Improving Burial and Thermal History Modeling Based on Geochemistry and Progressive Clay Mineralogical Transformation in Devonian Shales - Examples from the Duvernay and Muskwa Formations in Western Canada*

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Search and Discovery Article #51582 (2019)**
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Abstract

The Muskwa and Duvernay formations are contemporaneously deposited stratigraphic units of the Late Devonian (Frasnian) in the Western Canadian Sedimentary Basin. Both units are composed of organic-rich and fine-grained sediments deposited along the western shelf of the North American Craton within adjacent basins, north (Muskwa) and south (Duvernay) of the Peace River Arch. A new dataset of mostly cuttings samples from >1400 wells across the two formations has been established that contains both geochemical and mineralogical details. Regional mapping of total organic content, thermal maturity and mineralogical compositions reveals details of sediment origin, transport and diagenetic alterations. In addition, clay mineralogy of selected wells illustrates a progressive clay mineral structural transformation associated with burial depth.

In the Muswka Formation, smectitic clays are common in shales in the northeastern part of the basin buried to ~900 m (~3000 ft) depth, but are absent in rocks at ~1300 m (~4300 ft) depth where mixed-layer smectite-illite clay minerals are present. In rocks further west at >1600 m (>5200 ft) depth, mixed layer clay minerals are absent and only illite with high crystallinity is observed. Organic geochemical data of the same samples illustrate that thermal maturity also increases towards the west but depth/TMax details show that maturity is not only linked to burial depth but also to underlying basement residual heat flow. In the Duvernay Formation, burial depths are >1200 m (~4000 ft) and therefore both thermal maturity and clay mineral structures are different than in the Muskwa. Clay mineral analysis in these rocks illustrates the absence of smectites and the dominance of thin illite/poorly structured illite without swelling capacity. Geochemical analysis shows a complex thermal maturity of the organic matter with immature material (Tmax <430° C) in the shallow (~1400-2400 m, 4500-7800 ft depth) eastern part of the basin and high maturity (Tmax >470° C) along the deeper (>3300 m, 11,000 ft) western deformation front.

This presentation provides insights into regional geochemical and mineralogical changes across both the Muskwa and Duvernay formations and provides details of clay mineralogical structural changes (XRD) and organic thermal maturity (Tmax, TOC). Clay mineralogy in both basins allows interpretations about possible original detrital influx, paleo-ocean currents and paleo-topographic reliefs. Maturity trends and clay mineral transformation at local and regional scales provide specific basin model parameters and thermal maturity information associated with

both local basement heat flow and regional burial depth. The data improved both burial and diagenetic parameters and thus the resulting burial models.

AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Improving burial and thermal history modeling based on geochemistry and progressive clay mineralogical transformation in Devonian shales. Examples from the Duvernay and Muskwa Formations in Western Canada

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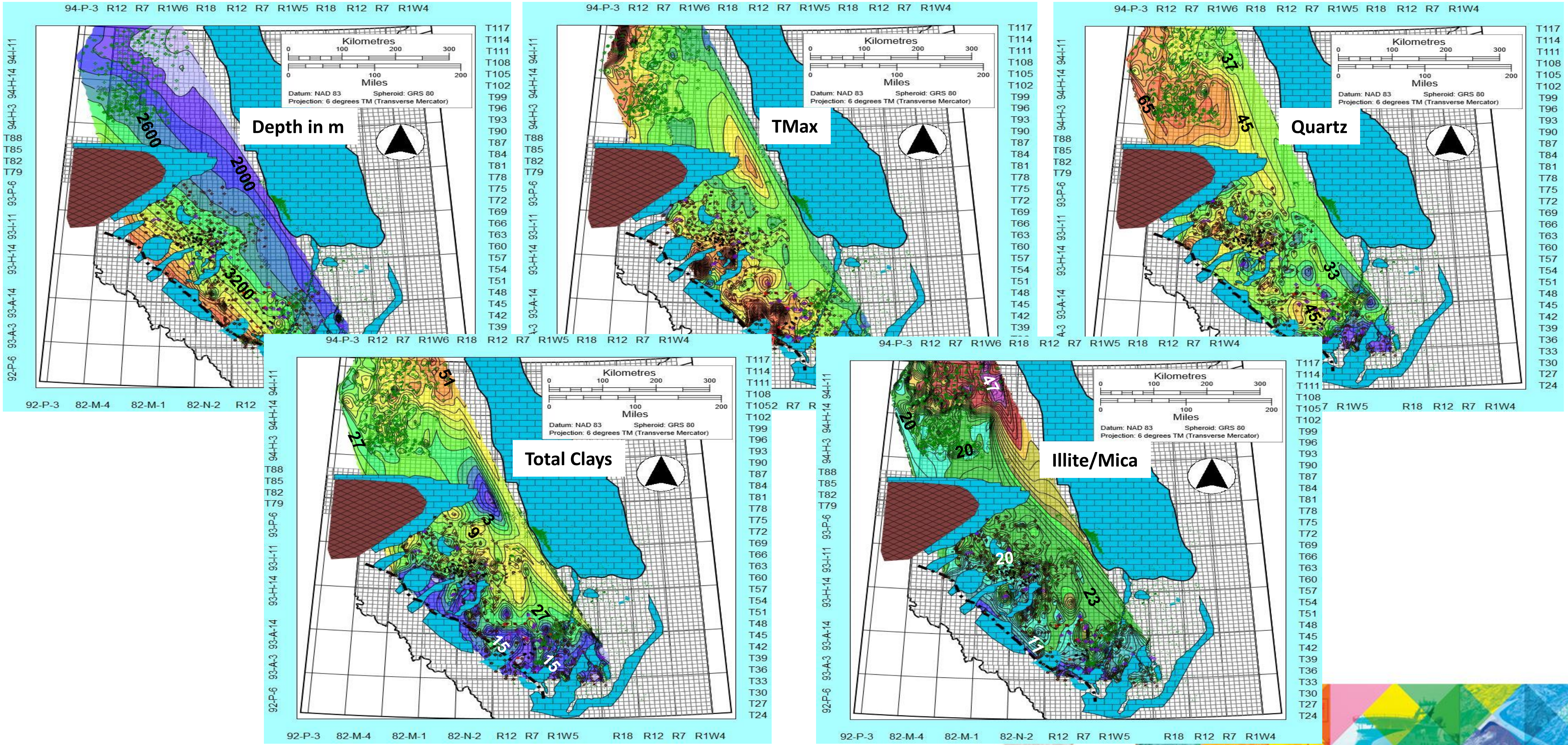
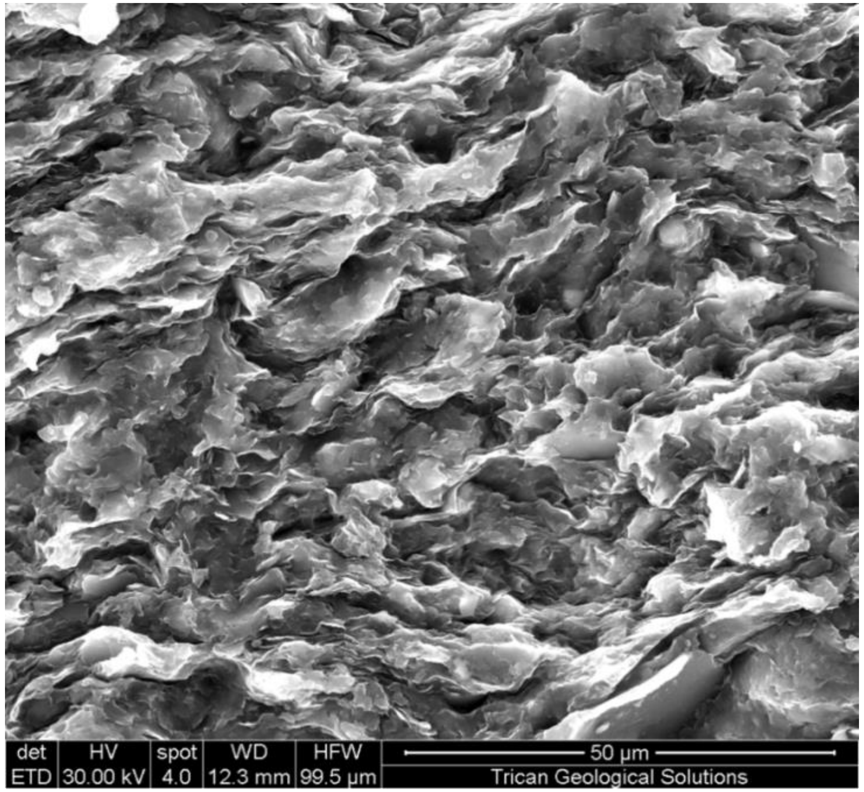
The Muskwa and Duvernay Formations: Maturity vs Quartz and Clay Distribution

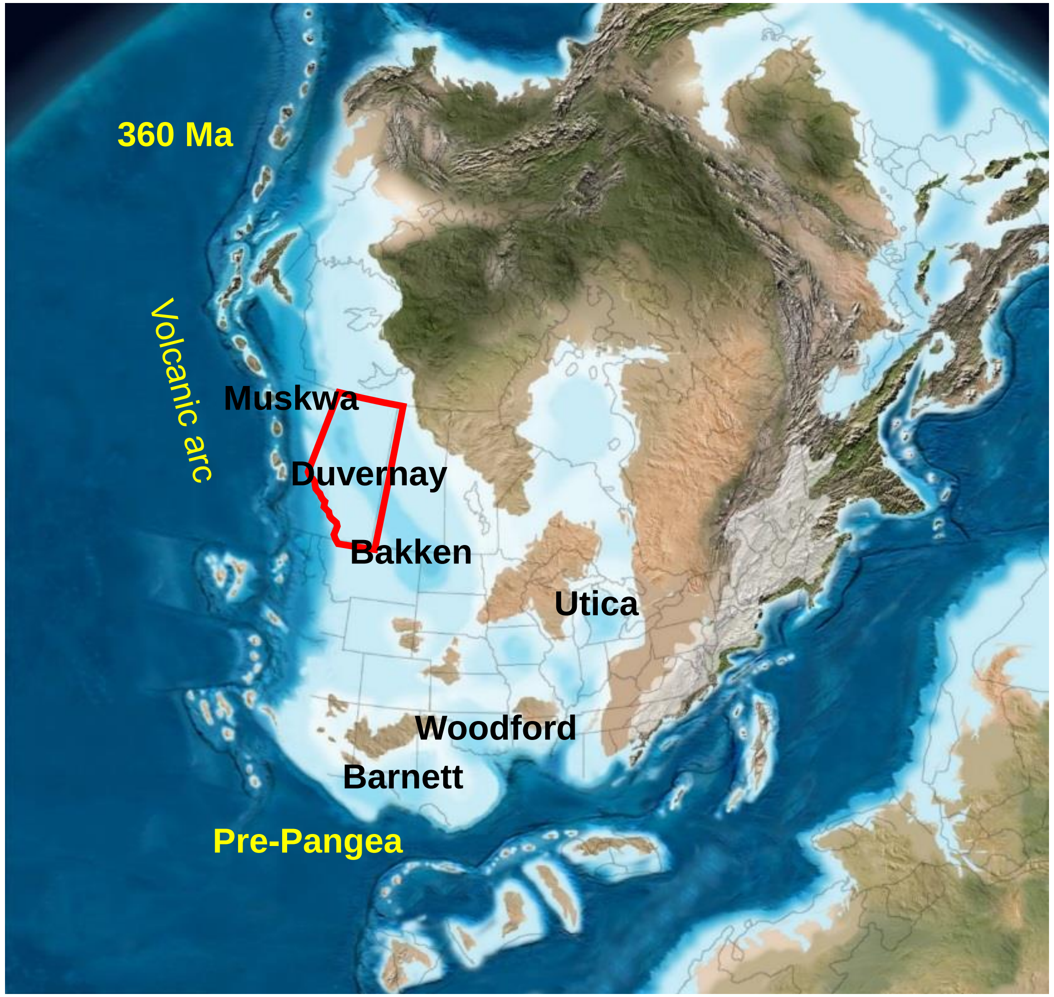


Outline

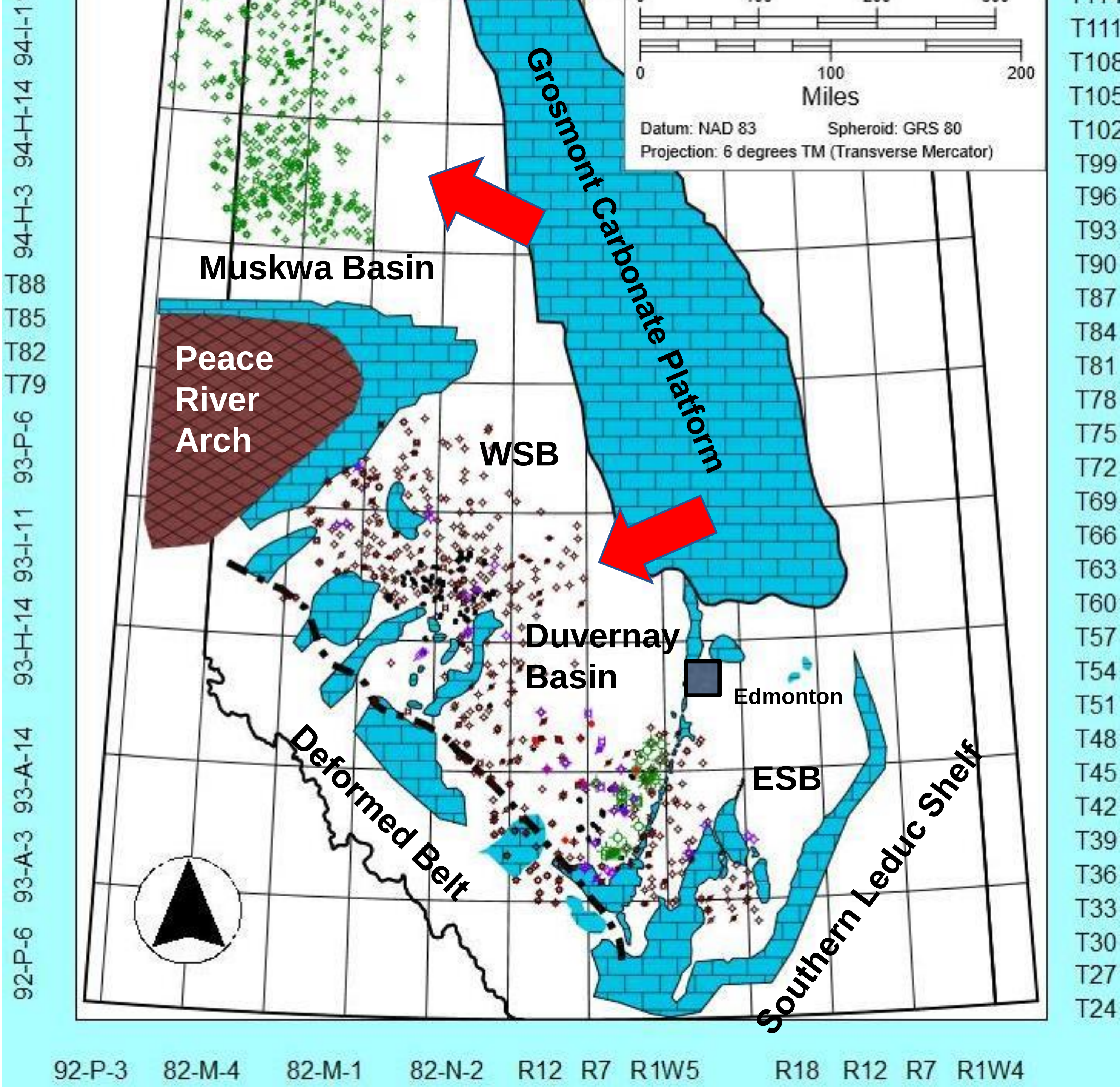
- **Paleodepositional settings of the Devonian Shale Formations in the Western Canada Sedimentary Basin (Duvernay, Muskwa)**
- **Muskwa and Duvernay Clay Mineralogy, Structures, Distribution and Diagenesis**
- **Discussion and Conclusions**



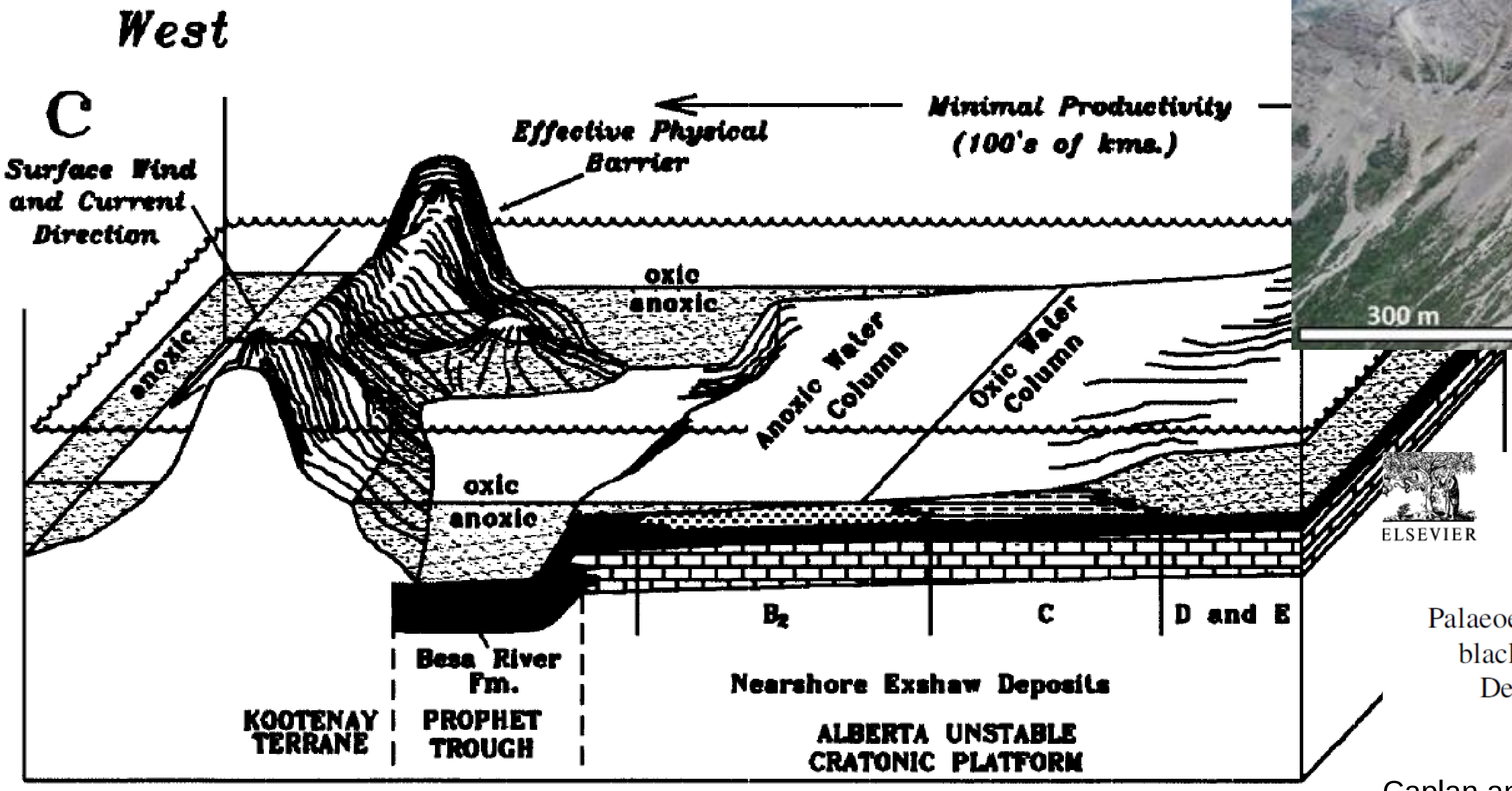
Upper Devonian W Canada



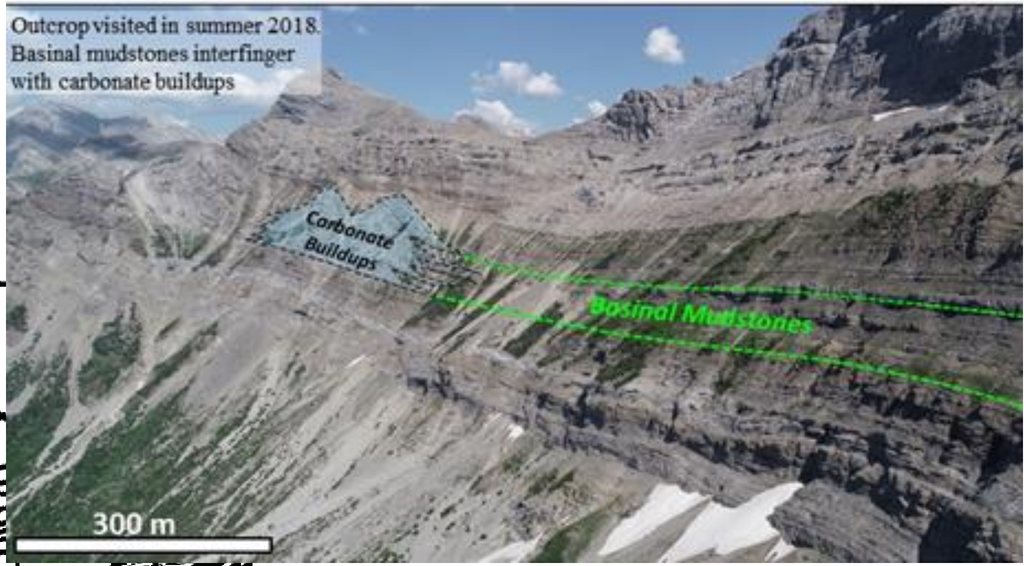
Blakey, http://www2.nau.edu/rcb7/namD360.jpg



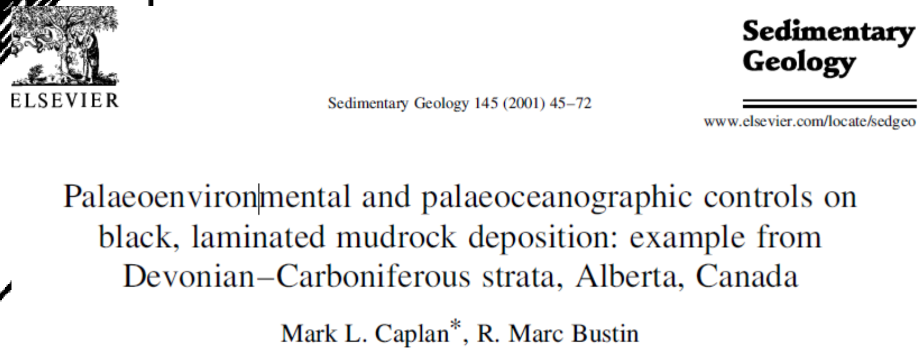
Duvernay Depositional Overview



Early Tournaisian Times--Eustatic Sea-Level Fall



Galvis-Portilla and Pedersen (2019)



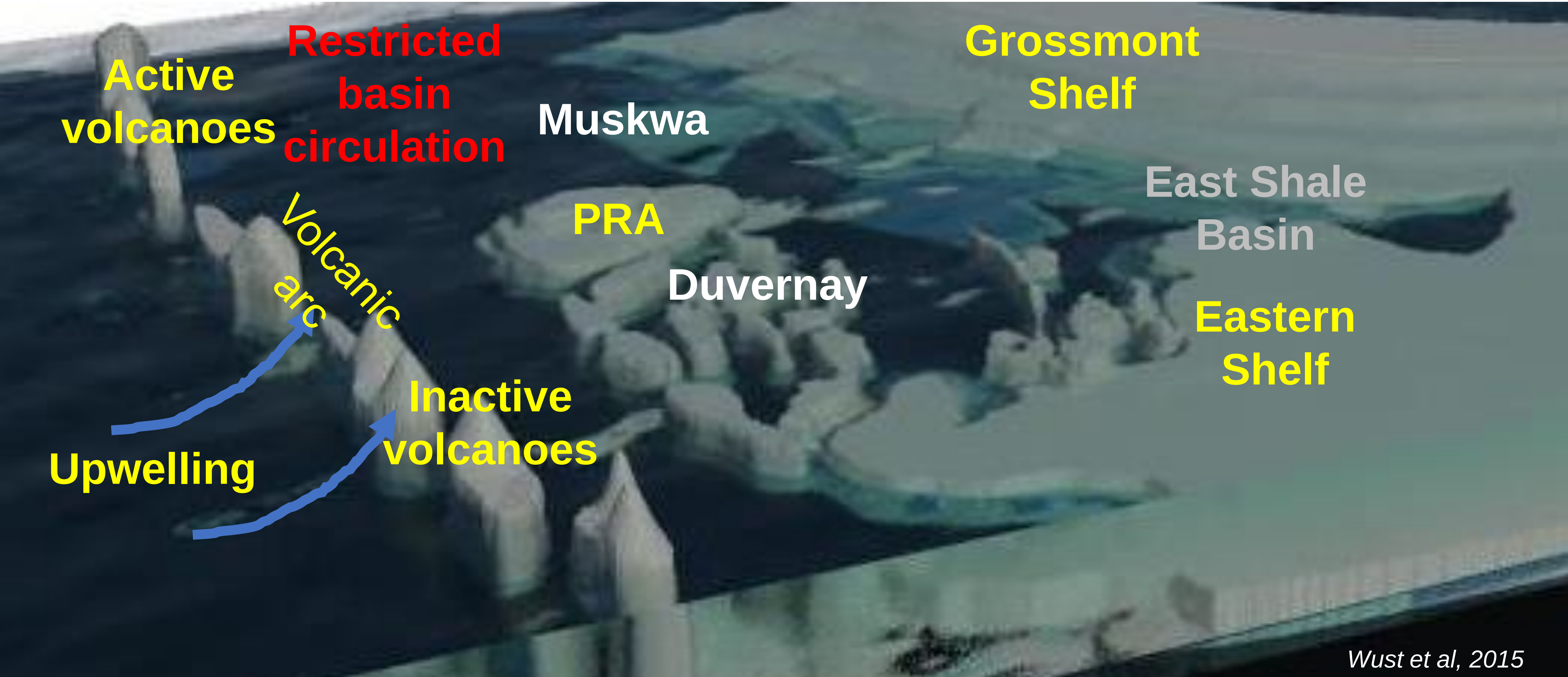
ELSEVIER
Sedimentary Geology 145 (2001) 45–72
Sedimentary Geology
www.elsevier.com/locate/sedgeo

Palaeoenvironmental and palaeoceanographic controls on black, laminated mudrock deposition: example from Devonian–Carboniferous strata, Alberta, Canada

Mark L. Caplan*, R. Marc Bustin

Caplan and Bustin, 2001

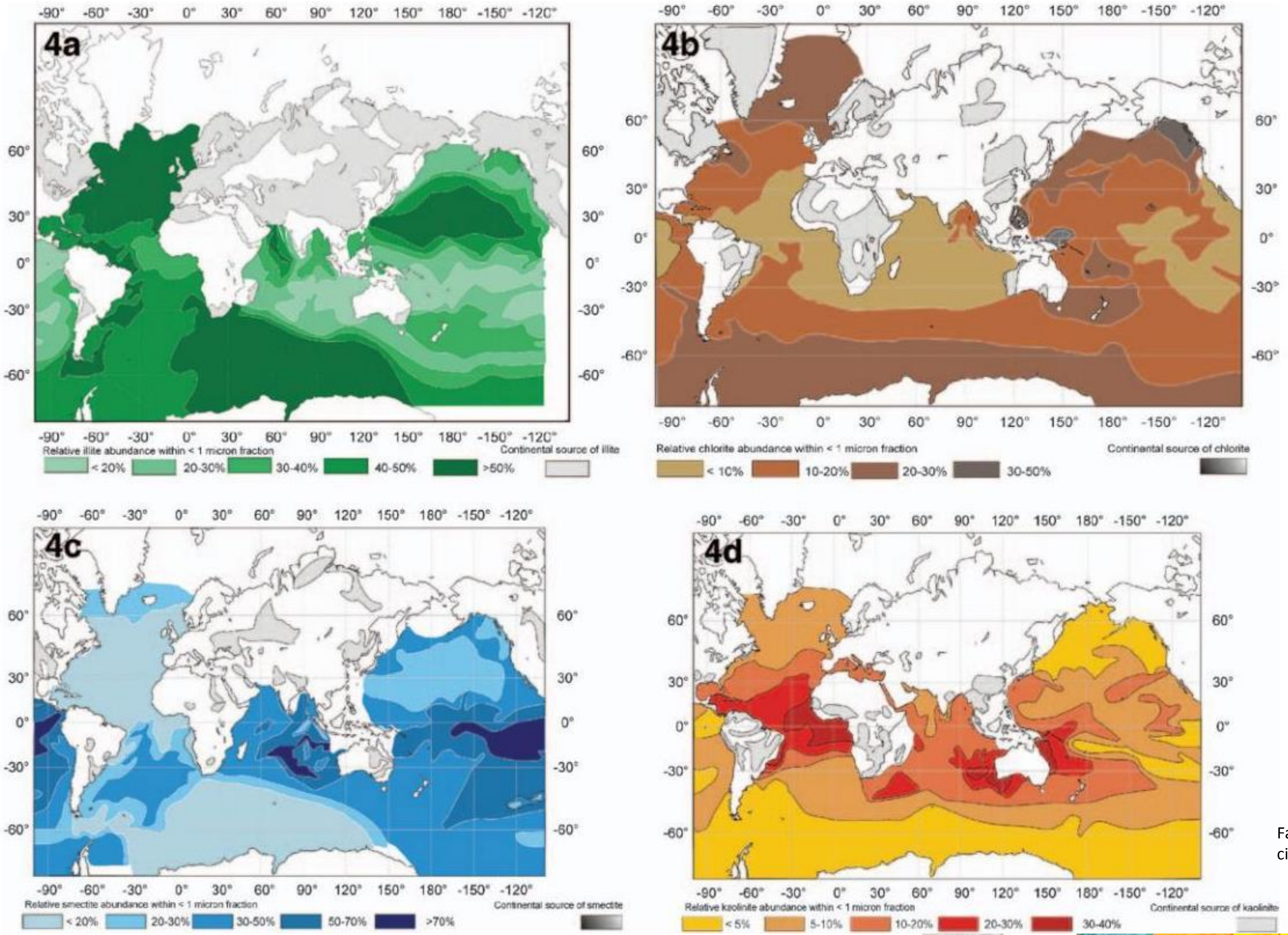
Duvernay Depositional Overview



Provenance Controls of Clay Minerals

Illite: areas of minimal chemical weathering

Chlorite dominates in high lat. zones with high mechanical weathering

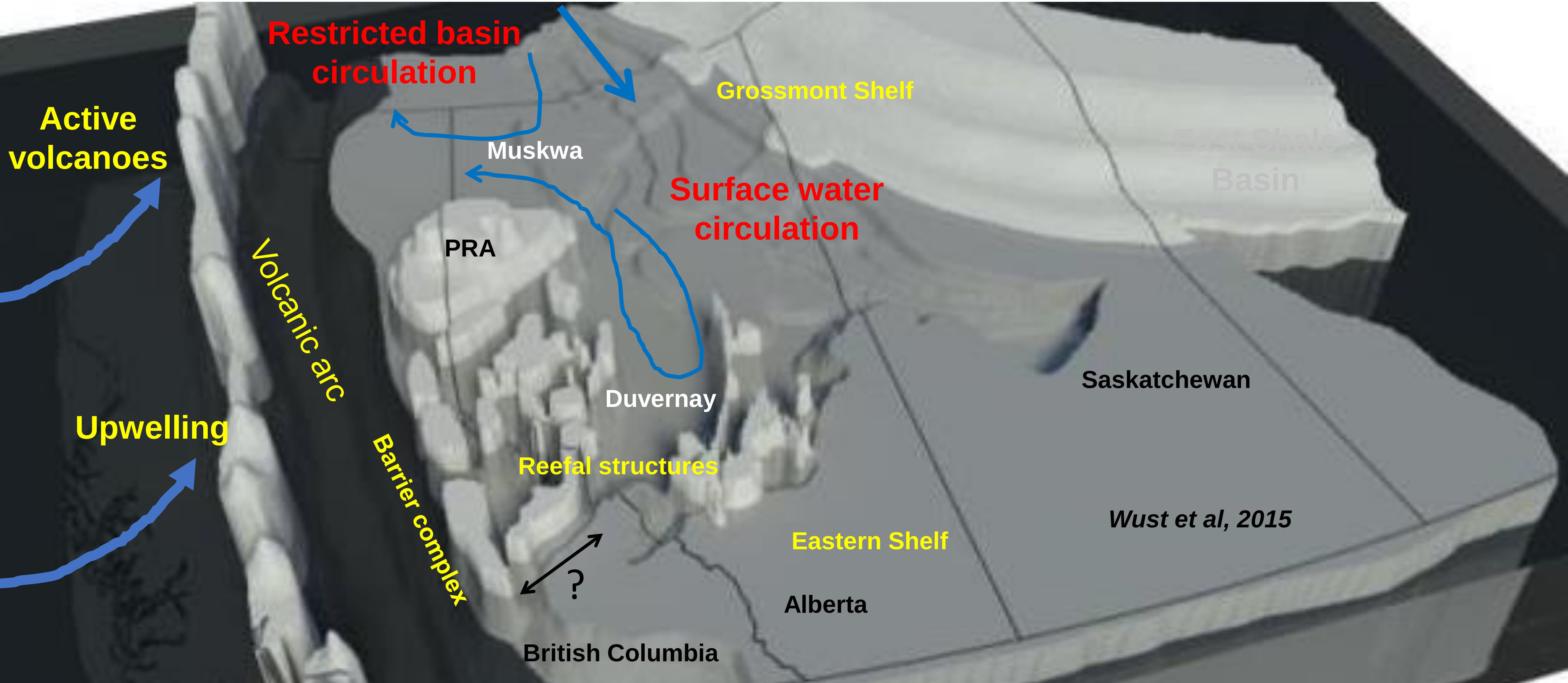


Smectites: areas of high volcanic influx and chemical weathering

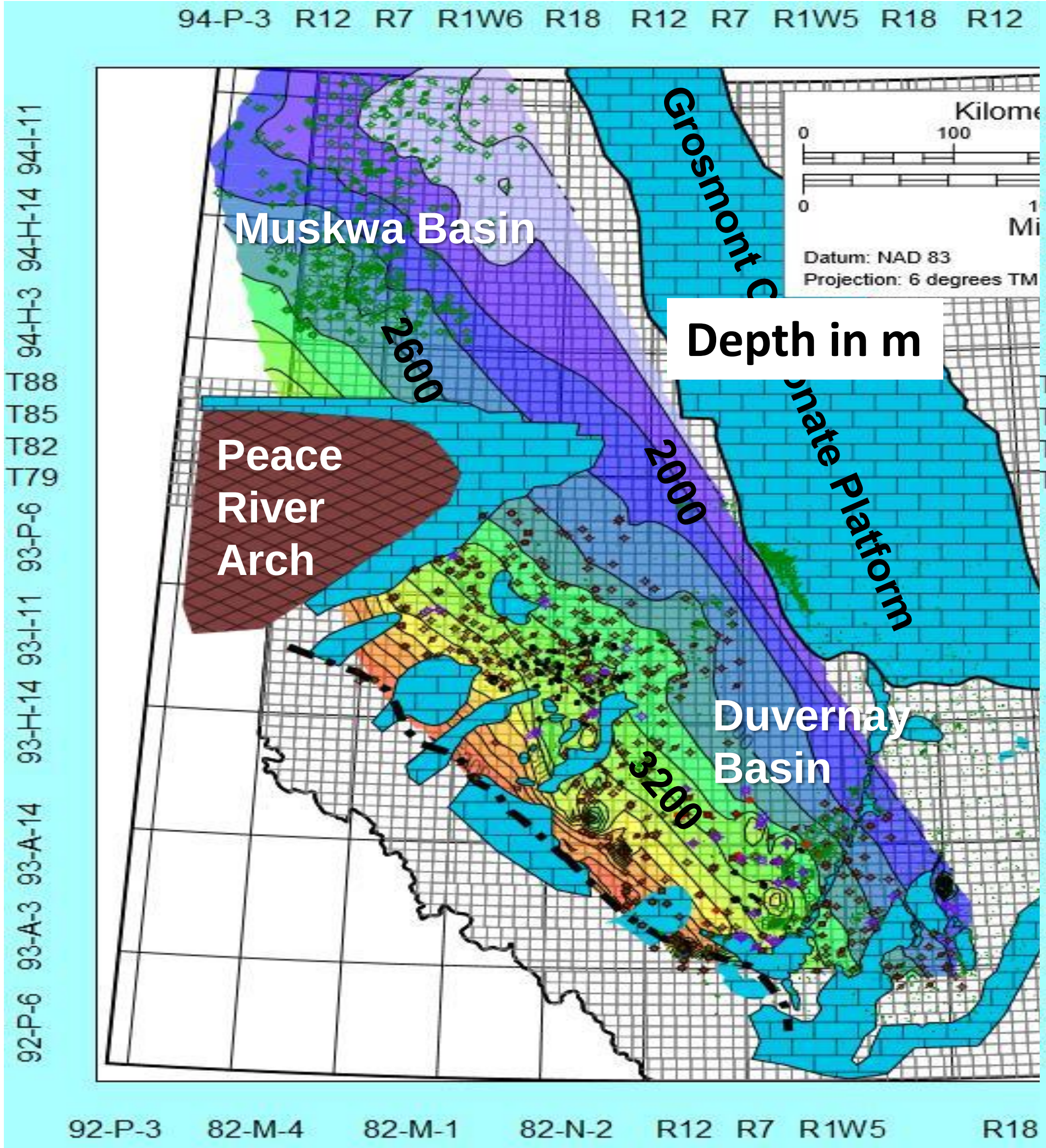
Kaolinite dominates in low lat. zones with intense chemical weathering (humid/tropical)

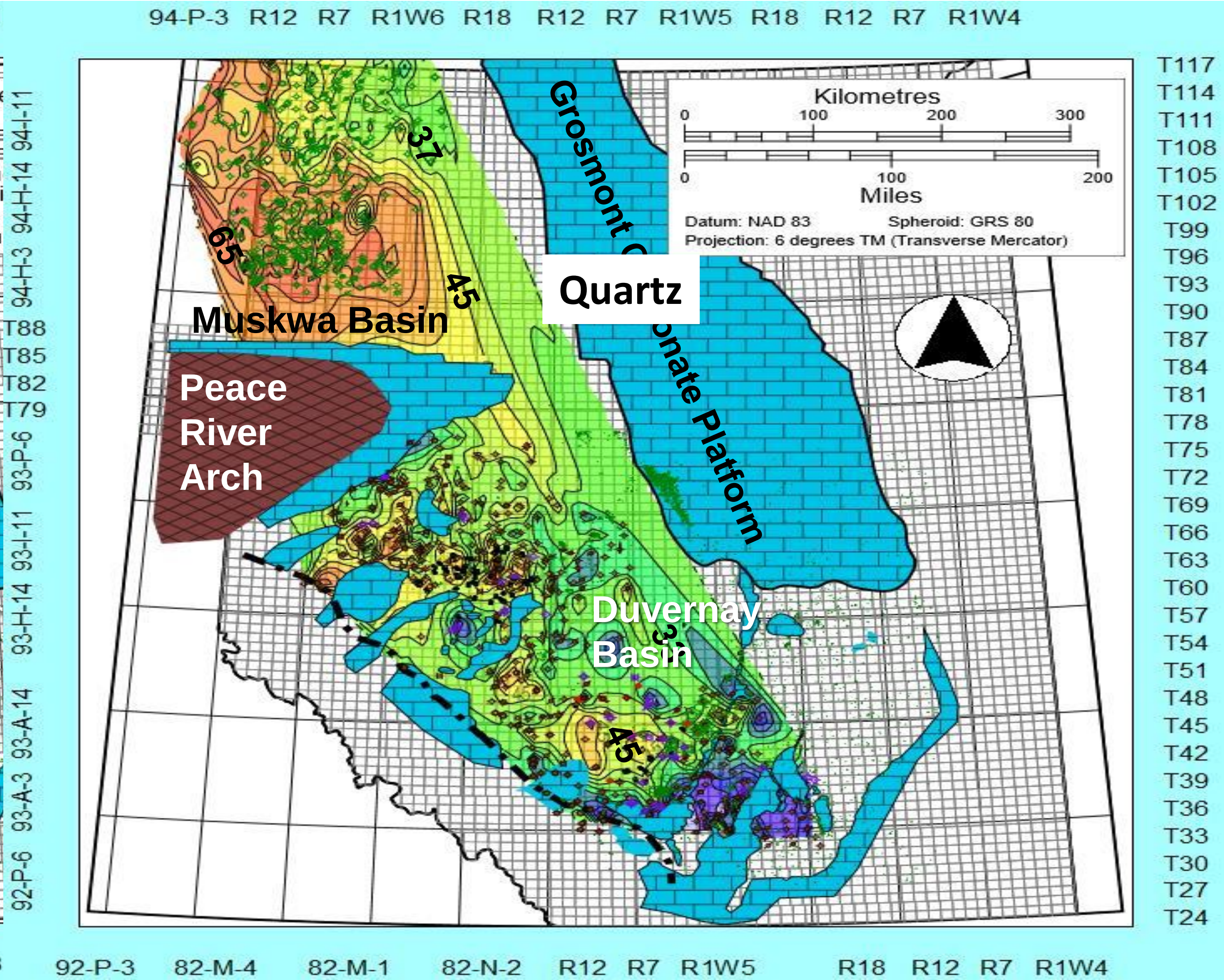
Fagel, 2007. Clay minerals, deep circulation and climate

Duvernay Depositional Overview

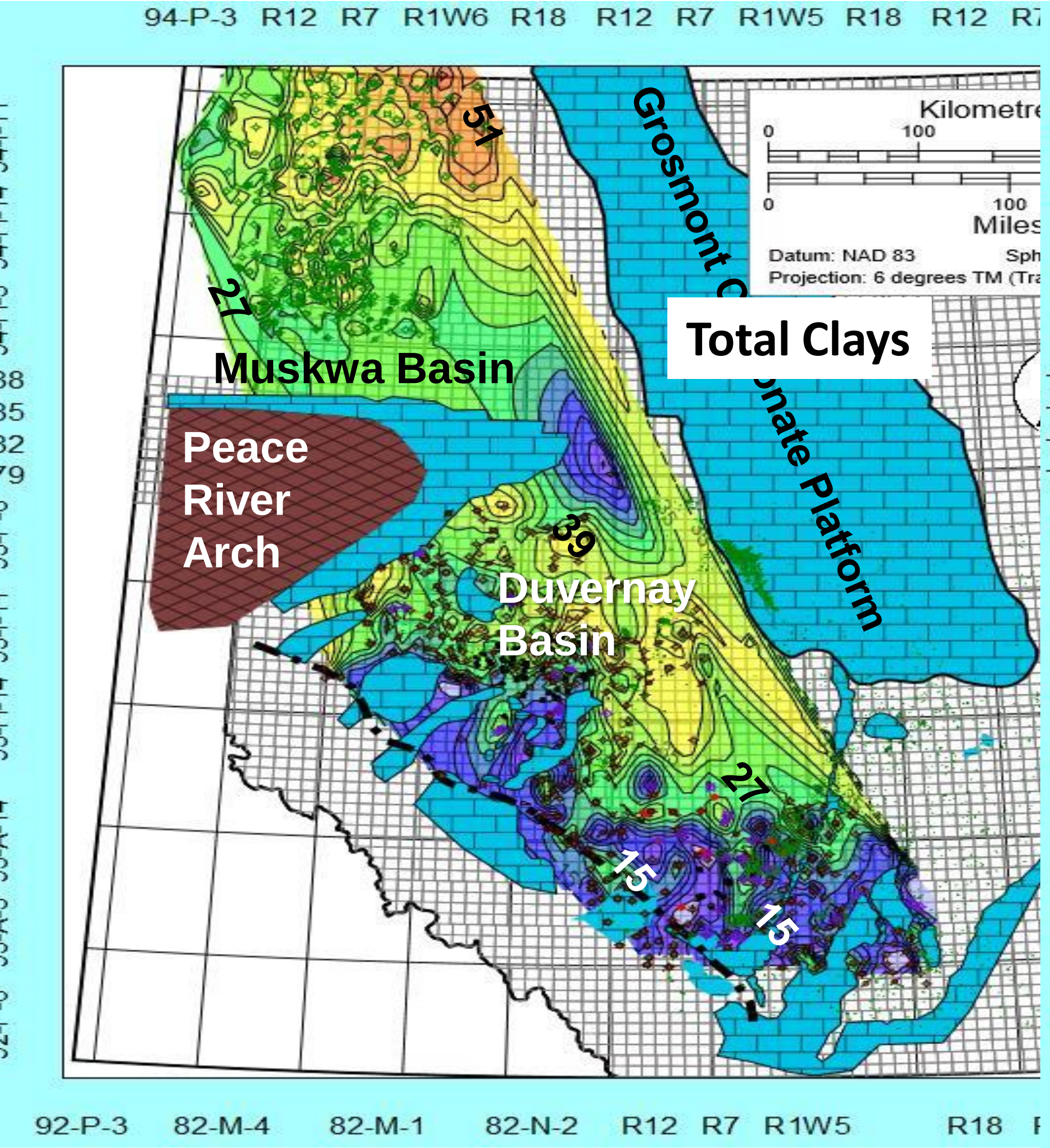


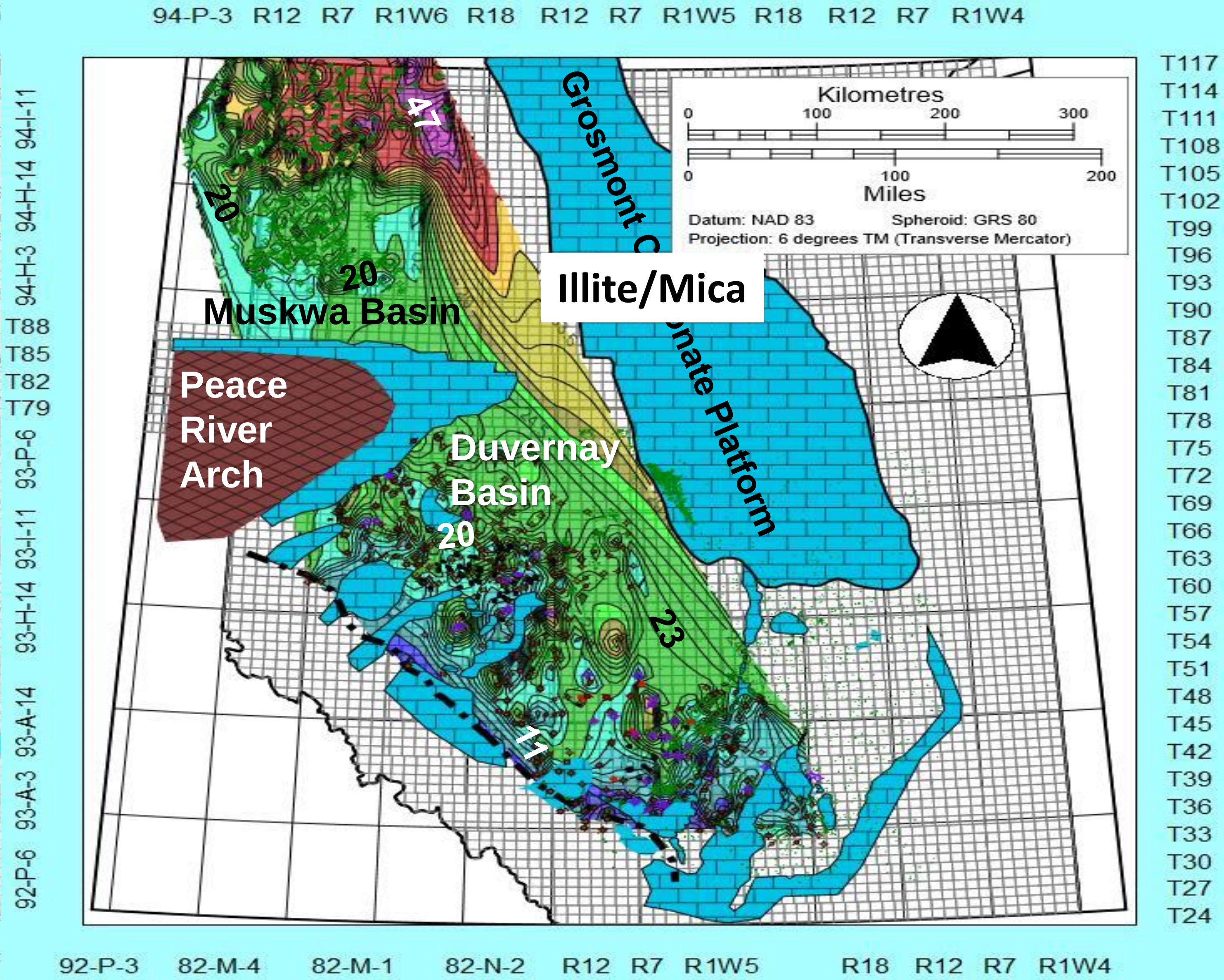
The Muskwa and Duvernay Formations: Depth and Quartz Distribution



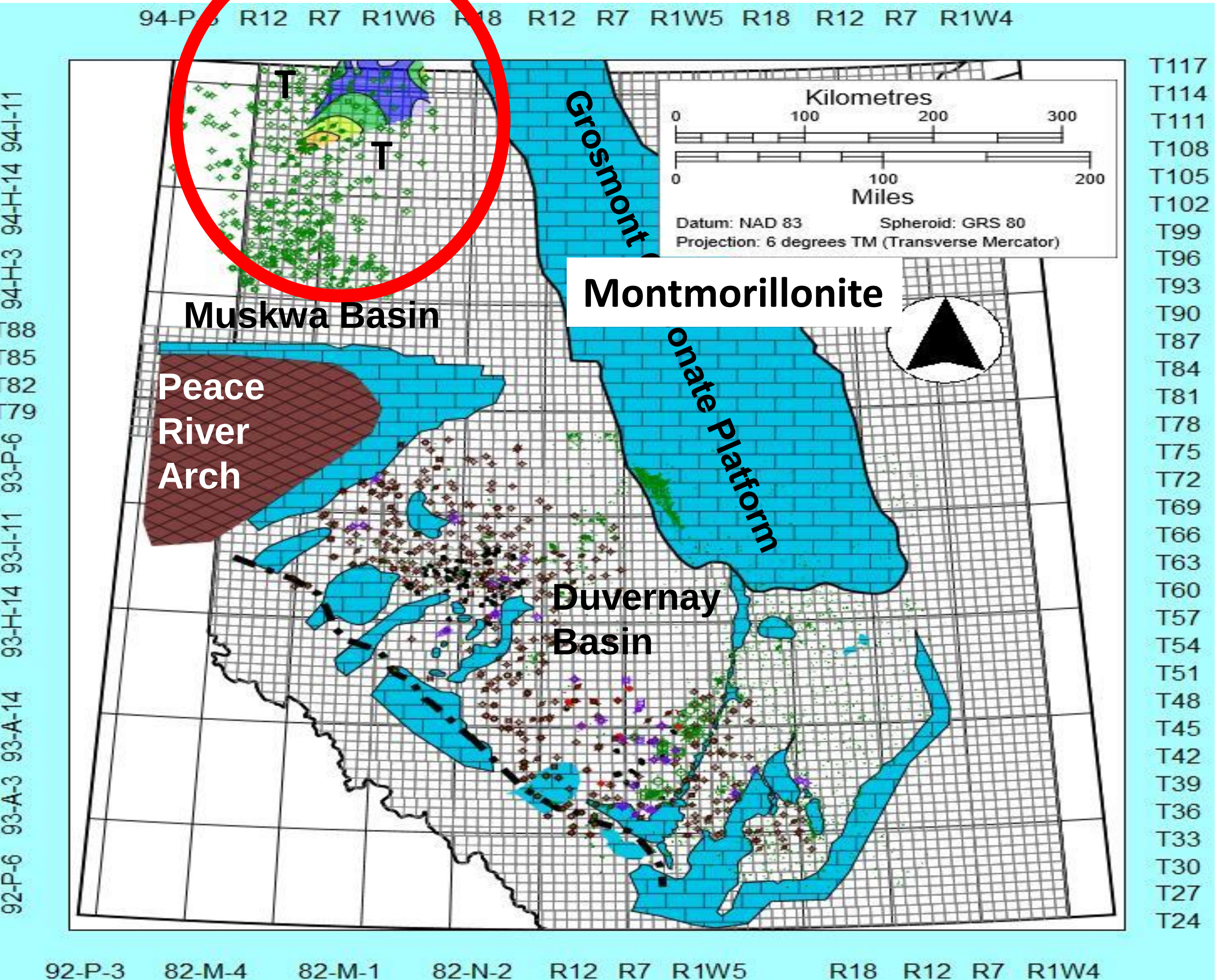


Total Clays and Illite/Mica

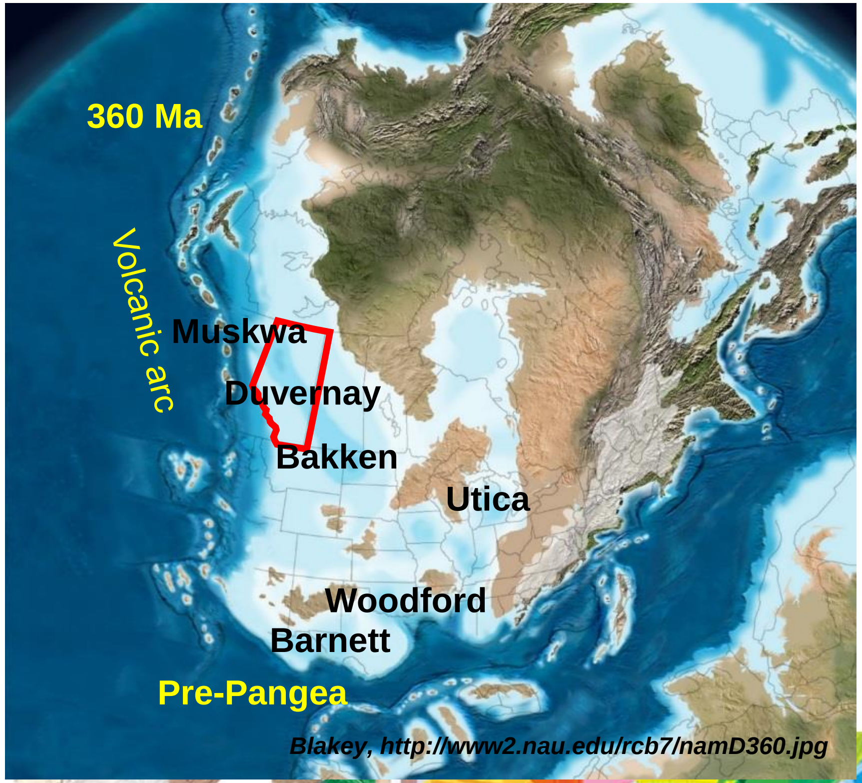




Swelling Clays in Muskwa and Duvernay Basin

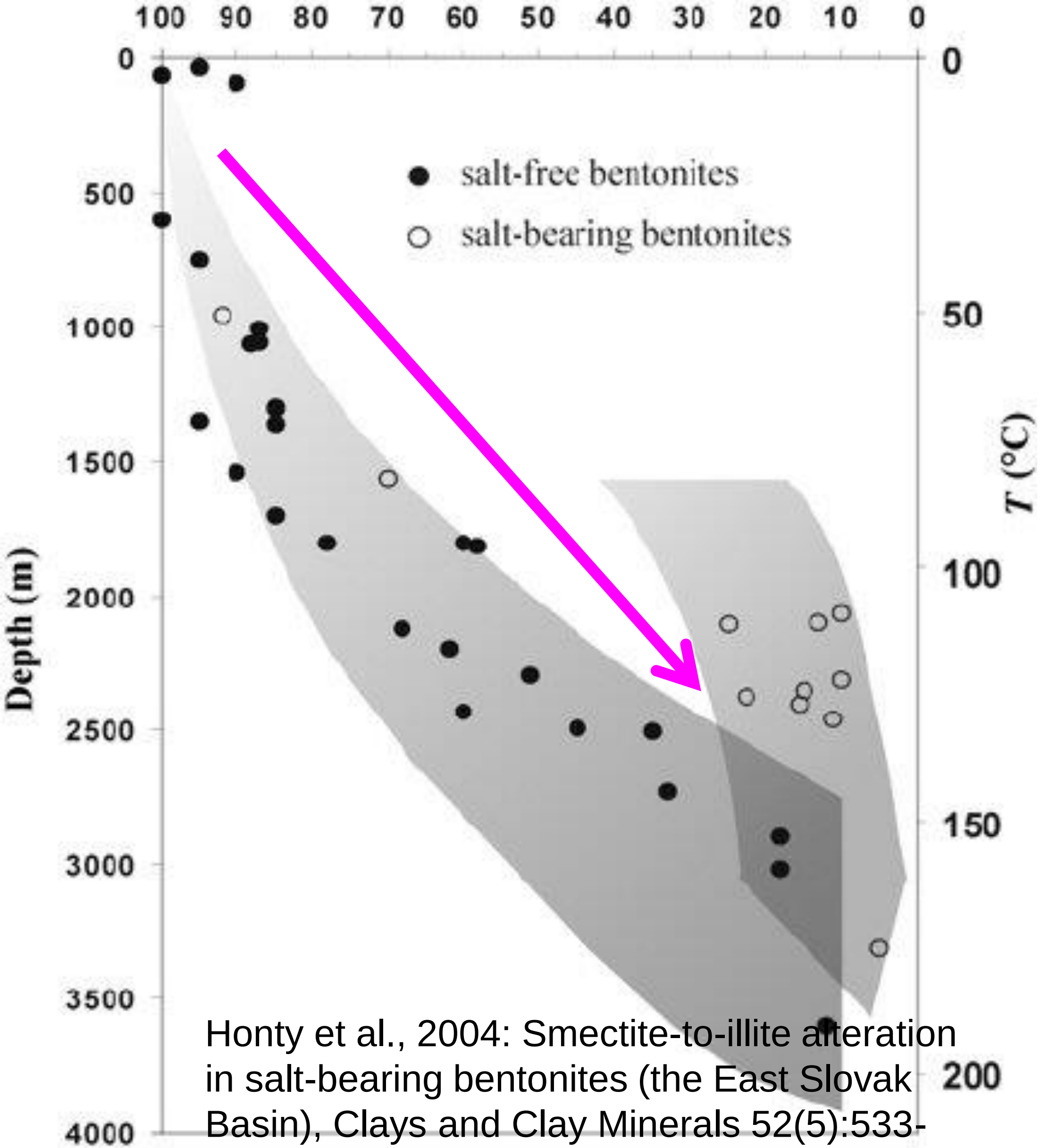


- Only NE corner of Muskwa Basin contains up to 15% of smectites.
- Smectite content decreases towards S and SW



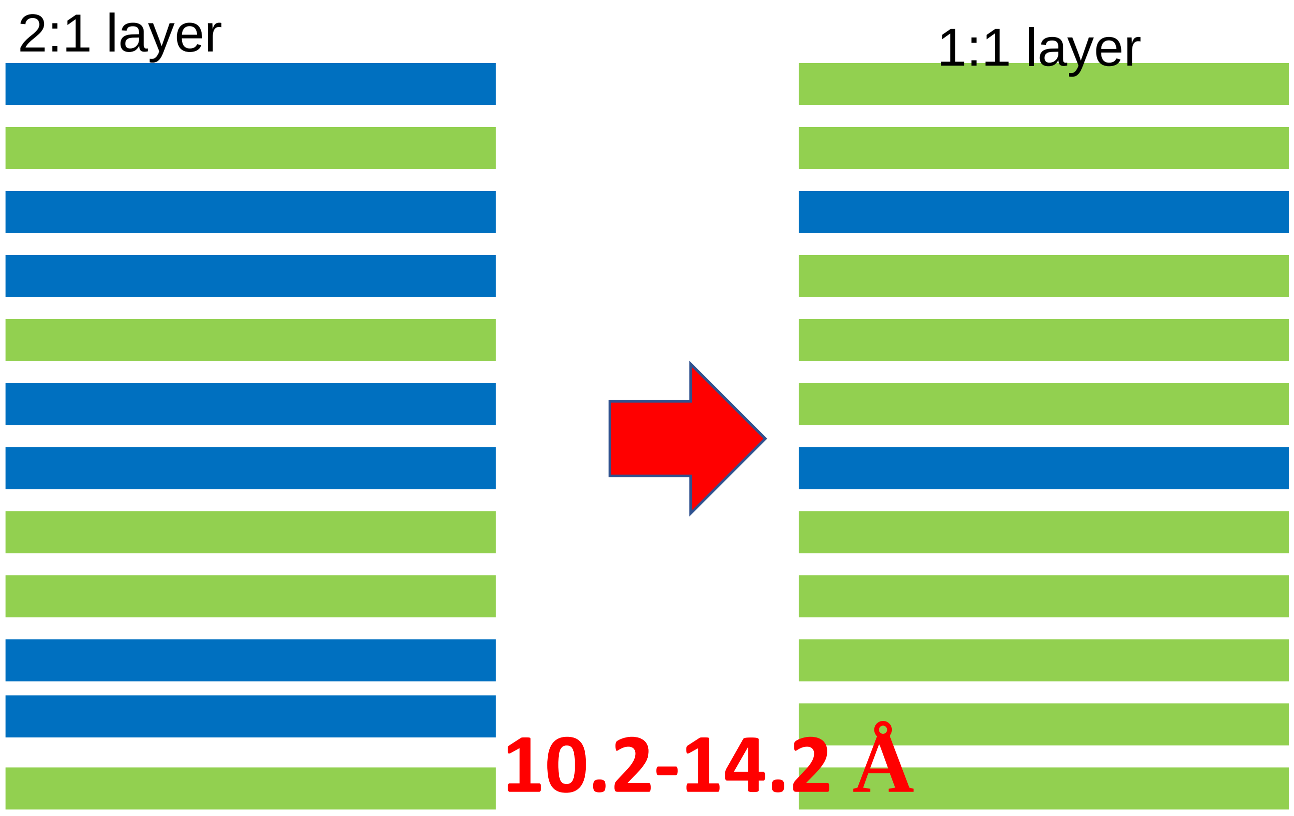
Blakey, http://www2.nau.edu/rcb7/namD360.jpg

Smectite to Illite transformation



Honty et al., 2004: Smectite-to-illite alteration in salt-bearing bentonites (the East Slovak Basin), Clays and Clay Minerals 52(5):533-

Mixed-layer clays (I/S)



The illitization process occurs as a progressive replacement of expandable layers by layers with illitic behavior, in a single illite-smectite phase.

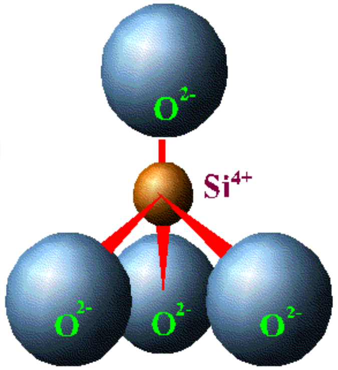
Clay Mineralogy - Structures

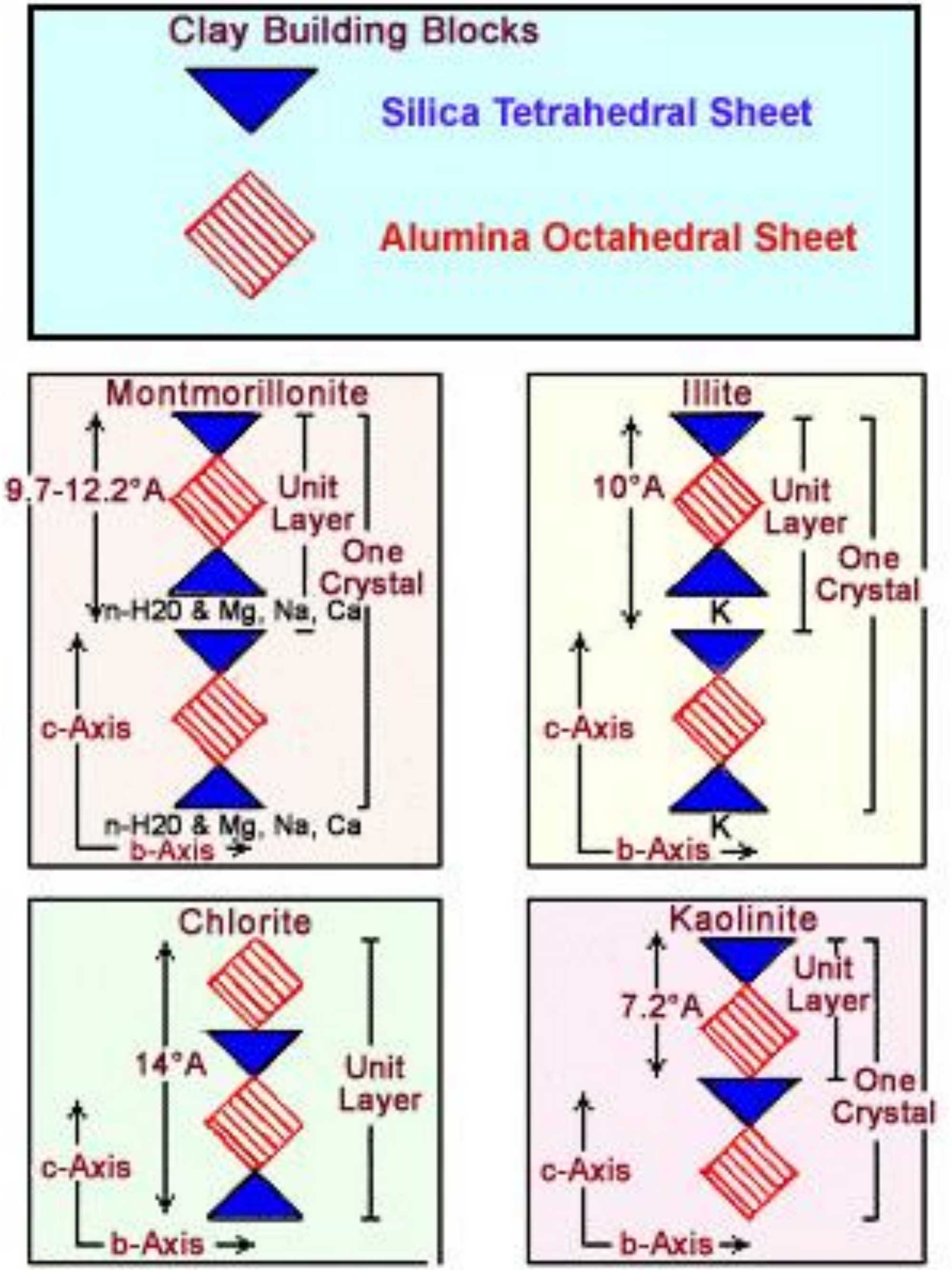
- **Kaolin** ($Al_2Si_2O_5[OH]_4$) (kaolinite, dickite, halloysite, nacrite)

- **Smectite** dioctahedral (montmorillonite, nontronite, beidelite) and trioctahedral (saponite) $(\underline{Na},Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$

- **Illite-mica** ($KAl_3Si_3O_{10}[OH]_2$) (illite, vermiculite, muscovite, etc)

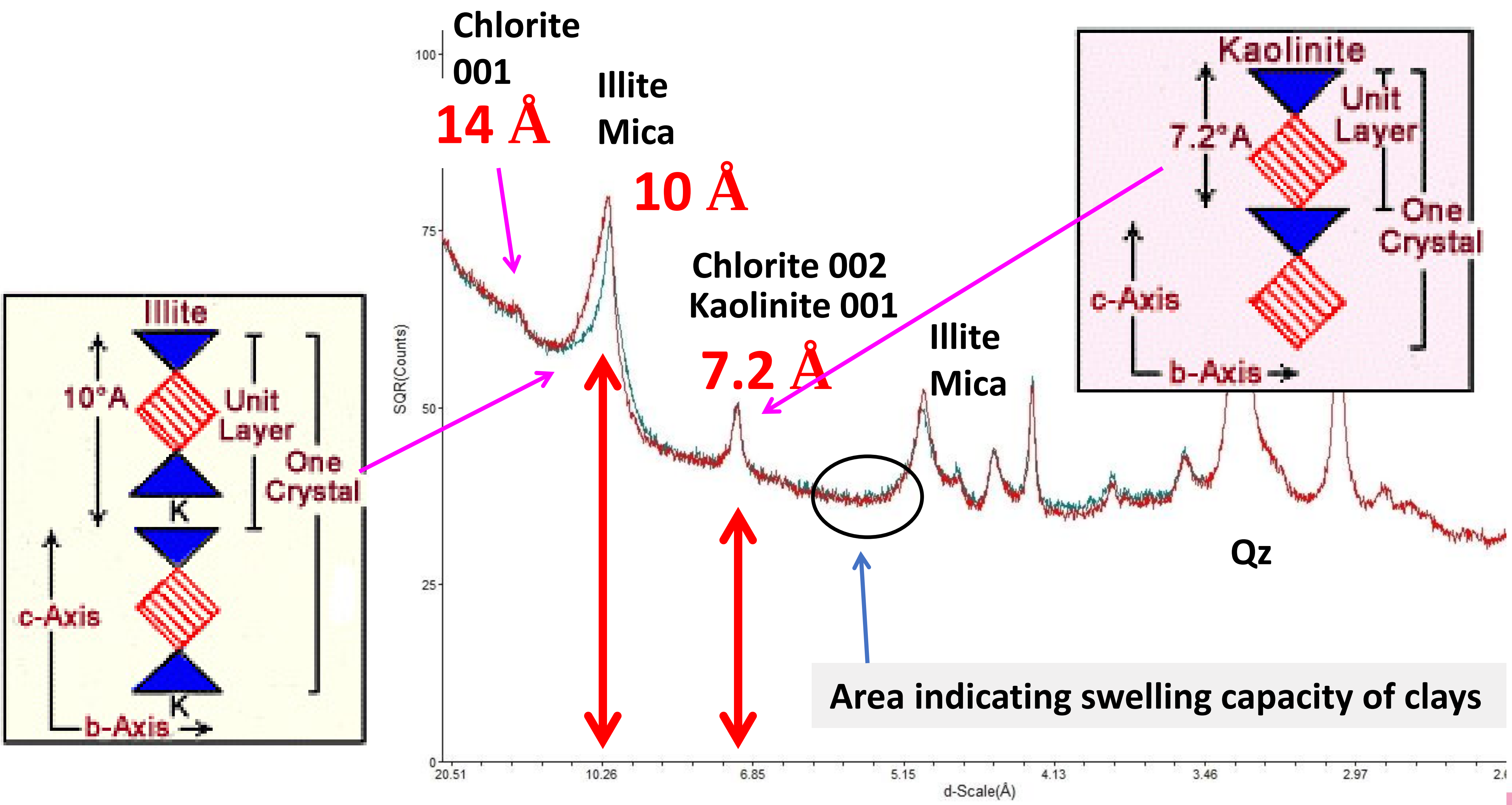
- **Chlorite** ($[Mg,Al]_6[Si,Al]_4O_{10}[OH]_8$) (high chemical variation, Mn, Fe, Ca, Cr, etc)





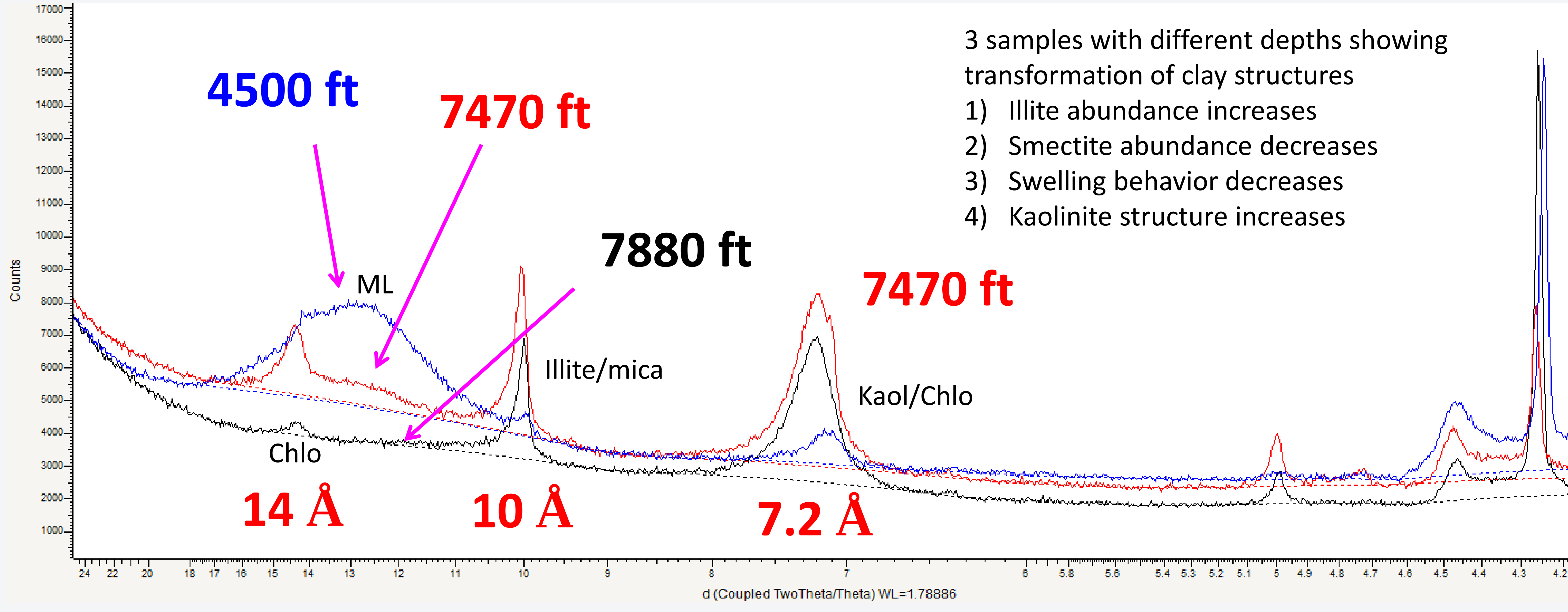
From Moore, 1960

X-Ray Diffraction Pattern



Mixed Layer Clay Mineral Transformations

South America

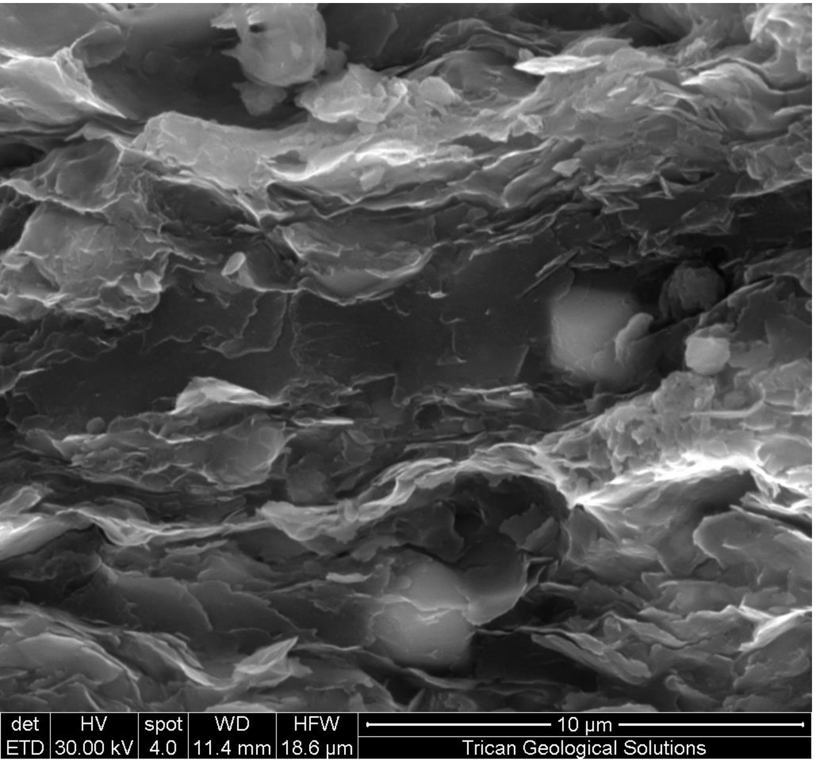


3 samples with different depths showing transformation of clay structures

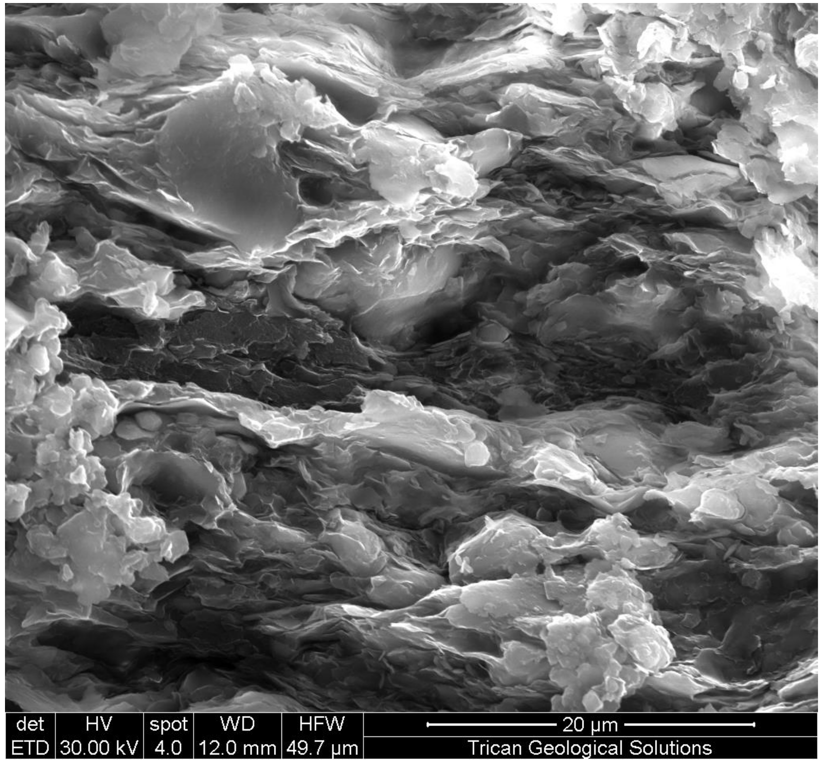
1) Illite abundance increases
2) Smectite abundance decreases
3) Swelling behavior decreases
4) Kaolinite structure increases

SEM of the Muskwa – 900-1900 m depth burial (2950-6233 ft)

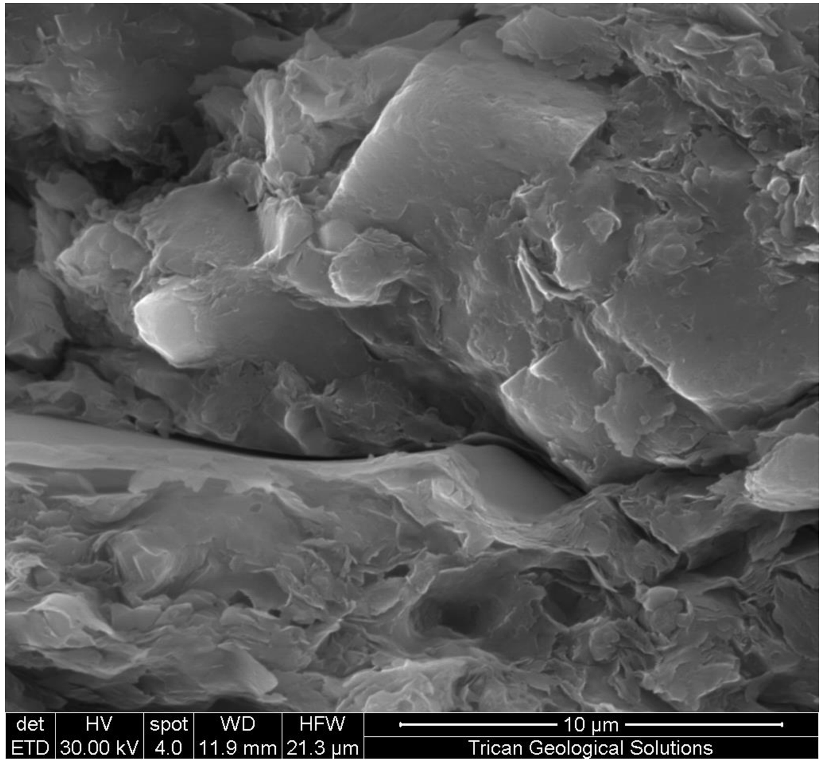
15-14-113-22W5 (945 m)



15-11-110-4W6 (4110-20 ft, 1250m)



C-94-I/94-I-1 (6140 ft, 1870m)

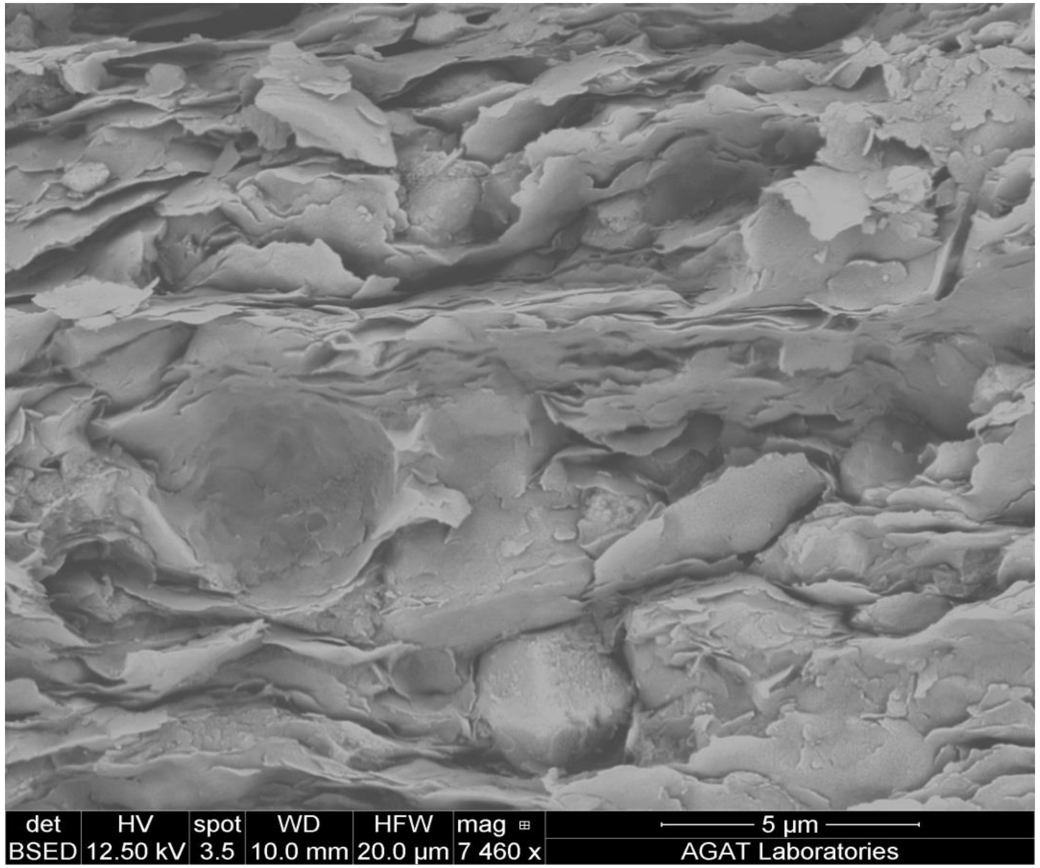


3100 ft ***4100 ft*** ***6135 ft***

Increased recrystallization, flakes appear more amalgamated

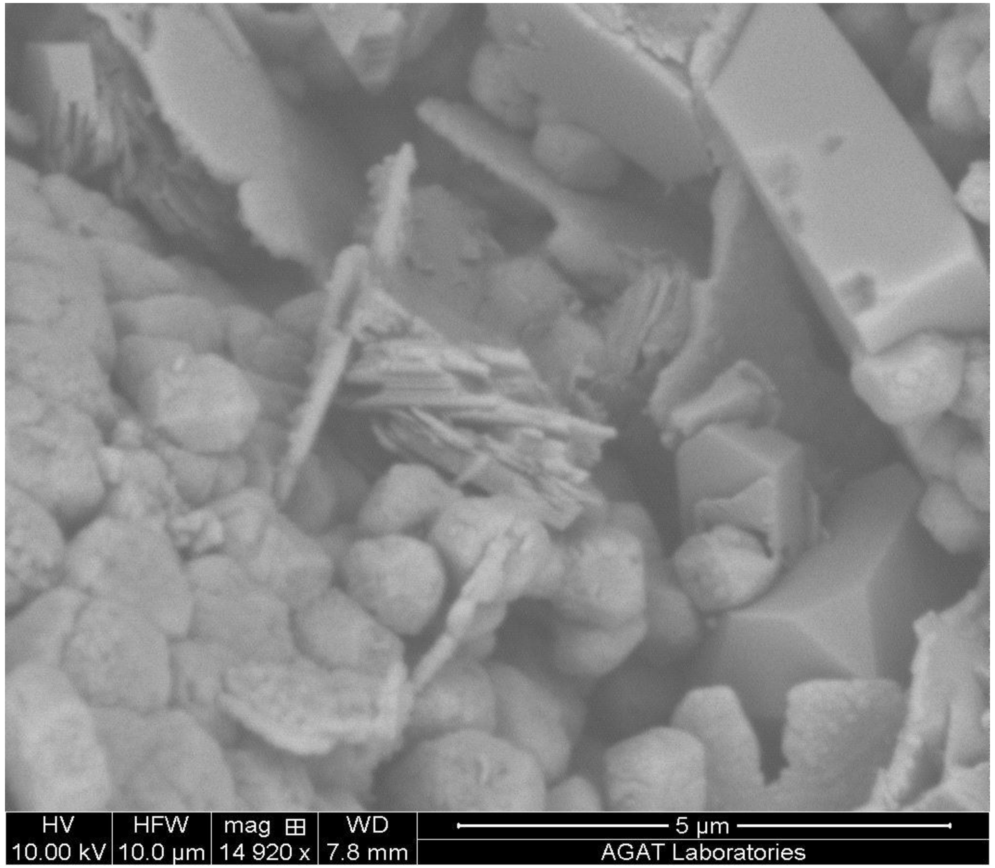
Clay structures under the microscope (SEM)

Muskwa 1400 m (4590 ft)



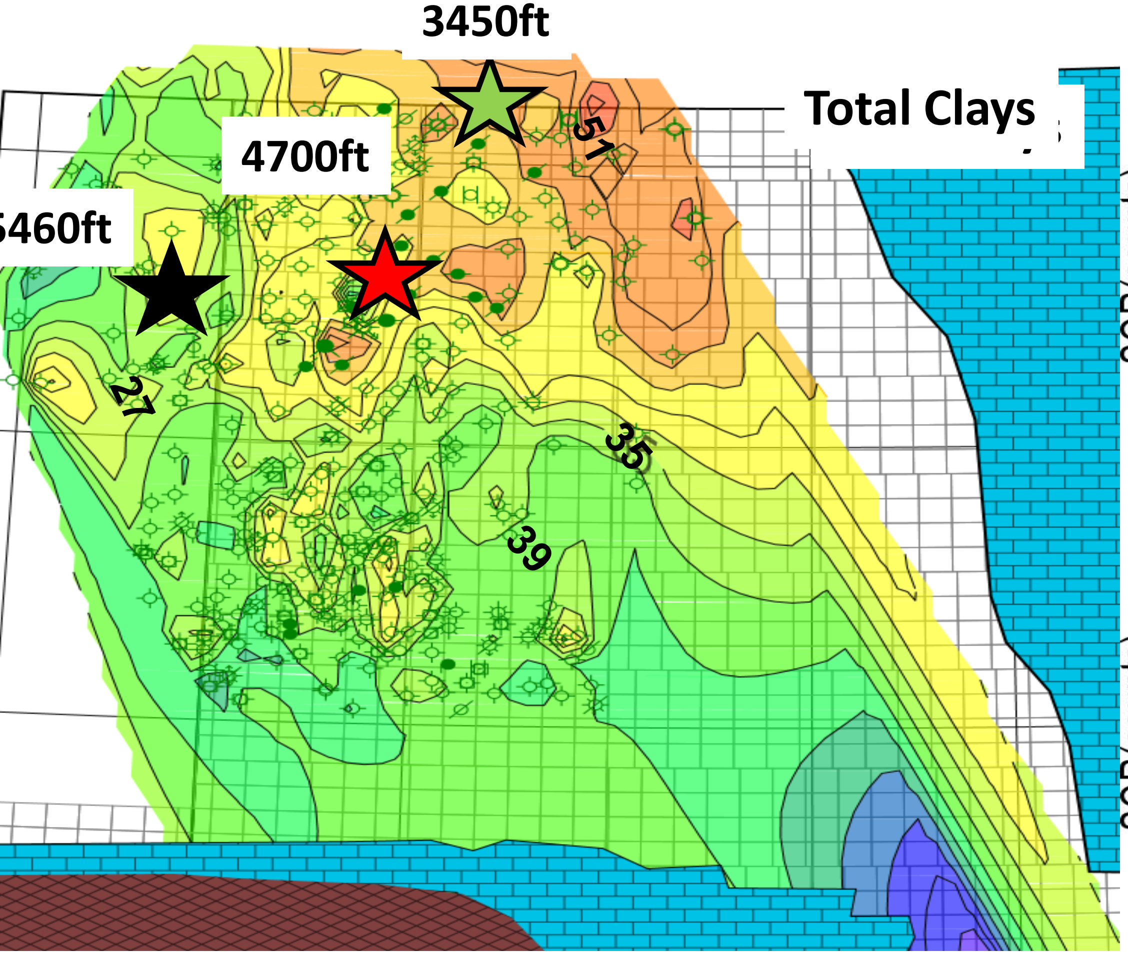
Abundant flakes, foliated fabric, mixed layer clay minerals

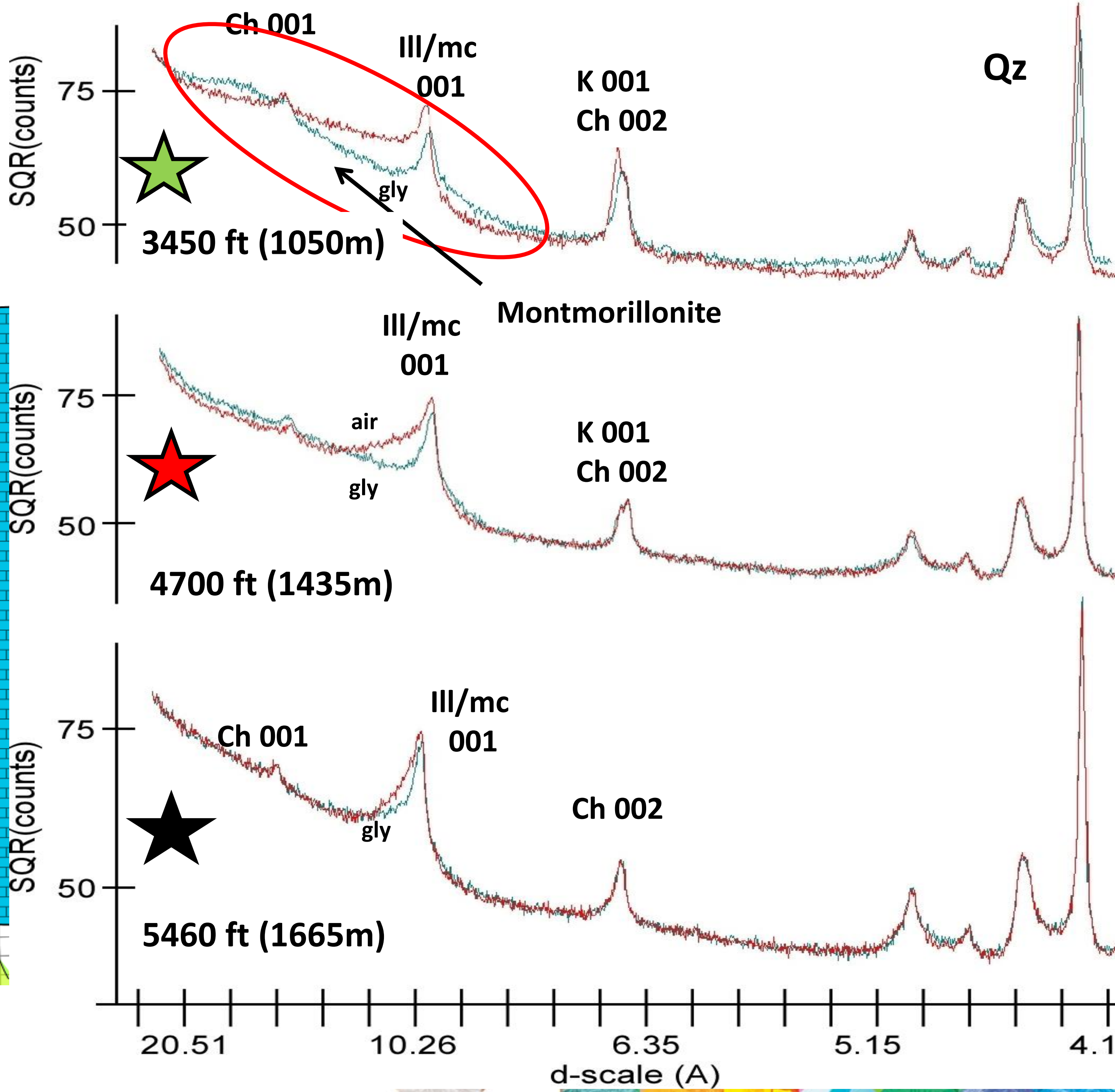
Duvernay 3400 m (11150 ft)



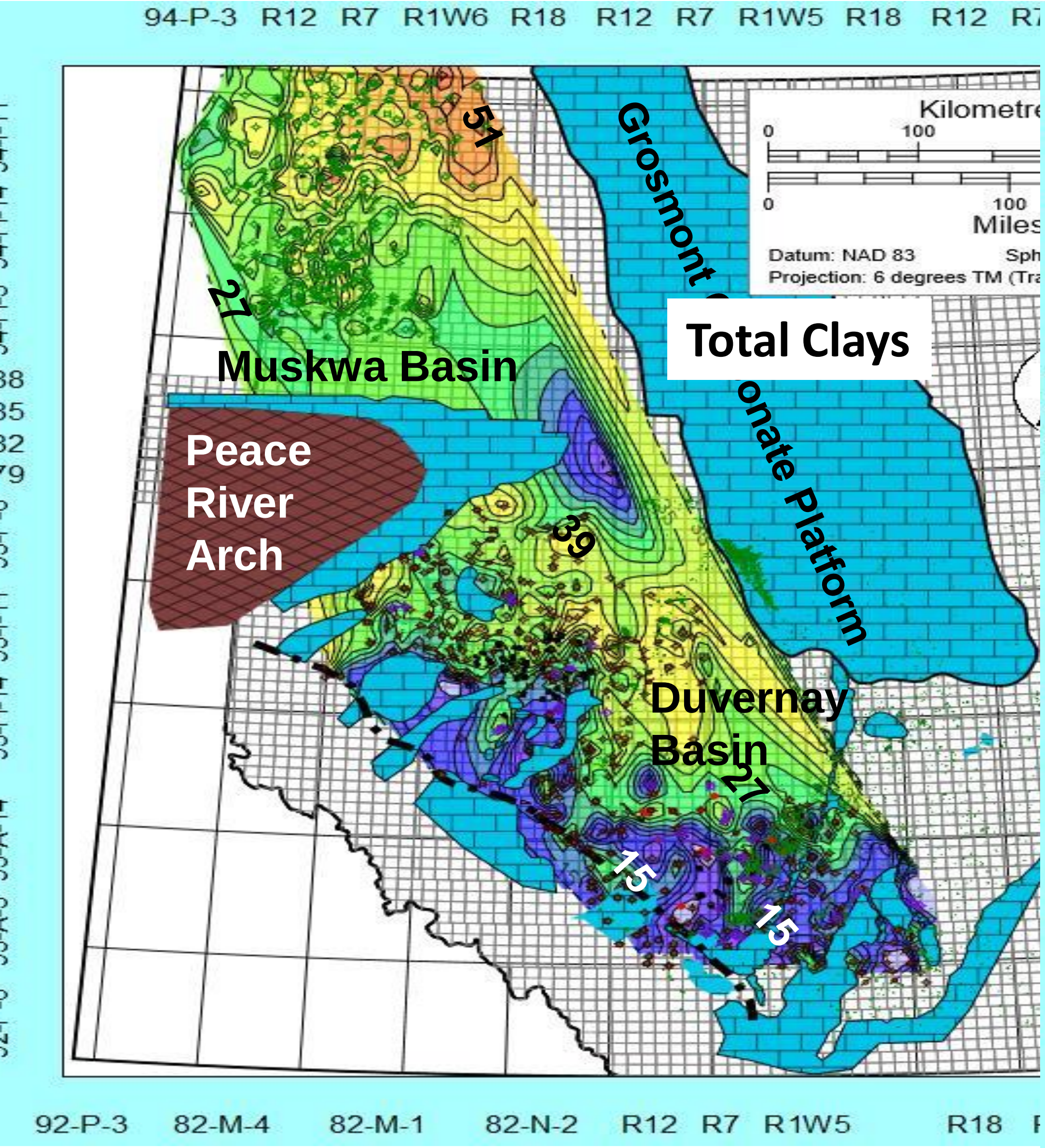
Highly crystalline clays, some clay neoformation and abundant euhedral quartz and feldspar

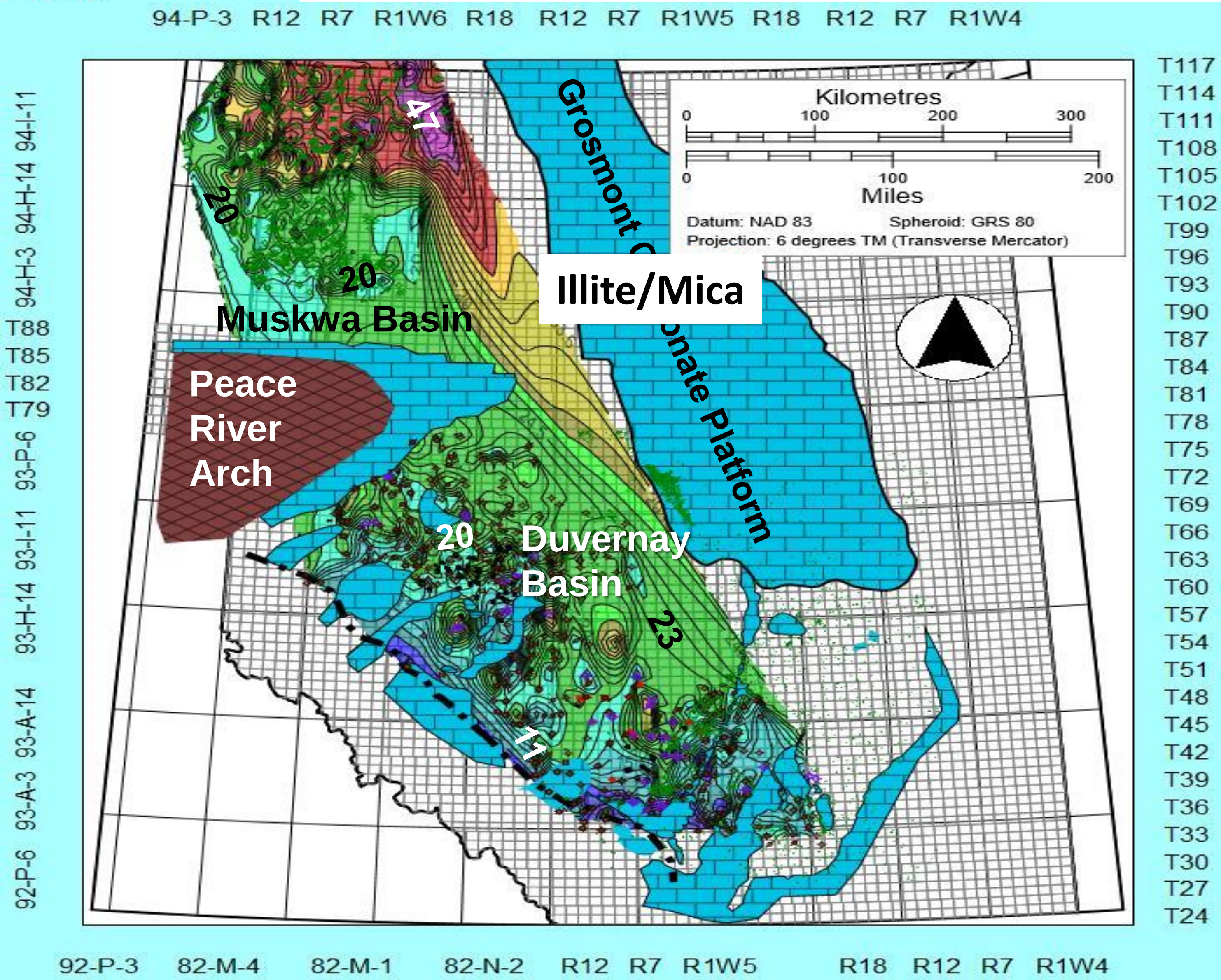
Clay structures Muskwa



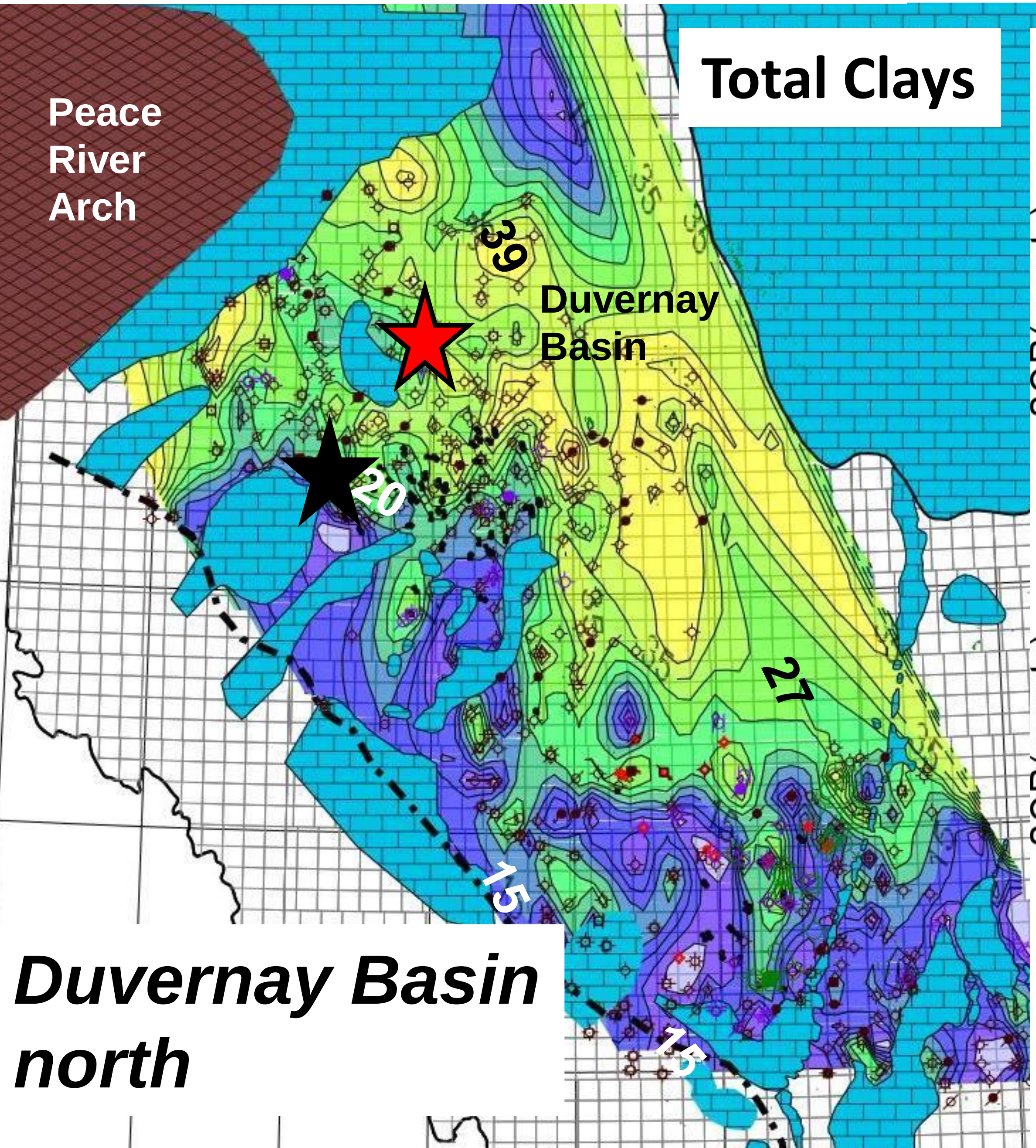


Total Clays and Illite/Mica

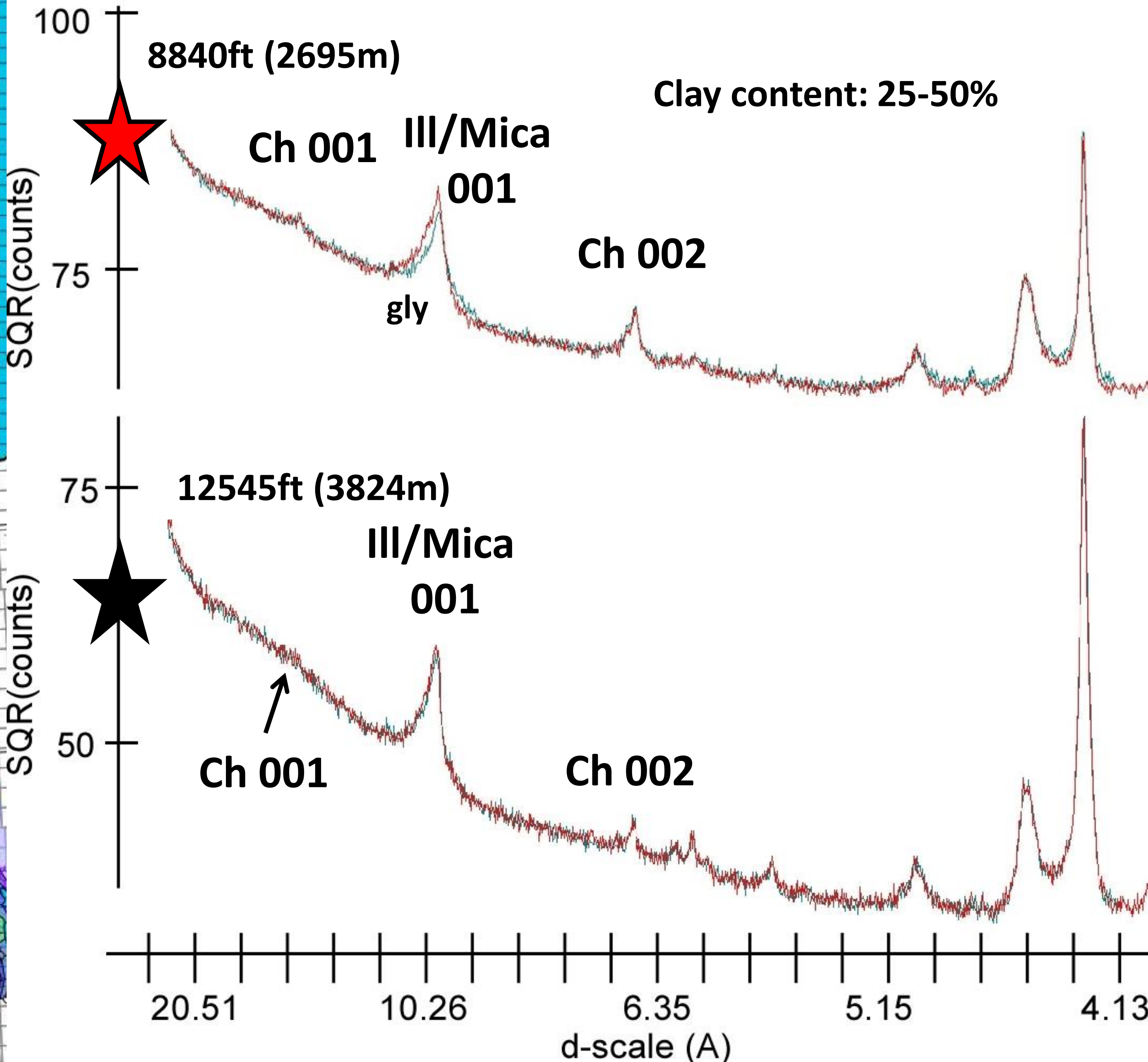


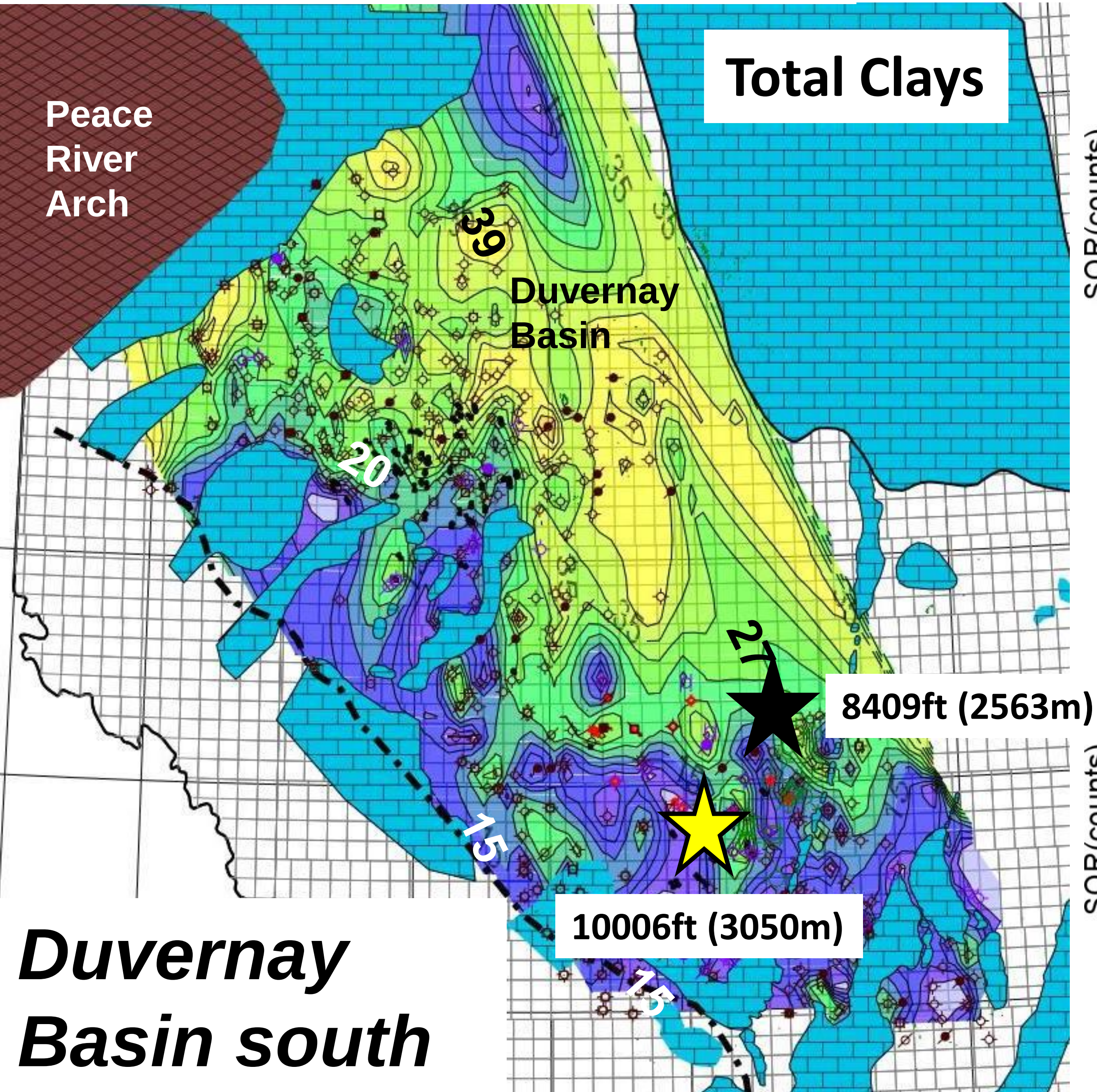


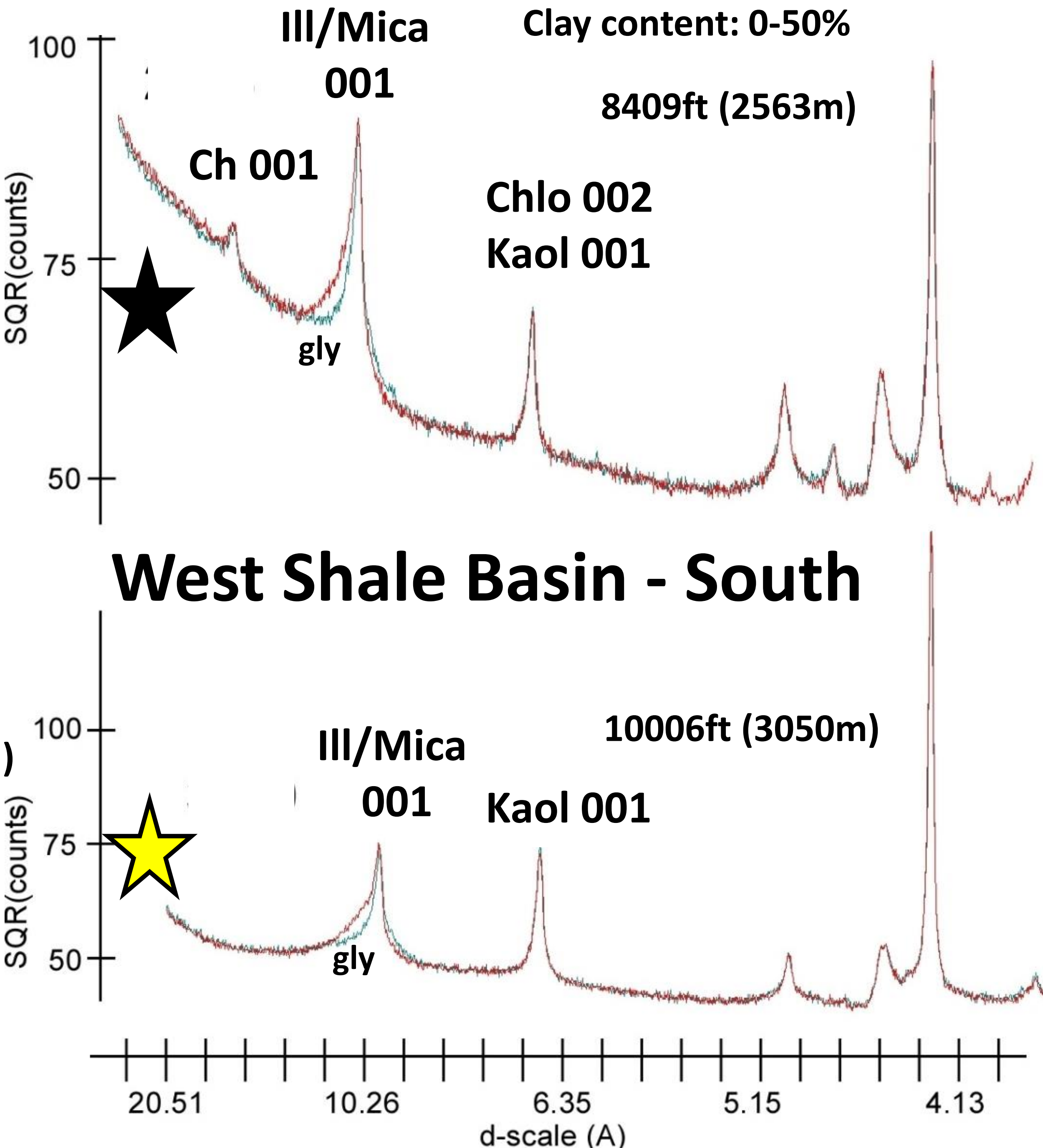
Clay Structures Duvernay



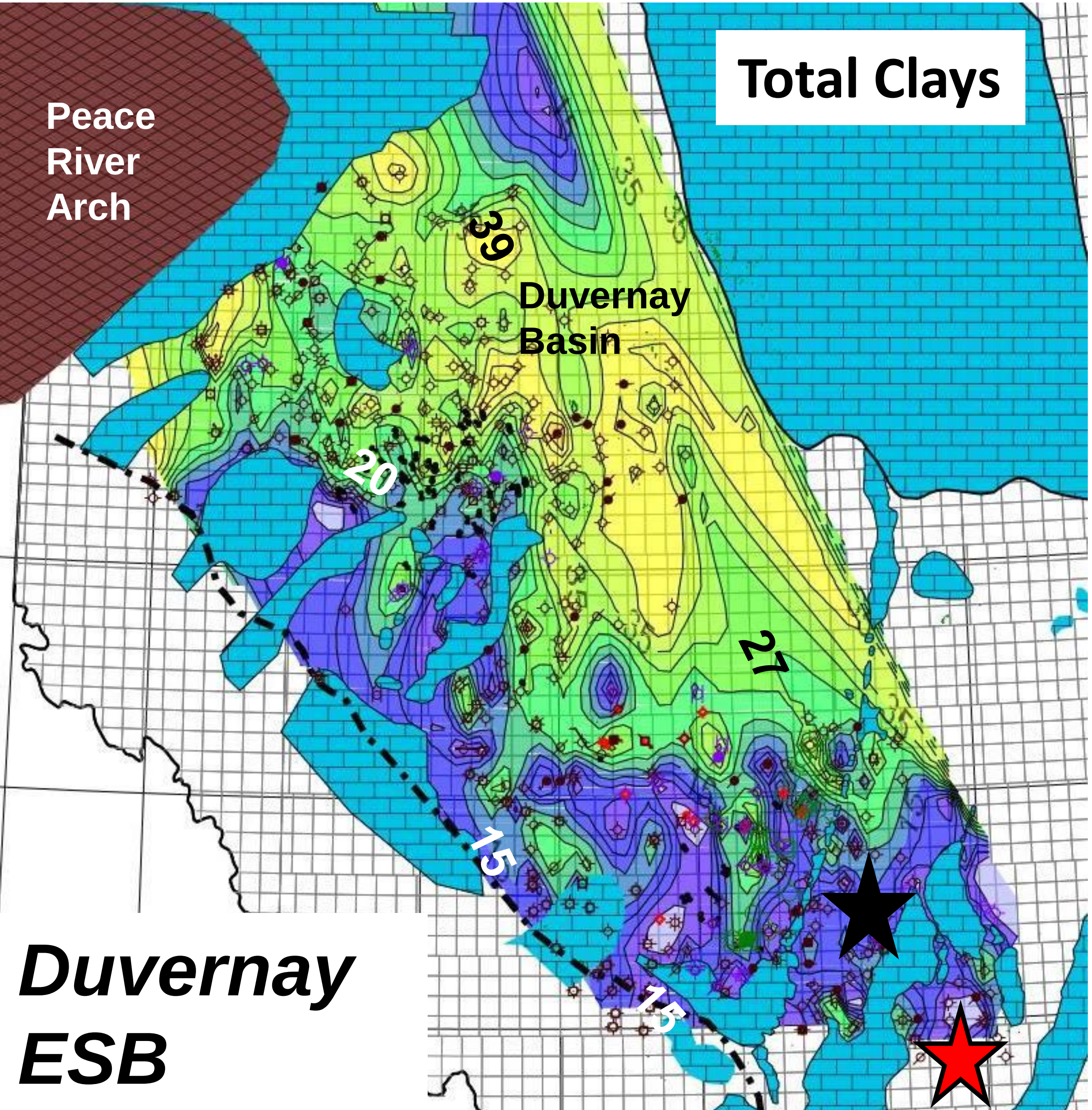
Duvernay Basin north

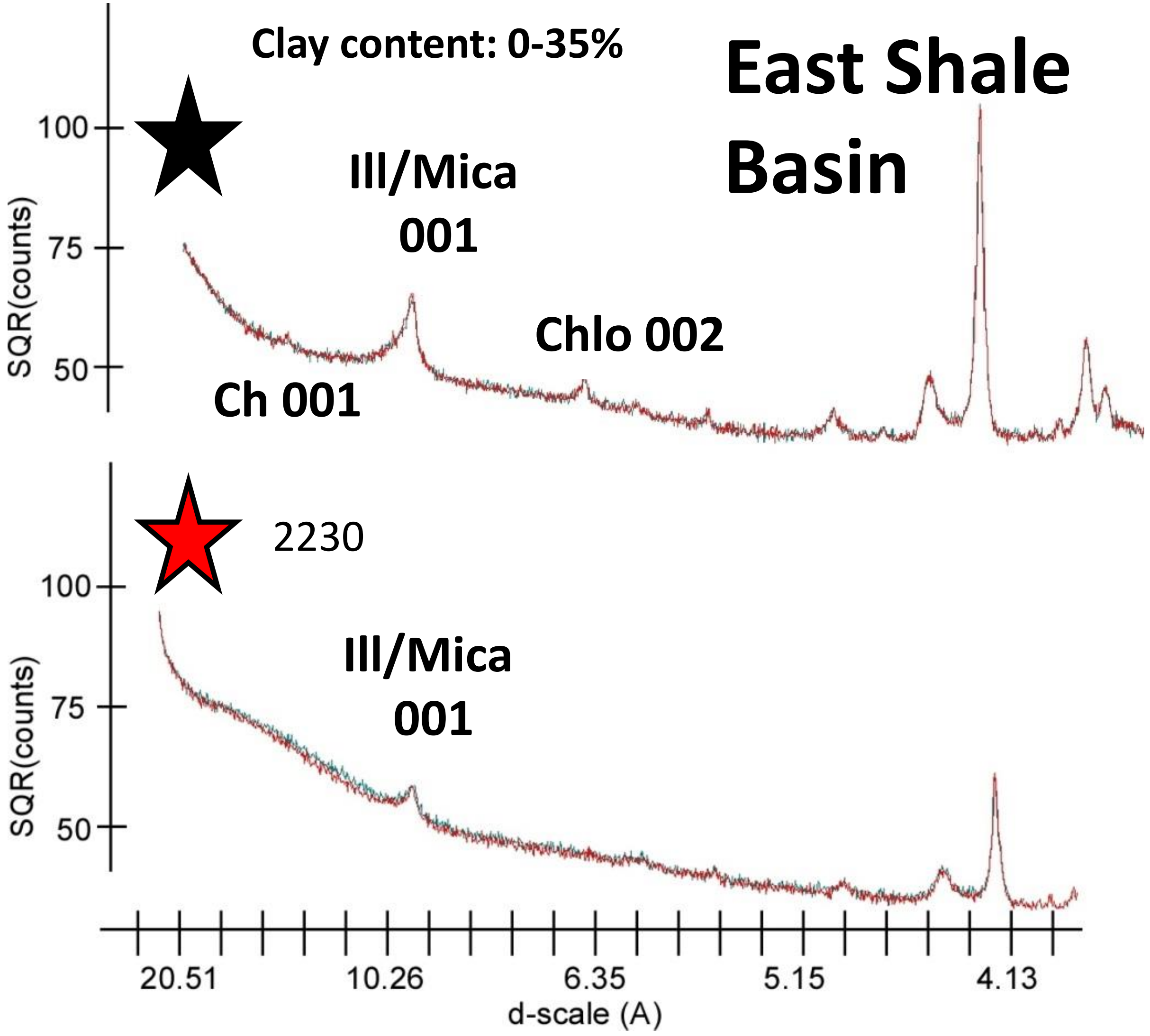



Total Clays
Peace
River
Arch
39
35
Duvernay
Basin
20
27
8409ft (2563m)
15
10006ft (3050m)
15
Duvernay
Basin south

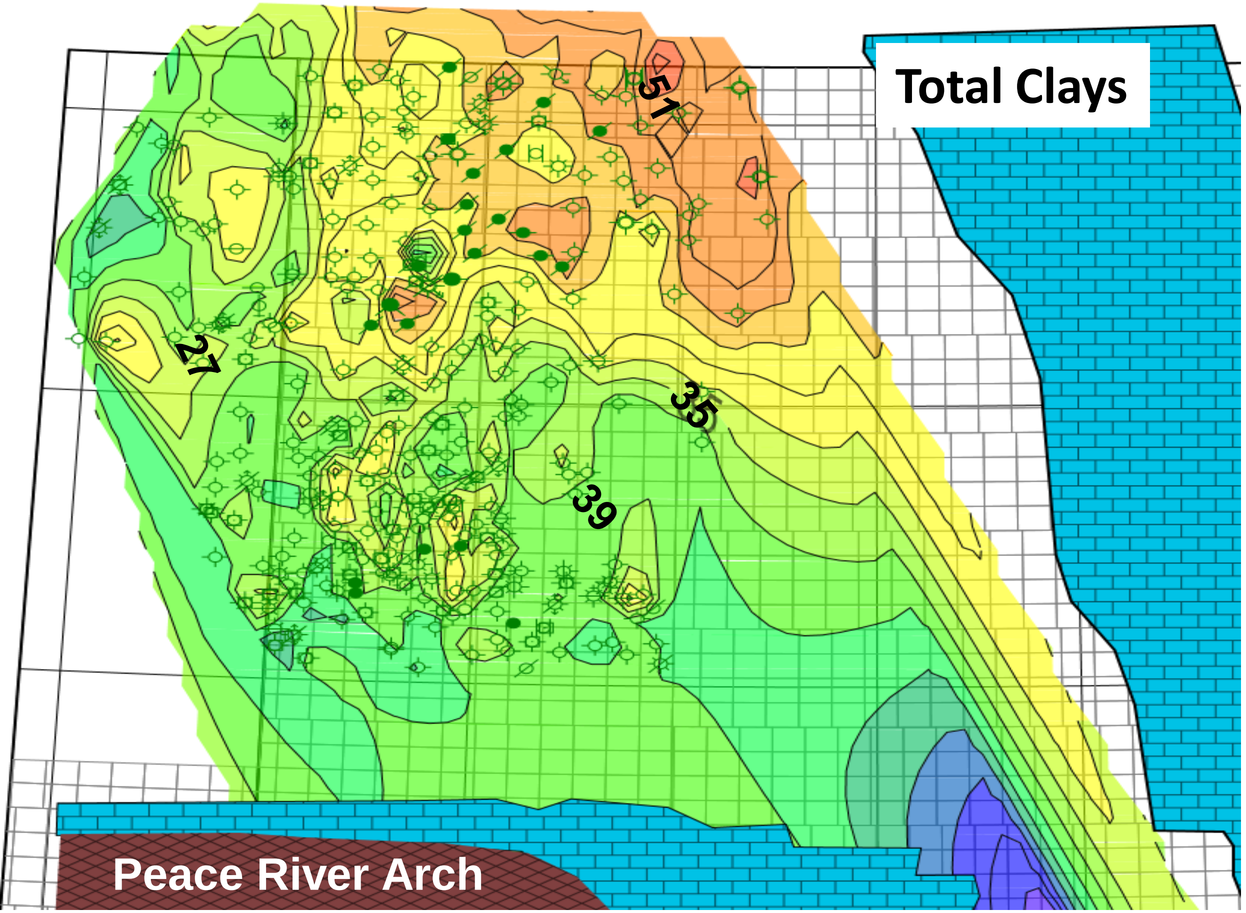

Clay content: 0-50%
Ill/Mica
001
8409ft (2563m)
Ch 001
Chlo 002
Kaol 001
gly
SQR(counts)
100
75
50
West Shale Basin - South
10006ft (3050m)
Ill/Mica
001
Kaol 001
gly
SQR(counts)
100
75
50
20.51
10.26
6.35
5.15
4.13
d-scale (A)

Clay Minerals Duvernay



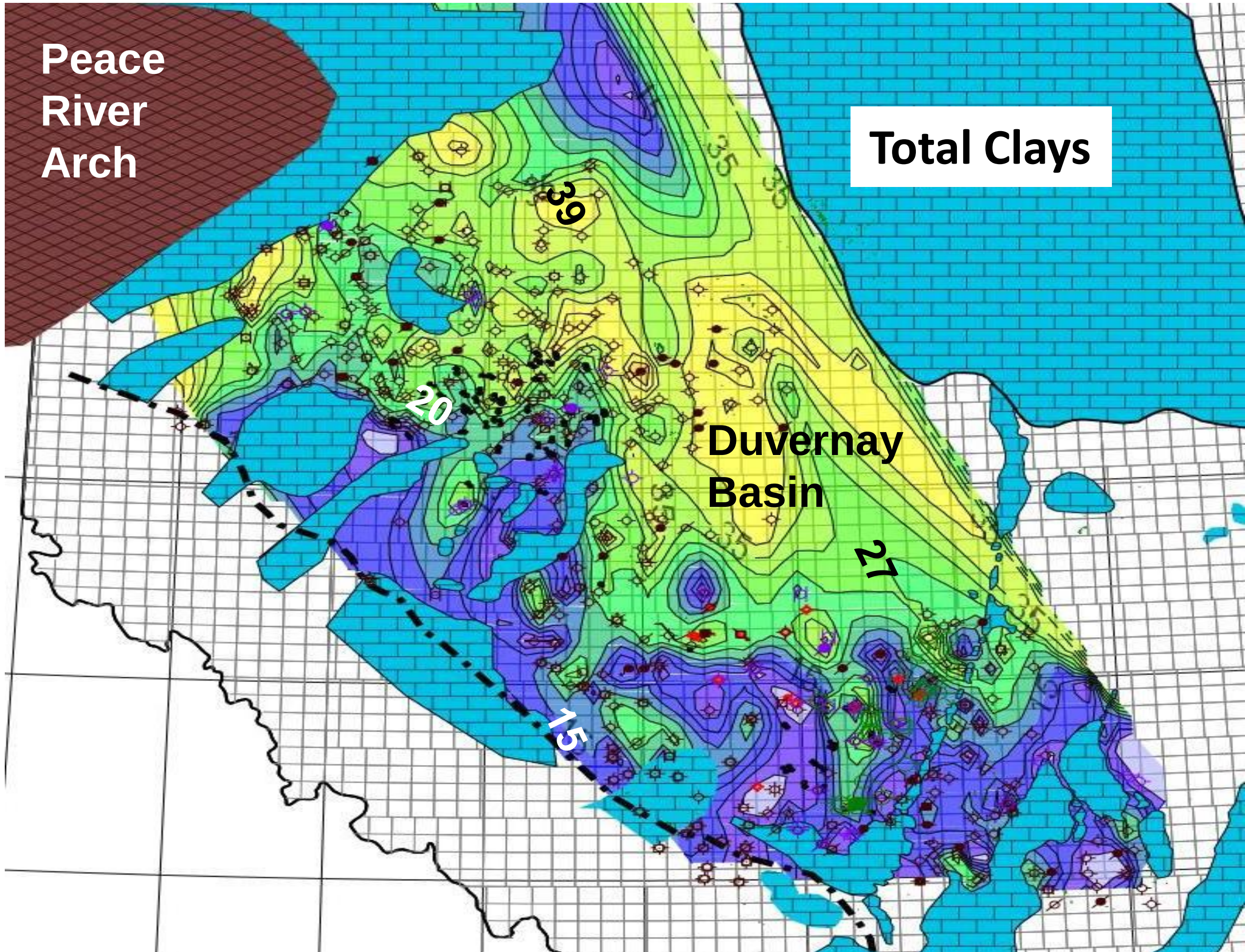


Total Clays in Muskwa and Duvernay Basin

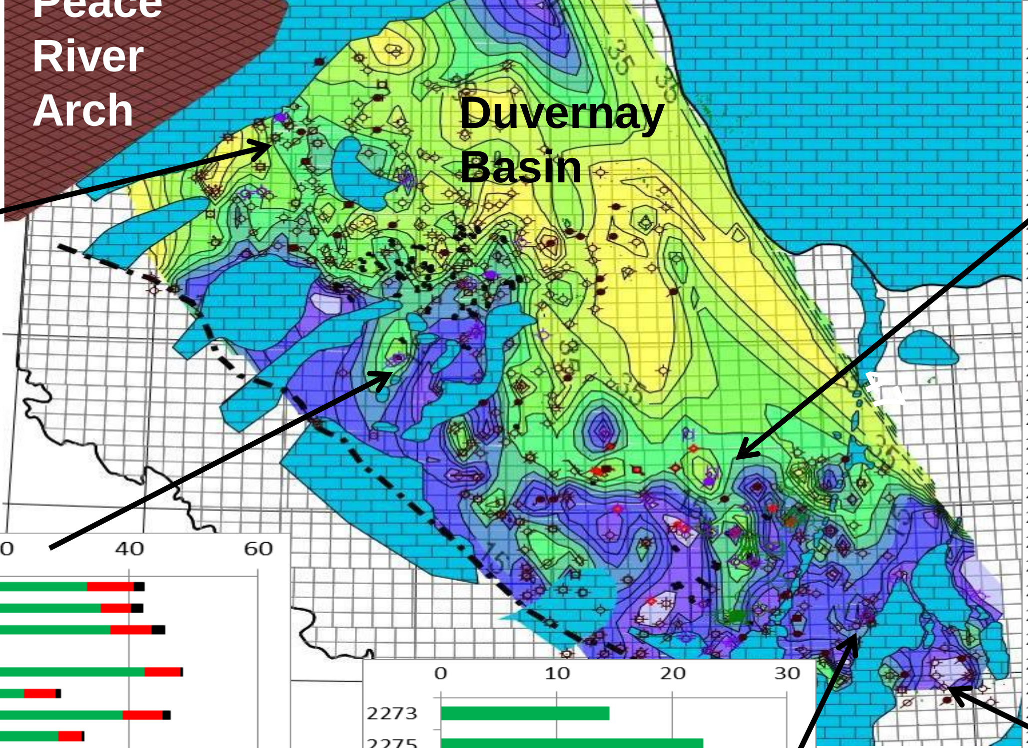


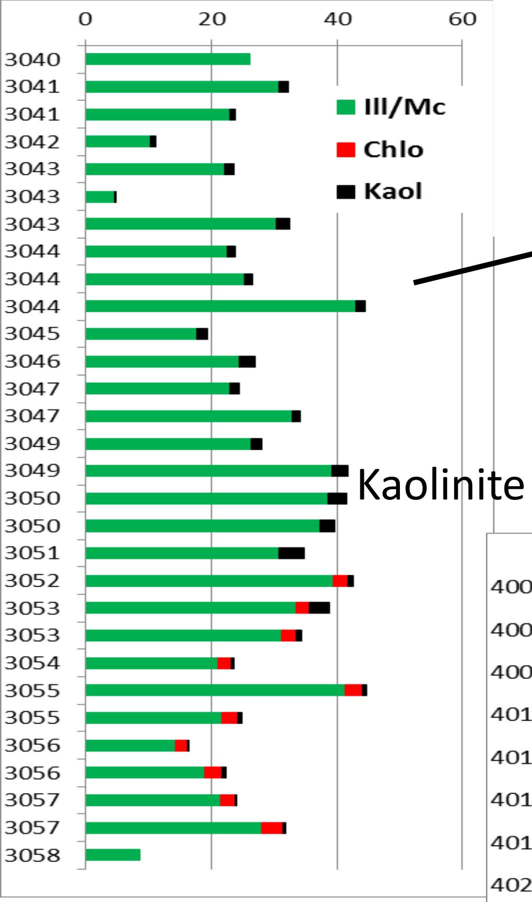
Muskwa Basin

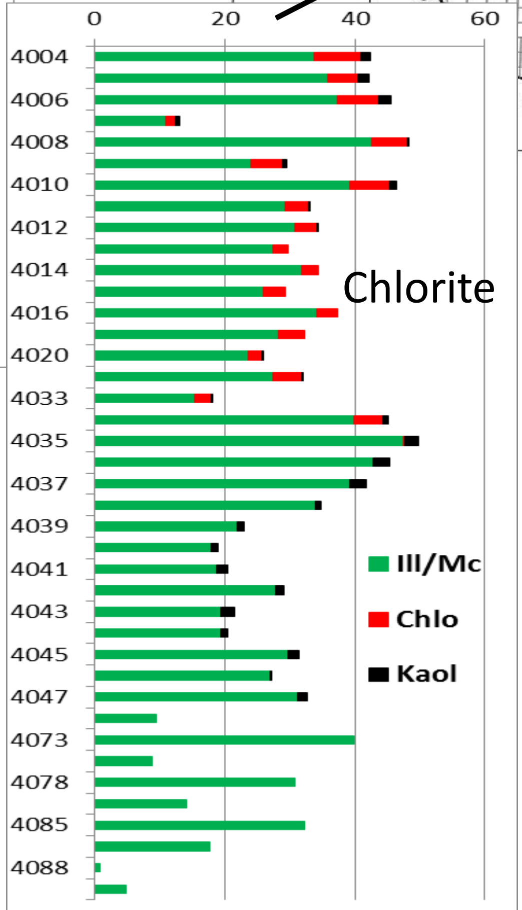
Duvernay Basin

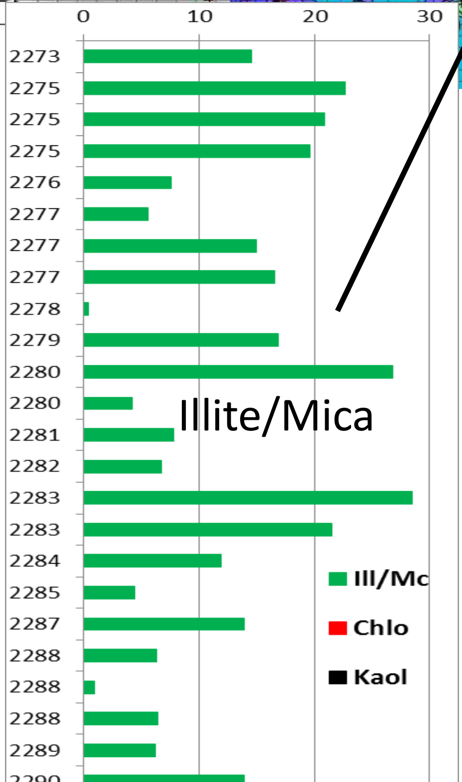


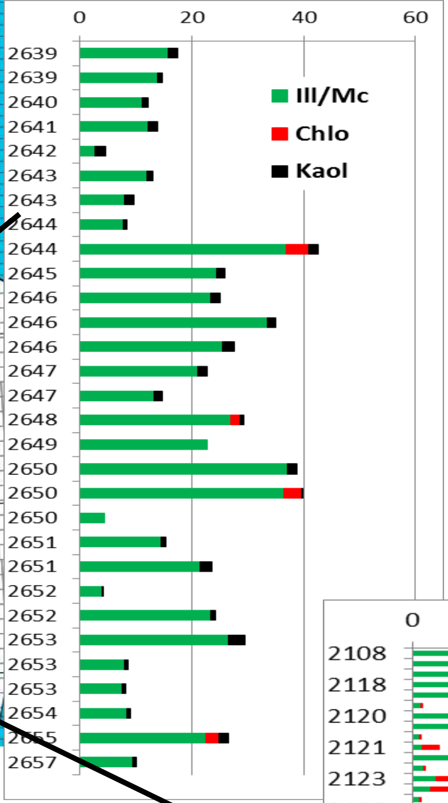
Downhole clays?

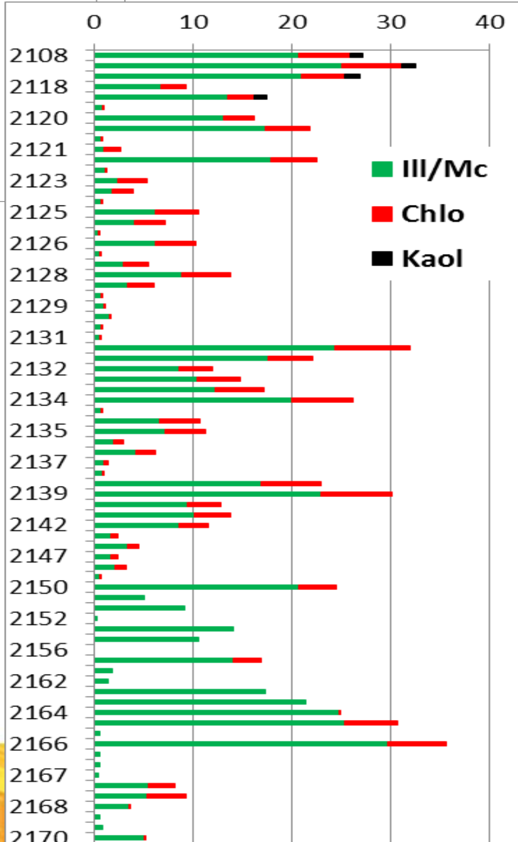












Clay Size Fraction (<2 µm) Duvernay Formation

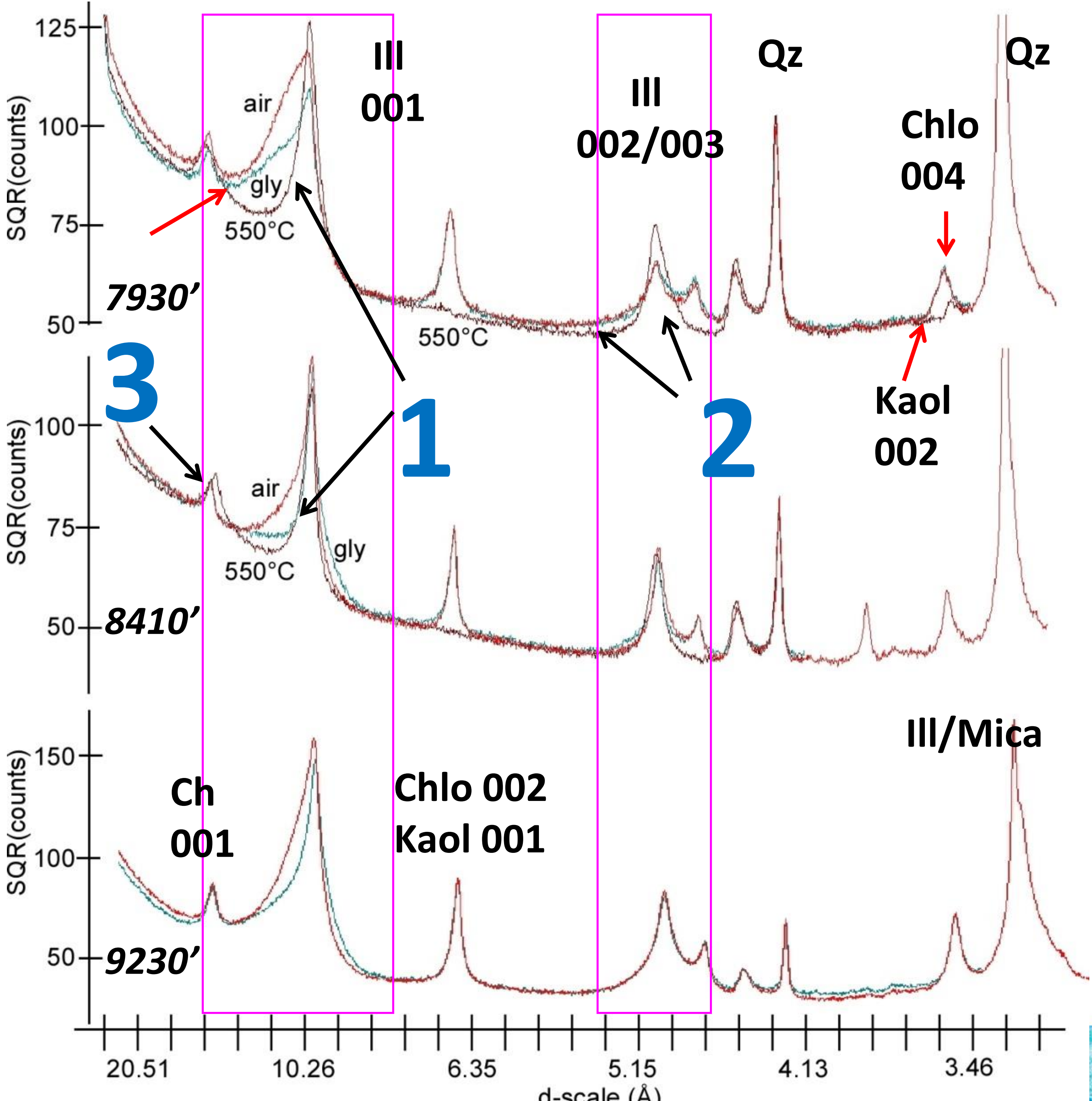
1) Partial peak shift of the illite, mixed-layer, microcrystalline illite peak position after glycolation. Structural changes present.

2) 002 illite peak <5.1Å implies no smectite interlayers

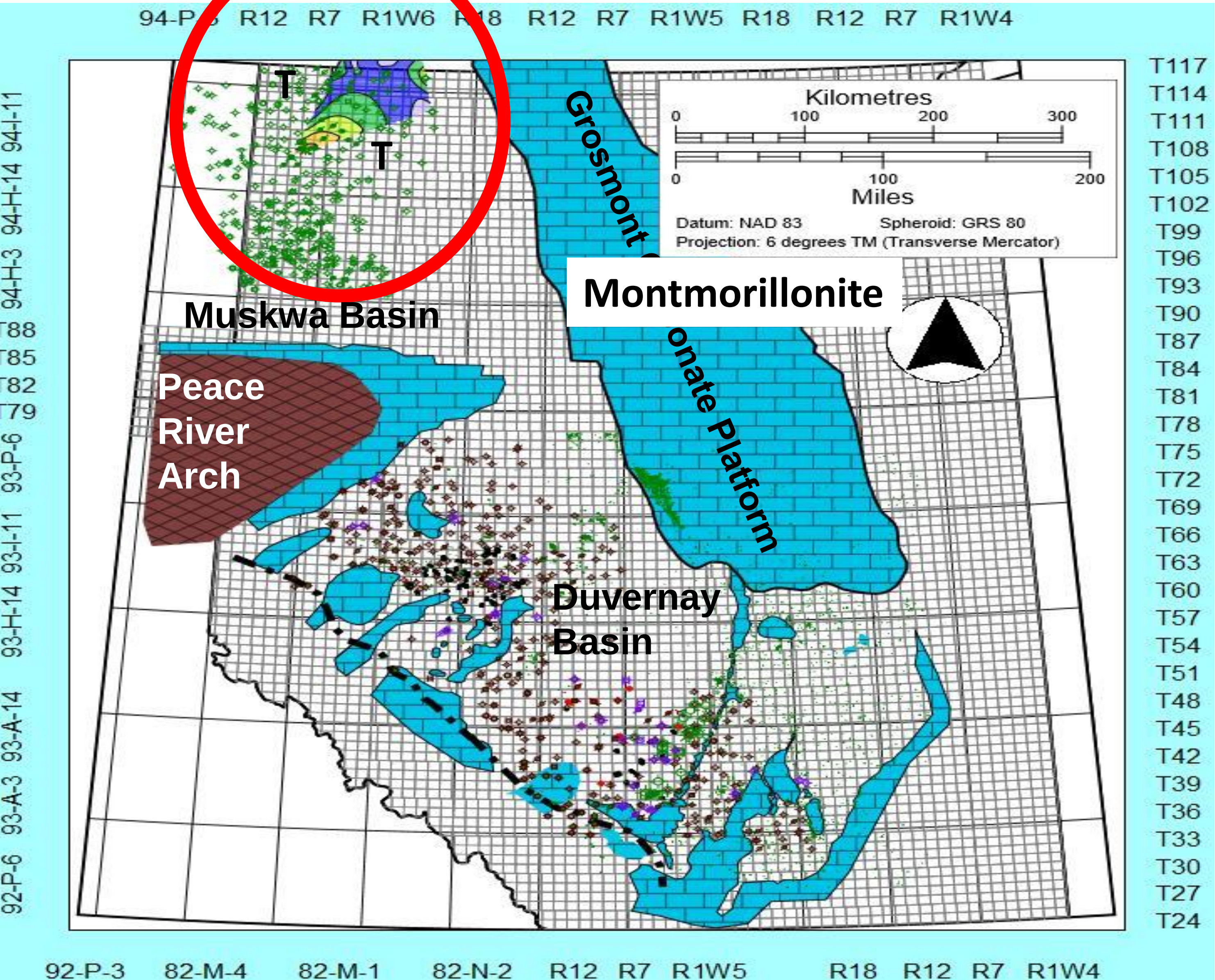
2) Zero shift of mixed-layer peak positions indicating no swelling capacity of the clays.

3) Slight shift of chlorite 001 peak illustrates small amounts of Fe in clay structure (i.e. Fe-chlorite).

Increasing crystallinity of illite with increasing depth!

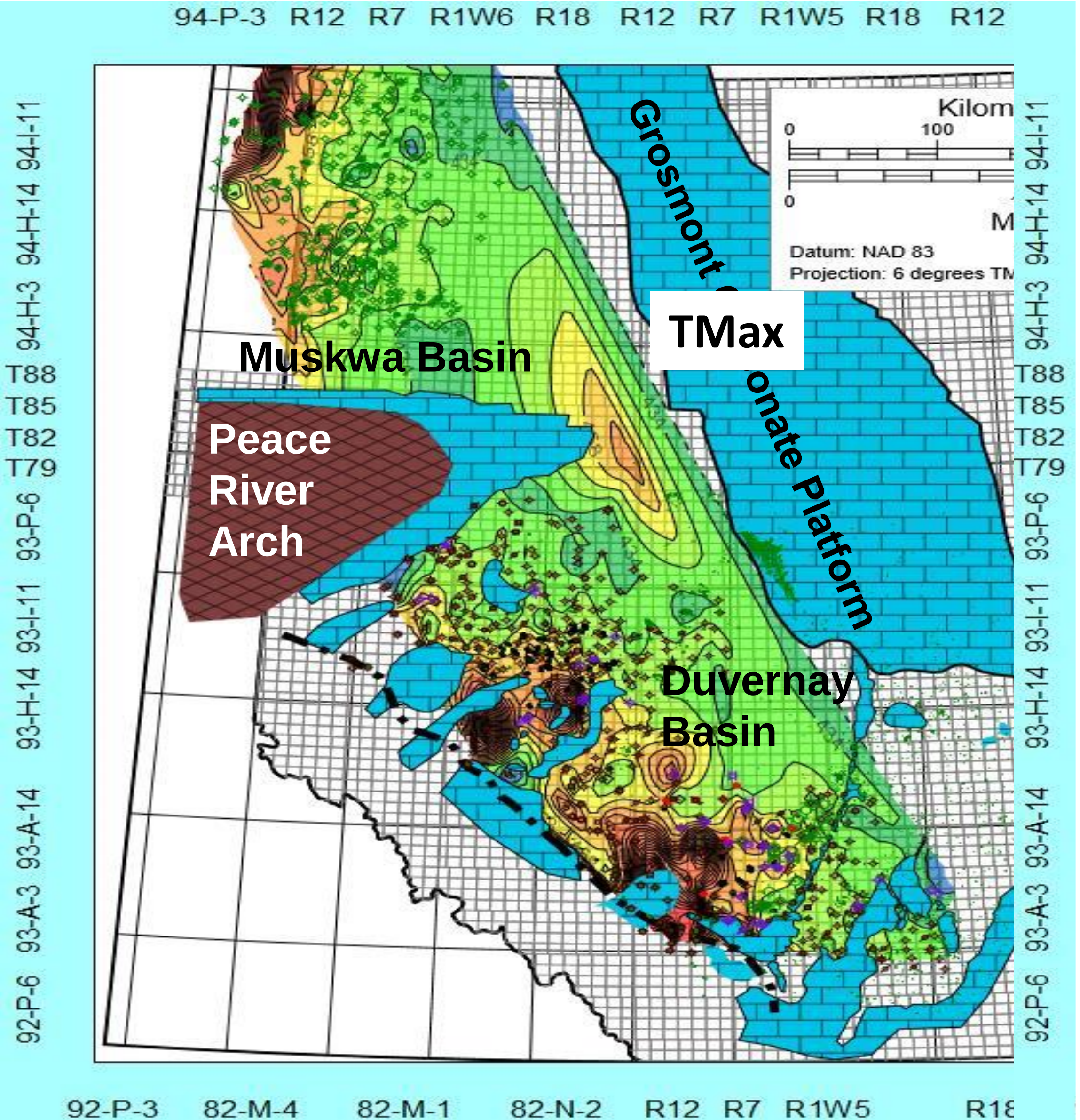


Swelling Clays in Muskwa and Duvernay Basin



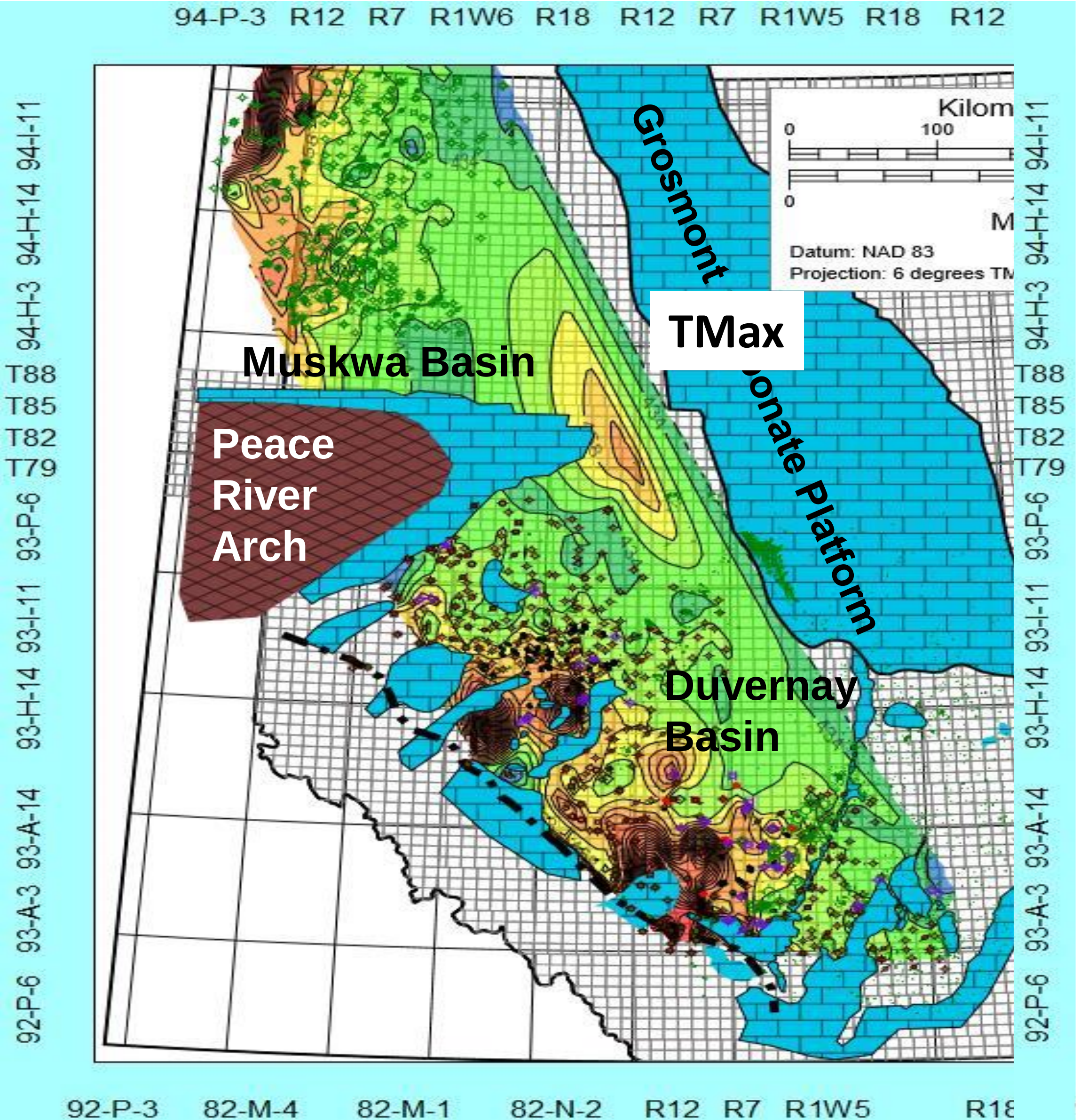
- Only NE corner of Muskwa Basin contains up to 15% of smectites.
- Smectite content decreases towards S and SW and quantification becomes difficult.
- Mixed layers present in the S part of the Muskwa Basin but crystallinity increases towards W with low to zero swelling capacity of the clays.
- Mixed layers present in the Duvernay Formation but no expandability

Summary – Muskwa Formation clay minerals



- Illite, chlorite, kaolinite, poorly structured (microcrystalline) or disintegrated illite/mica or mixed layers and montmorillonite clay minerals are determined within rock material of the Muskwa Formation.
- Total clay mineral contents are highest (>50%) in the NE part of the Muskwa Basin where burial depth is minimal.
- Clay mineral transformation trends are observed and follow depth-thermal heat patterns (i.e. maturity of rock and organics).
- The smectite clay minerals in the NE part of the basin infer both a source and burial control! (detritus and volcanic material during the time of deposition).

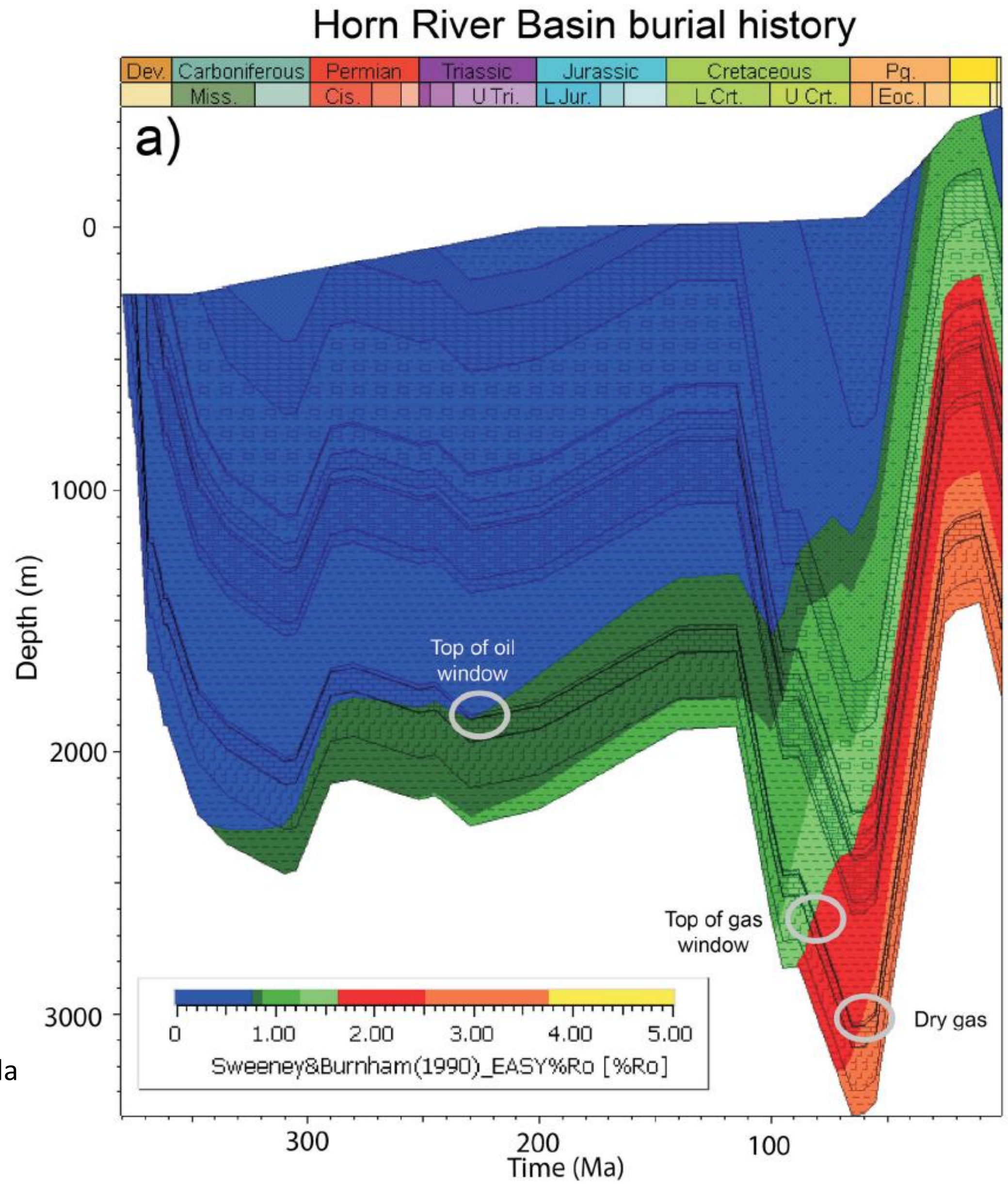
Summary – Duvernay Formation clay minerals



- Illite, chlorite, kaolinite clay, poorly structured (microcrystalline) or disintegrated illite/mica or mixed layers are determined.
- Total clay mineral contents are highest in the NE part of the Duvernay Basin close to the area that connected the two basins as well as locally where a close connection existed to PRA.
- Clay mineral composition trends are present and follow depth-thermal heat patterns (i.e. maturity of rock and organics).
- No smectite minerals are present throughout the Duvernay Formation (due to burial or lack of input?).

Conclusions

- Illitization and increased illite crystallinity in the Muskwa and Duvernay Formation are observed with increasing burial (and following a heat transfer gradient) from East to West.
- In the Muskwa Formation, a successive trend from smectite-rich rocks (Alberta) to rocks without smectite minerals (Horn River Basin, Liard Basin) is present which reflects burial profile.
- Clay mineral transformation associated with albite, quartz neoformation and increased clay crystallinity represent a valuable thermal history record.
- Clay mineral transformation influence other mineral neoformation which overall impact cementation, porosity and permeability (combined with organic matter maturation).



Wilson, T.K. and Bustin, R.M. (2019): Basin modelling and thermal history of the Horn River and Liard basins, Cordova Embayment, and adjacent parts of the Western Canada Sedimentary Basin; *in* Geoscience BC Summary of Activities 2018: Energy and Water, Geoscience BC, Report 2019-1, p. 1–20.

Thank You!

Cretaceous Shale outcrop – Utah (AGAT Shale Field trip)