Gradients in Sediment Geochemistry as a Constraint on Modeling Epeiric Sea Circulation*

Thomas J. Algeo[1], Achim Herrmann[2], and Bernd Haupt[3]

Search and Discovery Article #50265 (2010)
Posted June 21, 2010

*Adapted from oral presentation at AAPG Convention, New Orleans, Louisiana, April 11-14, 2010

[1]Geology, University of Cincinnati, Cincinnati, OH (thomas.algeo@uc.eduv)
[2]Barrett Honors College, Arizona State University, Tempe, AZ
[3]Earth and Environmental Systems Institute, Pennsylvanian State University, University Park, PA

Abstract

Ancient epeiric sea deposits commonly exhibit lateral gradients in chemistry that are a reflection of spatial variation in environmental conditions. Such gradients place constraints on paleocirculation patterns and may be used to define regions of chemically distinct water masses termed “aquafacies” in which the residence time of a proxy is less than the oceanic mixing time. Tracers such as Nd isotopes and clay-mineral assemblages provide evidence of spatial variation in the provenance of the detrital fraction. Oxygen isotopes can provide information concerning spatial variation in watermass $\delta^{18}O$ (e.g., as a function of salinity variation) or temperature. Carbon isotopes, although subject to more numerous controls, can provide information about spatial variation in marine primary productivity and carbon cycling. Various proxies including DOP, trace metals, and Fe_T/Al have been used to discern spatial gradients in paleoredox conditions. All of these proxies provide indirect clues to paleocirculation patterns, although such information has rarely been integrated in a systematic manner, even for those few ancient epeiric seas that have been extensively studied to date, such as the Late Ordovician Mohawkian Sea1.

We are in the early stages of an integrated data-model study of the North American "Midcontinent Sea" (Middle-Late Pennsylvanian) that will investigate spatial gradients in the proxies above for the purpose of evaluating the robustness of model simulations of paleocirculation patterns. This sea provides a useful case study for internal circulation in ancient epeiric seas owing to its large area (~2.1 x 106 km^2 at highstands), relatively uniform seafloor bathymetry, and pronounced lateral gradients in sediment geochemistry.

Acknowledgments

Ron Blakey (ANU), Phil Heckel (U. Iowa), James C. Hower (U. Kentucky), Barry Maynard (U. Cincinnati), Jeff Over (SUNY Geneseo), Lorenz Schwark (U. Cologne).

Selected References

Algeo, T.J., and N. Tribovillard, 2009, Environmental analysis of paleoceanographic systems based on molybdenum-uranium covariation: Chemical Geology, v. 268, p. 211-225.

Algeo, T.J., H. Rowe, J.C. Hower, L. Schwark, A. Hermann, and P.H. Heckel, 2008, Oceanic denitrification during Late Carboniferous glacial-interglacial cycles: Nature Geoscience, v. 1, p. 709-714.

Algeo, T.J., and J.B. Maynard, 2008, Trace metal covariation as a guide to water-mass conditions in ancient anoxic marine environments: Geosphere, 4:5, p. 872-887.

Algeo, T.J., and P.H. Heckel, 2008, The Late Pennsylvanian Midcontinent Sea of North America: A review: Palaeogeography Palaeoclimatology Palaeoecology, v. 268, p. 205-221.

Algeo, T.J., P.H. Heckel, J.B. Maynard, R. Blakey, and H. Rowe, 2008, Modern and ancient epicratonic seas and the superestuarine circulation model of marine anoxia, *in* C. Holmden, and B.R. Pratt, (Eds.), Dynamics of Epeiric Seas: Sedimentological, Paleontological and Geochemical Perspectives: Geological Association of Canada Special Publication, v. 48, p. 7-38.

Algeo, T.J., L. Schwark, and J.C. Hower, 2004, High-resolution geochemistry and sequence stratigraphy of the Hushpuckney Shale (Swope Formation, eastern Kansas): Chemical Geology, v. 206, p. 259-288.

Algeo, T.J. , and J.B. Maynard, 2004, Trace element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems: Chemical Geology, v. 206, p. 289-318.

Cruse, A.M. and T.W. Lyons, 2004, Trace metal records of regional paleoenvironmental variability in Pennsylvanian (Upper Carboniferous) black shales: Chem. Geol. v. 206, p. 319-345.

Fanton K.C. and C. Holmden, 2007, Sea level forcing of carbon isotope excursions in epeiric seas: implications for carbon isotope chemostratigraphy: Canadian Journal of Earth Science, v. 44, p. 807-818.

Fanton K.C., C. Holmden, G.S. Nowlan, and F.M. Haidl, 2002, $^{143}Nd/^{144}Nd$ and Sm/Nd stratigraphy of Upper Ordovician epeiric sea carbonates: Geochimica et Cosmochimica Acta, v. 66, p. 241-255.

Holmden, C., R.A. Creaser, K. Muehlenbachs, S. Leslie, and S.M. Bergstrom, 1998, Isotopic evidence for geochemical decoupling between ancient epeiric seas and bordering oceans: implications for secular curves: Geology, v. 26, p. 567-570.

Immenhauser, A., et al., 2008, *in* Dynamics of Epeiric Seas, Holmden and Pratt (eds.),: Geol. Assoc. Canada Spec. Publ. 48, pp. 137-174.

Joachimski, M.M., P.H. von Bitter, and W. Buggisch, 2006, Constraints on Pennsylvannian glacioeustatic sea-level changes using oxygen isotopes of conodont apatite: Geology, v. 34, p. 277-280.

Kolata, D.R., W.D. Huff, and S.M. Bergstrom, 2001, The Ordovician Sebree Trough; an oceanic passage to the Midcontinent United States: GSA Bulletin, v. 113/8, p. 1067-1078.

Kolata, D.R., S.M. Bergstrom, and W.D. Huff, 2001, Impact of the Sebree Trough on Middle and Late Ordovician paleoceanography of the Midcontinent USA: Abstracts with Programs, GSA, v. 33/6, p. 213.

Panchuk, K. M., C. Holmden, and S.A. Leslie, 2006, Local controls on carbon cycling in the Ordovician Midcontinent region of North America with implications for carbon isotope secular curves: Journal of Sedimentary Research, v. 76, p. 200-211

Rahm, L. and A. Danielsson, 2007, The spatial heterogeneity of nutrients in the Baltic Proper, Baltic Sea: Estuarine, Coastal and Shelf Science, v. 73, p. 268-278.

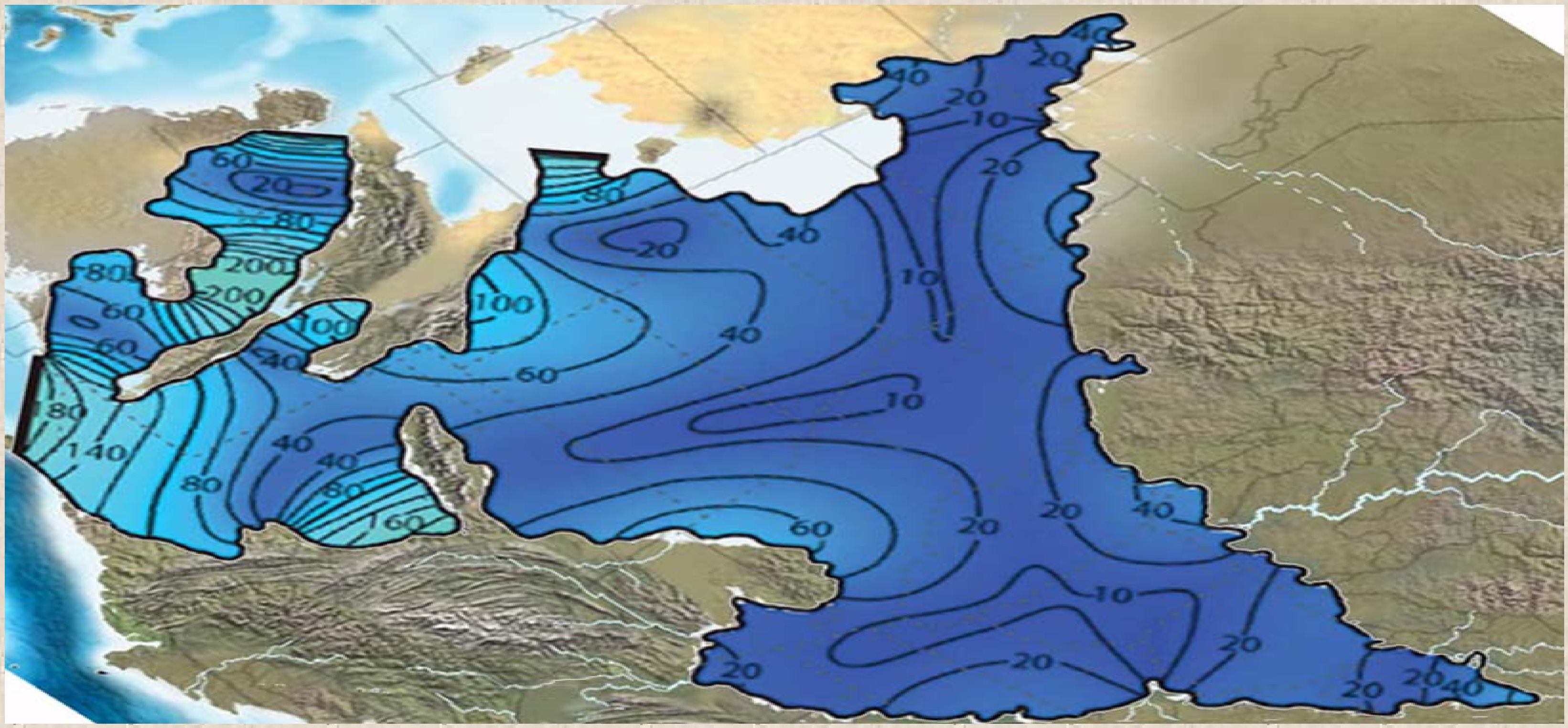
Wells, M.R.,P.A. Allison, M.D. Piggott, G.J. Gorman, G.J. Hampson, C.C. Pain, and F.Fang, 2007, Numerical modeling of tides in the Late Pennsylvanian Midcontinent Seaway of North America with implications for hydrography and sedimentation: Journal of Sedimentary Research, v. 77/10, p. 843-865.

Witzke, B.J.. 1987, Models for circulation patterns in epicontinental seas applied to Paleozoic facies of North America Craton: Paleoceanography, v. 2/2, p. 229-248.

Witzke, B.J., 1987, Middle and Upper Ordovician stratigraphy in the Iowa subsurface: Report of Investigations, Minnesota Geological Survey, v. 35, p.40-43.

Witzke, B.J., 1987, Depositional cycles and facies in the Maquoketa Formation, Upper Ordovician of Iowa, Abstracts with Programs, GSA, v. 19/4, p. 253.

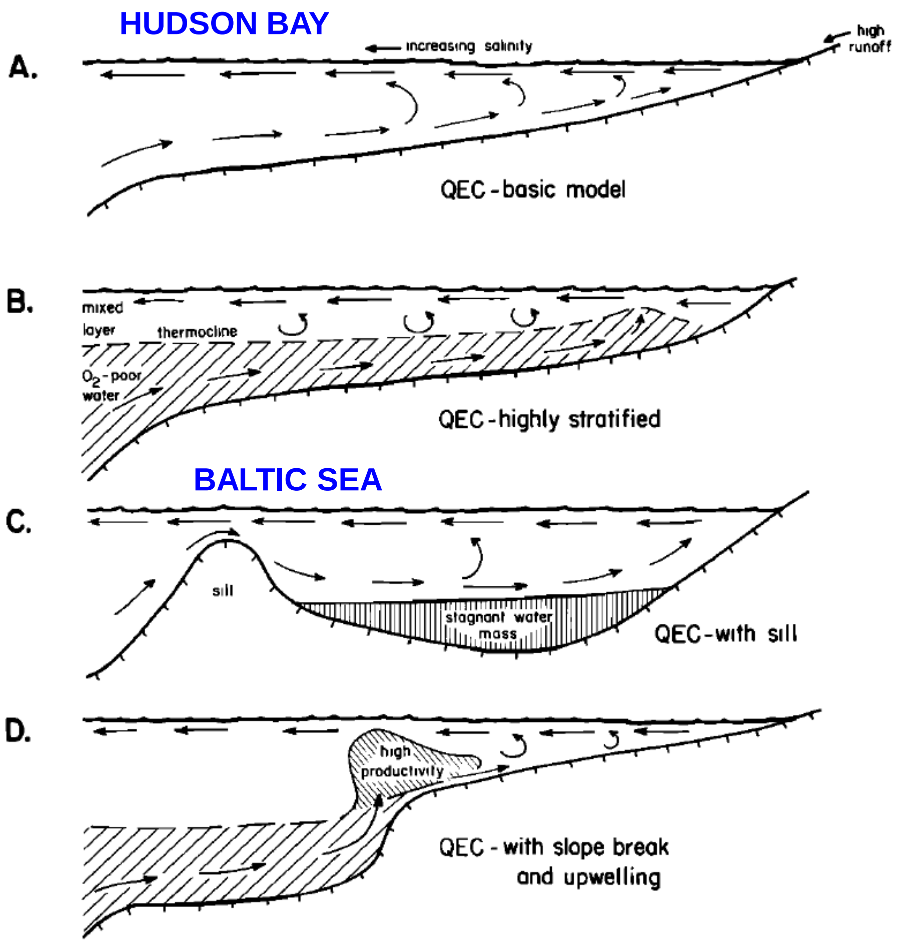
Gradients in sediment geochemistry as a constraint on modeling epeiric sea circulation



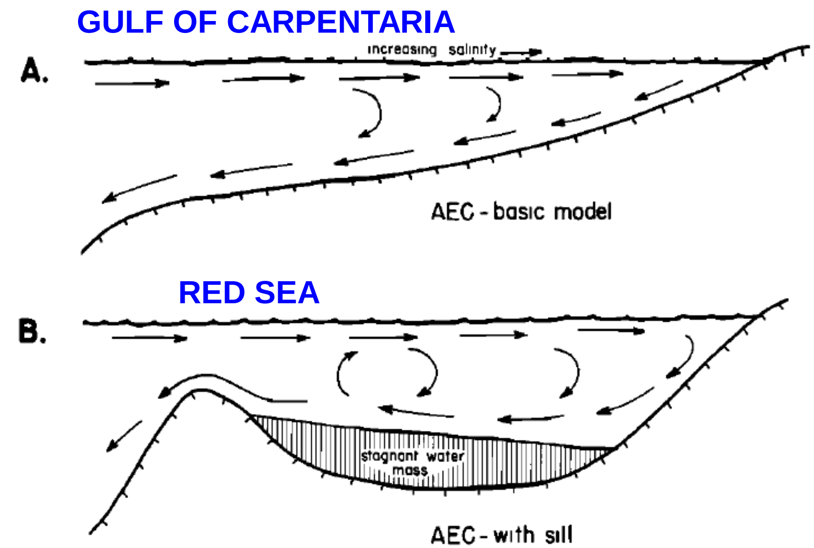
Thomas Algeo, University of Cincinnati
Achim Herrmann, Arizona State University
Bernd Haupt, Pennsylvania State University

Circulation patterns in epeiric seas

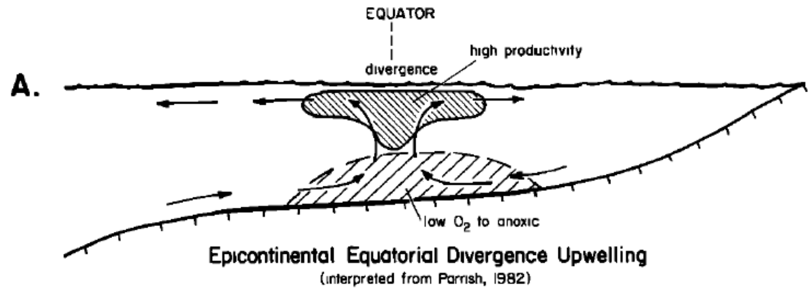
Quasi-estuarine circulation (positive water balance)



Anti-estuarine circulation (negative water balance)

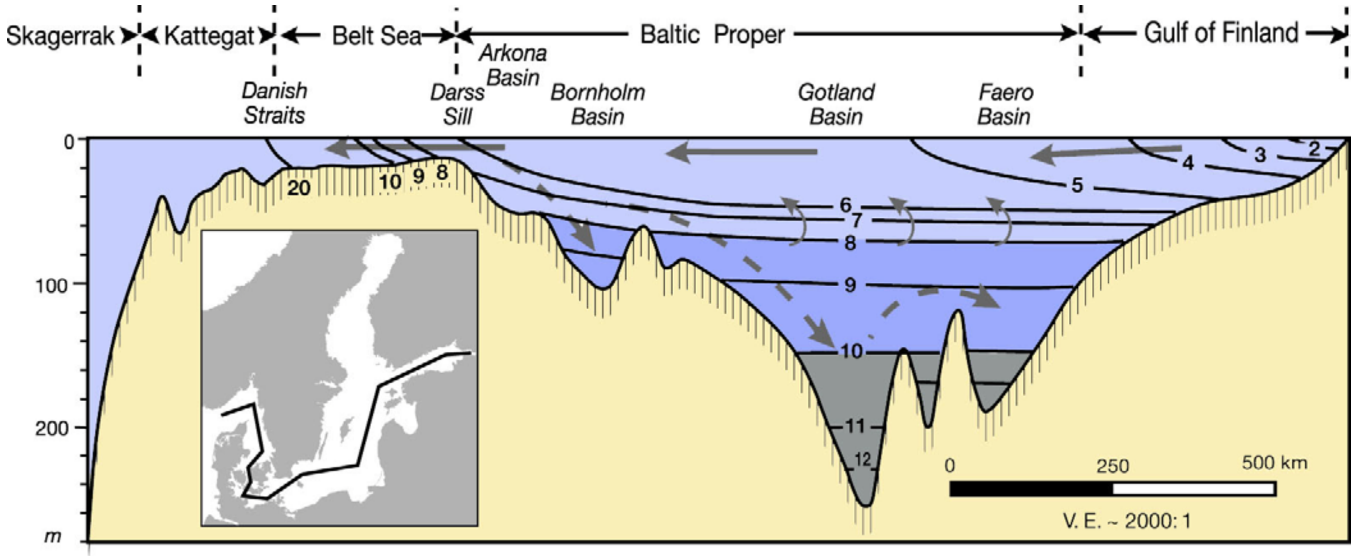


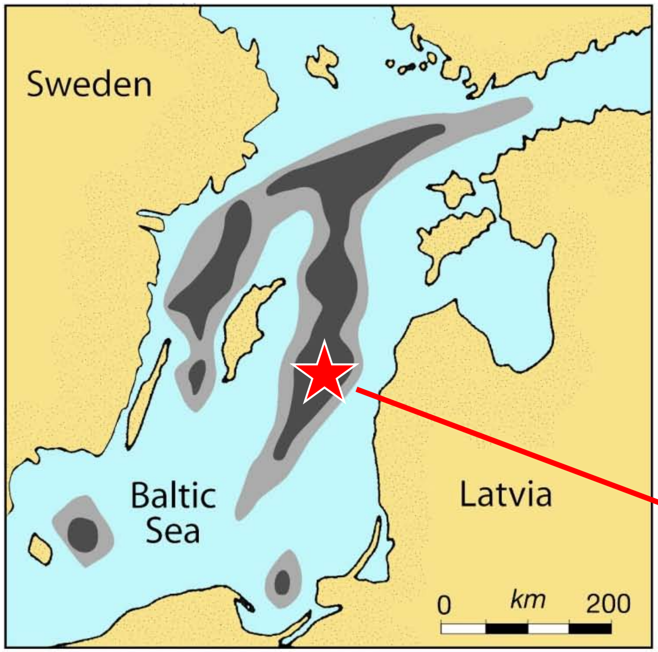
Equatorial divergence

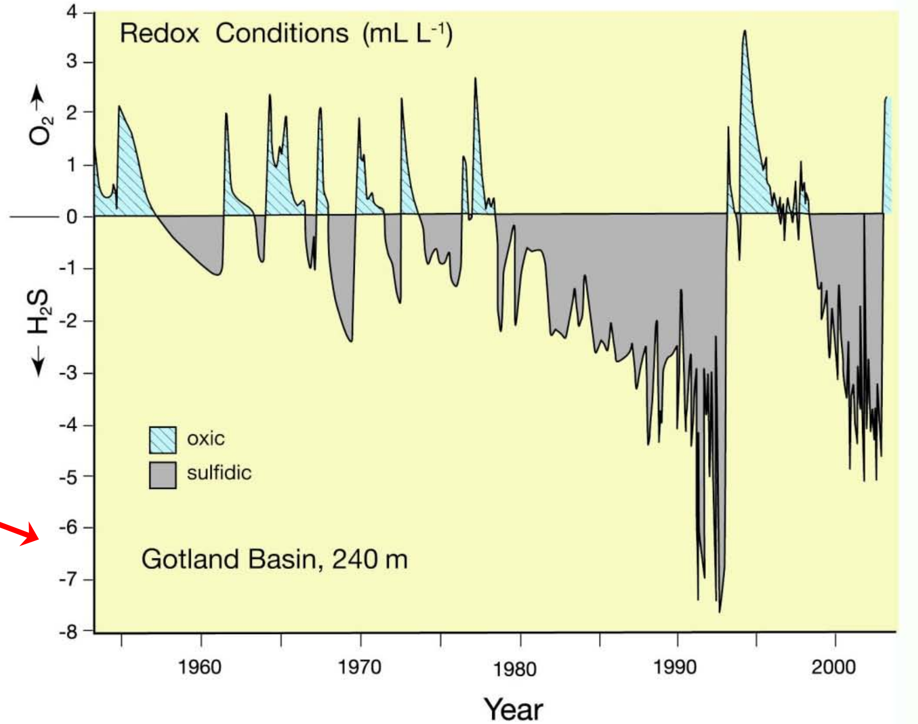


Witzke (1987)

Baltic Sea:
silled anoxic basin; episodic deepwater renewal; basin-centered anoxia



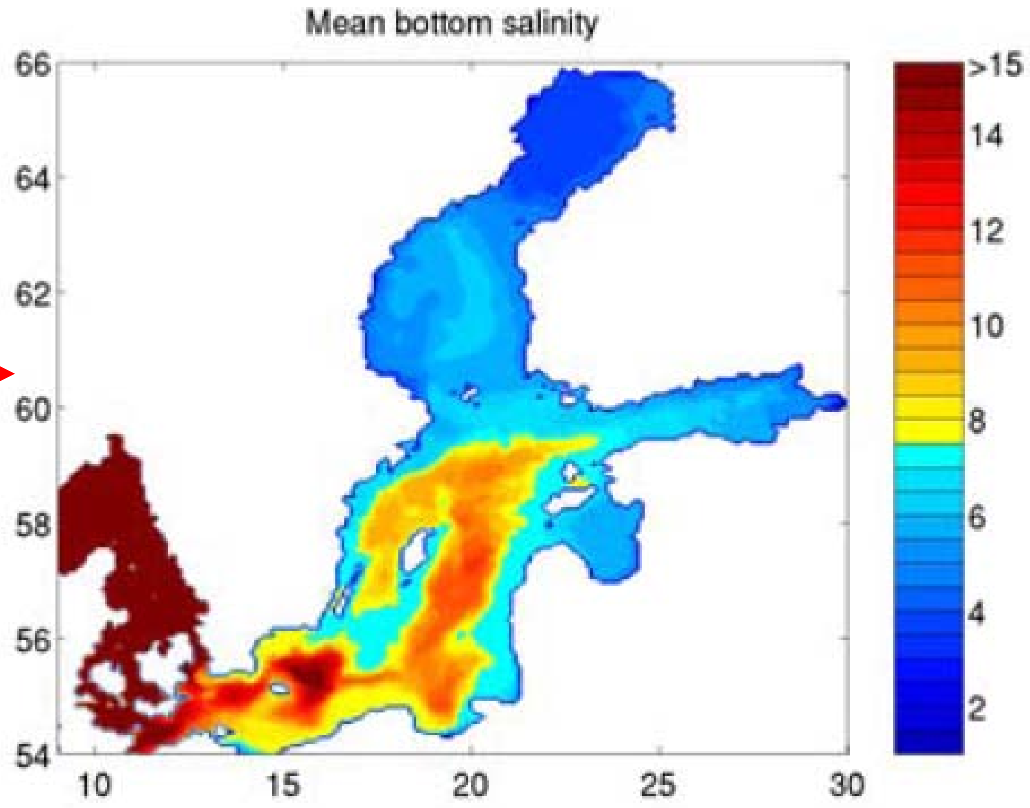




Algeo et al. (GAC, 2008)

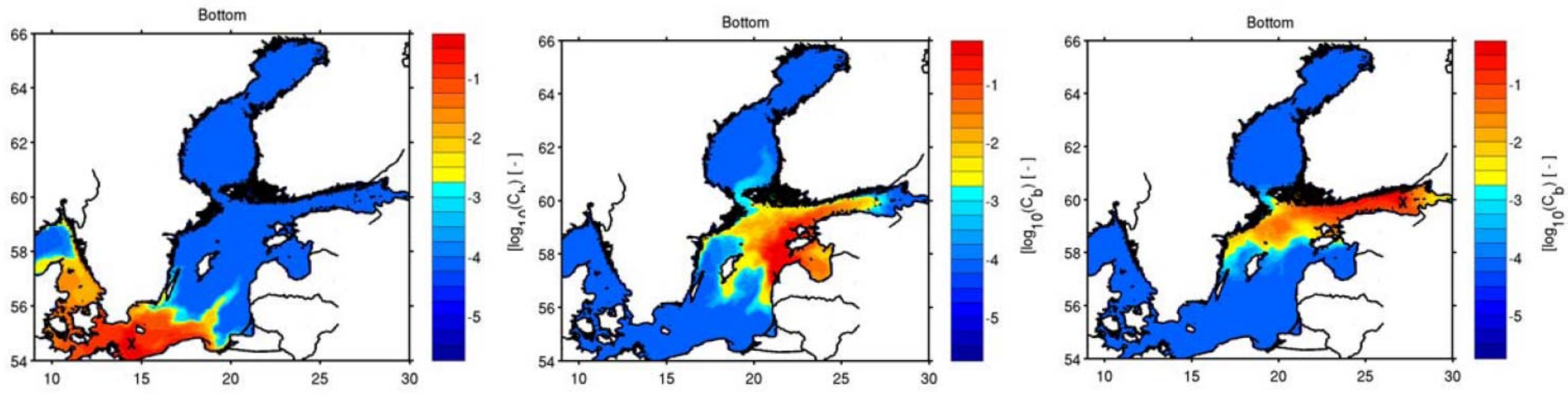
Circulation patterns in the Baltic Sea

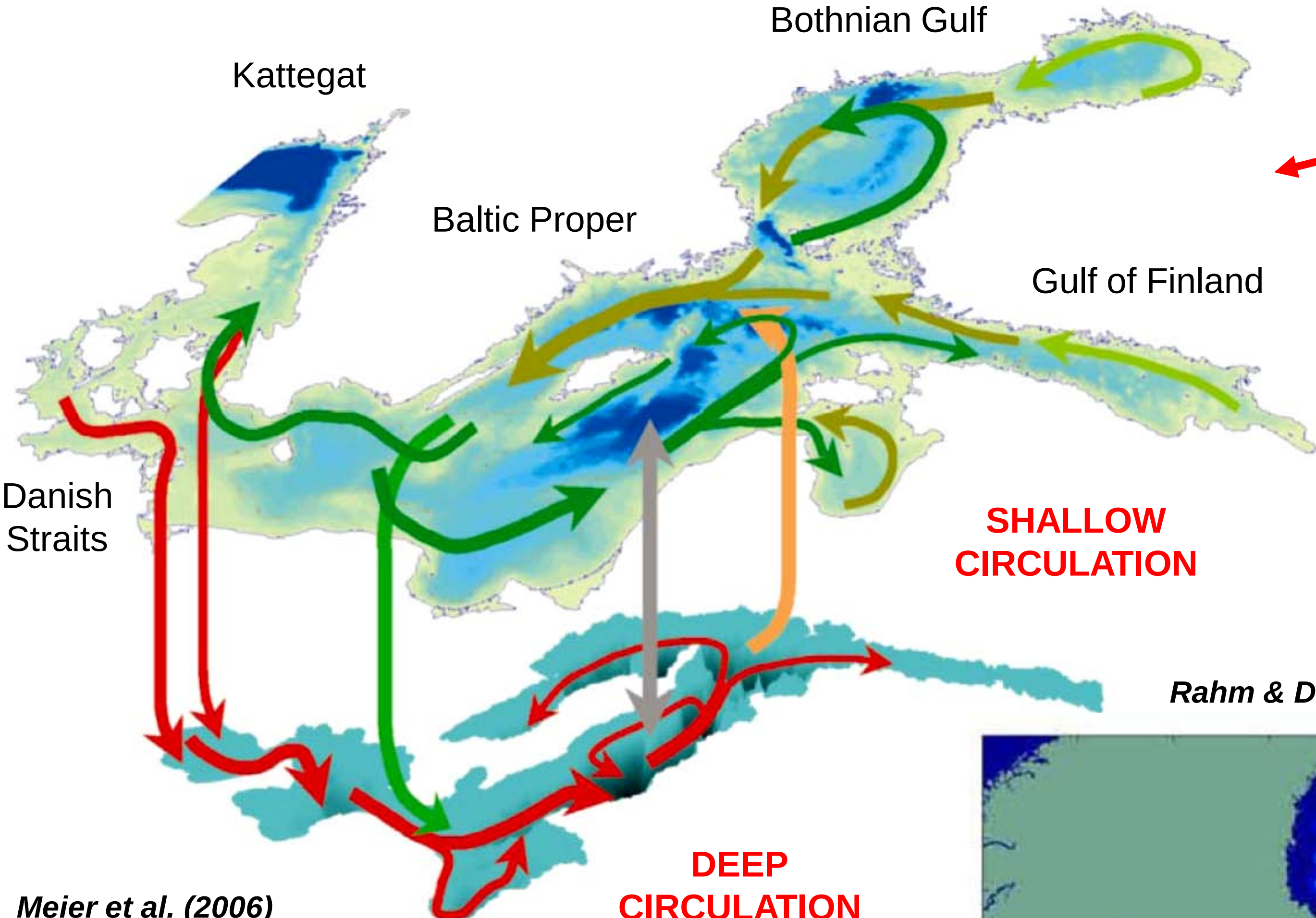
Circulation reflected in gradients in physico-chemical variables, such as salinity



Bendtsen et al. (2007)

Circulation determined through tracer studies



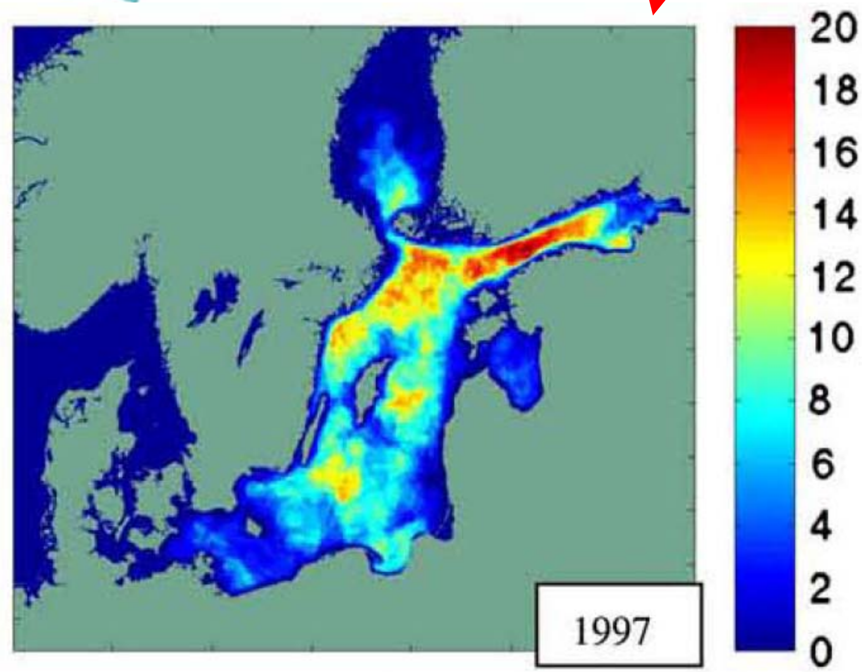


Meier et al. (2006)

Generalized circulation pattern

Primary productivity in the Baltic Sea

Rahm & Danielsson (2007)



Utility: Information about circulation patterns can further our understanding about controls on primary productivity, redox conditions, and other paleoceanographic parameters.

Proxies for circulation patterns in ancient epeiric seas

Elemental

Trace metals

(Mo, U, etc.)

REEs

Isotopic

$\delta^{13}C_{carb}$

$\delta^{13}C_{org}$

$\delta^{18}O$

$\delta^{15}N$

εNd

$^{87}Sr/^{86}Sr$

Other Proxies

Mineral assemblages

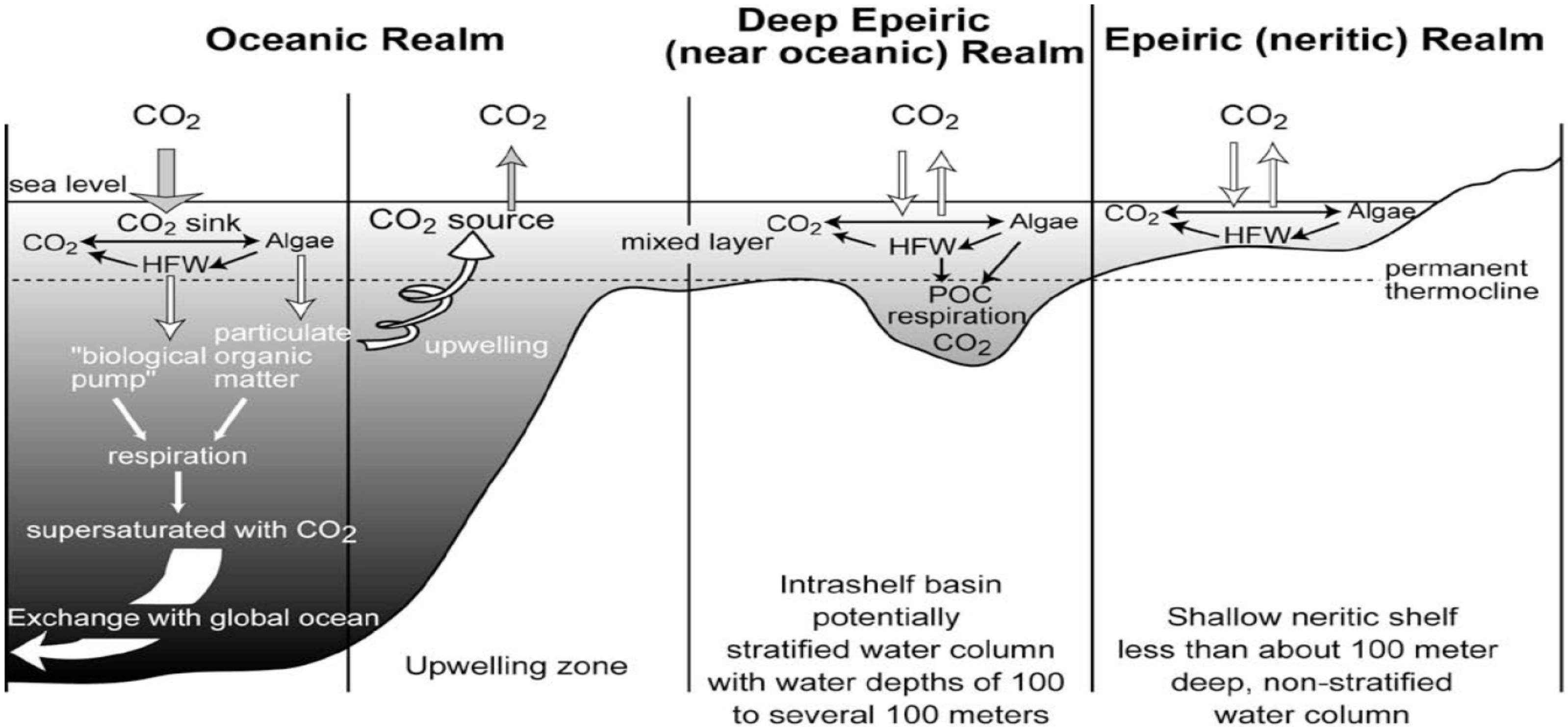
Organic fraction

(maceral types,

biomarkers,

Rock Eval parameters)

Spatial variation in proxy residence time



Immenhauser et al. (2008)

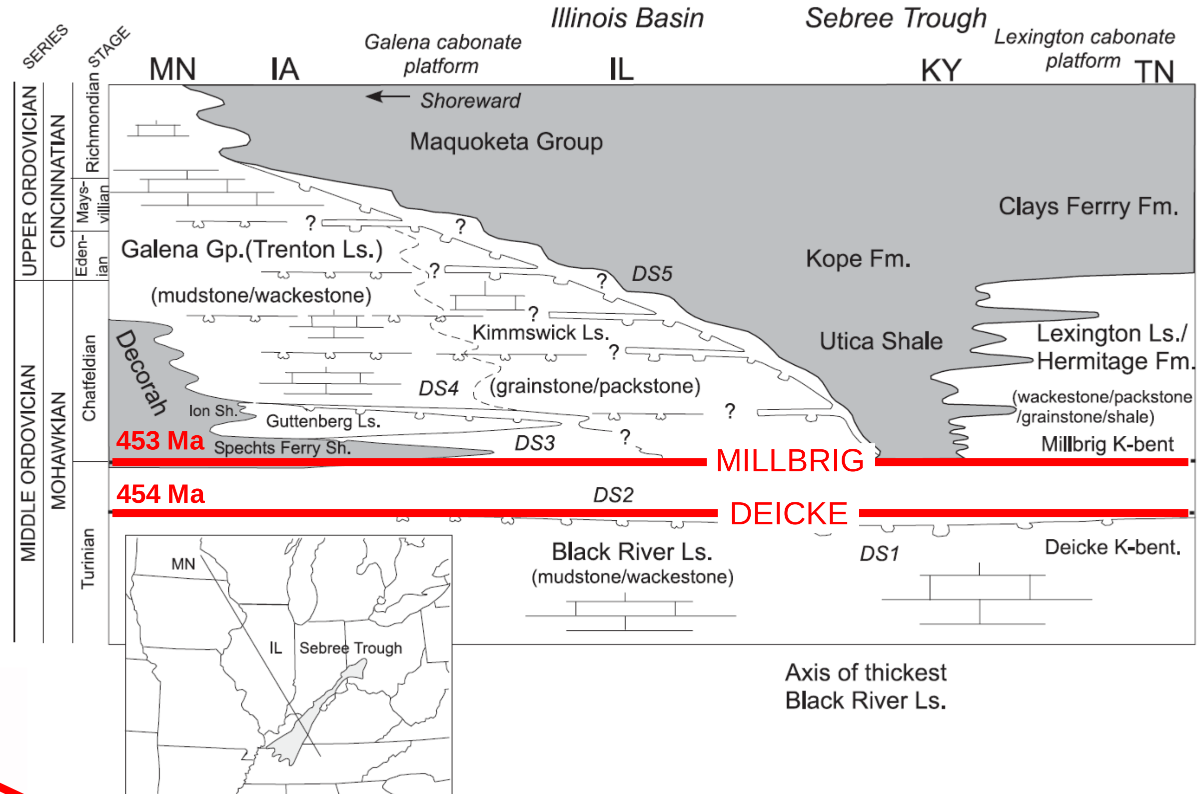
RESIDENCE TIMES: SEAWATER VS. RESTRICTED BASINS

Seawater,	τ~750,000 yr	Aqueous Mo residence times (of deep water for restricted basins)
Cariaco Basin,	τ~320,000 yr	
Black Sea,	τ ~80,000 yr	
Saanich Inlet,	τ ~15,000 yr	
Framvaren Fjord,	τ ~1,000 yr	

Key factor:

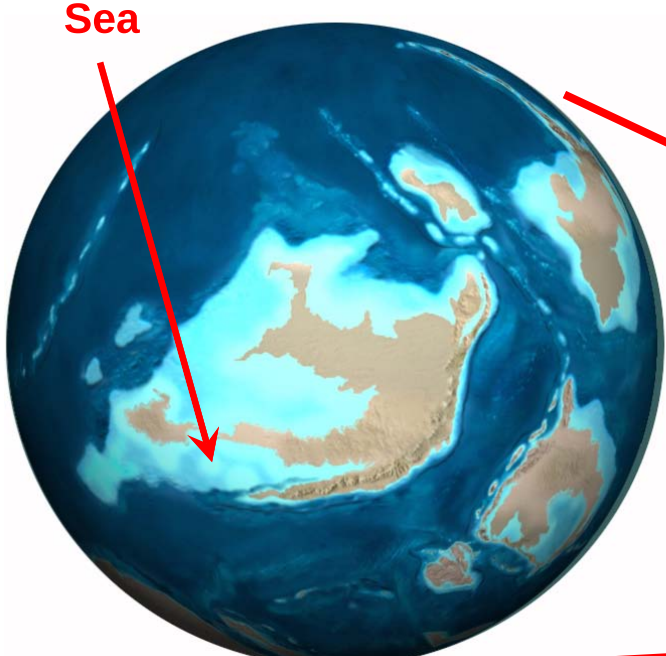
Proxy residence time versus watermass mixing time

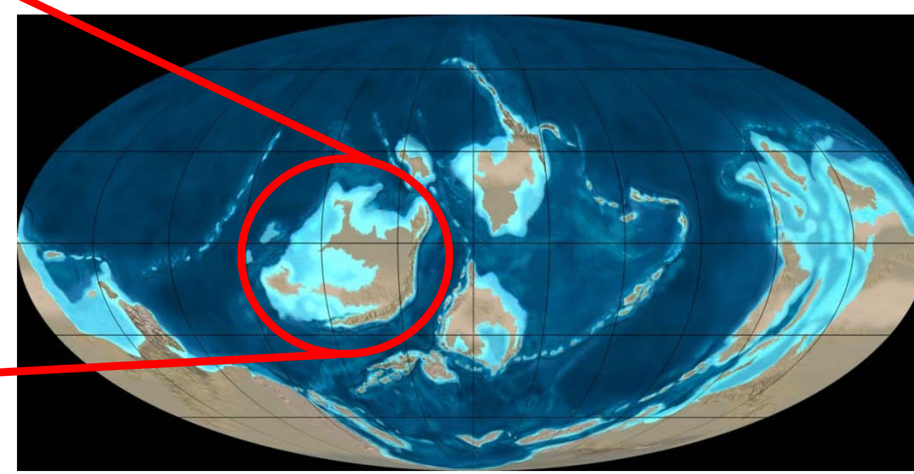
Late Ordovician
Mohawkian Sea
(~454 Ma)



Fanton and Holmden (2007)

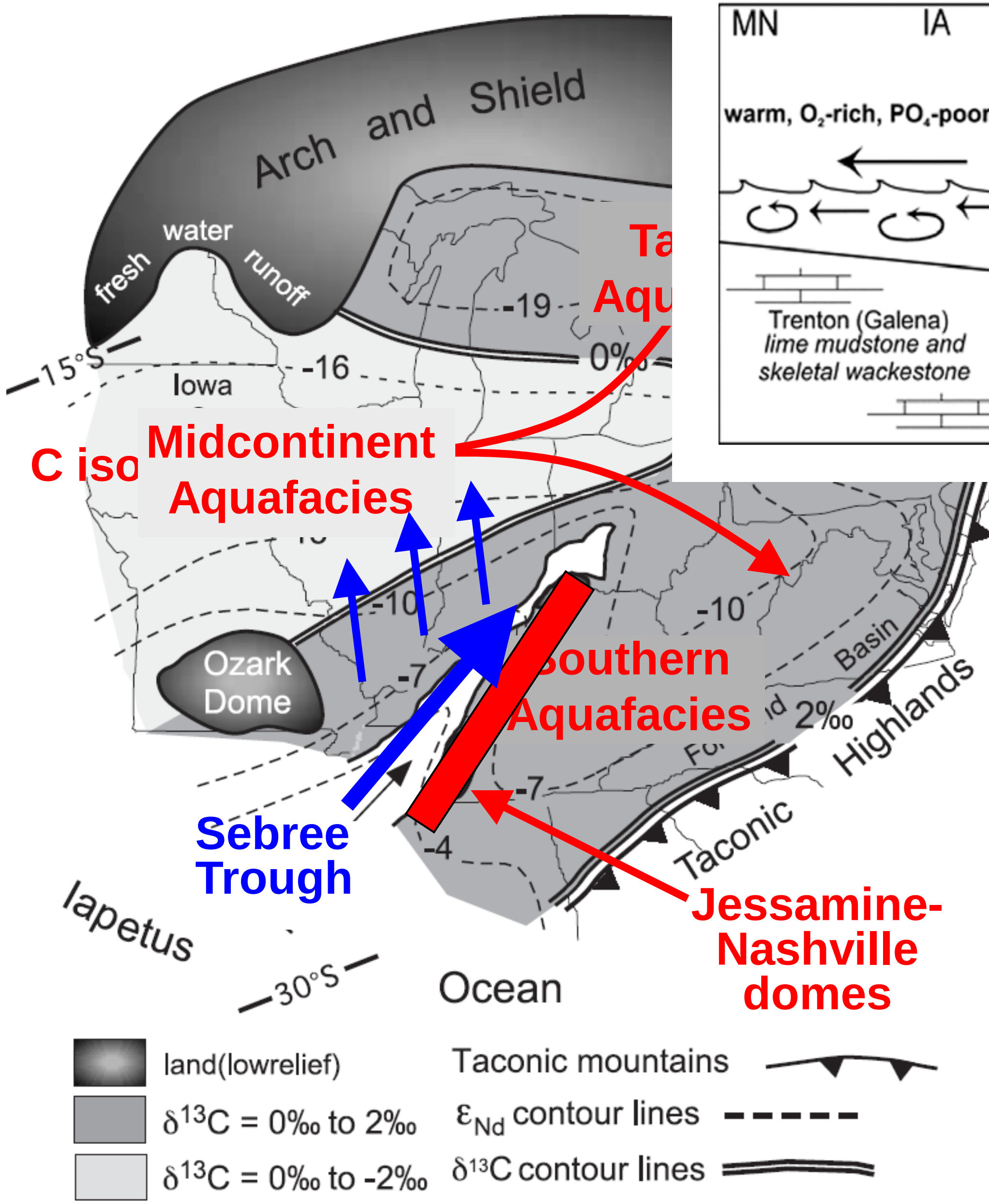
Mohawkian Sea

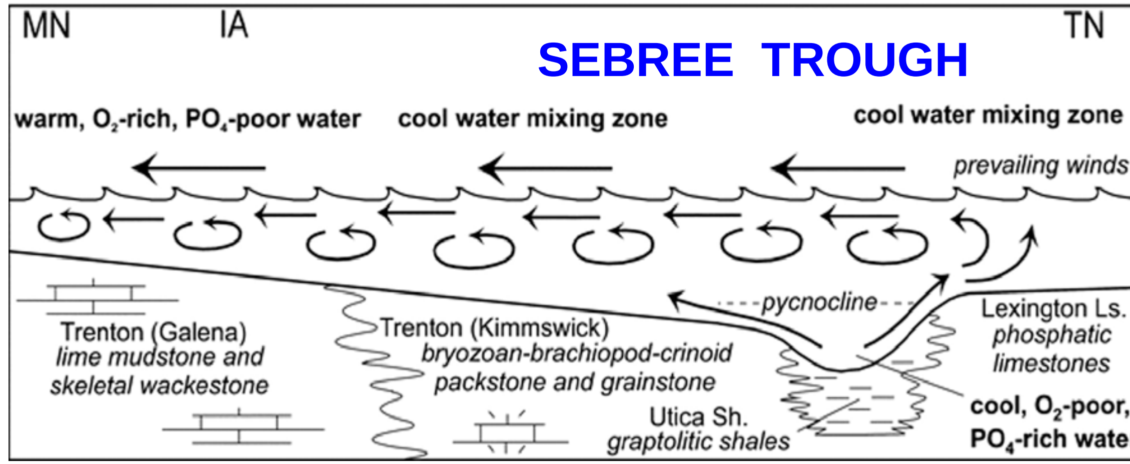




Maps: Ron Blakey

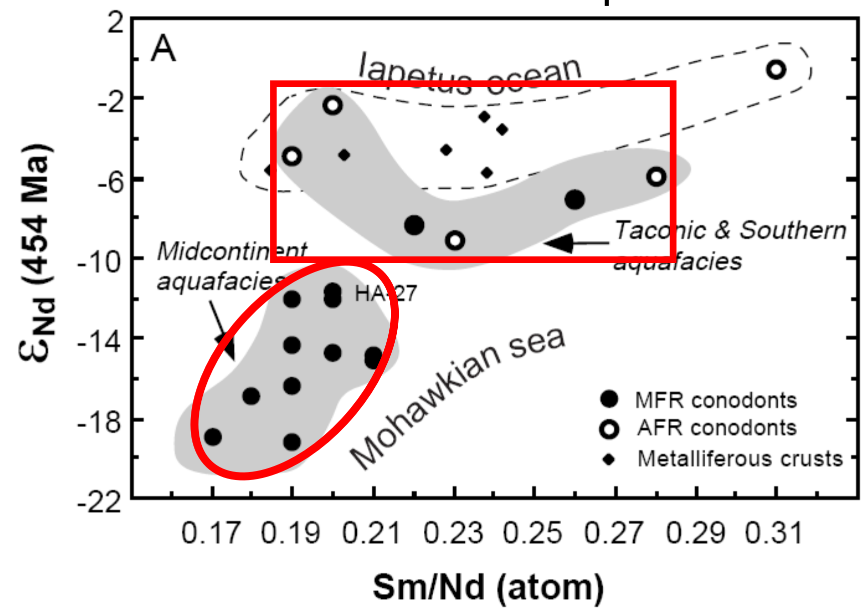
"Aquafacies" – Chemically distinct watermasses



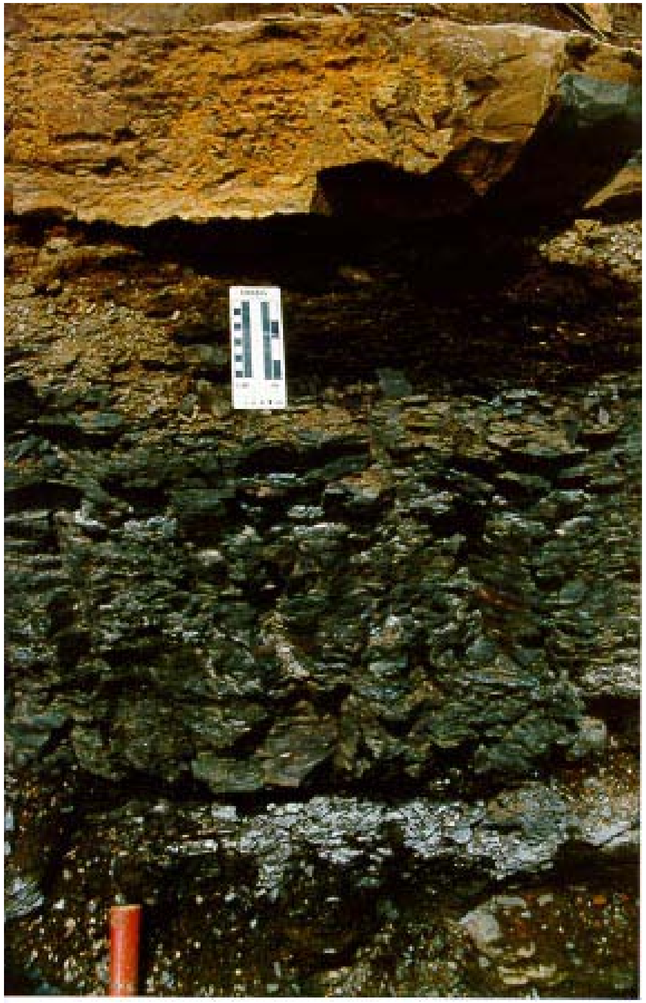


Kolata et al. (2001)

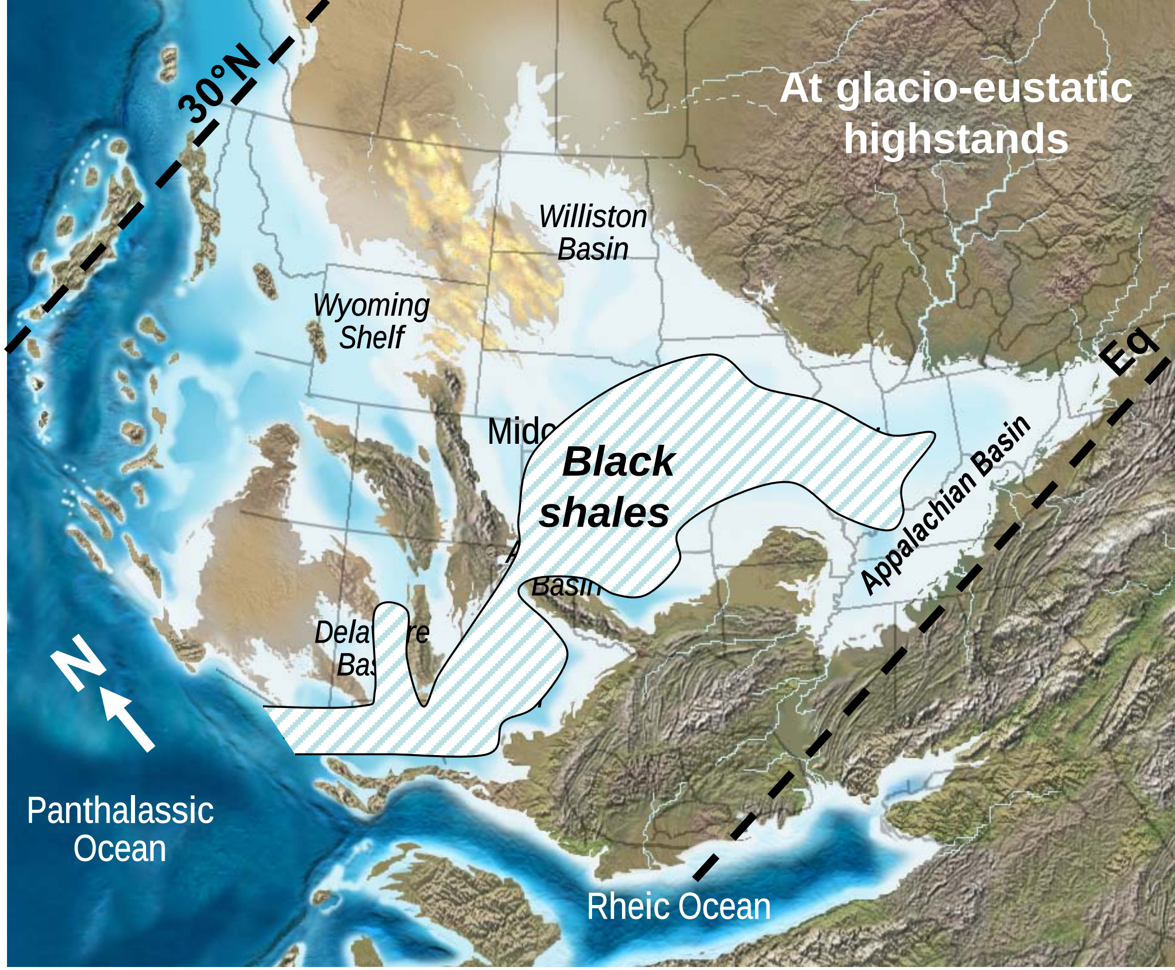
Discriminant plot



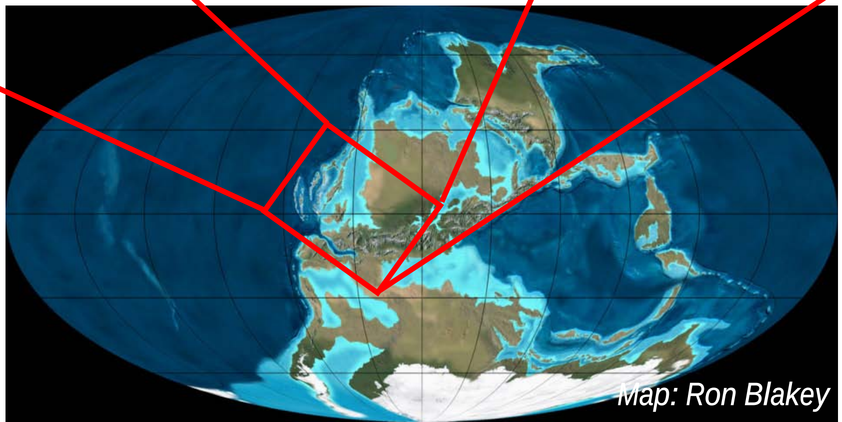
Late Pennsylvanian Midcontinent Sea



Missourian Stage Hushpuckney Shale



Global paleogeography ~300 Ma

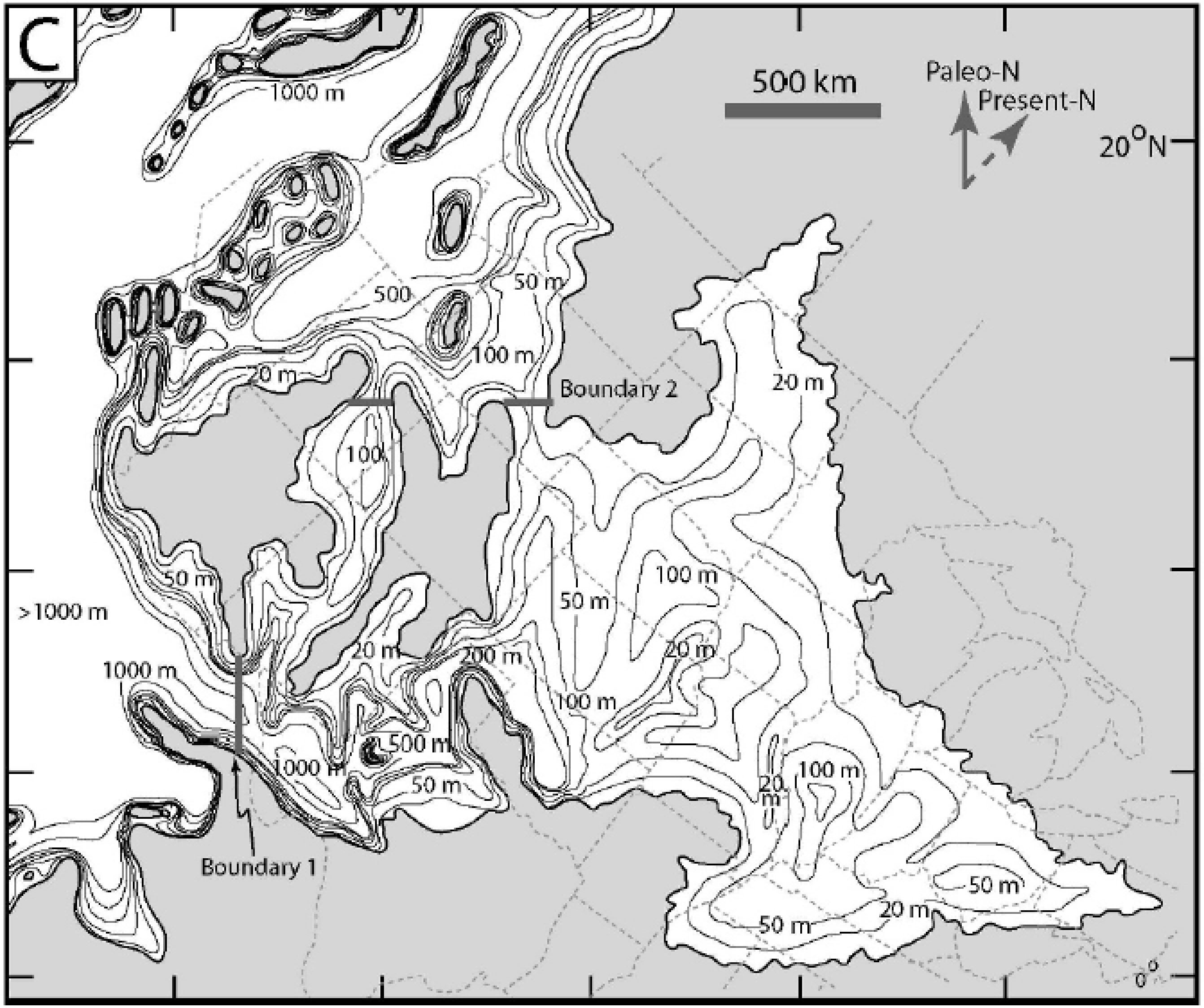


Bathymetry of Late Pennsylvanian Midcontinent Sea

Relatively shallow depths (<100 m)

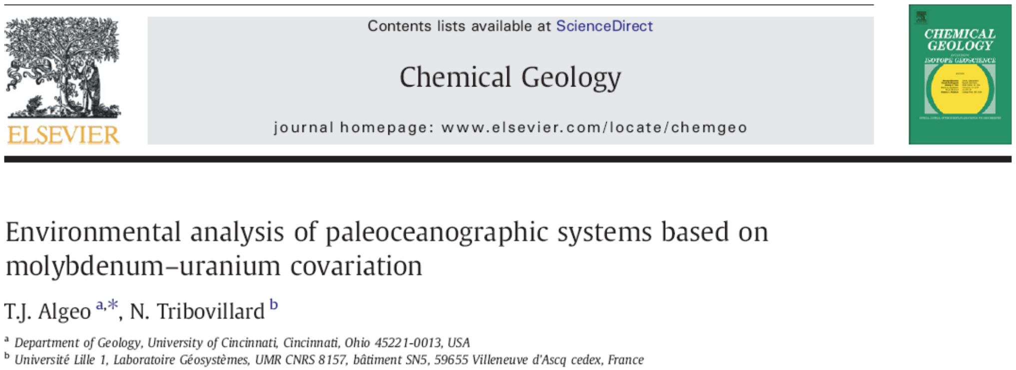
Muted bottom topography

Large latitudinal (~0 to 20ºN) and climatic ranges



Wells et al. "Numerical Modeling of Tides in the Late Pennsylvanian Midcontinent Seaway of North America with Implications for Hydrography And Sedimentation" (JSR, 2007)

Publications on the paleoceanography of the LPMS of North America


Contents lists available at ScienceDirect

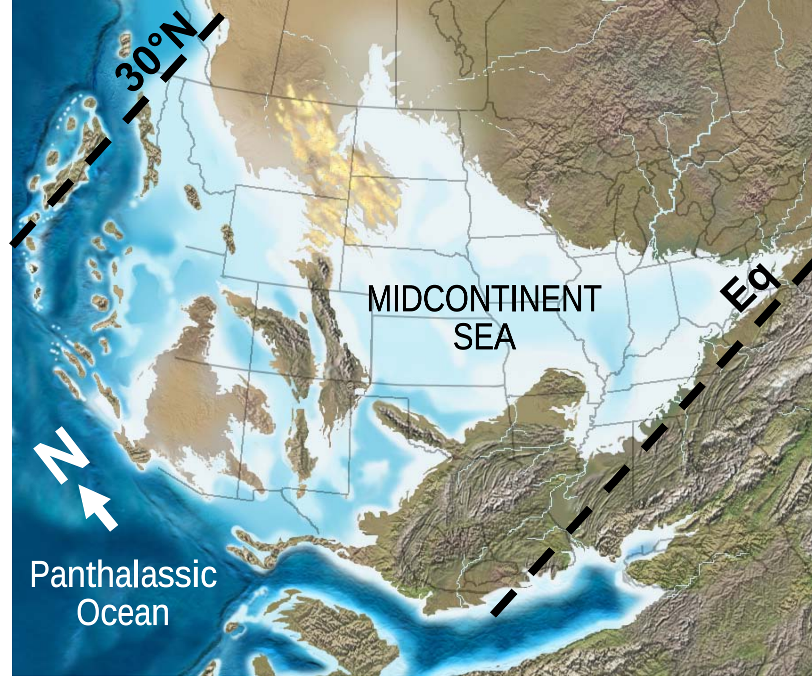
Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Environmental analysis of paleoceanographic systems based on molybdenum–uranium covariation

T.J. Algeo [a,*], N. Tribovillard [b]

[a] Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221-0013, USA
[b] Université Lille 1, Laboratoire Géosystèmes, UMR CNRS 8157, bâtiment SN5, 59655 Villeneuve d'Ascq cedex, France



Algeo, T.J. & Tribovillard, N. 2009. Environmental analysis of paleoceanographic systems based on molybdenum-uranium covariation. *Chemical Geology,* v. 268, p. 211-225.

Algeo, T.J., Rowe, H., Hower, J.C., Schwark, L., Hermann, A. & Heckel, P.H., 2008, Oceanic denitrification during Late Carboniferous glacial-interglacial cycles. *Nature Geoscience*, v. 1, p. 709-714.

Algeo, T.J. & Maynard, J.B., 2008, Trace metal covariation as a guide to water-mass conditions in ancient anoxic marine environments. *Geosphere*. v. 4; no. 5; p. 872-887.

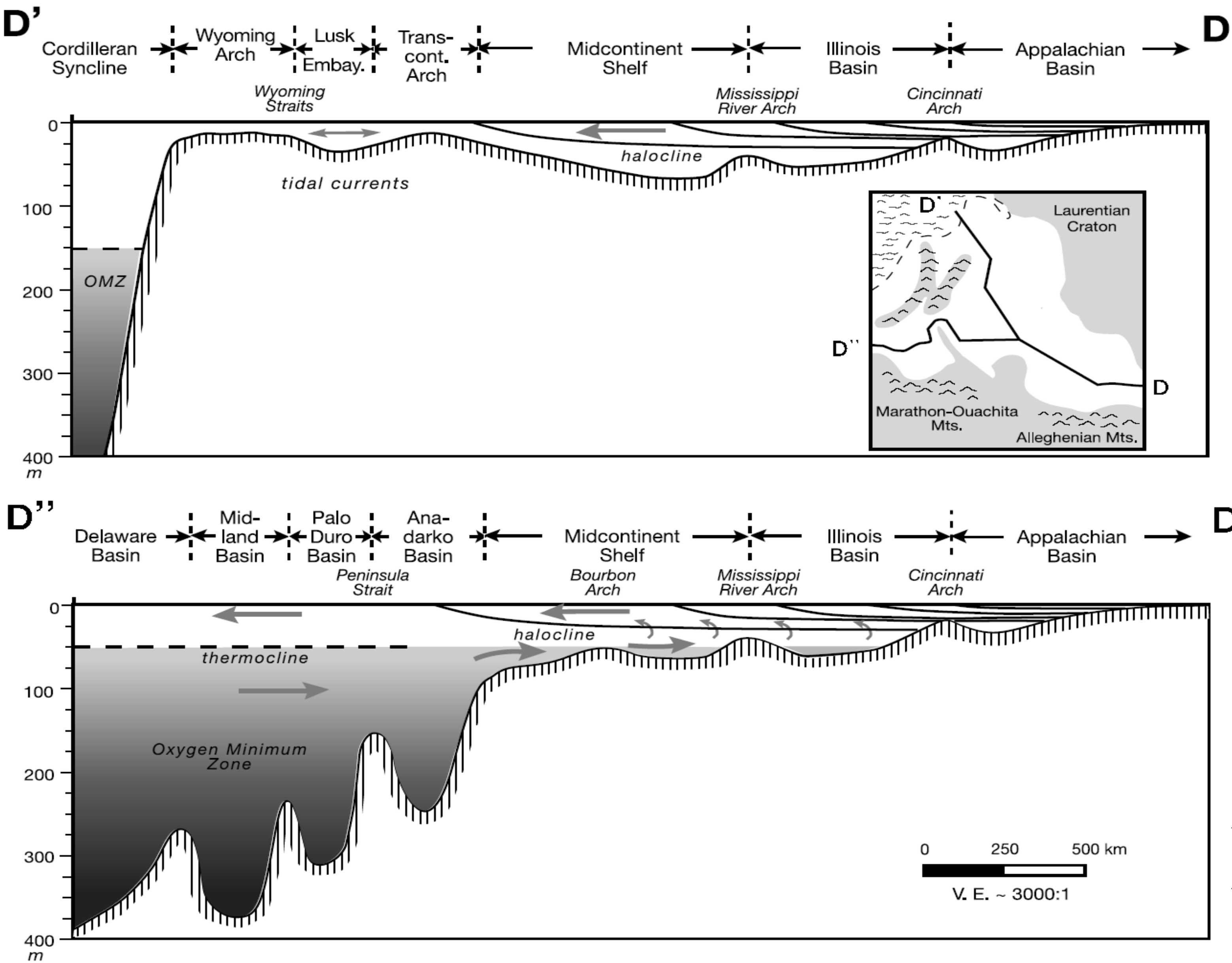
Algeo, T.J. & Heckel, P.H., 2008, The Late Pennsylvanian Midcontinent Sea of North America: A review. *Palaeogeography Palaeoclimatology Palaeoecology*, v. 268, p. 205-221.

Algeo, T.J., Heckel, P.H., Maynard, J.B., Blakey, R. & Rowe, H., 2008. Modern and ancient epicratonic seas and the superestuarine circulation model of marine anoxia. In: Holmden, C., Pratt, B.R. (Eds.), *Dynamics of Epeiric Seas: Sedimentological, Paleontological and Geochemical Perspectives*. Geological Association of Canada Special Publication, v. 48, p. 7-38.

Algeo, T.J., Schwark, L. & Hower, J.C., 2004, High-resolution geochemistry and sequence stratigraphy of the Hushpuckney Shale (Swope Formation, eastern Kansas): *Chemical Geology*, v. 206, p. 259-288.

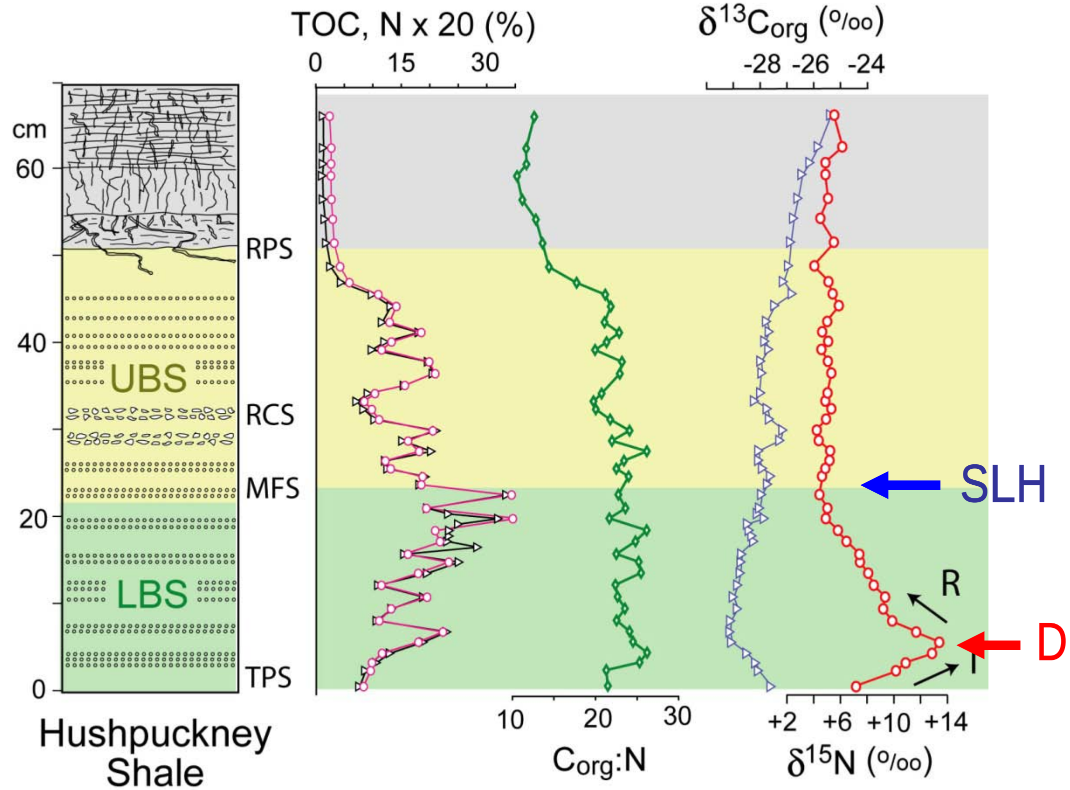
Algeo, T.J. & Maynard, J.B., 2004, Trace element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems. *Chemical Geology*, v. 206, p. 289-318.

Paleoceanographic profiles – connections to global ocean

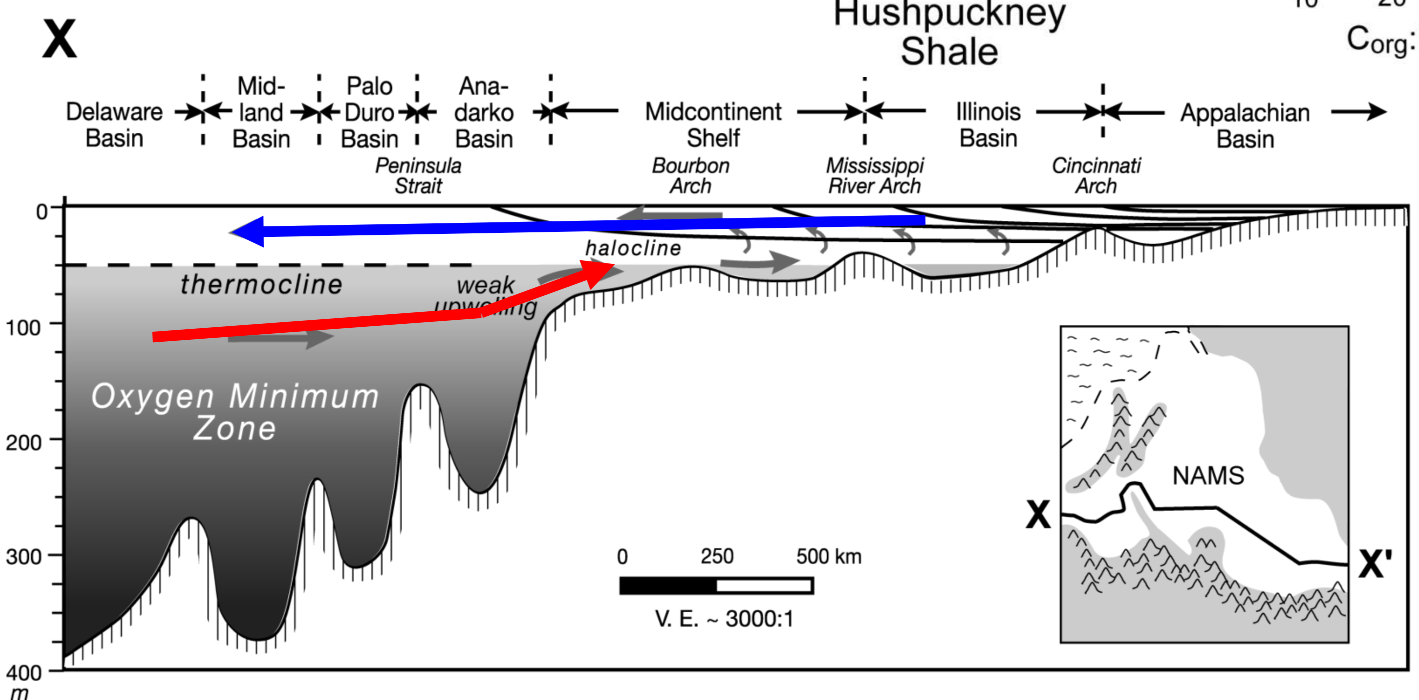


Algeo et al. (2008); Algeo & Heckel (2008)

Nitrogen isotopic evidence for lateral advection of O_2-deficient watermasses from the Eastern Tropical Panthalassic Ocean to the LPMS



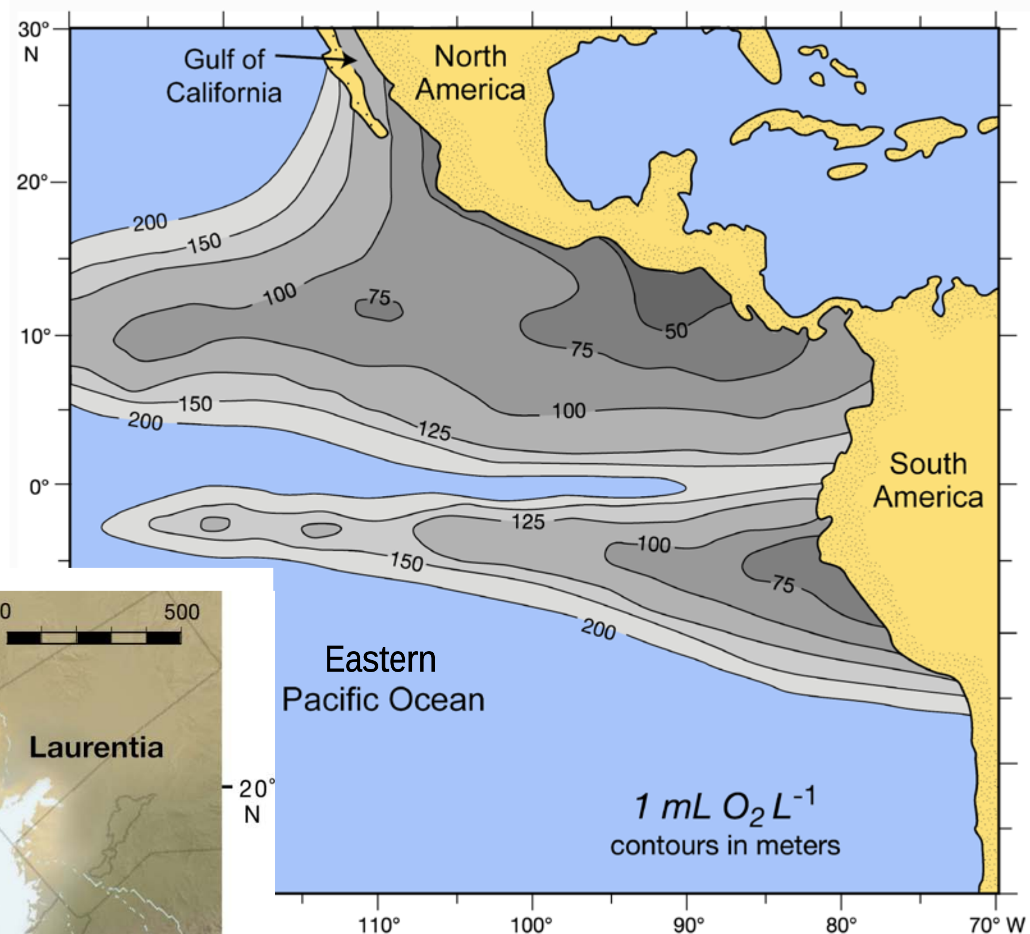
Algeo et al. (2008)



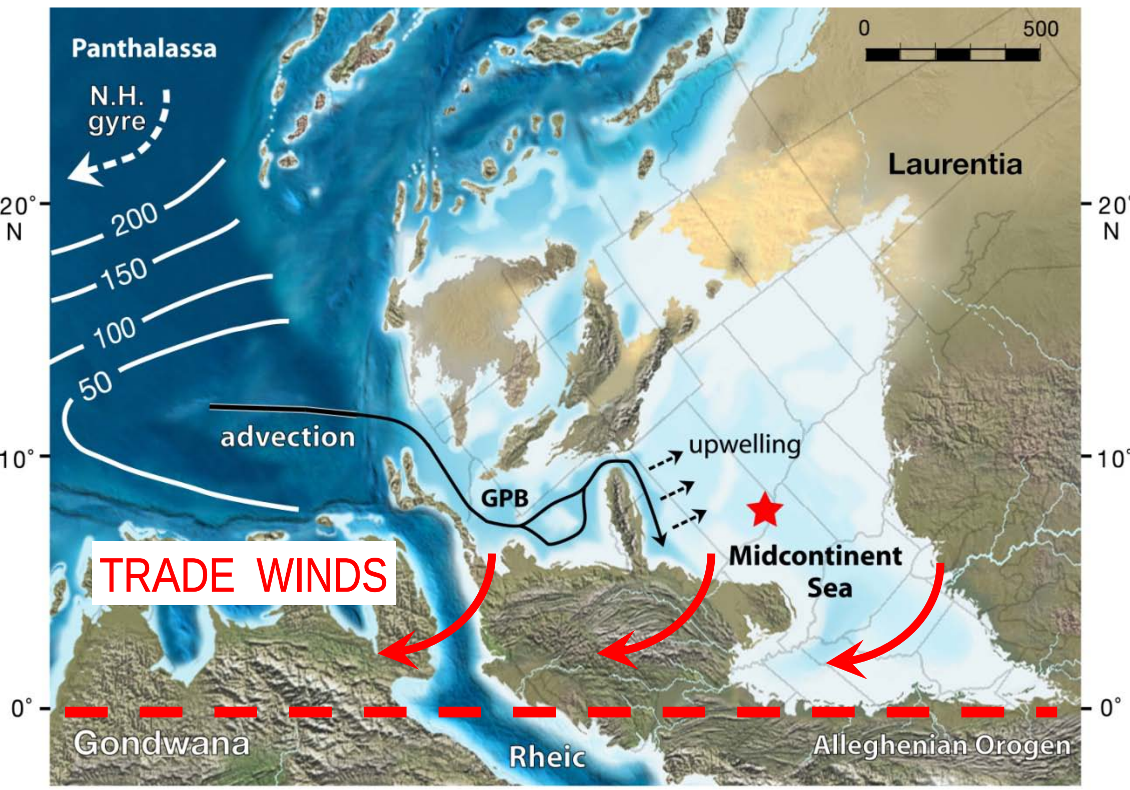
Algeo et al. (2008); Algeo & Heckel (2008)

Modern: oxygen-deficient intermediate waters in the modern eastern tropical Pacific Ocean rise to <100 m at latitudes of 5-12ºS and 5-20ºN

Advection into the Gulf of California contributes to benthic anoxia in that sea



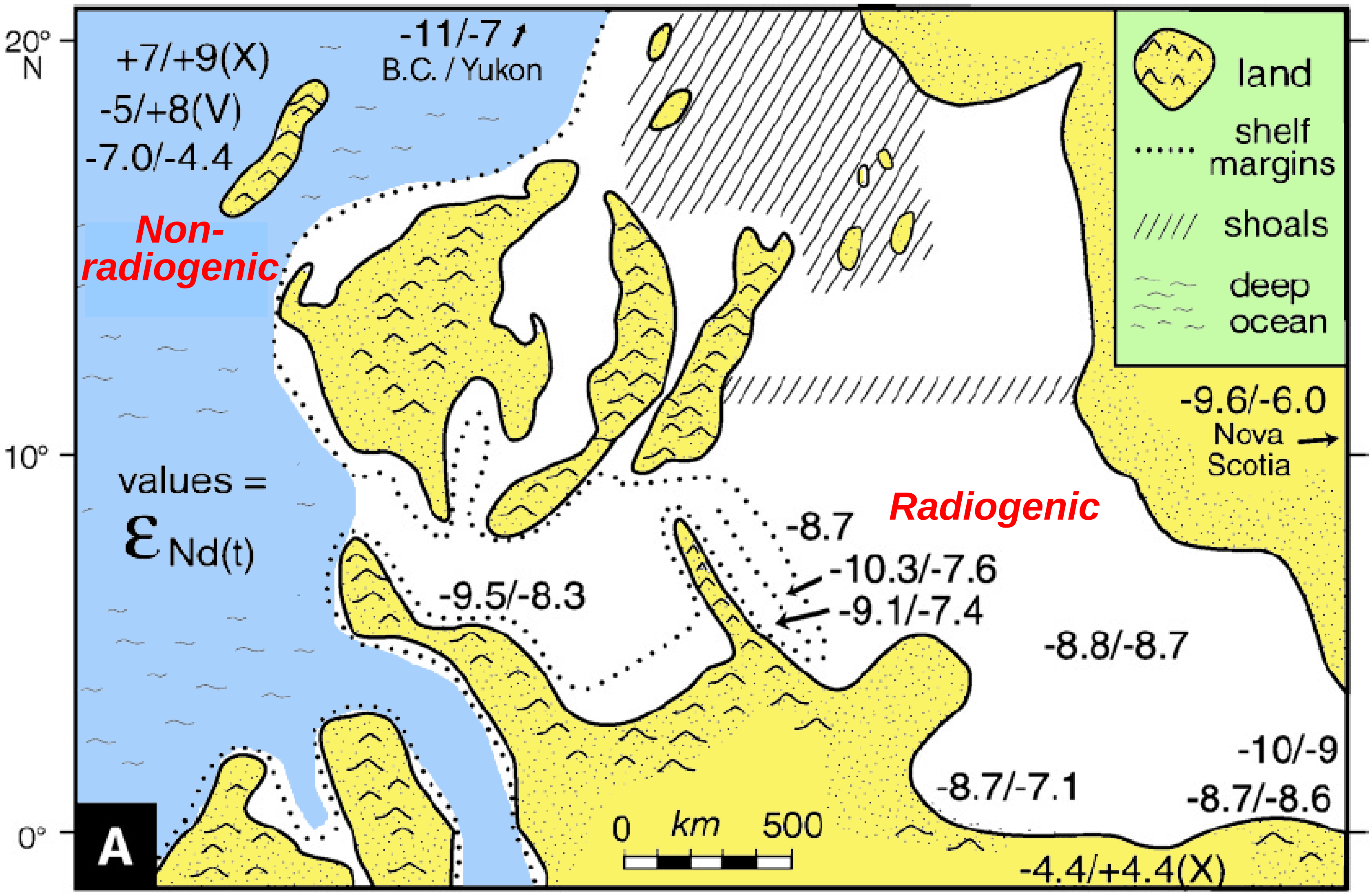
Algeo et al. (2008)



Trade winds enhance productivity through upwelling of nutrient-rich intermediate waters

Intermediate waters are oxygen-deficient owing to "cul-de-sac" effect, only weakly connected to subtropical gyres

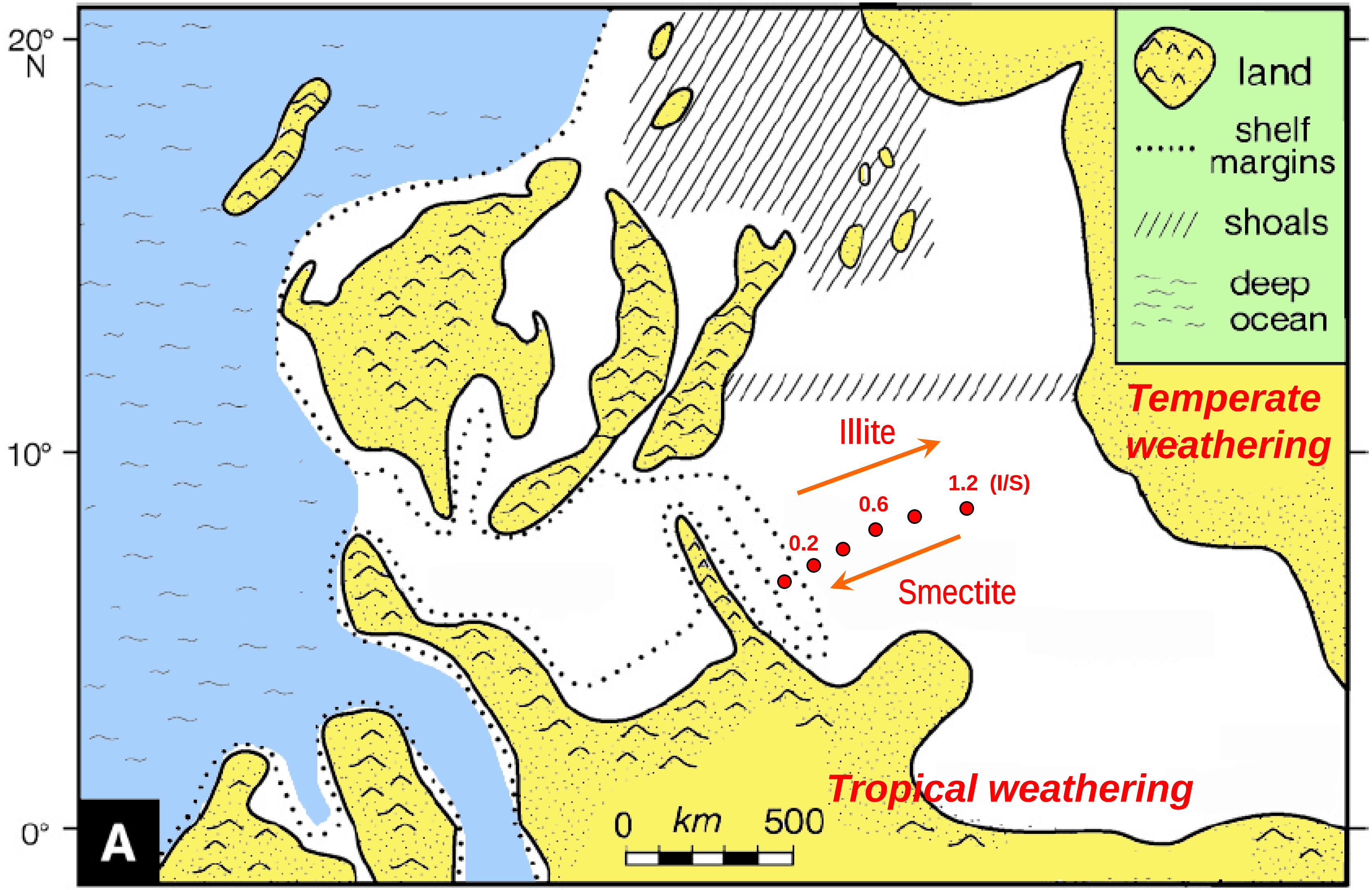
Nd isotopes as a tracer in the LPMS



Uniform εNd across the LPMS, indicating good watermass exchange

Algeo & Heckel (2008)

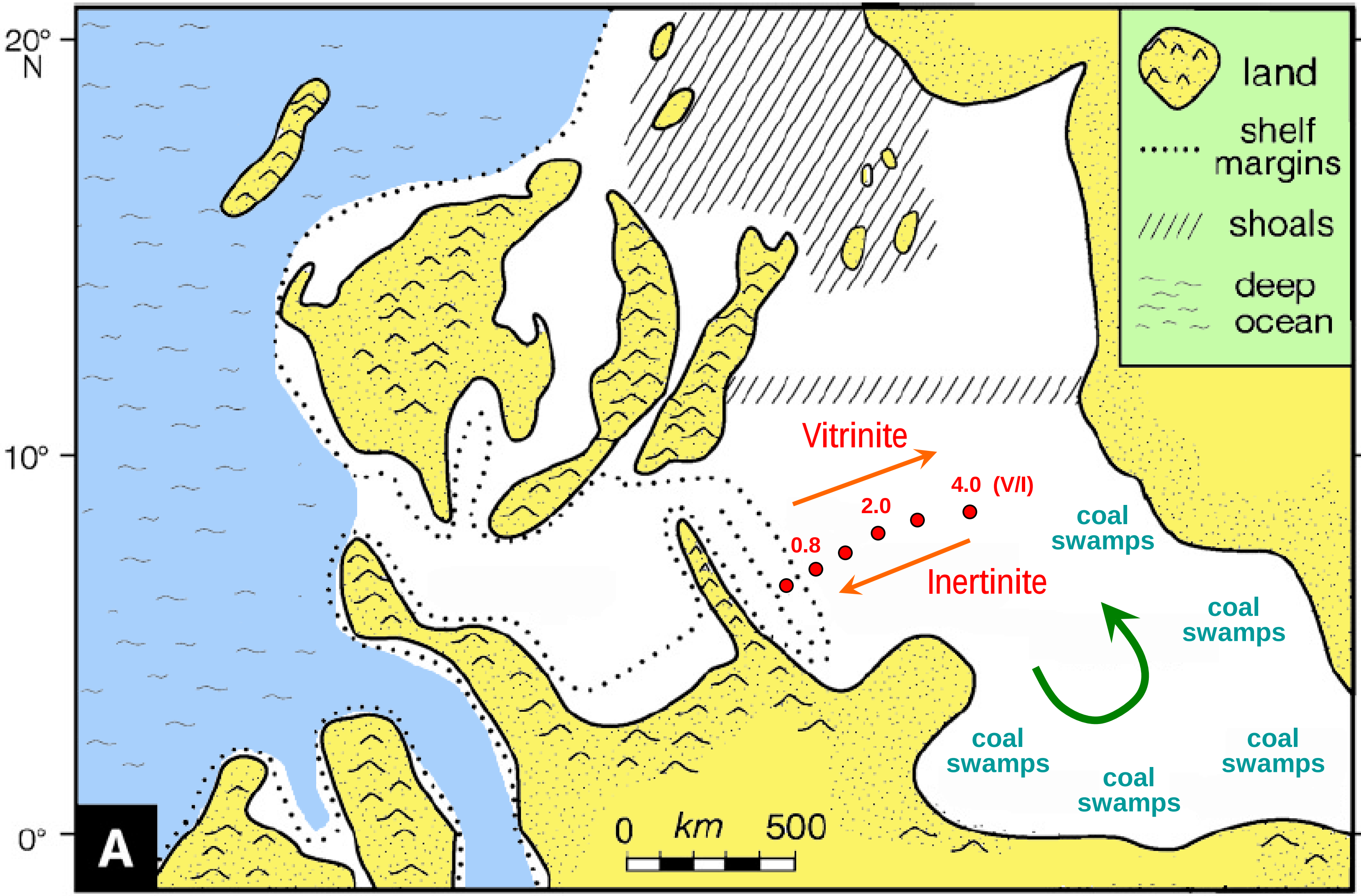
Clay mineral assemblages as a tracer in the LPMS



Algeo & Heckel (2008)

Smectite from S = stronger chemical weathering; illite from N = stronger physical weathering

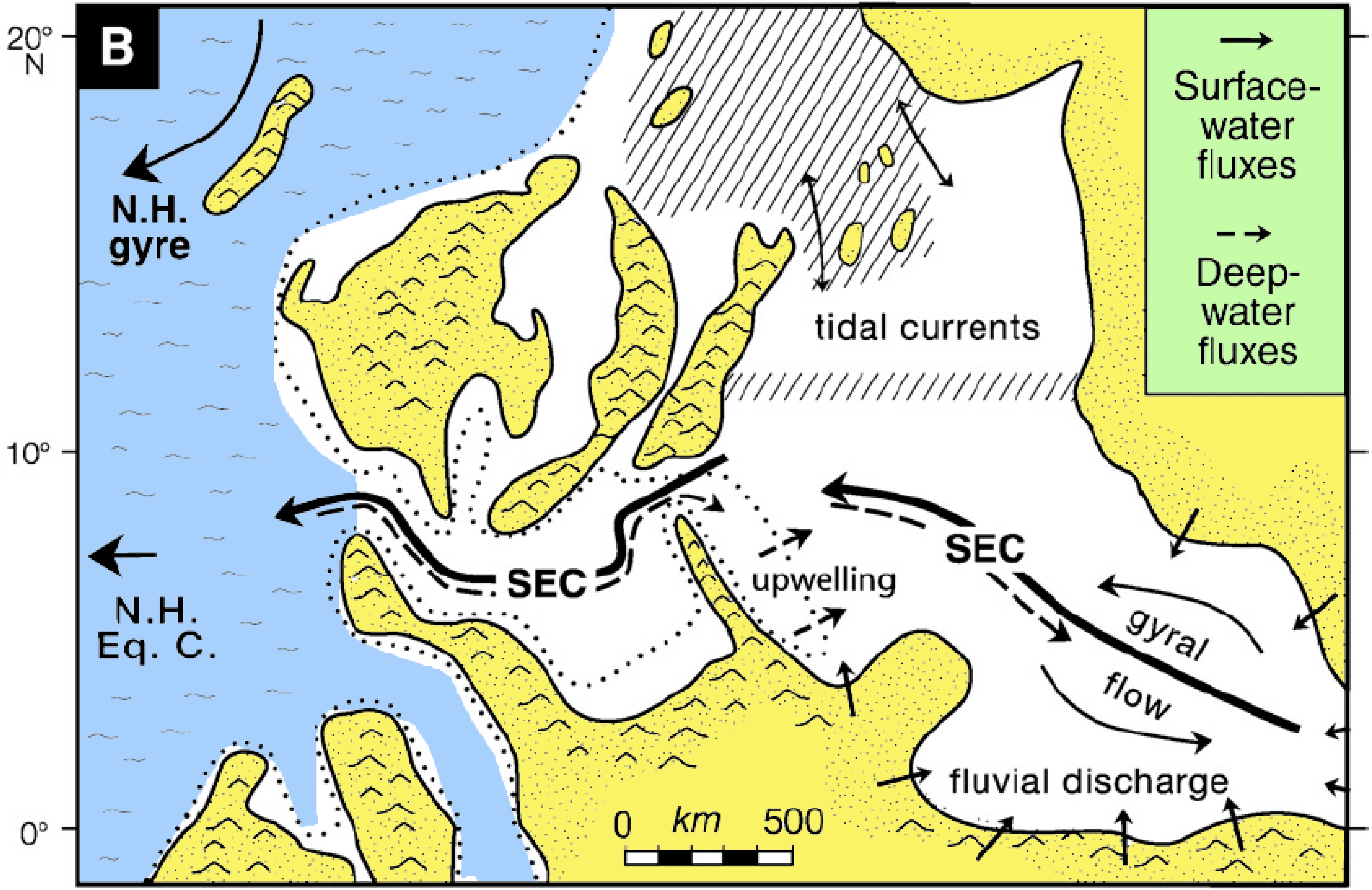
Organic macerals as a tracer in the LPMS



Algeo & Heckel (2008)

Vitrinite from LPMS interior coal swamps, possibly transported NW by CCW gyre

Inferred circulation patterns in the LPMS



Algeo & Heckel (2008)

Conclusions:

(1) Internal circulation patterns can be reconstructed in ancient epeiric seas using a variety of proxies

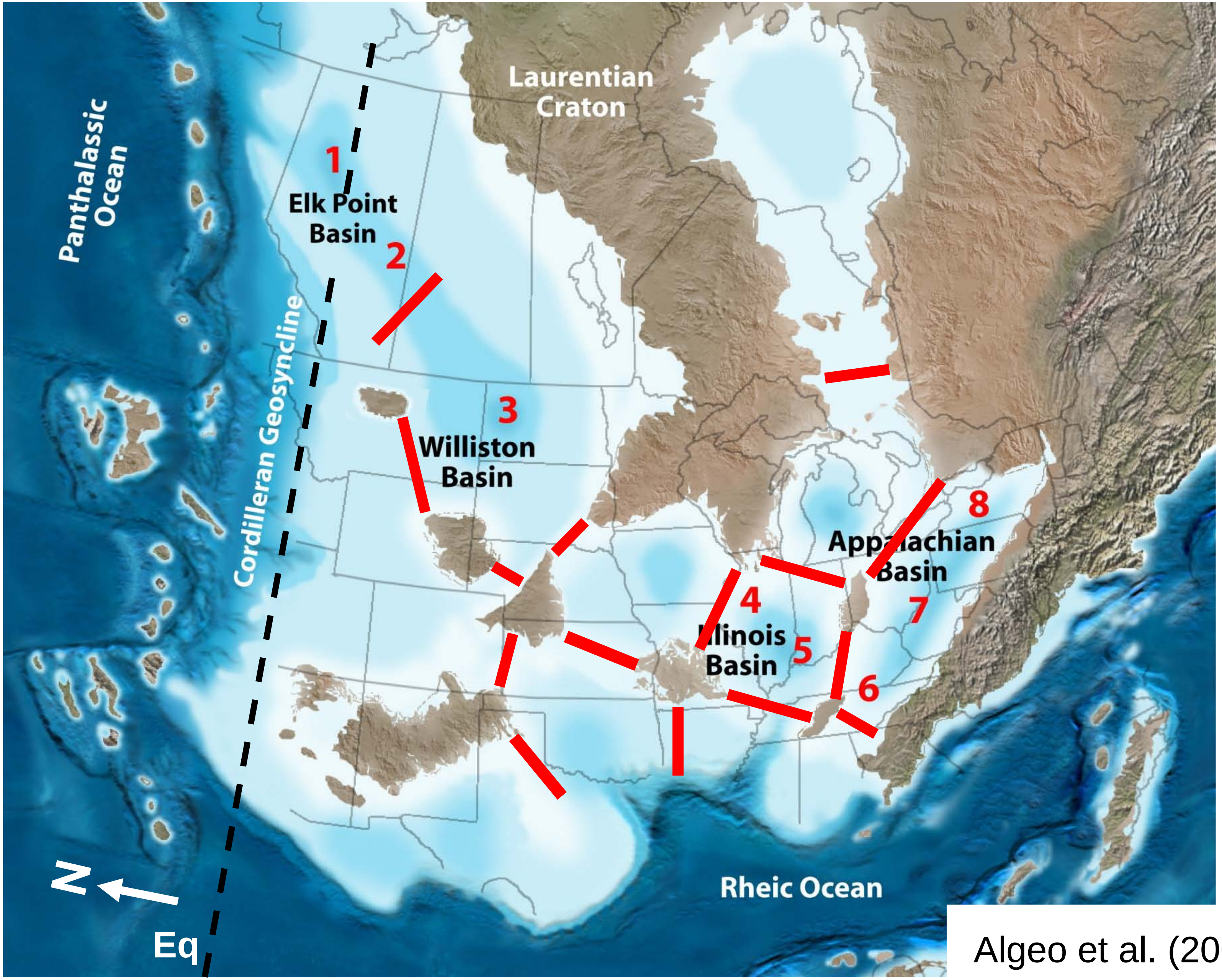
(2) Such reconstructions can be useful in understanding controls on primary productivity, redox conditions, and other paleoceanographic variables

(3) Such reconstructions can provide boundary conditions for paleoceanographic modeling studies, the results of which can provide information about controls on paleocirculation.

Acknowledgments: Ron Blakey (ANU), Phil Heckel (U. Iowa), James C. Hower (U. Kentucky), Barry Maynard (U. Cincinnati), Jeff Over (SUNY Geneseo), Lorenz Schwark (U. Cologne)

Research support: U.S. National Science Foundation (EAR-0310072, EAR-0618003, and EAR-0745574) and the University of Cincinnati Research Council

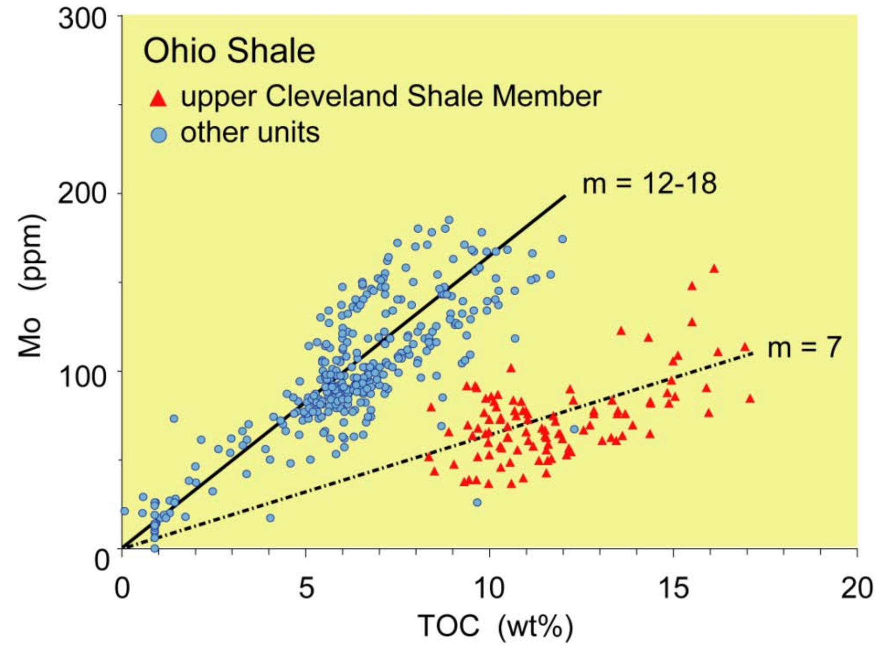
The North American Late Devonian Seaway: a series of restricted cratonic-interior basins

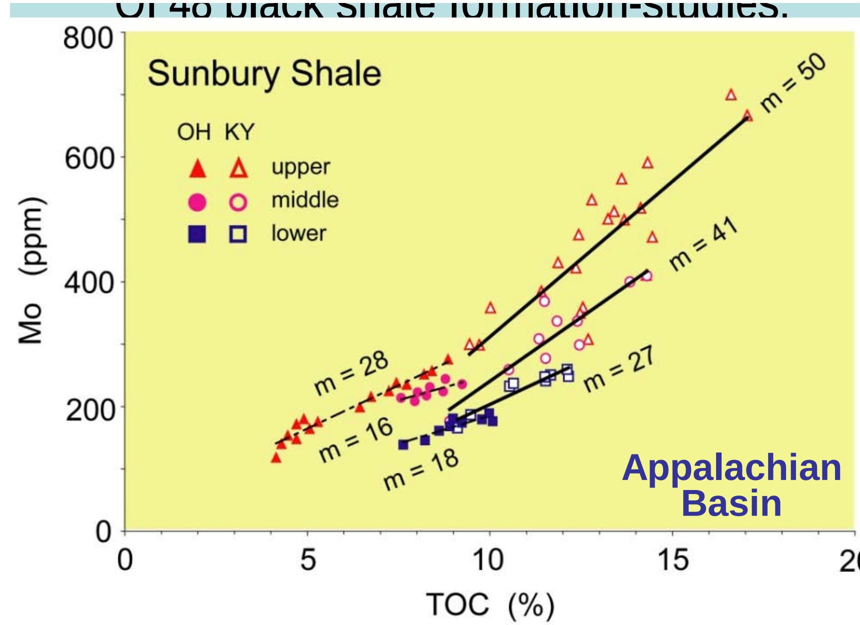


Algeo et al. (2007)

Analysis of Mo-TOC covariation → paleohydrographic conditions

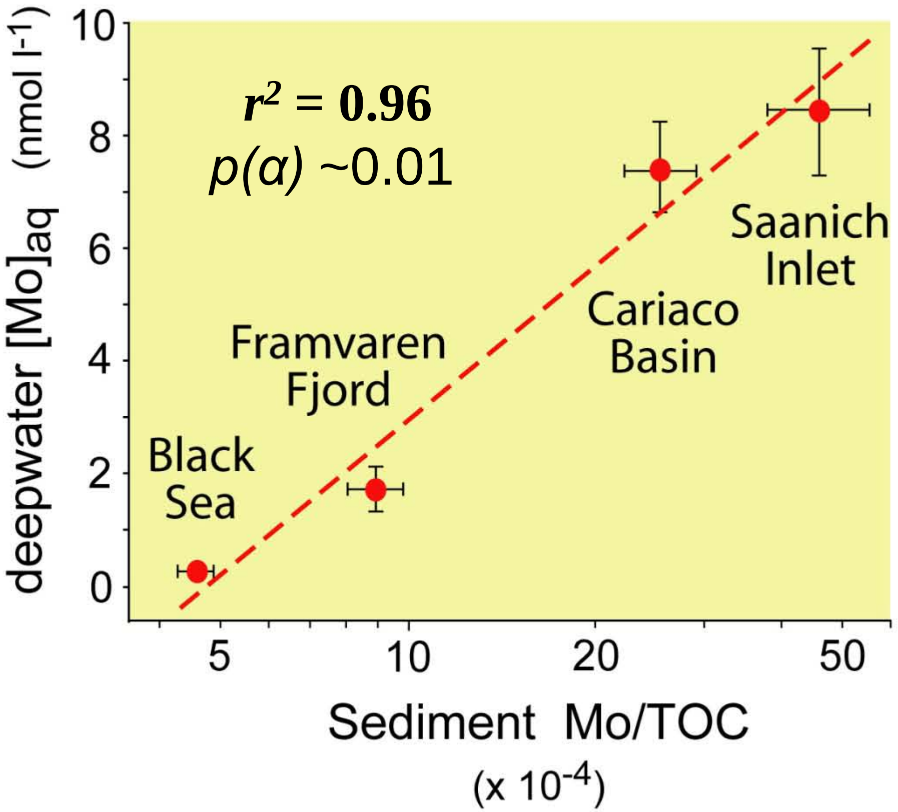
Late Devonian Ohio Shale, Ohio

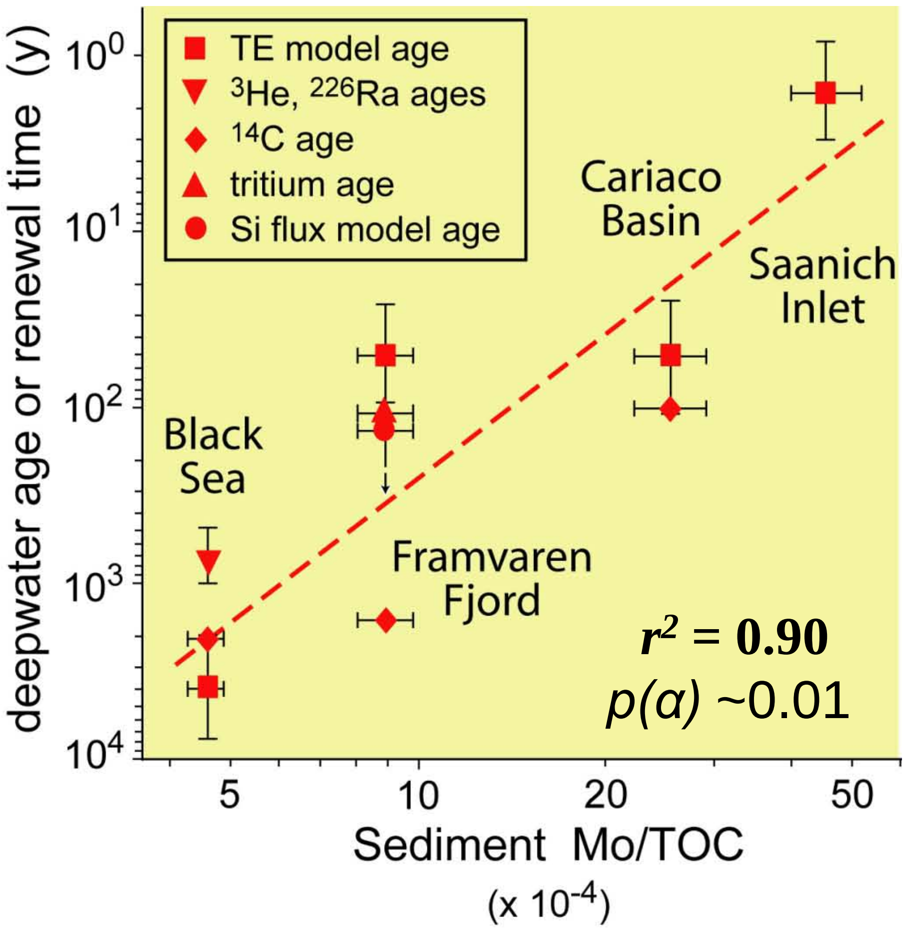




Algeo et al. (2007)

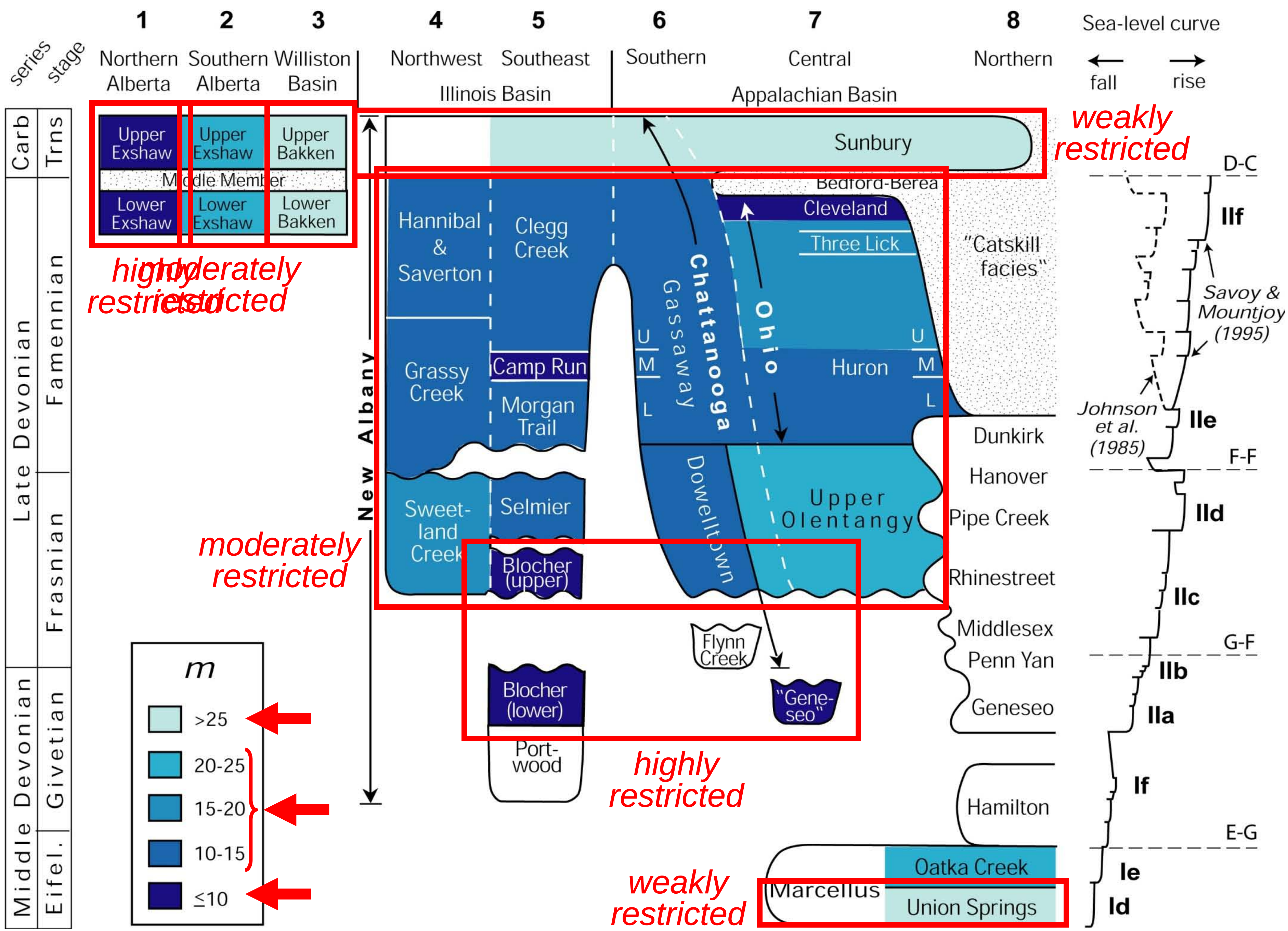
Significance: m shows a strong relationship to both deepwater aqueous Mo concentration and deepwater renewal age; hence, it has predictive value for these parameters in paleomarine systems



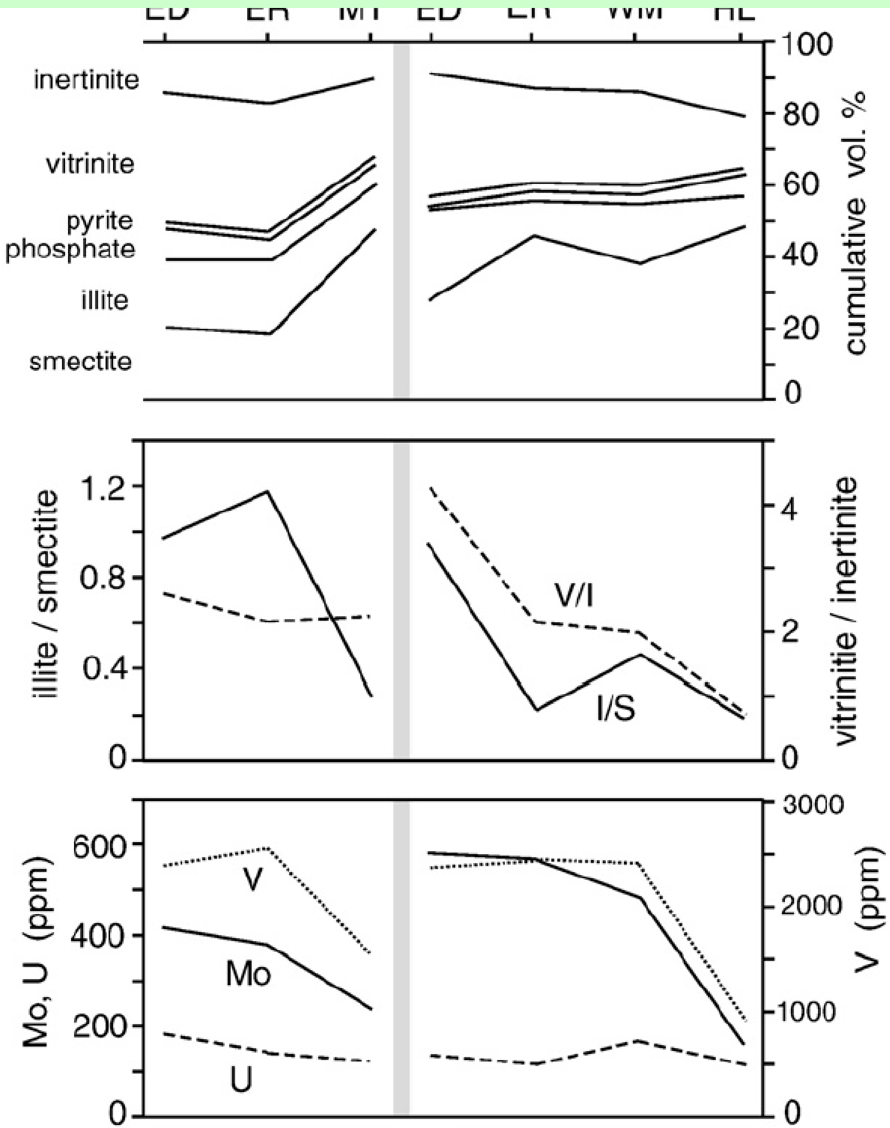


$[Mo]_{sed}$ is determined by the concentration of both TOC in the sediment and Mo in the watermass:

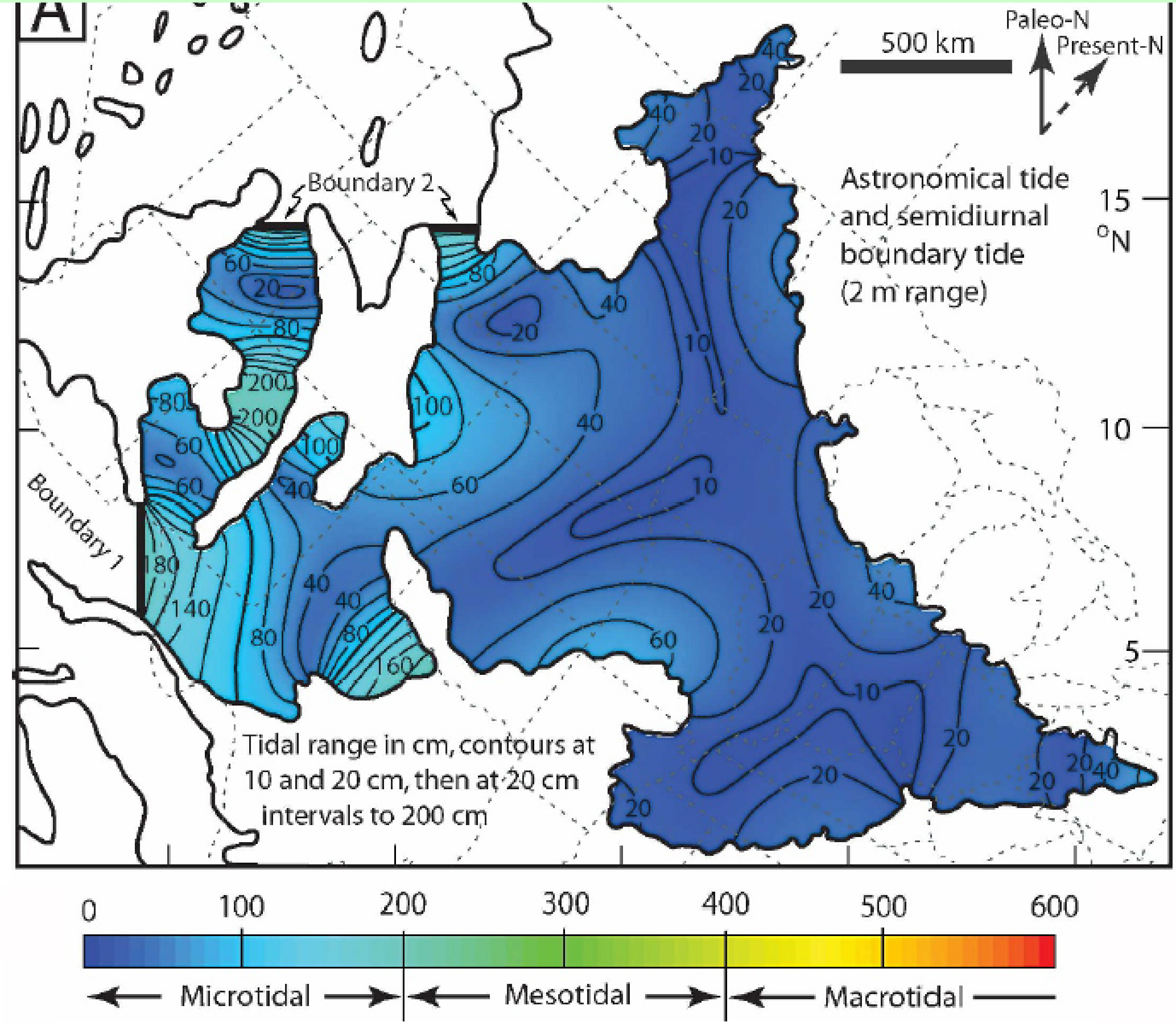
$$[Mo]_{sed} \equiv [TOC]_{sed} \cdot [Mo]_{aq} \rightarrow [Mo/TOC]_{sed} \equiv [Mo]_{aq}$$



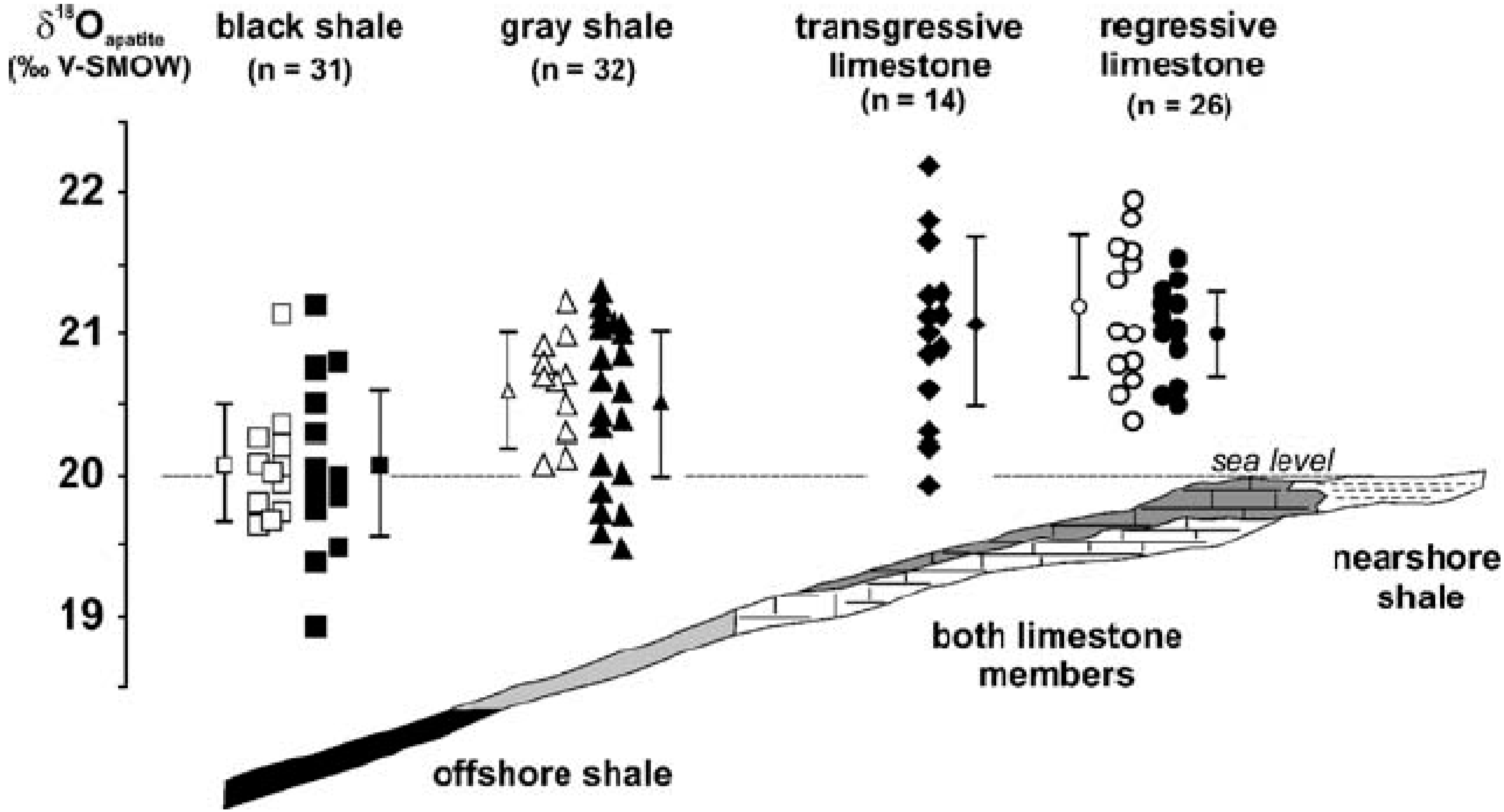
series
stage
1 Northern Alberta
2 Southern Alberta
3 Williston Basin
4 Northwest
5 Southeast
Illinois Basin
6 Southern
7 Central
8 Northern
Appalachian Basin
Sea-level curve
fall
rise
Carb
Trns
Late Devonian
Famennian
Frasnian
Middle Devonian
Givetian
Eifel.
Upper Exshaw
Upper Exshaw
Upper Bakken
Middle Member
Lower Exshaw
Lower Exshaw
Lower Bakken
highly restricted
moderately restricted
weakly restricted
Sunbury
Bedford-Berea
Cleveland
Three Lick
"Catskill facies"
Hannibal & Saverton
Clegg Creek
Chattanooga
Gassaway
Ohio
Huron
U
M
L
Grassy Creek
Camp Run
Morgan Trail
New Albany
Dunkirk
Hanover
Sweet-land Creek
Selmier
Dowelltown
Upper Olentangy
Pipe Creek
moderately restricted
Blocher (upper)
Rhinestreet
Flynn Creek
Middlesex
Penn Yan
Blocher (lower)
"Gene-seo"
Geneseo
Port-wood
highly restricted
Hamilton
Oatka Creek
Marcellus
weakly restricted
Union Springs
m
>25
20-25
15-20
10-15
≤10
D-C
IIf
Savoy & Mountjoy (1995)
Johnson et al. (1985)
IIe
F-F
IId
IIc
G-F
IIb
IIa
If
E-G
Ie
Id



ED
ER
MT
ED
ER
WM
HL
inertinite
vitrinite
pyrite
phosphate
illite
smectite
100
80
60
40
20
0
cumulative vol. %
1.2
0.8
0.4
0
illite / smectite
V/I
I/S
4
2
0
vitrinitie / inertinite
600
400
200
0
Mo, U (ppm)
V
Mo
U
3000
2000
1000
0
V (ppm)



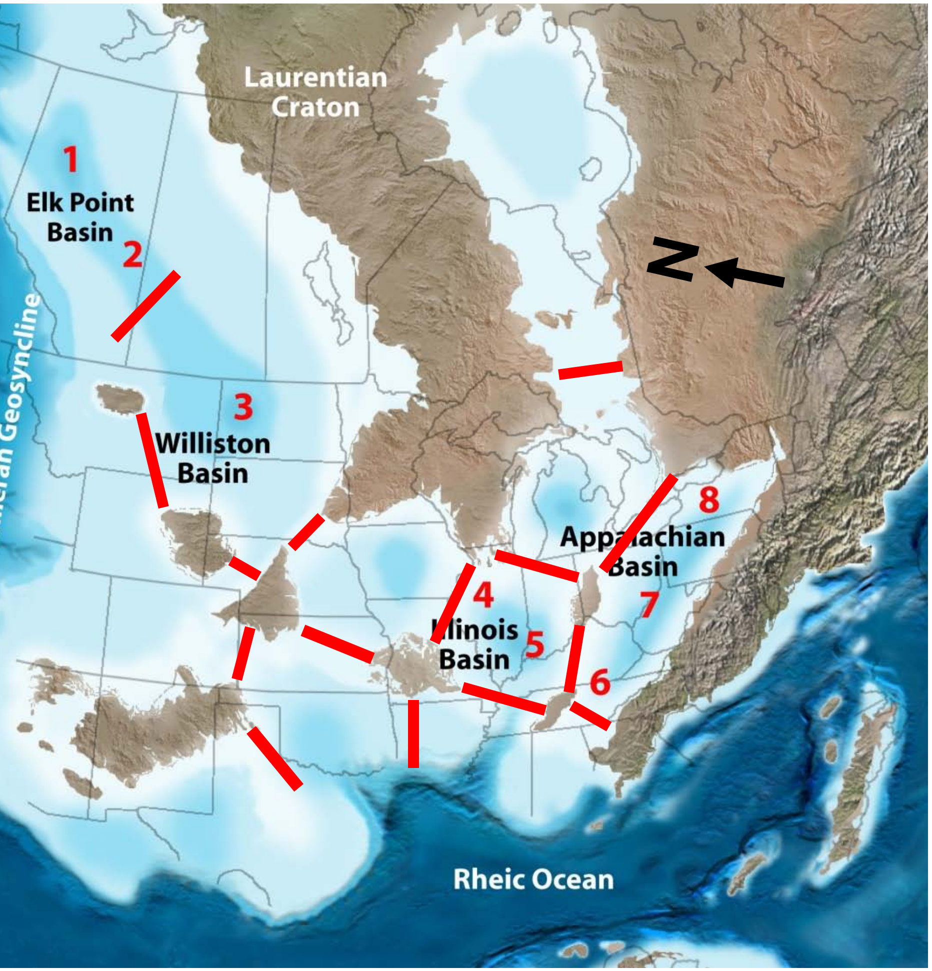
Wells et al. (2007)

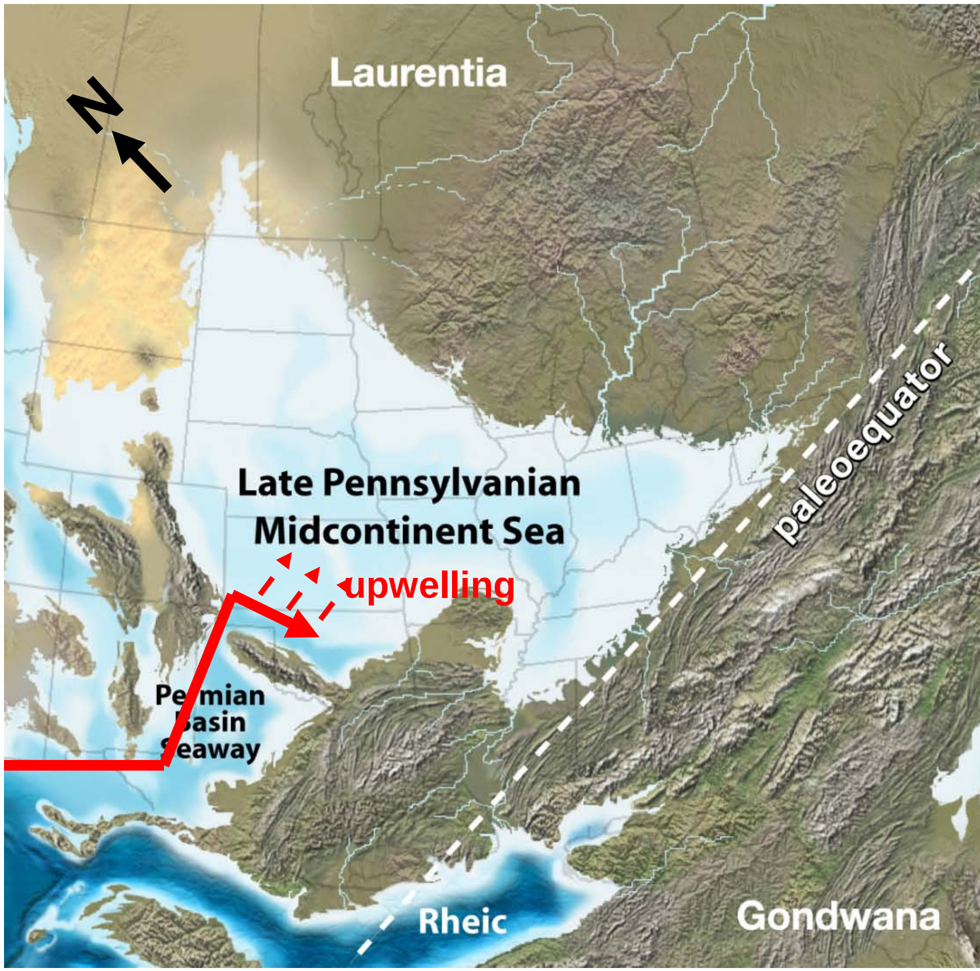


$\delta^{18}O_{apatite}$
(‰ V-SMOW)
black shale
(n = 31)
gray shale
(n = 32)
transgressive
limestone
(n = 14)
regressive
limestone
(n = 26)
22
21
20
19
sea level
nearshore
shale
both limestone
members
offshore shale

series of deep basins separated by shallower sills → hence, <u>restricted</u> deepwater circulation

deepwater connection to the Panthalassic Ocean through the Permian Basin Seaway → hence, probably <u>unrestricted</u> deepwater circulation



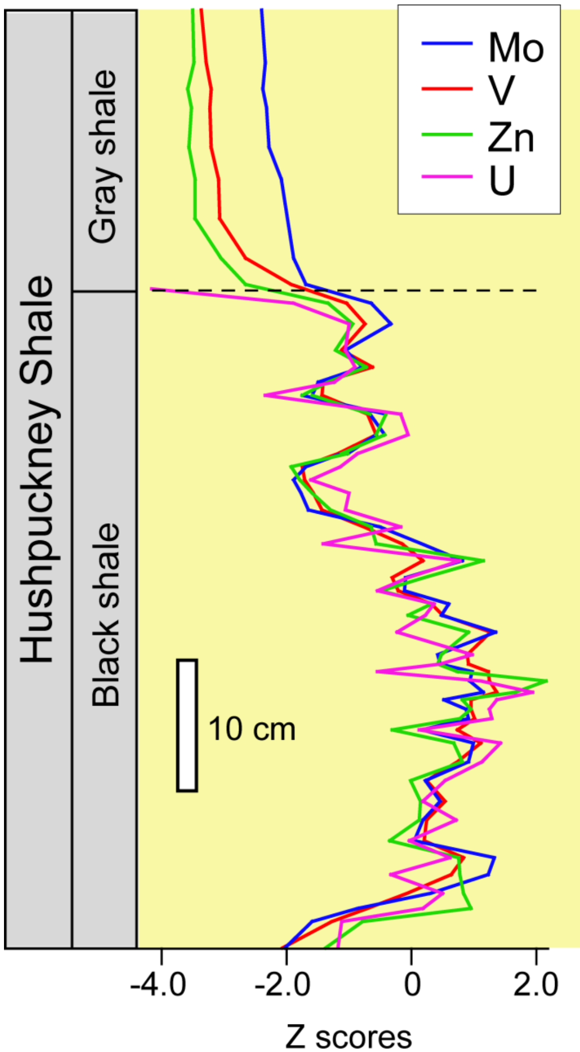


Major differences in bathymetry, circulation & hydrographic conditions

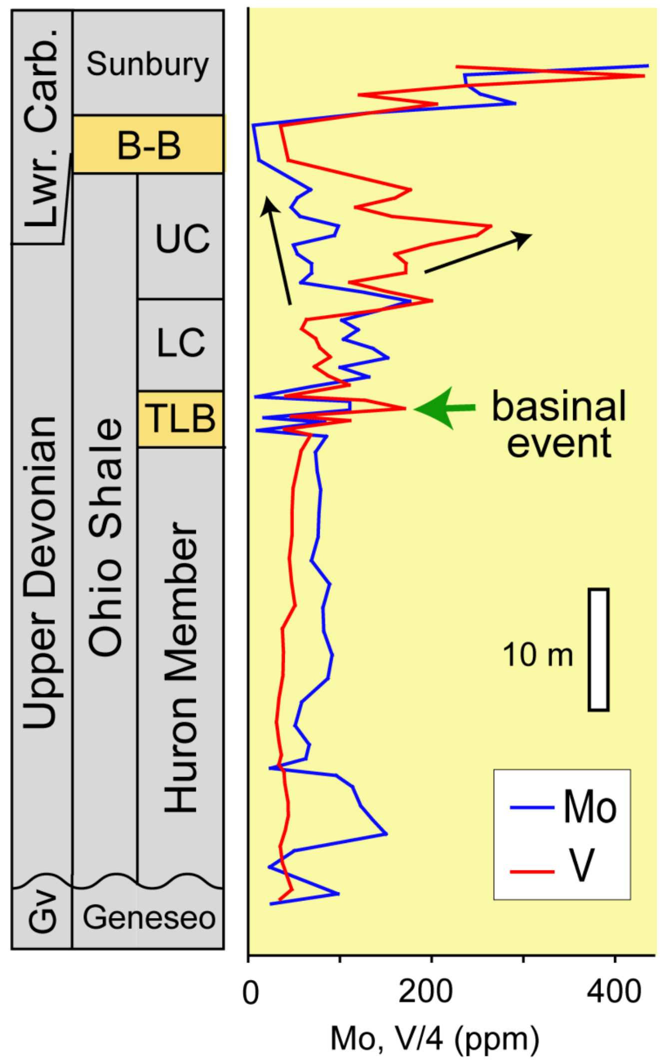
Late Pennsylvanian Midcontinent Sea:
Strong trace-metal covariation → constant watermass chemistry indicative <u>unrestricted</u> deepwater renewal

Late Devonian Seaway:
Divergent trace-metal concentration patterns → evolution of watermass chemistry indicative of <u>restricted</u> deepwater renewal

Upper Pennsylvanian, Midcontinent USA

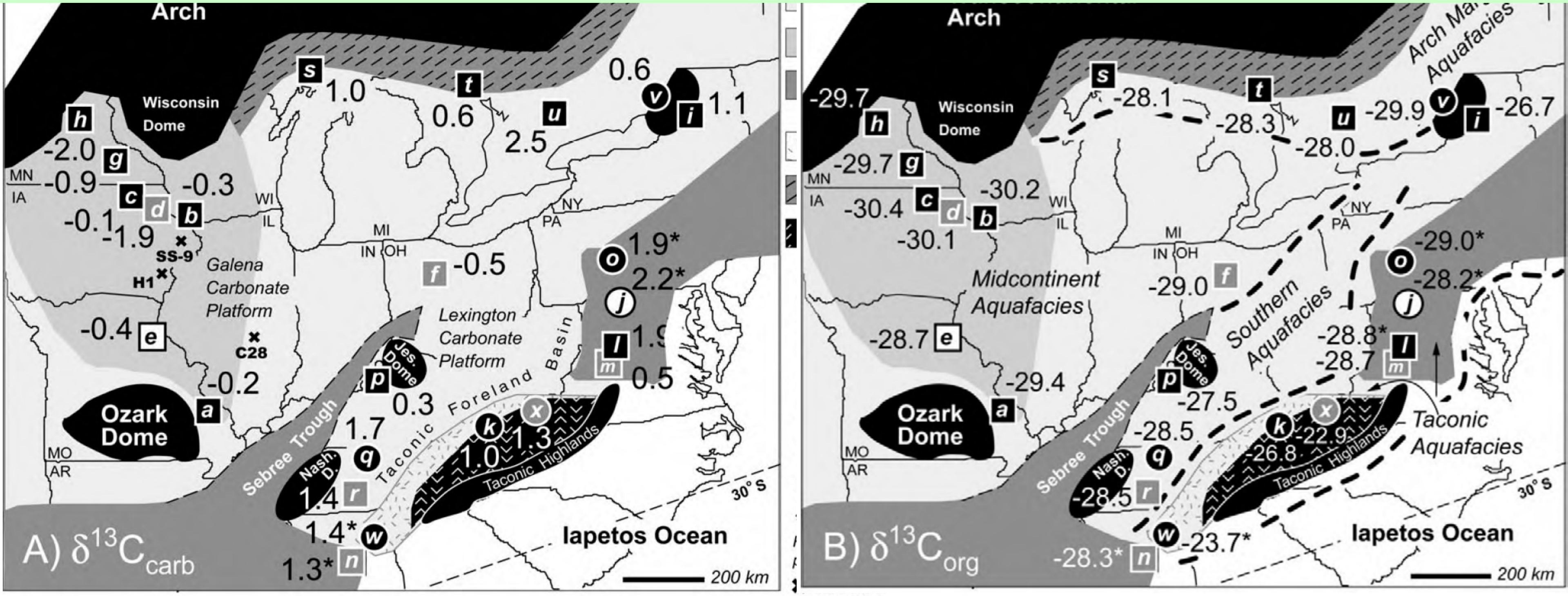


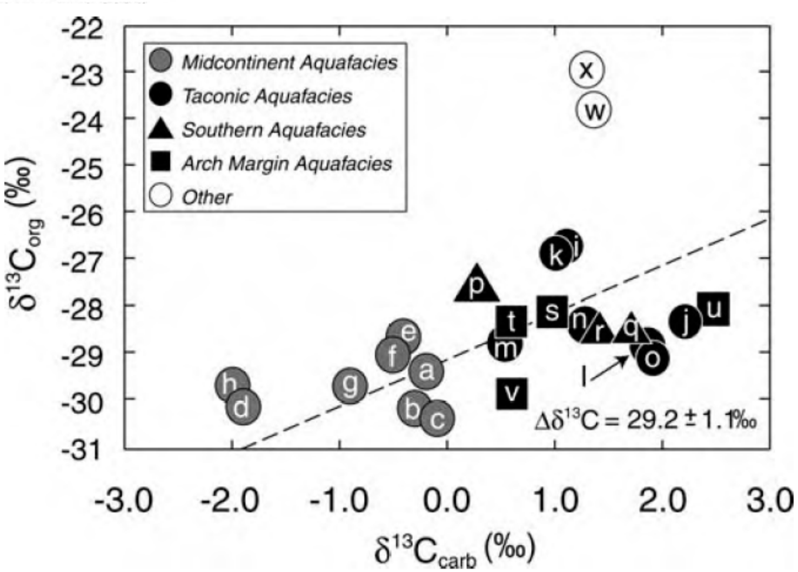
Dominant control: Benthic redox variation



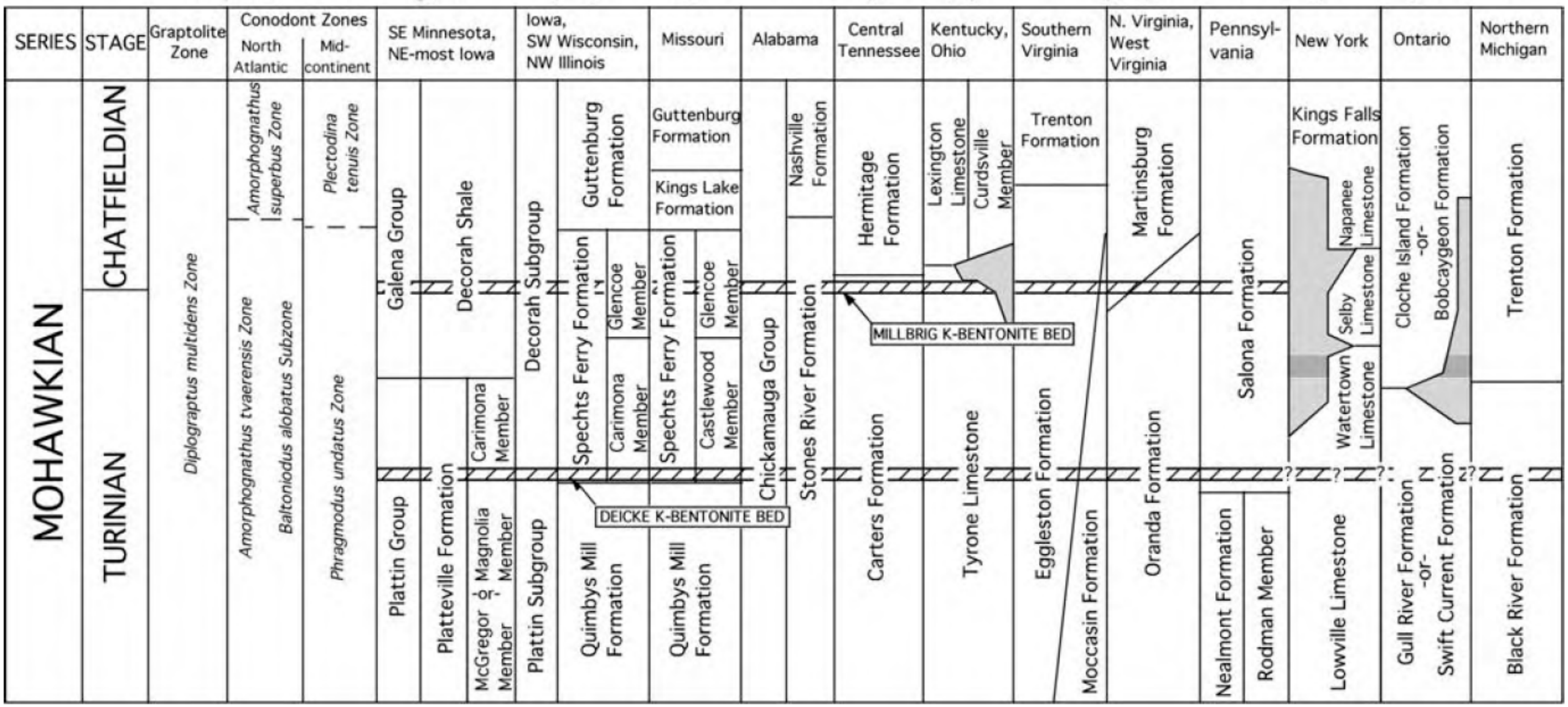
Upper Devonian, Appalachian Basin

Dominant control: Degree of deepwater restriction



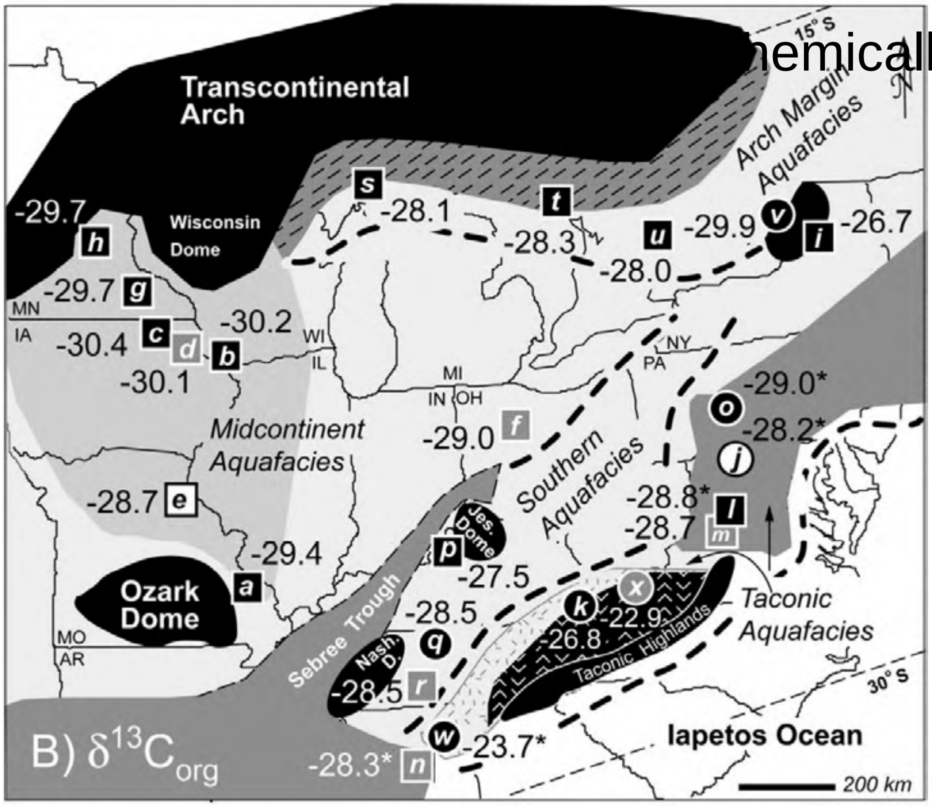


Panchuk et al. (2006)

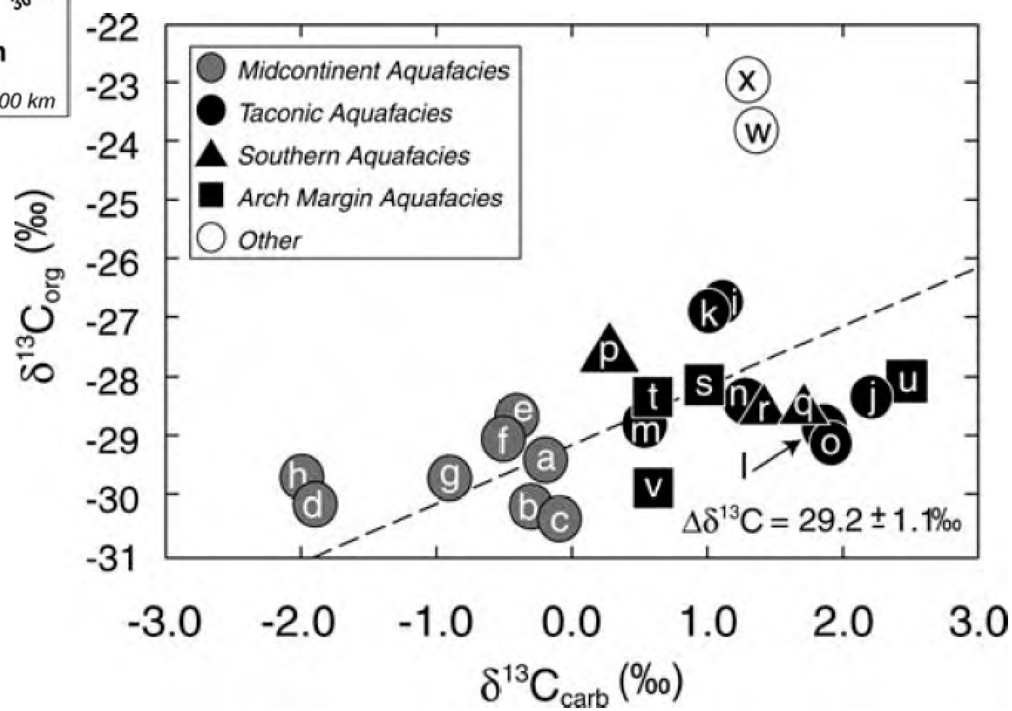


Panchuk et al. (2006)

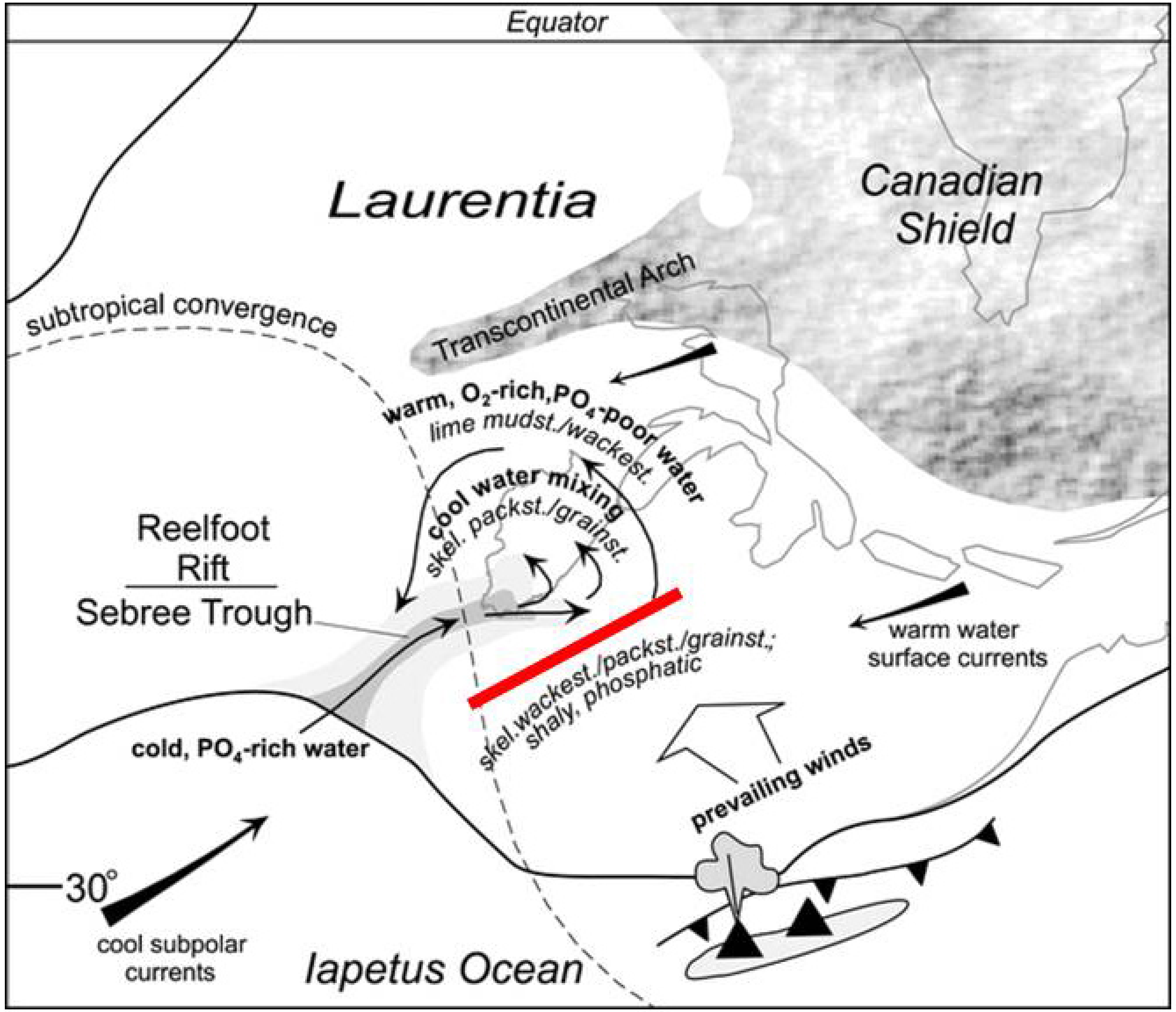
hemically distinct watermasses



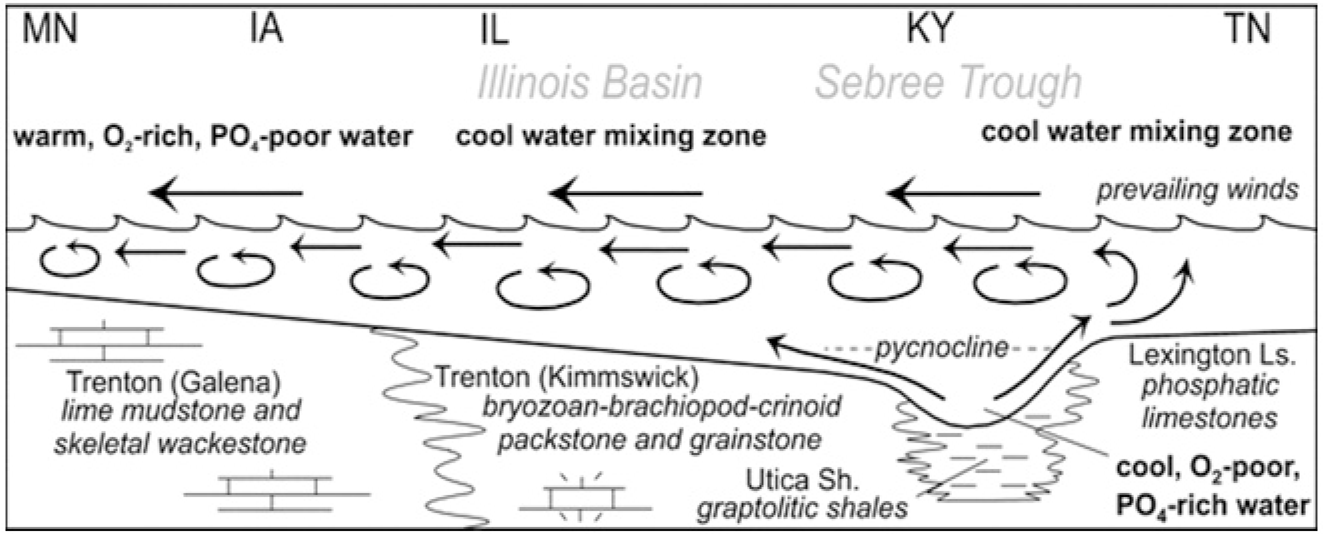
δ^{13}Corg



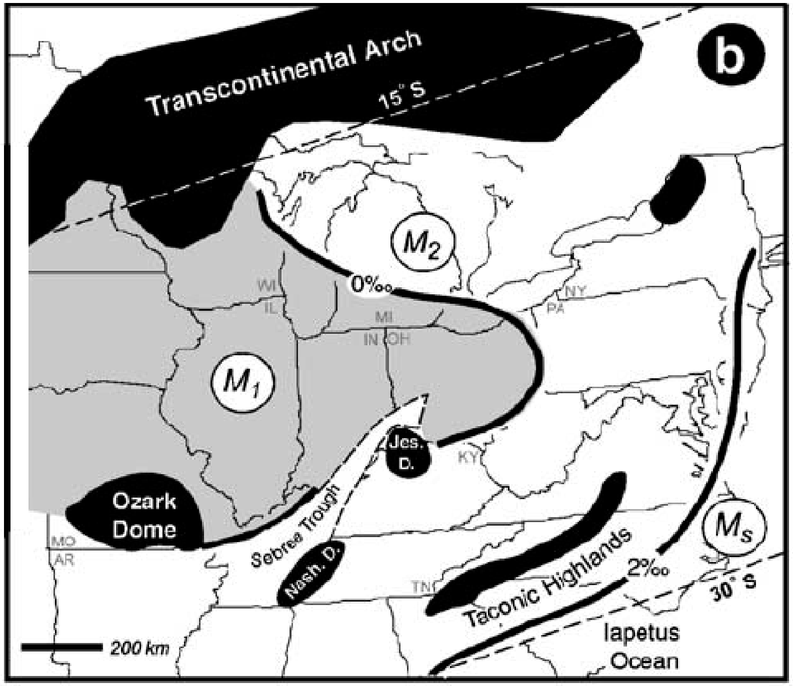
Panchuk et al. (2006)



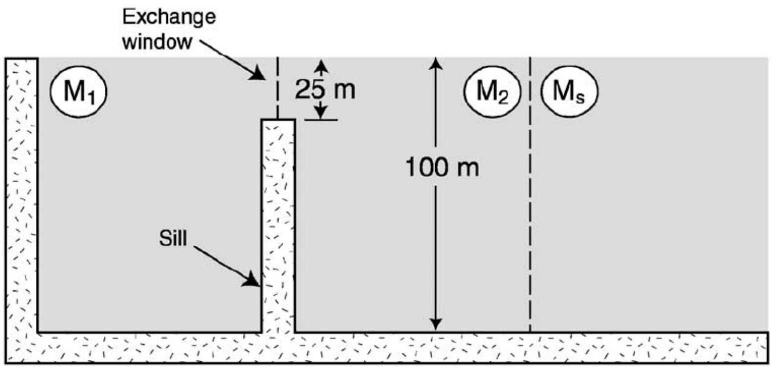
Kolata et al. (2001)



Paleoceanographic modeling of Mohawkian Sea

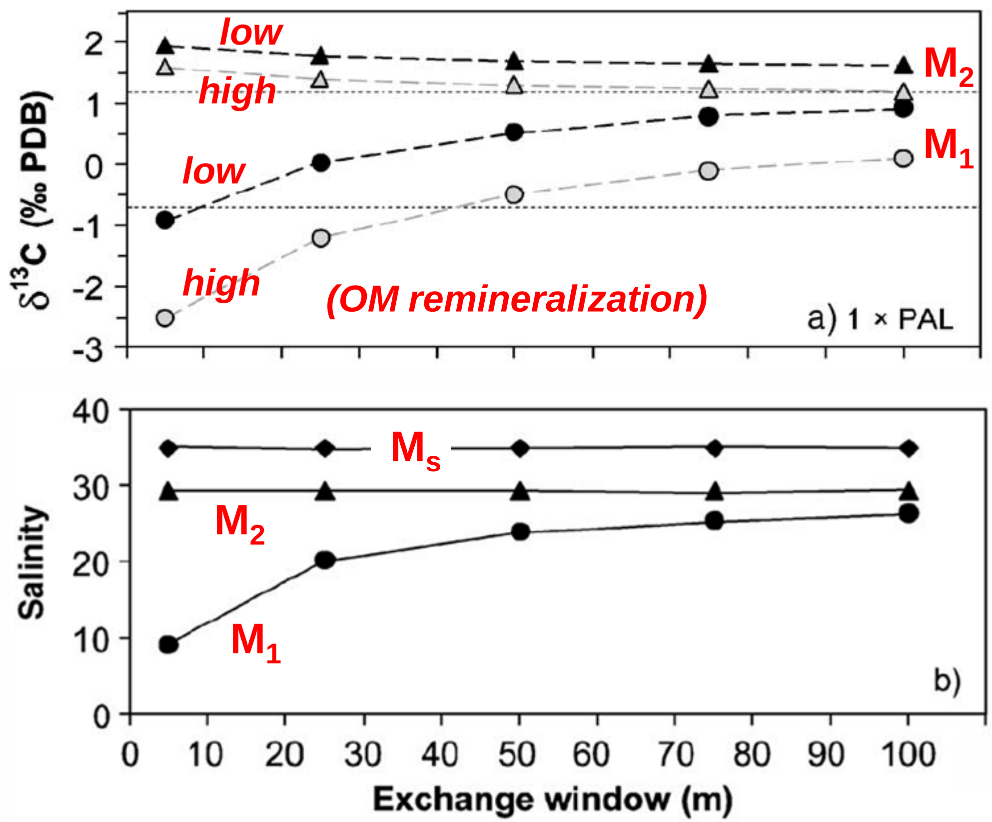


Paleogeography



Boundary conditions

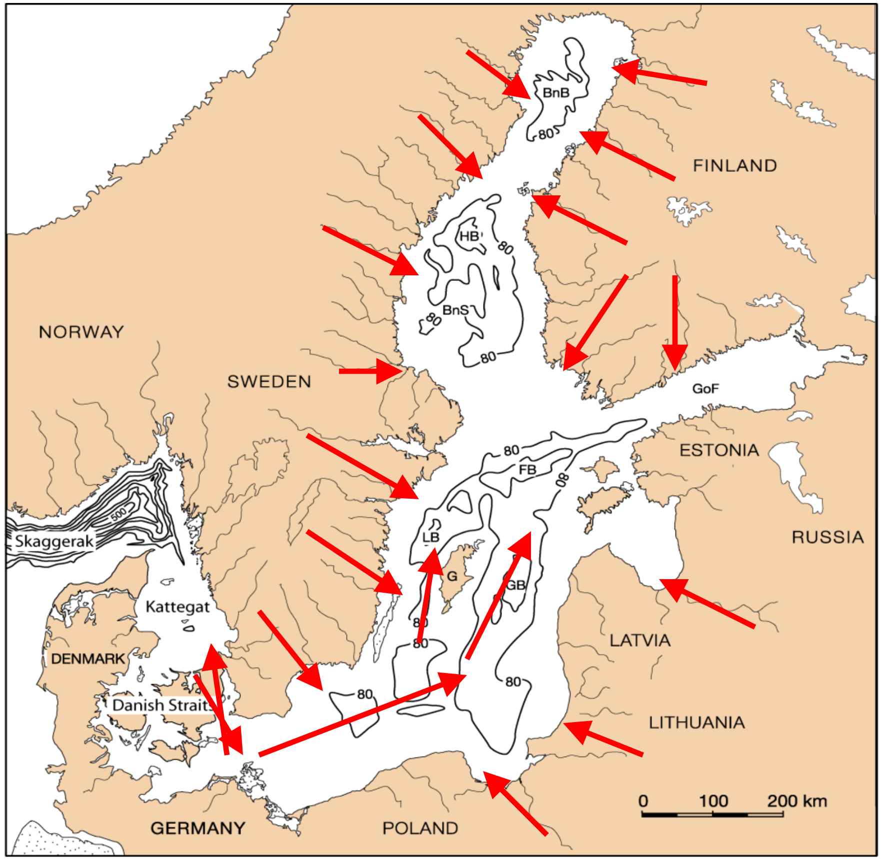
Model results

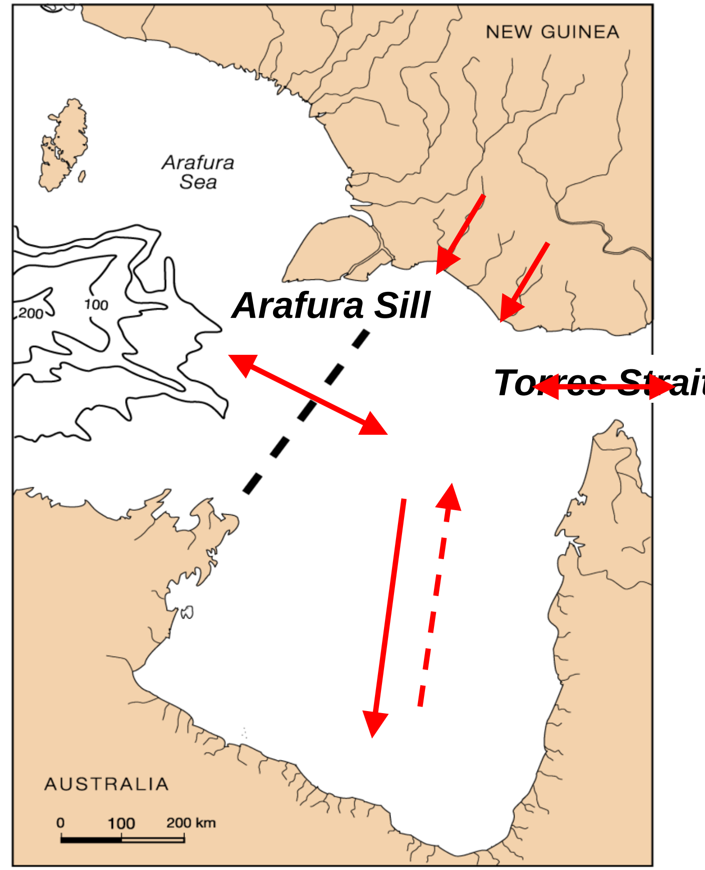


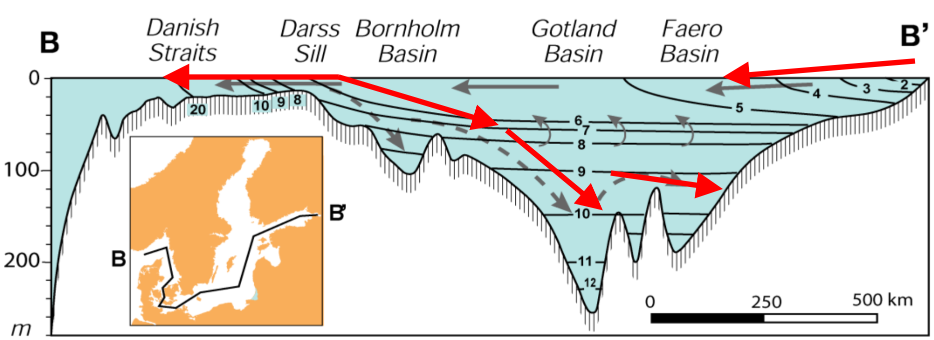
Panchuk et al. (2005)

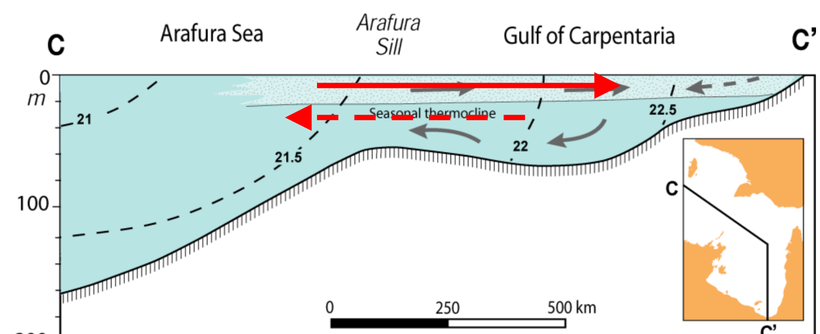
BALTIC SEA

GULF OF CARPENTARIA

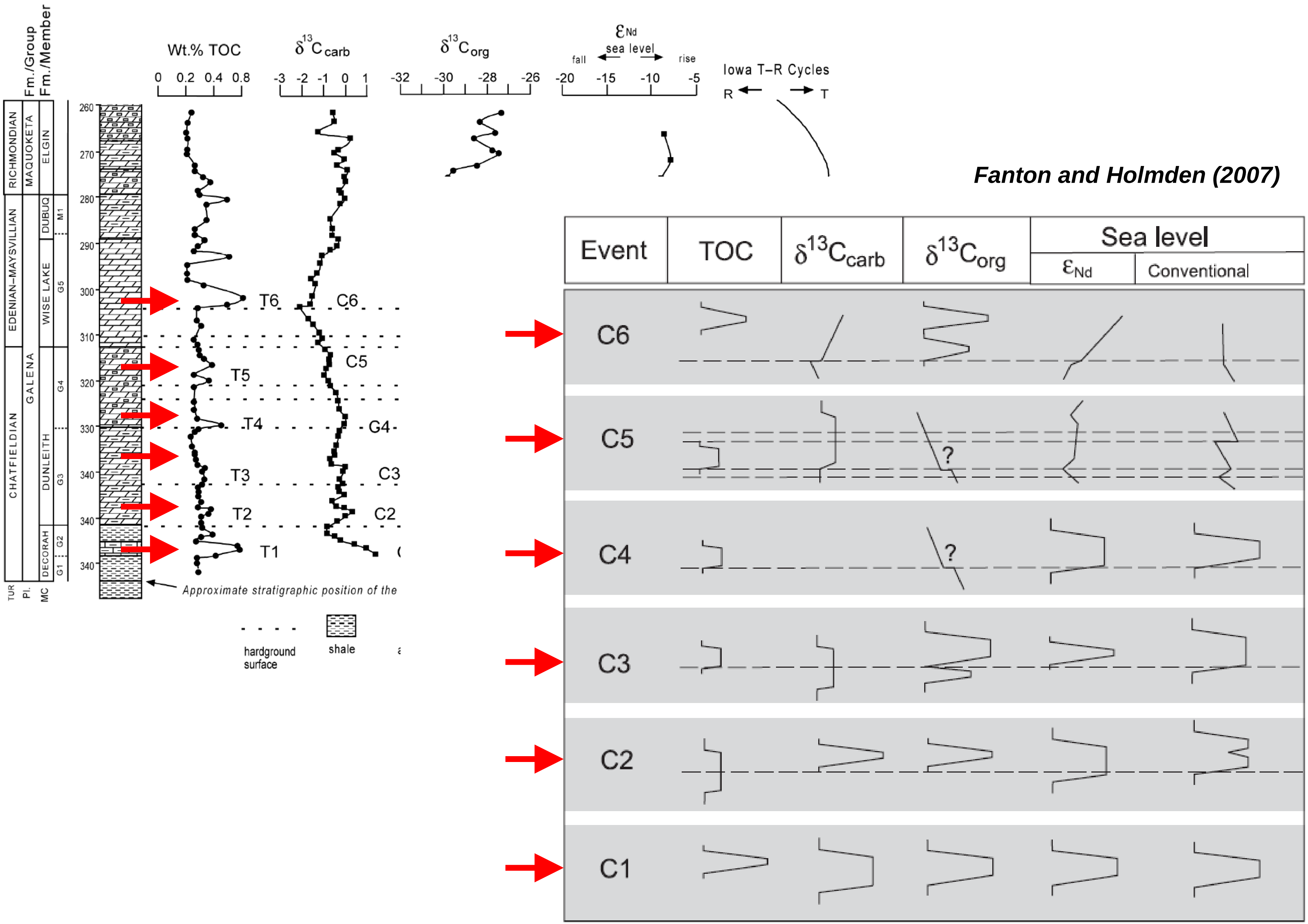




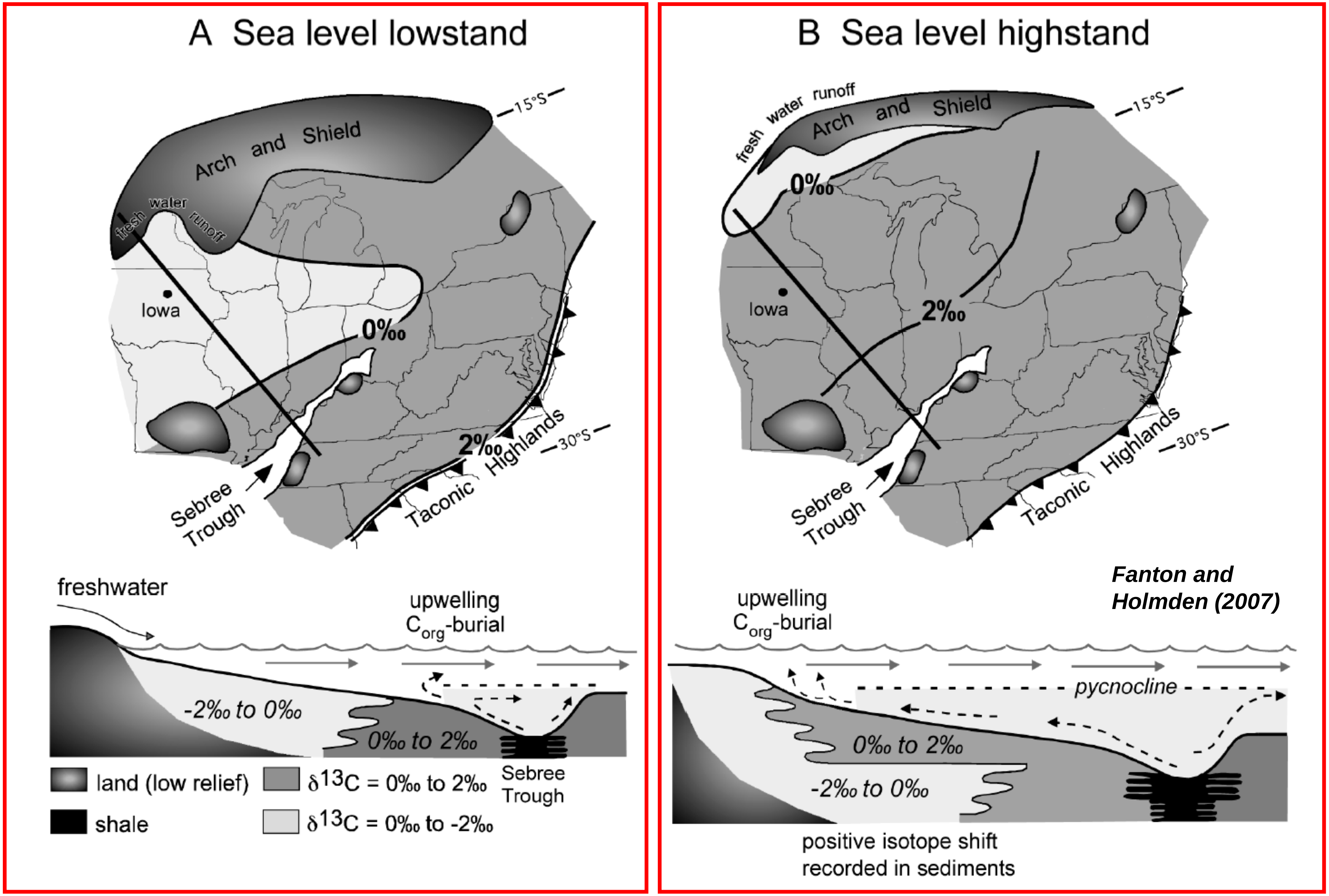




Highstand / lowstand cycles → changes in epeiric sea circulation



Highstand / lowstand cycles → changes in epeiric sea circulation



Fanton and Holmden (2007)