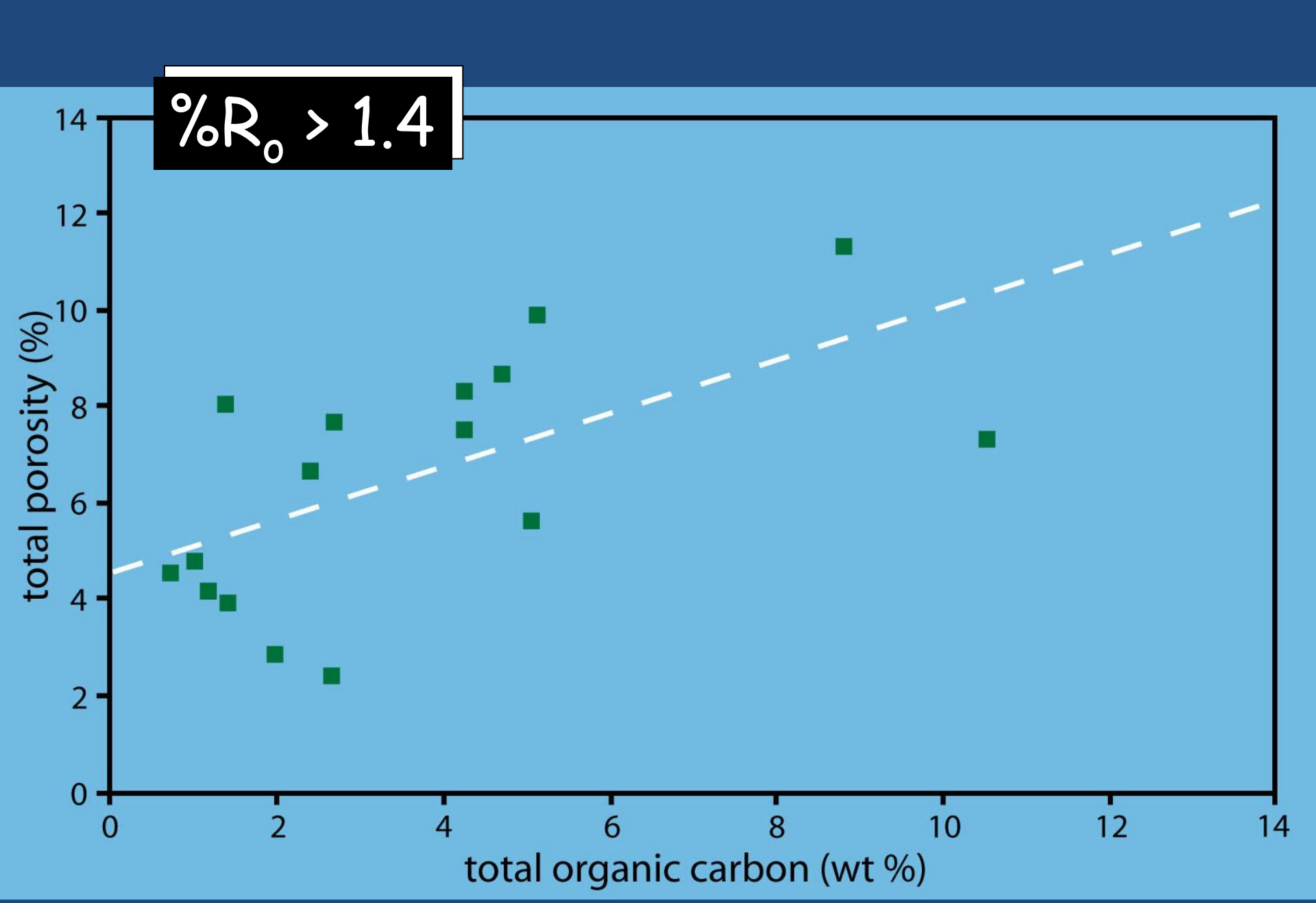


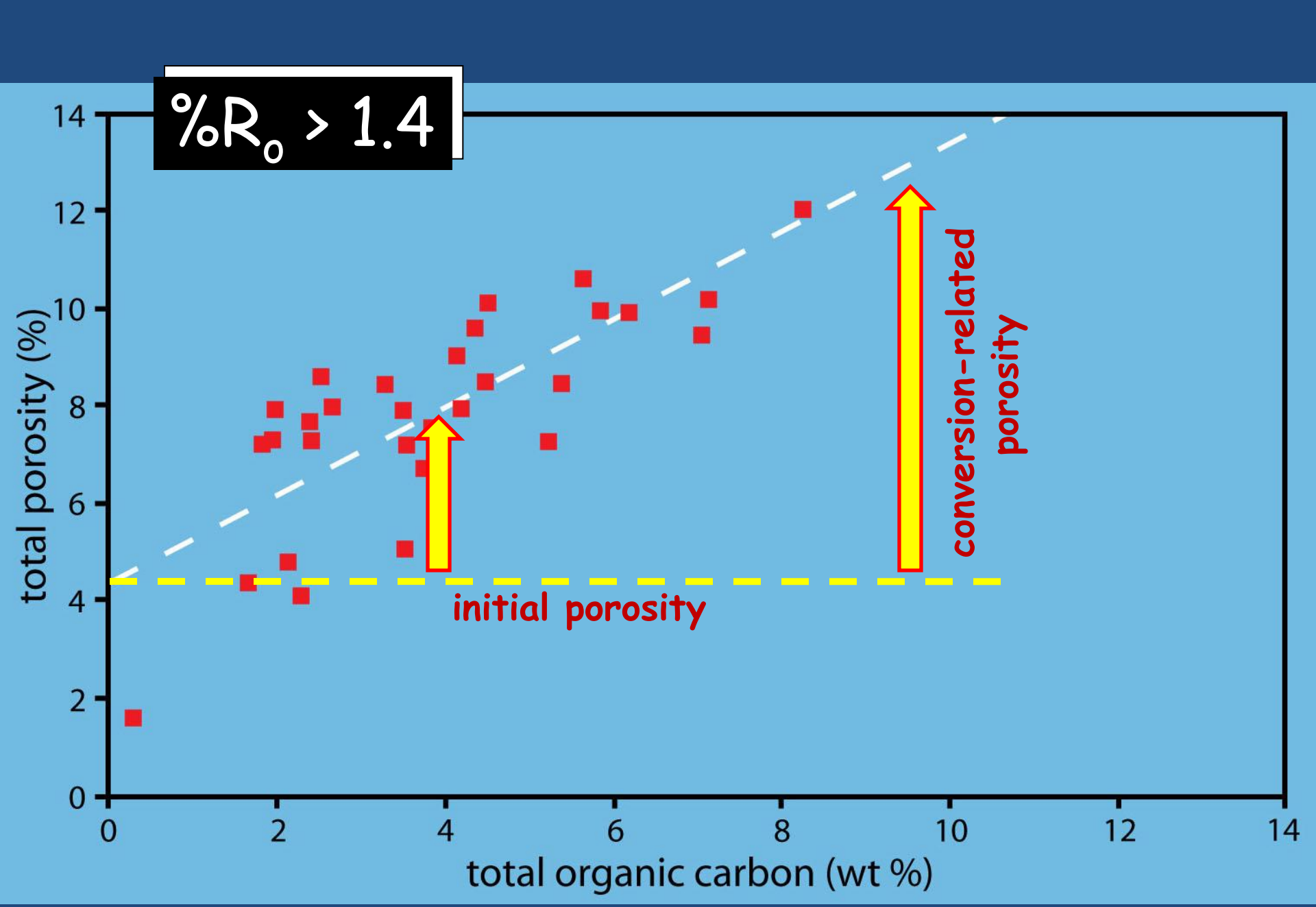
Loucks et al., 2009



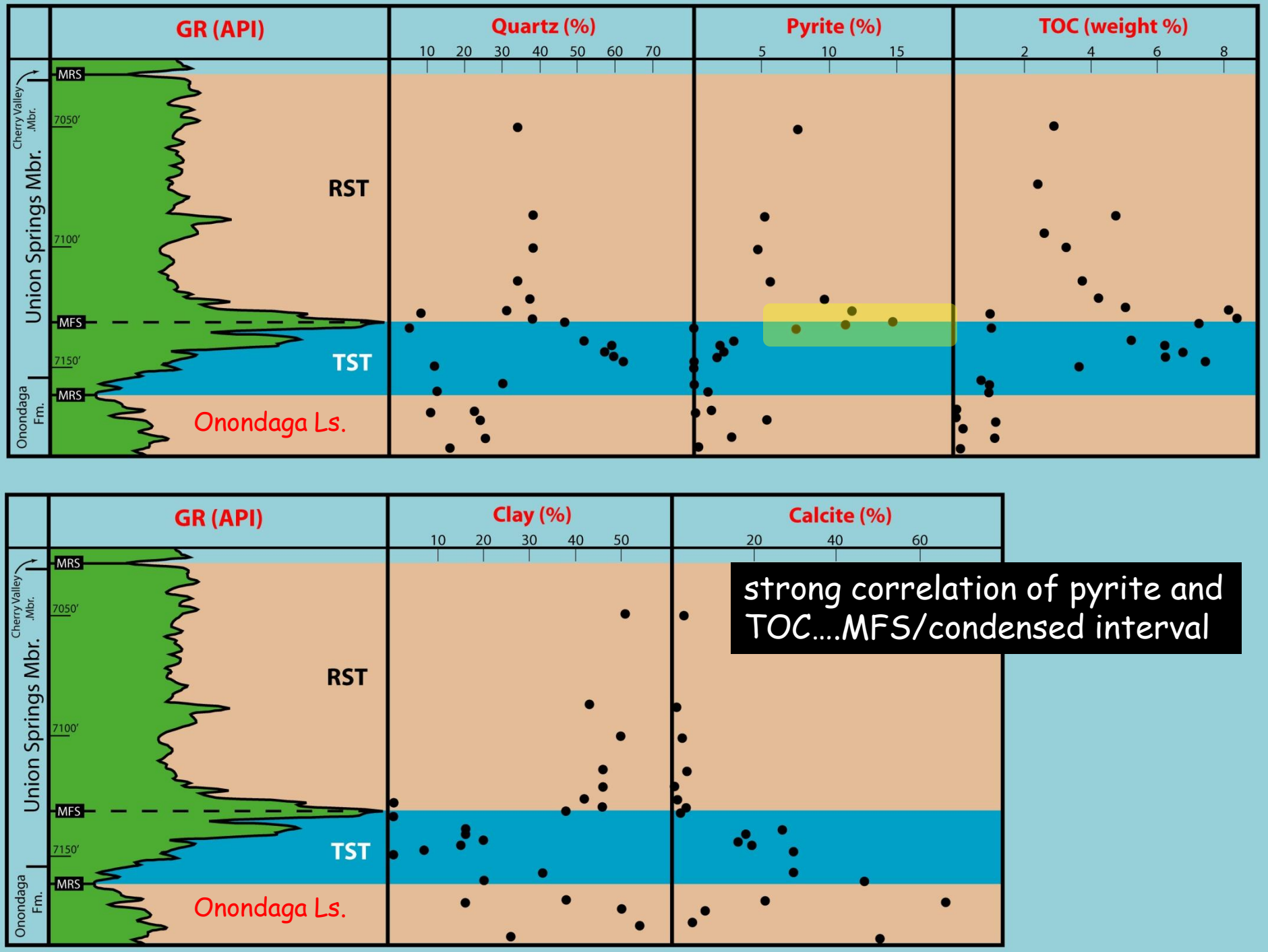
Loucks et al., 2009


%R0 > 1.4
total porosity (%)
total organic carbon (wt %)
0
2
4
6
8
10
12
14

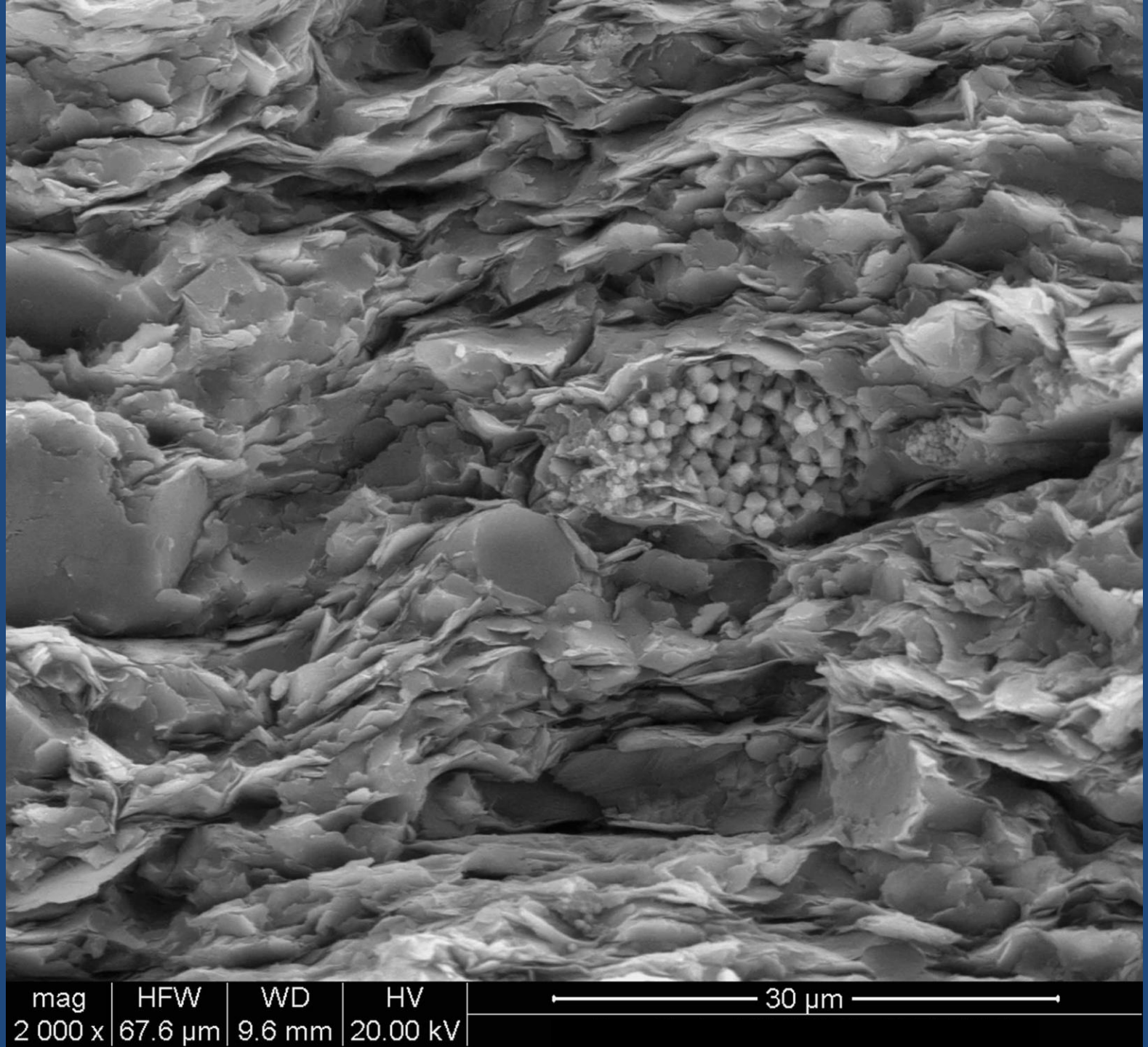

%R0 > 1.4
total porosity (%)
total organic carbon (wt %)
0
2
4
6
8
10
12
14

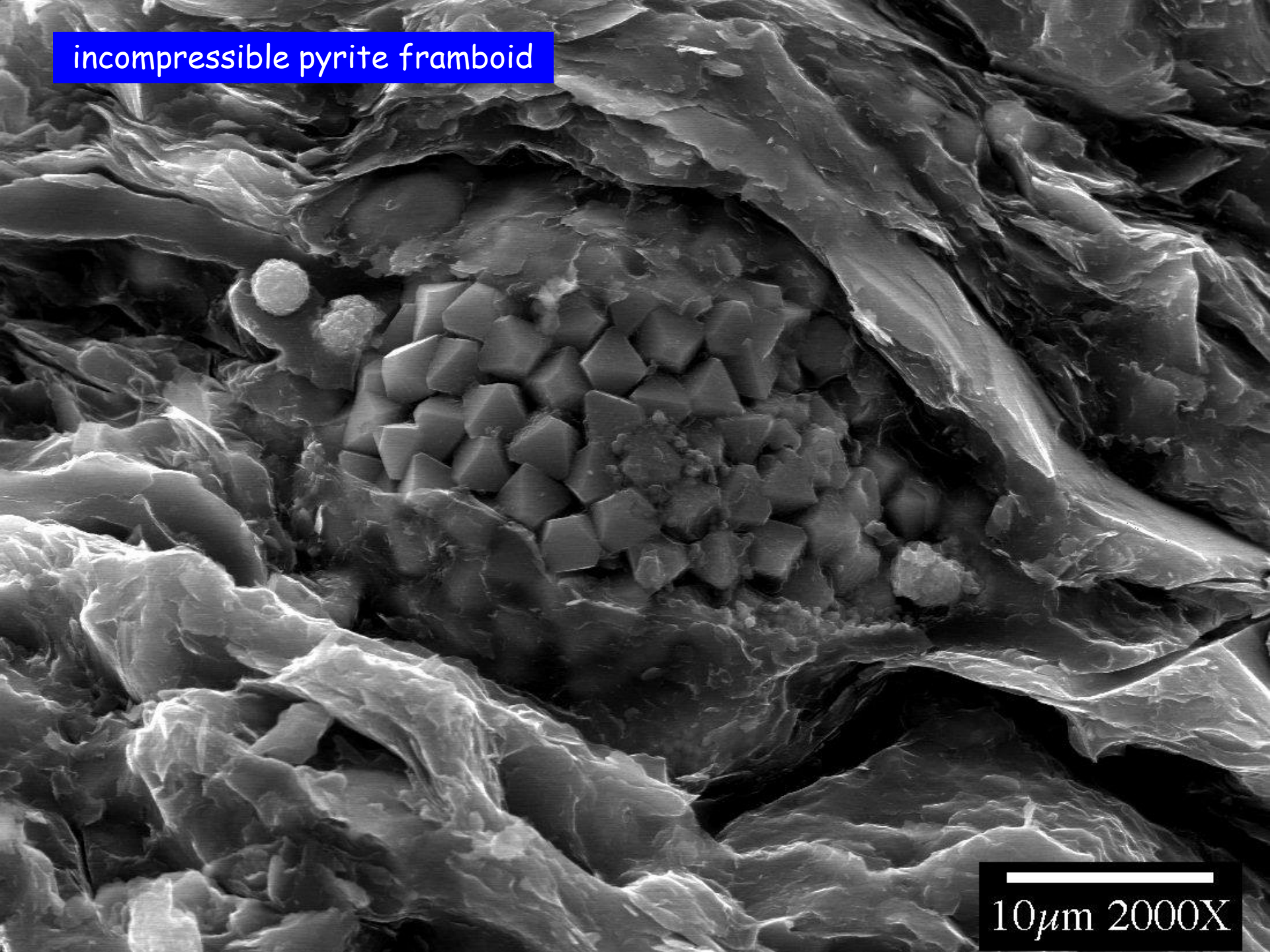

%R0 > 1.4
total porosity (%)
total organic carbon (wt %)
0
2
4
6
8
10
12
14
initial porosity
conversion-related porosity

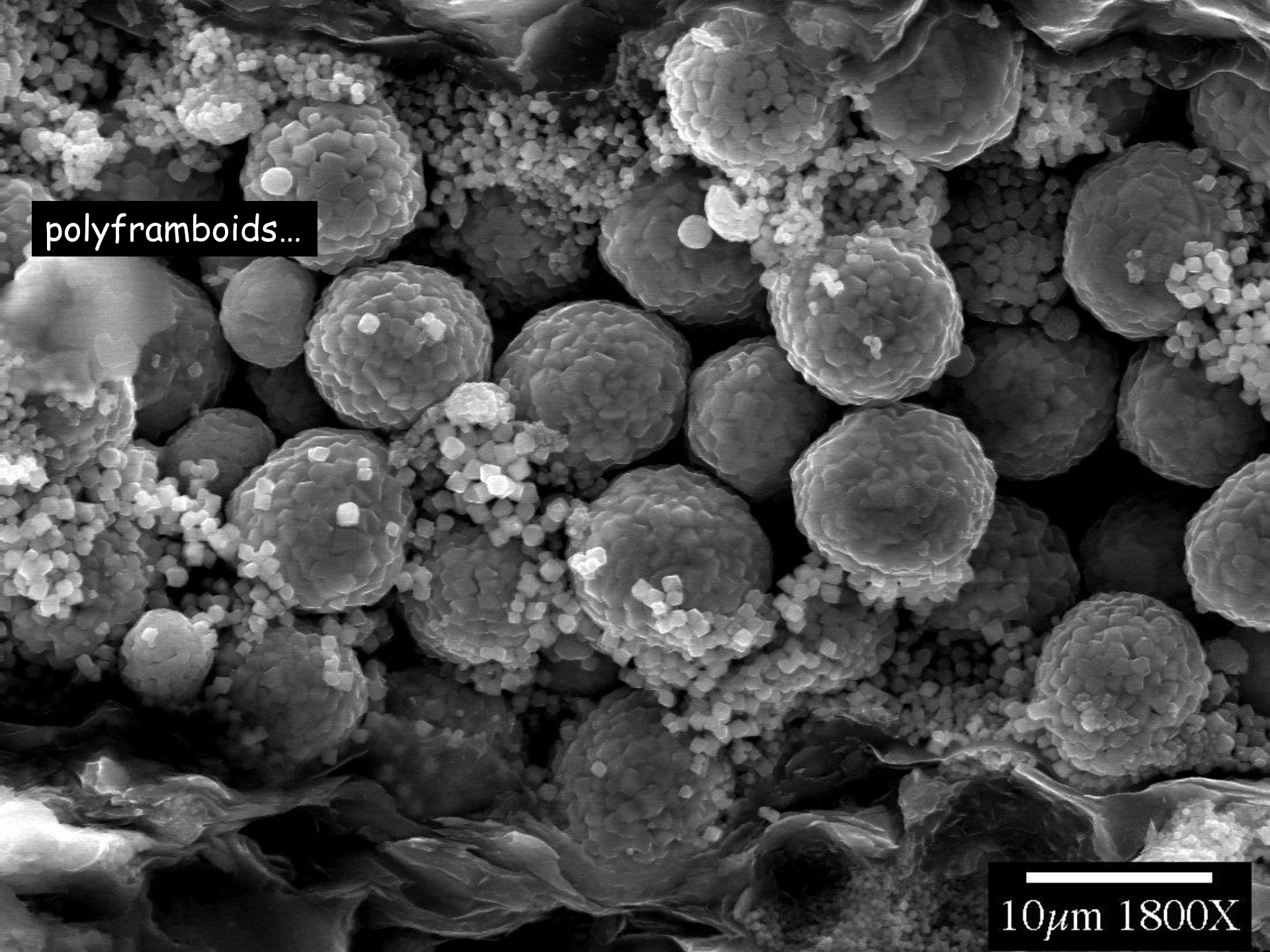
…TST… depending on thermal stress (%Ro), porosity and permeability may increase from the base to top of the TST in response to increasing TOC…

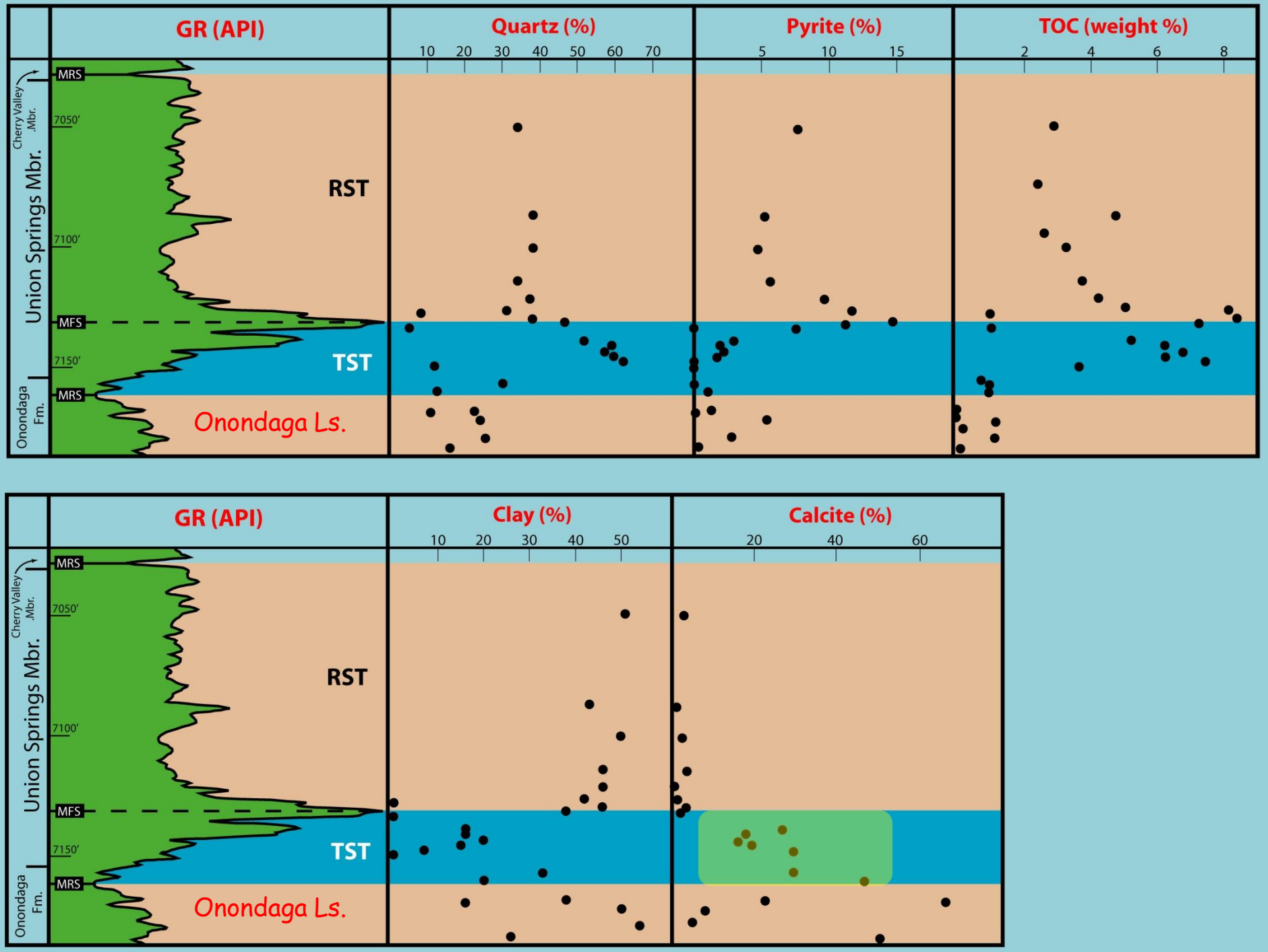

GR (API)
Quartz (%)
10 20 30 40 50 60 70
Pyrite (%)
5 10 15
TOC (weight %)
2 4 6 8
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.
GR (API)
Clay (%)
10 20 30 40 50
Calcite (%)
20 40 60
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.
strong correlation of pyrite and TOC….MFS/condensed interval


pyrite lag – basal black shale
CM


mag
2 000 x
HFW
67.6 µm
WD
9.6 mm
HV
20.00 kV
30 µm


incompressible pyrite framboid
10μm 2000X


polyframboids…
10μm 1800X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TOC (weight %)
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RST
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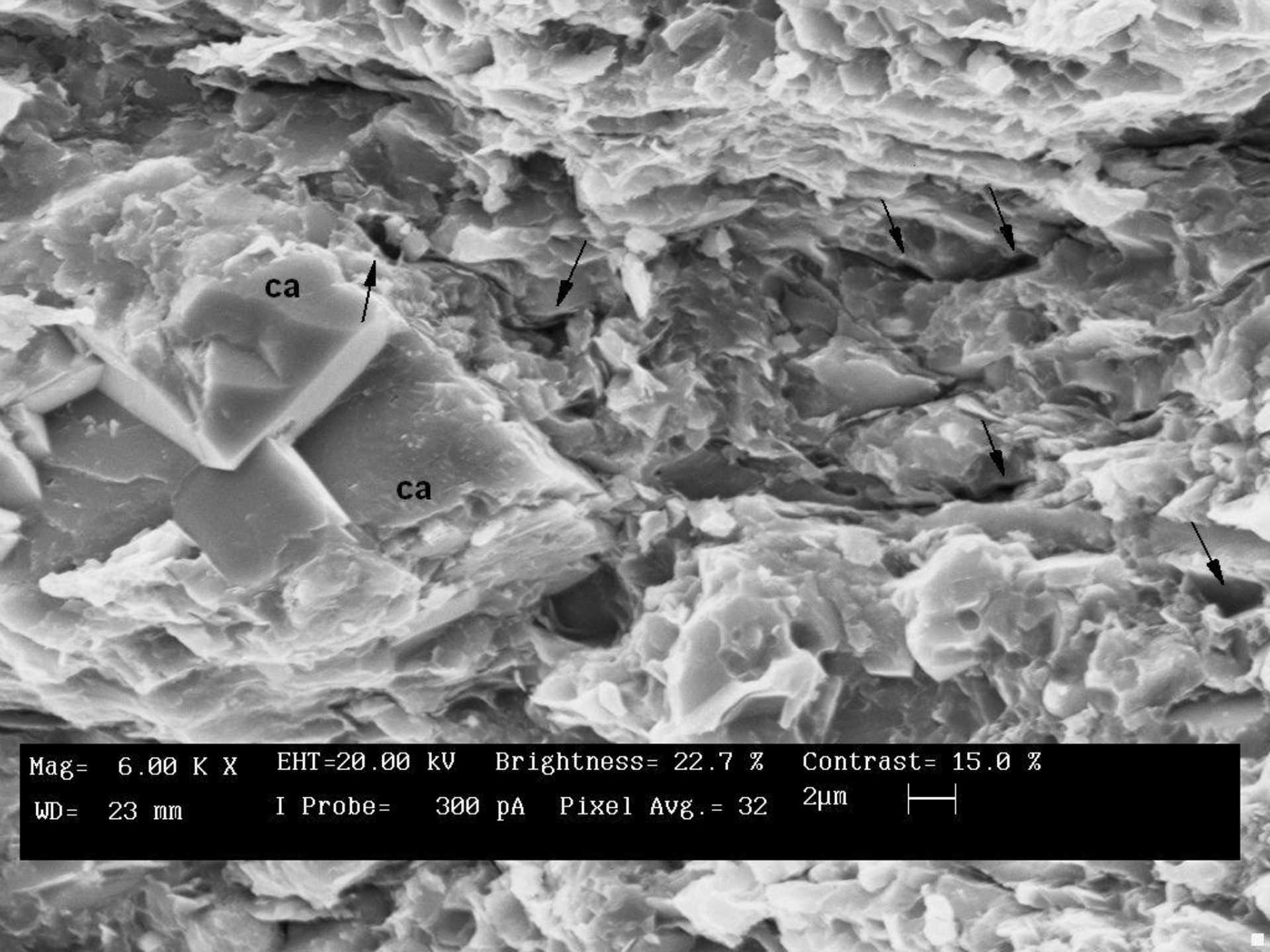
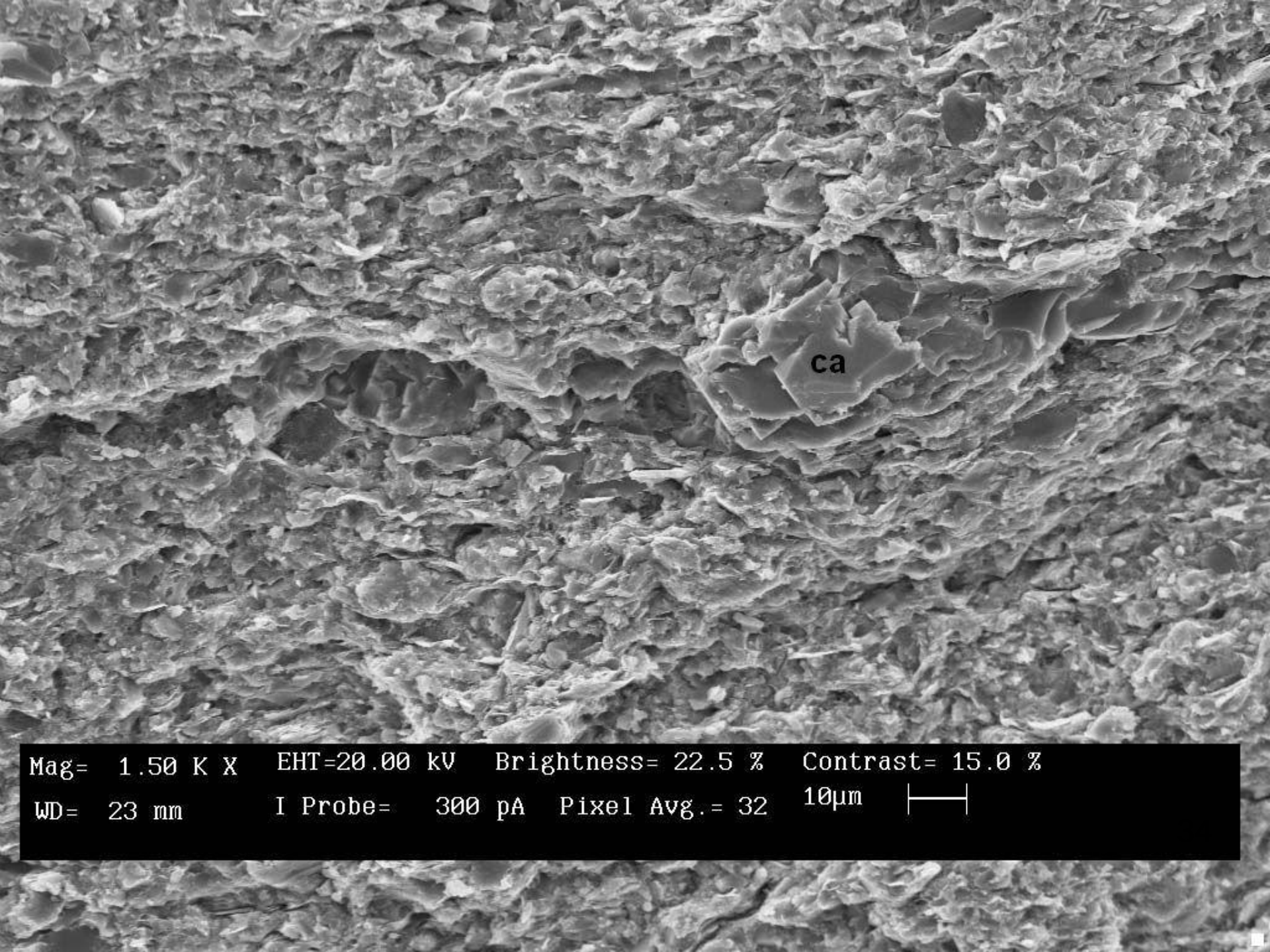
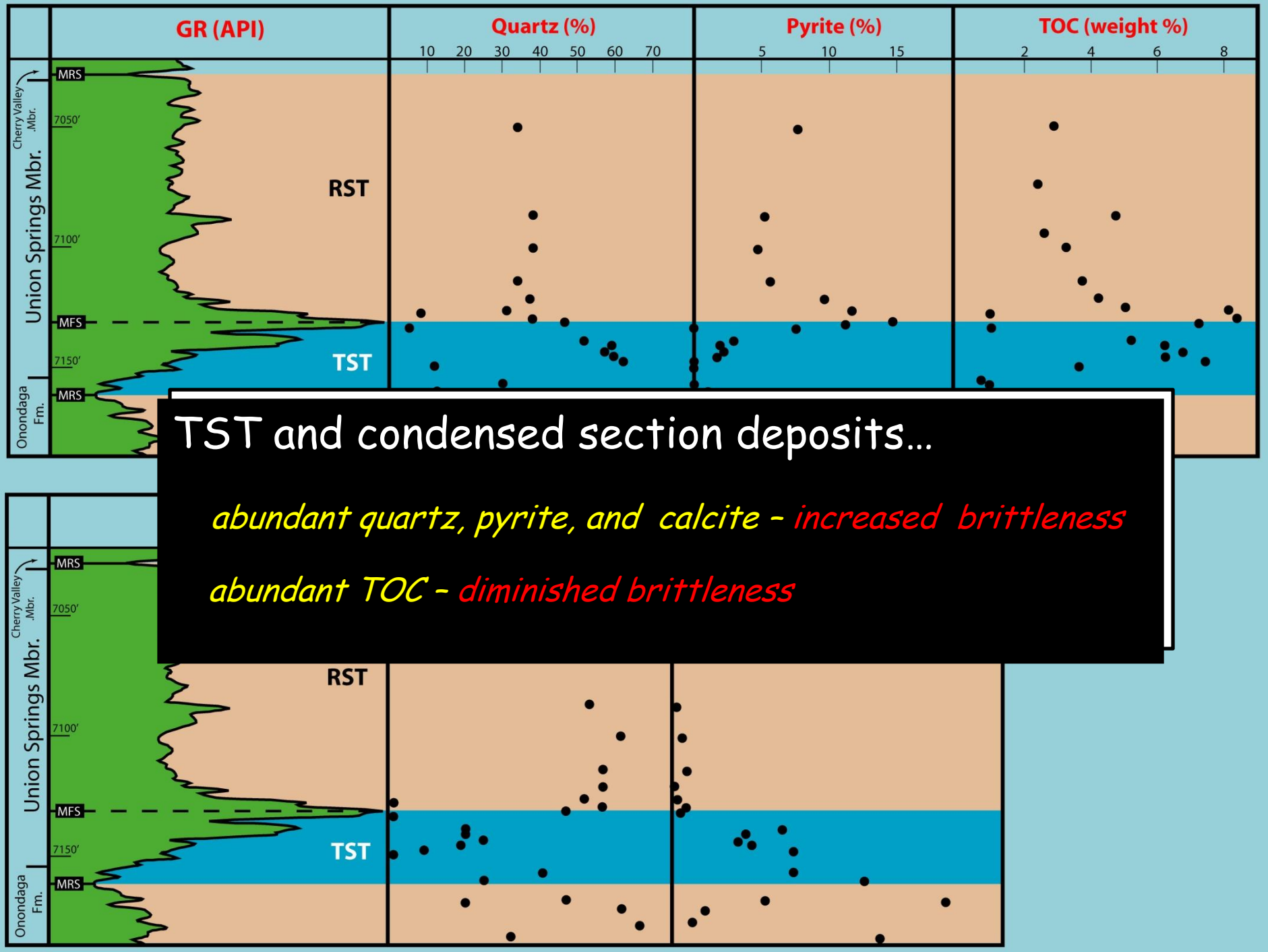
20 40 60
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
Onondaga Ls.


ca
ca
Mag= 6.00 K X
EHT=20.00 kV
Brightness= 22.7 %
Contrast= 15.0 %
WD= 23 mm
I Probe= 300 pA
Pixel Avg.= 32
2µm


ca
Mag= 1.50 K X
EHT=20.00 kV
Brightness= 22.5 %
Contrast= 15.0 %
WD= 23 mm
I Probe= 300 pA
Pixel Avg.= 32
10µm


GR (API)
Quartz (%)
10 20 30 40 50 60 70
Pyrite (%)
5 10 15
TOC (weight %)
2 4 6 8
Cherry Valley Mbr.
Union Springs Mbr.
Onondaga Fm.
MRS
7050′
7100′
MFS
7150′
MRS
RST
TST
TST and condensed section deposits…
abundant quartz, pyrite, and calcite – increased brittleness
abundant TOC – diminished brittleness

SUMMARY

…base level fluctuations are accompanied by changes in sedimentary regime, sedimentation rate, clastic versus biogenic flux rates, environmental energy, and geochemical characteristics…

…such a dynamic interaction among such factors influences a multitude of reservoir properties important to exploration and production strategies…

…mineralogy (porosity, permeability, brittleness) …

…microfabric (porosity, permeability) …

…organic carbon content (reservoir quality, permeability, porosity) …

…diagenetic components (microfabric, porosity, permeability)…

…fracture density (natural hydraulic fractures as well as fractures formed under absolute tension)…

…log response…

…maturity parameters – vitrinite reflectance…

Acknowledgements