Shale Gas and Muddy Shelves: Comparing the Neogene-Quaternary Eridanos System (NW Europe) with the Devonian Catskill Delta (USA)*

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Abstract

The recent worldwide focus on gas and oil shales contrasts with our limited knowledge of the processes and geological context of environments dominated by fine clastic sedimentation. Development of such resources requires refined models that relate biogenic gas generation and storage to facies and architectural elements at depositional system scale, and to systems tracts and geotectonic setting at basin scale. A comparative research approach can relate palaeoenvironmental conditions and allogenic forcing of well studied depositional systems with those of shale prospects still under exploration.

We discuss sedimentological and architectural analogies and differences between the Neogene-Quaternary ‘Eridanos Delta' of northern Europe, which drained the Fennoscandian and Baltic shields westward through the present-day Baltic Sea, and the Devonian ‘Catskill Delta', which prograded into the Appalachian Foreland Basin (eastern USA) during the Acadian orogenic phase. In spite of their common denomination as ‘deltas', these clastic wedges actually represent fluvial to coastal environments linked to shallow-marine, mud-dominated shelves in a proximal-to-distal continuum. The Eridanos system hosts numerous productive shallow-gas plays in the southern North Sea offshore, whereas the Catskill system contains important black-shale formations (Marcellus, Rhinestreet, Dunkirk, etc.) that charge an Appalachian hydrocarbon system.

Changes in base level and sediment supply, partly influenced by climate during the Plio-Pleistocene onset of glaciation, controlled the complex proximal architecture of the Eridanos Delta, and they are reflected by compositional and architectural changes in its mud-prone, basinal portion. The Eridanos Delta provides an example of well constrained relationships between different forcing factors, sedimentary properties and the hydrocarbon potential of its shaly domain. These insights may support new predictive genetic models for black shales of the Catskill and other systems, especially if applied to high-order heterogeneities within and between shale bodies which were probably driven by allogenic factors at time scales of millions of years and shorter. The potential for future hydrocarbon production from such plays, especially in areas with

surface footprint constraints (e.g., Europe), depends on the ability to unravel their internal variability, and thus, to target intelligently the most productive stratigraphic intervals.

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--Shale Gas and Muddy Shelves

Comparing the Neogene-Quaternary Eridanos System (NW Europe) with the Devonian Catskill Delta (USA)

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About TNO

TNO is a technology development and consulting company with over 30 years of experience in the Oil & Gas industry

- Technology development, consulting, and contract R&D
- Approximately 4500 employees
- 2/3 revenue from industry, 1/3 Dutch government

- Active in many other markets

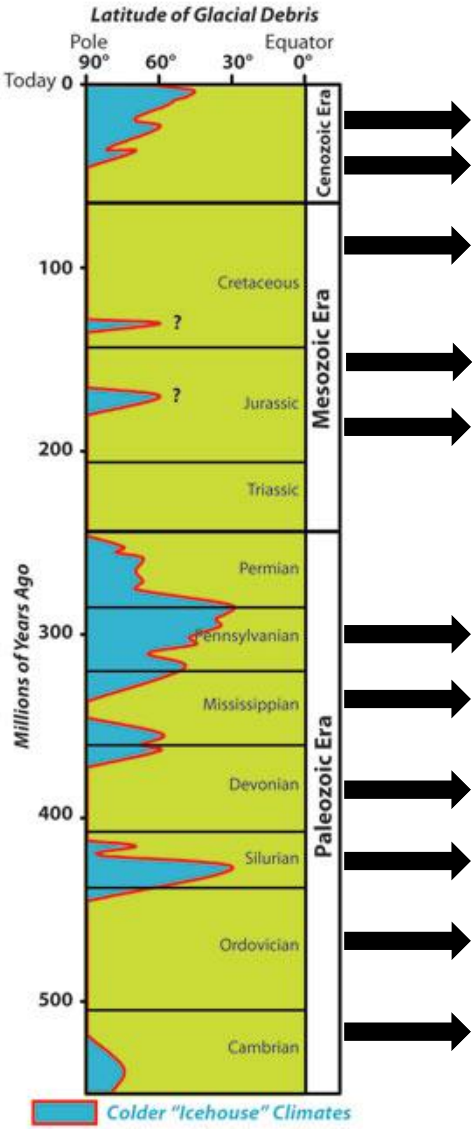
Shale reservoirs are not new…

- First commercial production 1821 (Fredonia, NY)
- Over 28.000 wells
- Recent boom through technical advancements

But..

- Knowledge on the processes and geological context of environments dominated by shale sedimentation is in a juvenile stage

- This contrasts with our in-depth knowledge/concepts of clastic- and carbonate reservoirs that more successfully serves exploration



http://nature.nps.gov/geology/nationalfossilday/climate_change_earth_history.cfm

Icehouse vs. Greenhouse gas shales

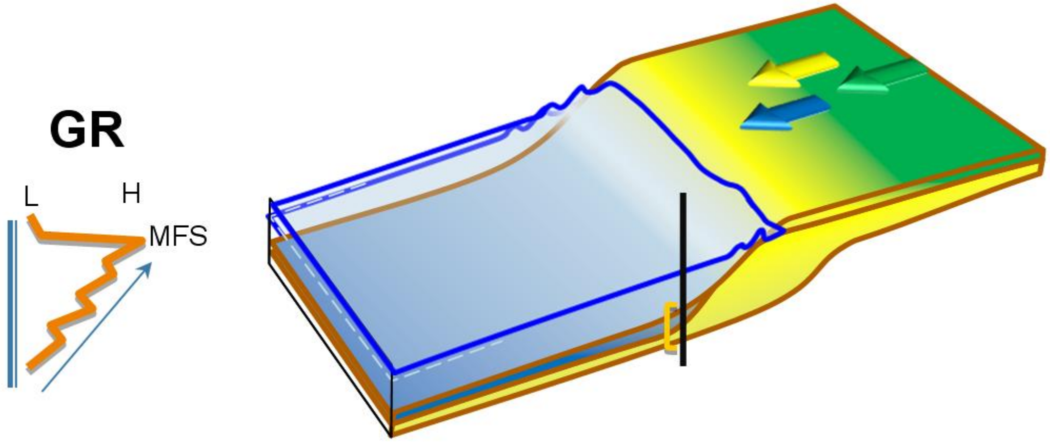
- Much of the geological concepts based on greenhouse world organic-rich rocks (ORR)

- Are these greenhouse concepts applicable to ice house world?

NO?


(classical) Greenhouse Transgression

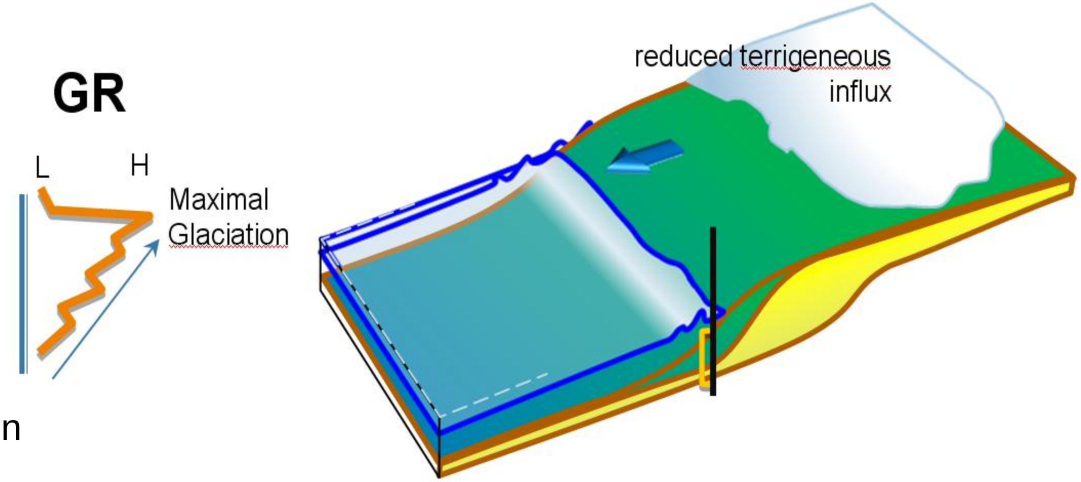
- Low dilation potential
- GR peak = maximum flooding
- High TOC at transgression and MFS



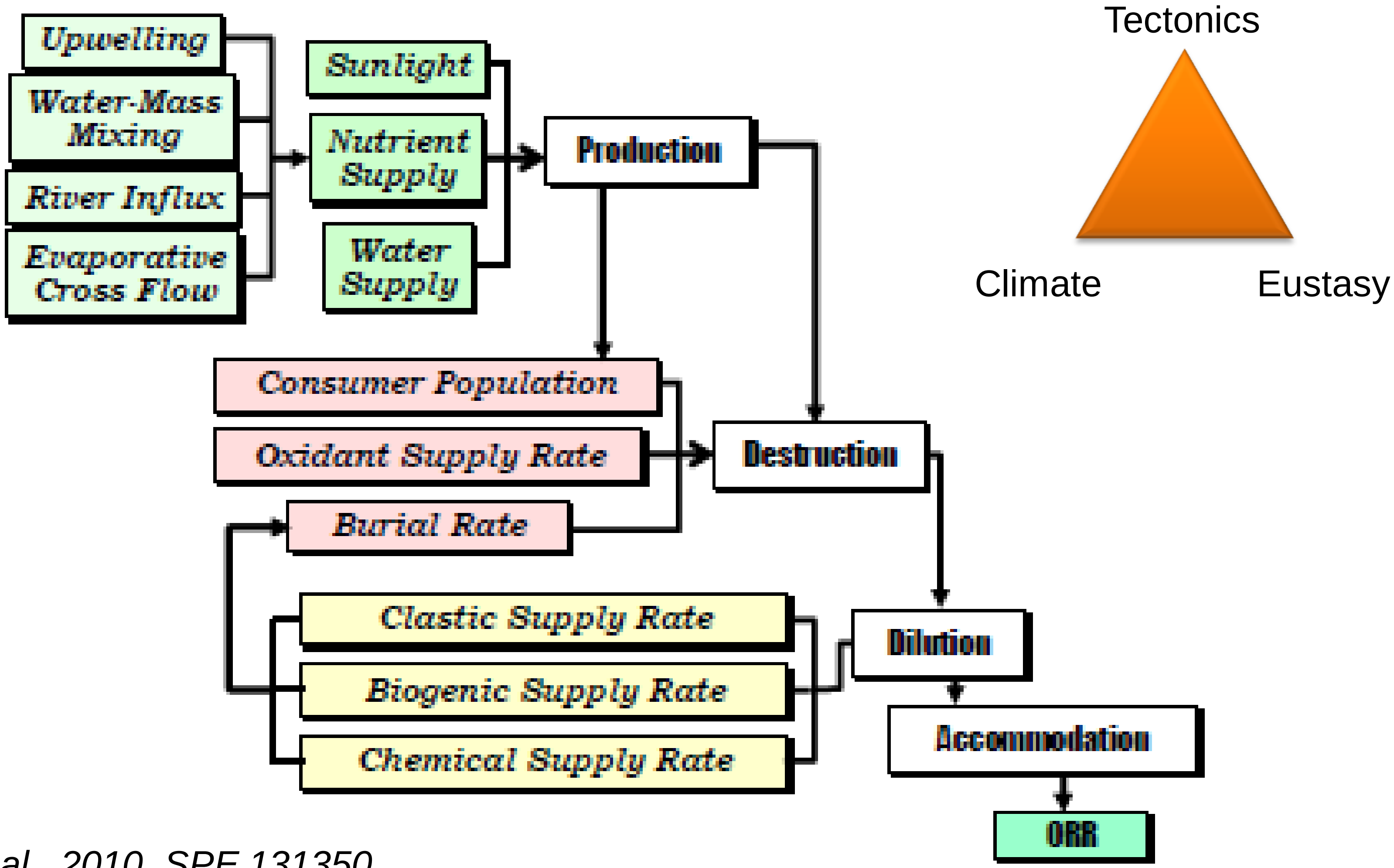
ICEHOUSE vs GREENHOUSE

Icehouse Regression

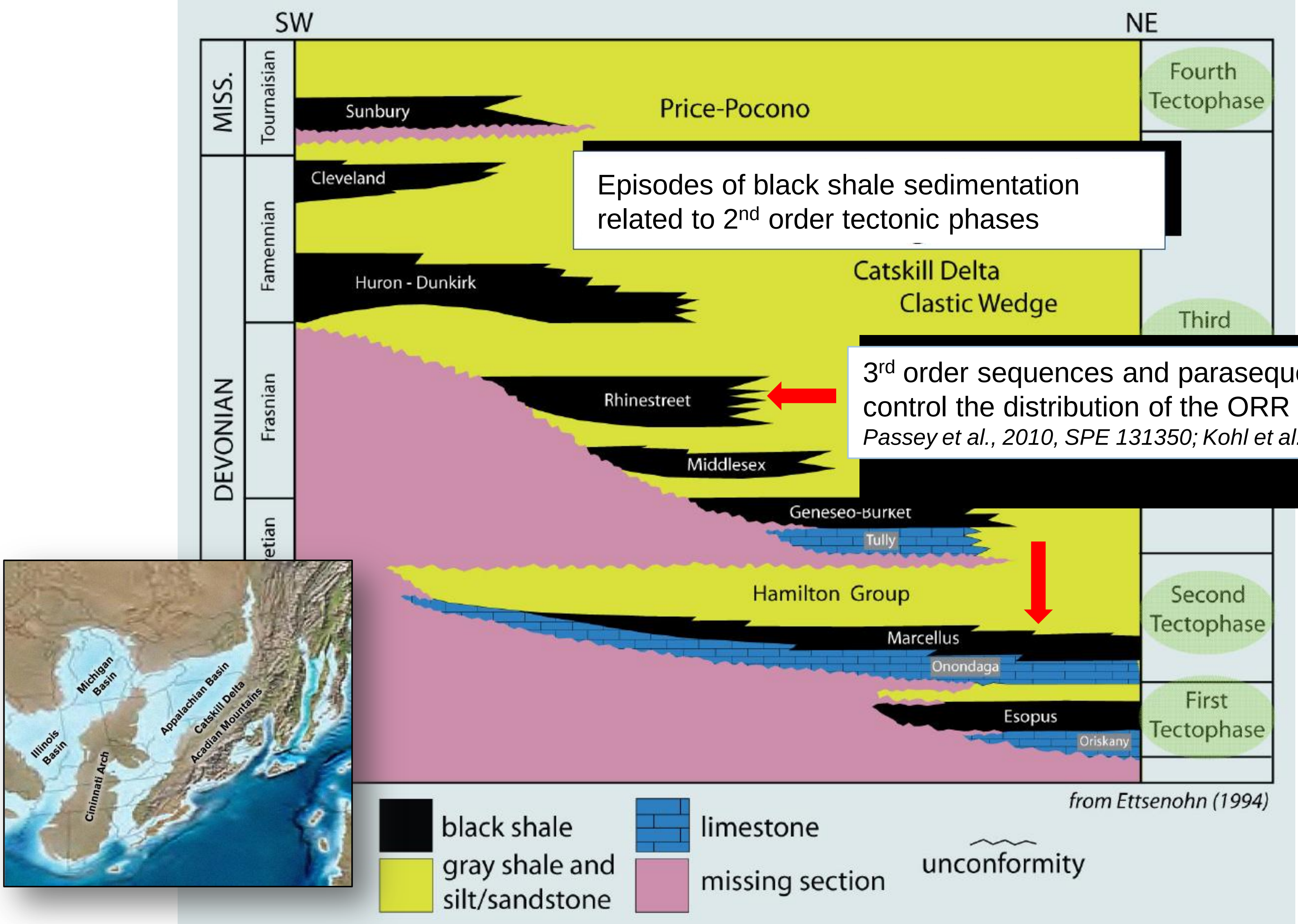
- Reduced clastic/nutrients influx
- Higher clay content/no organics
- GR peak = maximum glaciation
- High TOC during highstand progradation



TOC of organic-matter-rich rocks (ORR's)



Passey et al., 2010, SPE 131350



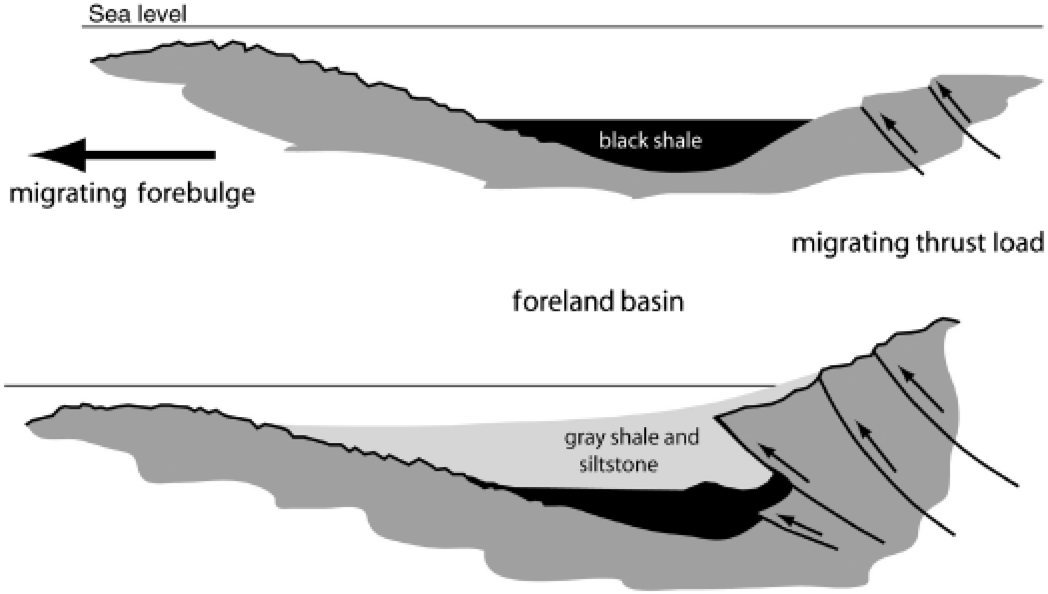
from Ettsenohn (1994)

Episodes of black shale sedimentation related to 2nd order tectonic phases

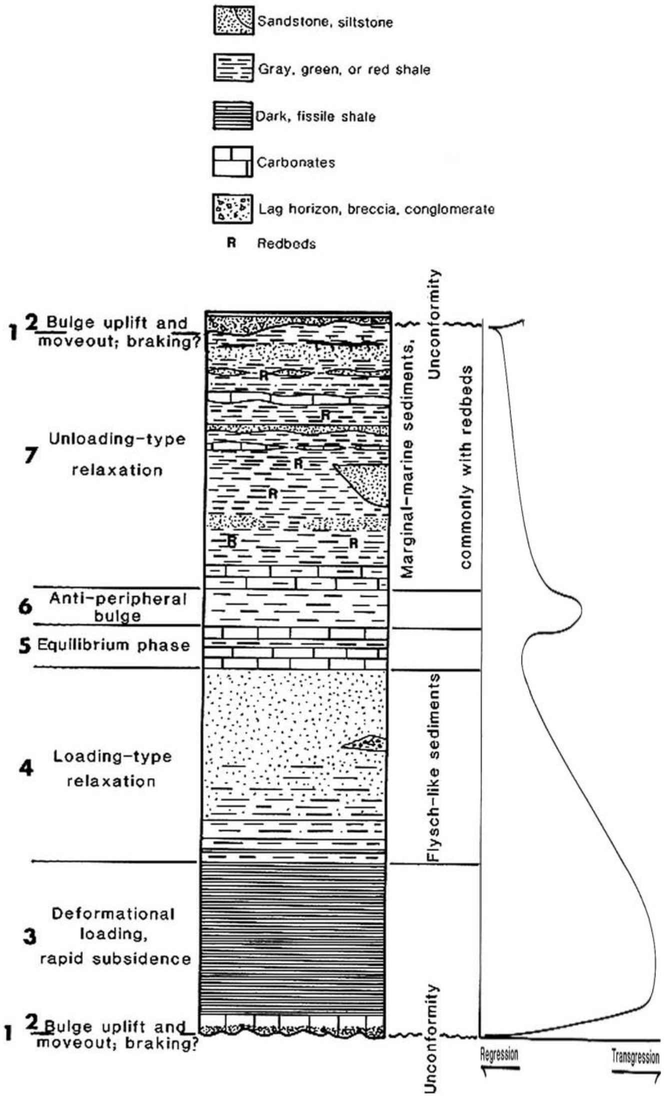
3rd order sequences and parasequences, control the distribution of the ORR

Passey et al., 2010, SPE 131350; Kohl et al. (2013)

Catskill depositional model

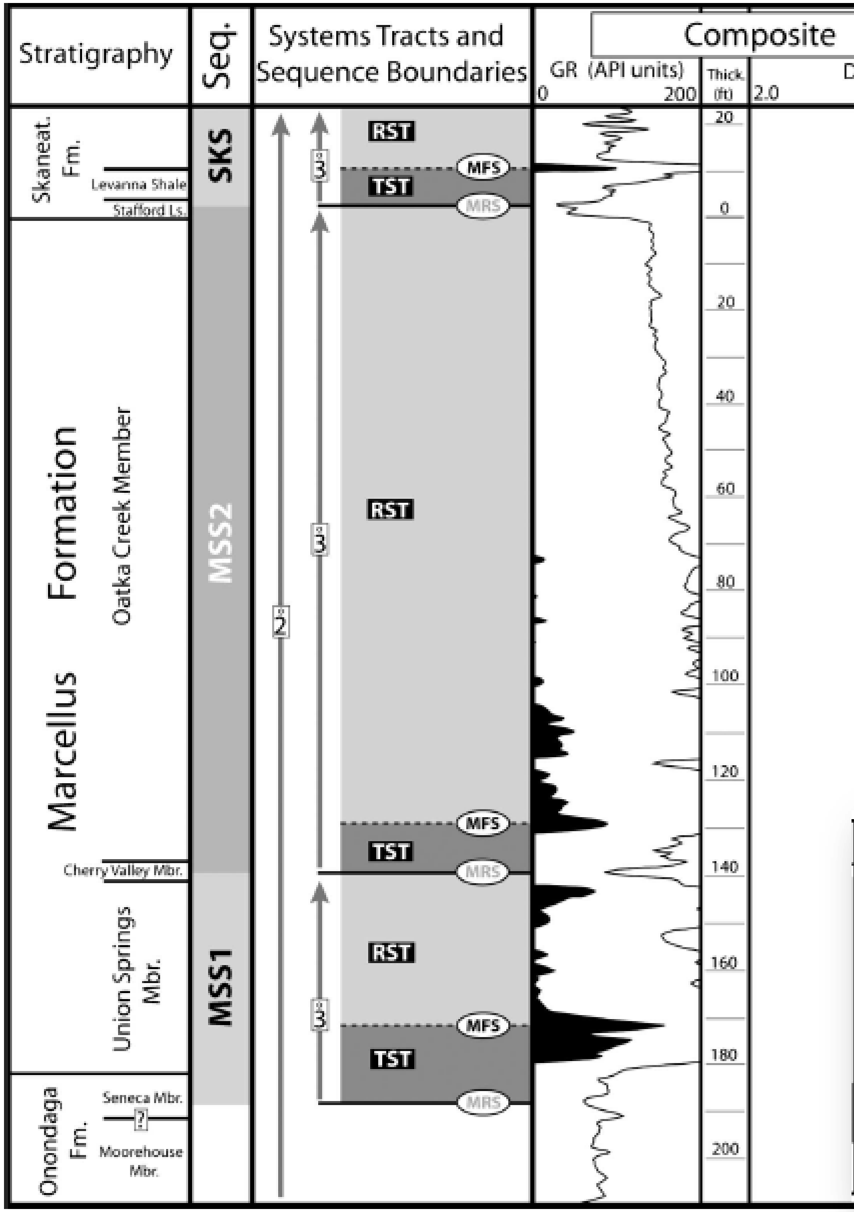


Modified from Ettensohn, 1994, 2008

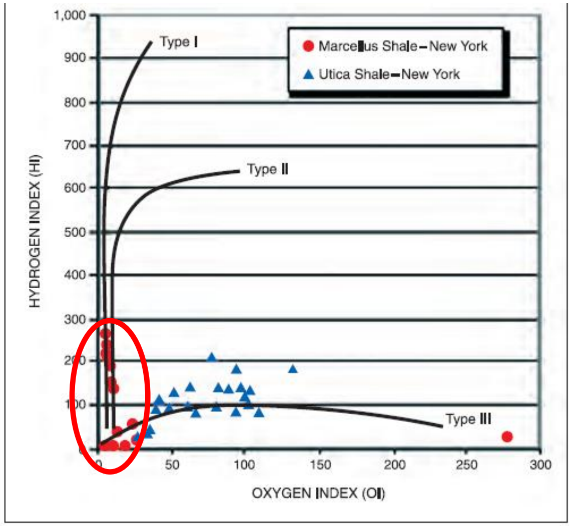


- ORR during transgression & highstand
- Higher supply at relative lowstand
- Low eustatic amplitude
- Greenhouse world

High GR = MFS = high TOC = high brittleness

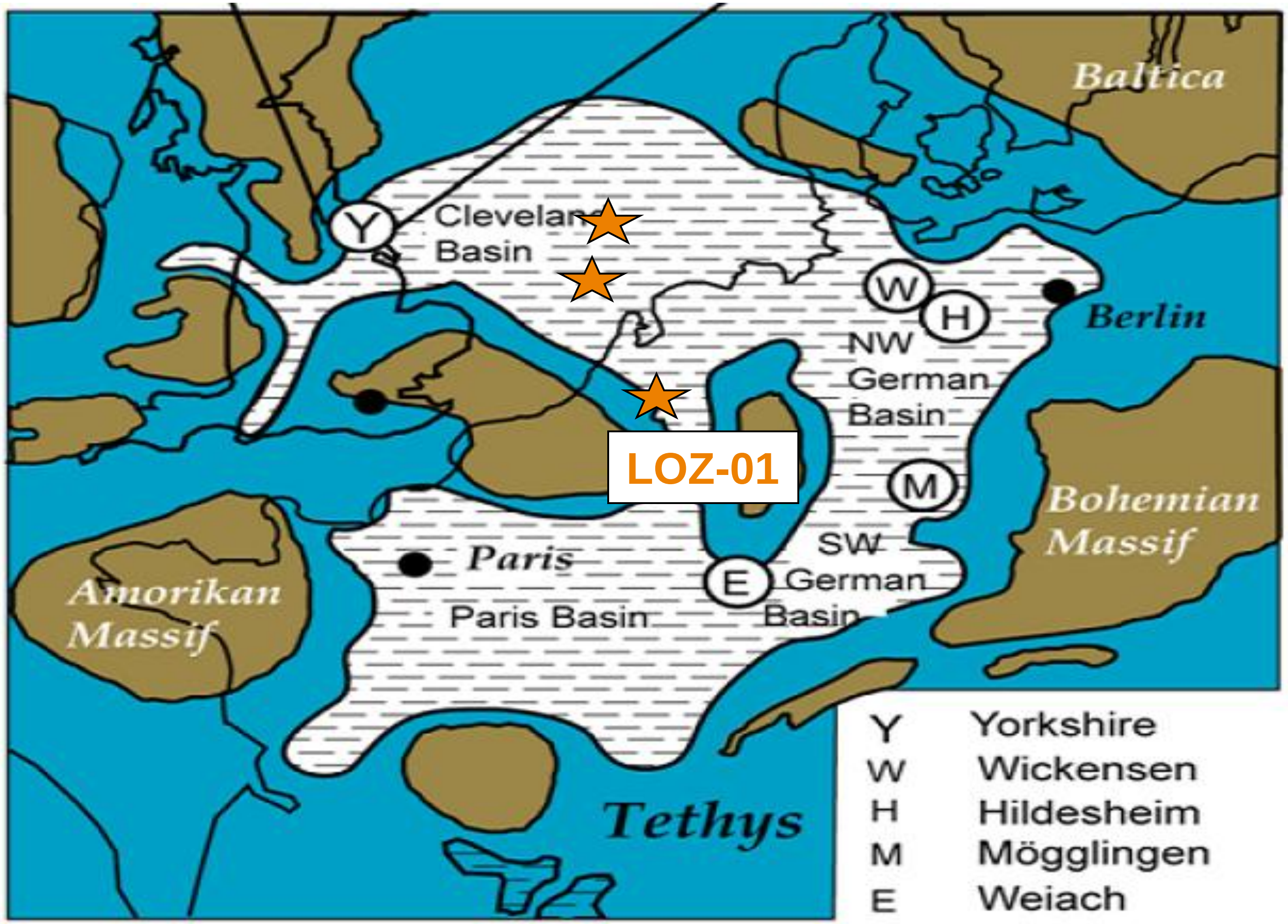


Lash & Engelder, 2011

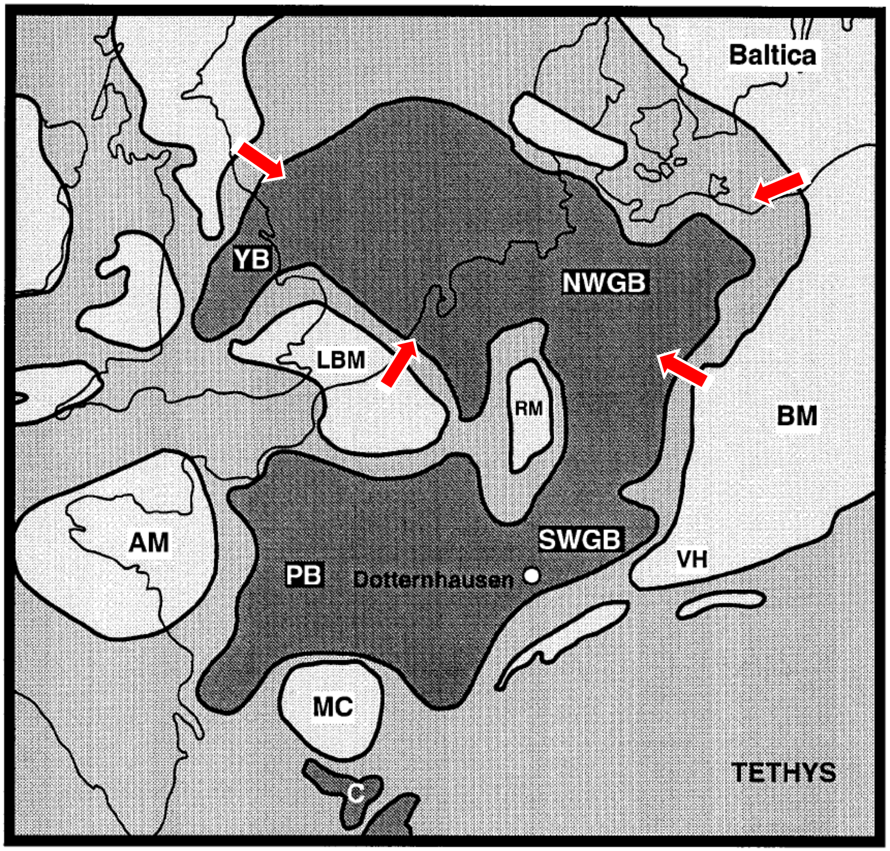


Hill et al., 2004

Applicability of concept to other greenhouse world shales – the Posidonia FM (UJ Europe)



from *Röhl and Schmid-Röhl (2005)*



░ **emerged areas:**
LBM: London-Brabant Massif, RM: Rhenish Massif, BM: Bohemian Massif, VH: Videlician High, AM: Amoricanian Massif, MC: Massif Central.

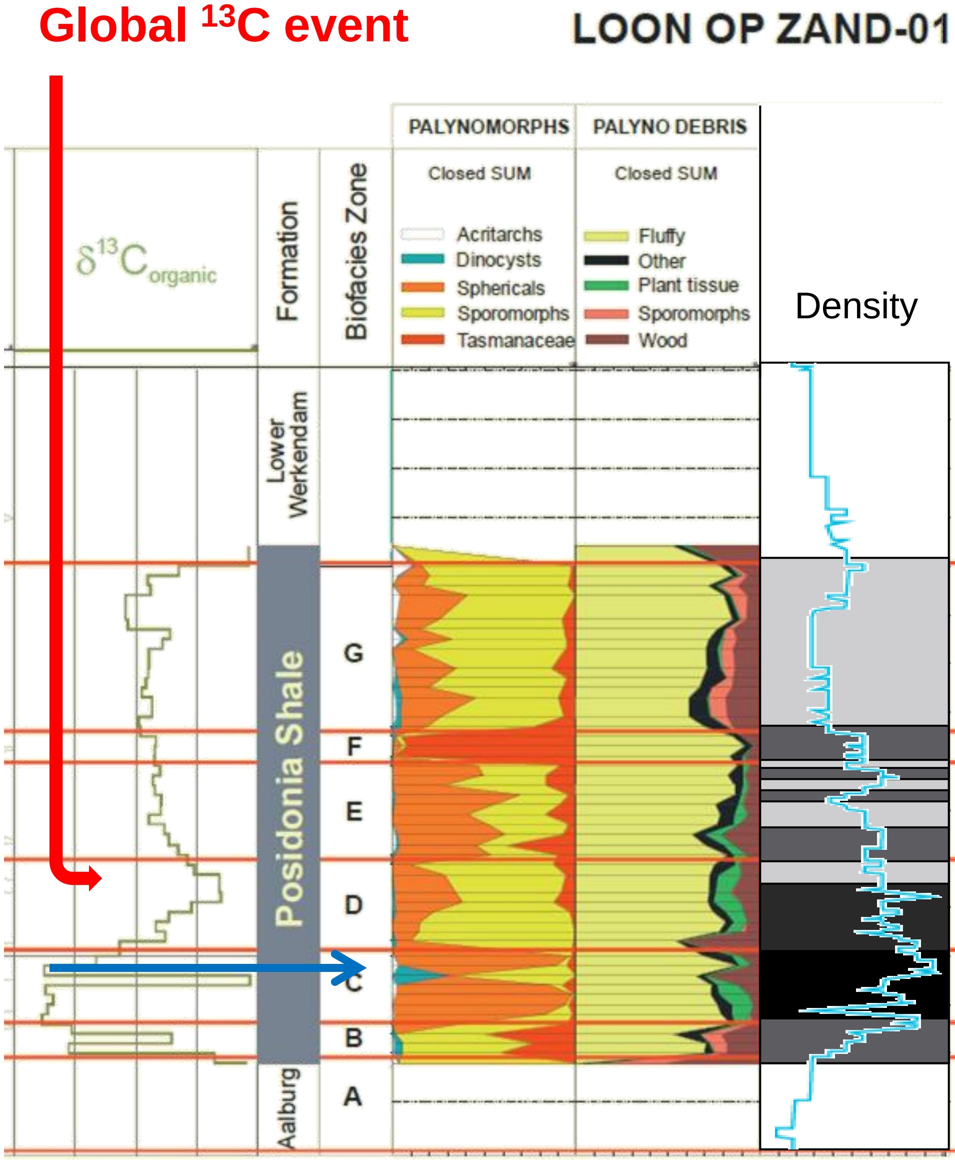
▓ **distribution of the bitumimous facies:**
YB: Yorkshire Basin, NWGB: NW German Basin, SWGB: SW German Basin, PB: Paris Basin, C: Chalhac.

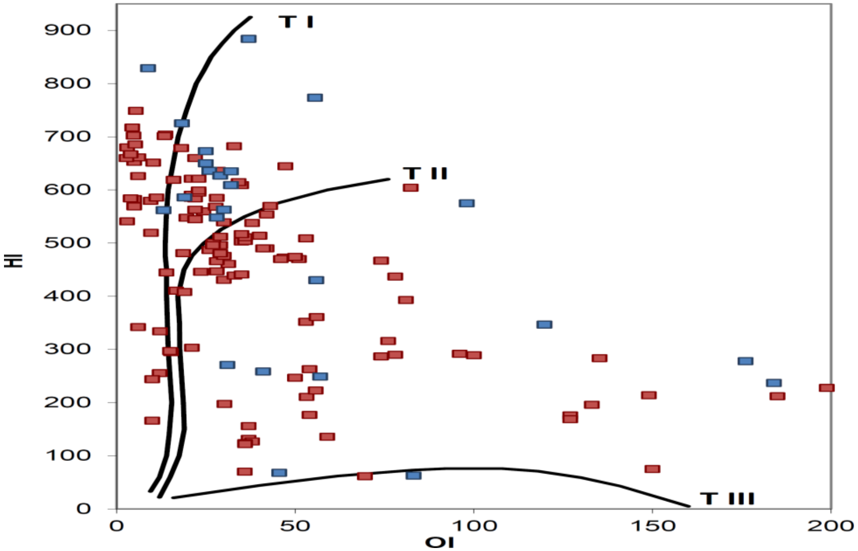
▒ **shallow water**

- Similar carbonate-dominated shallow-marine domains…
- Similar basin-centered ORR

Biofacies zonation

Global ^{13}C event





Palaeoenvironmental development

Warm and dry climate
Decrease freshwater influence nearshore
Gradual return to normal marine conditons

Stratification restricted to coastal zone

Second Tasmanites acme

Decrease swamps
Increasing aridity
End of anoxia in basin center
Freshwaer influence far offshore is waning

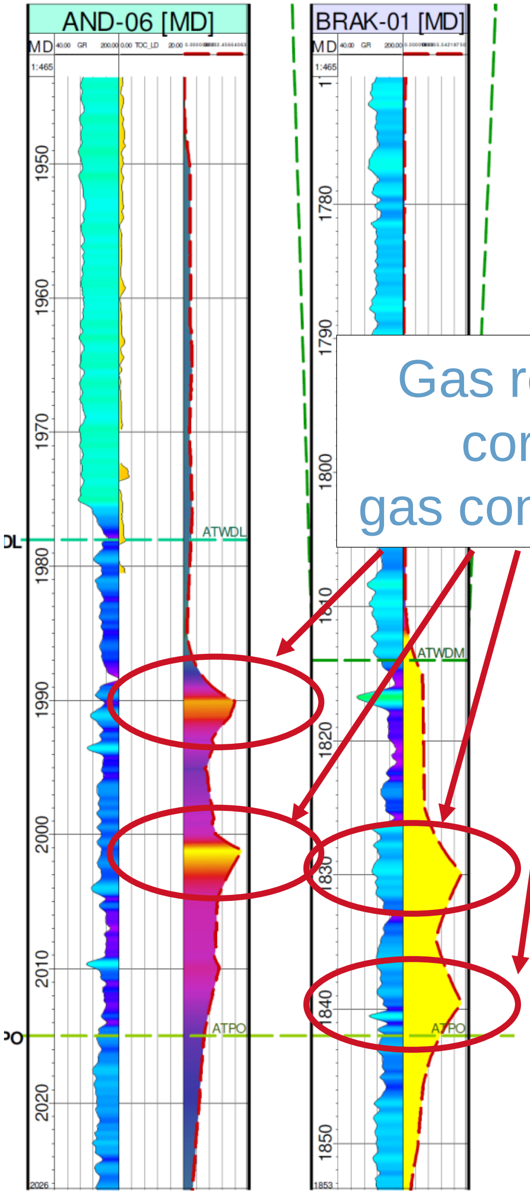
Vegetation change > expansion of swamps
Stratification of water column

Increased river activity
Strong stratification; persistent low salinity surface layer

Increase in runoff; first Tasmanites acme; start stratification

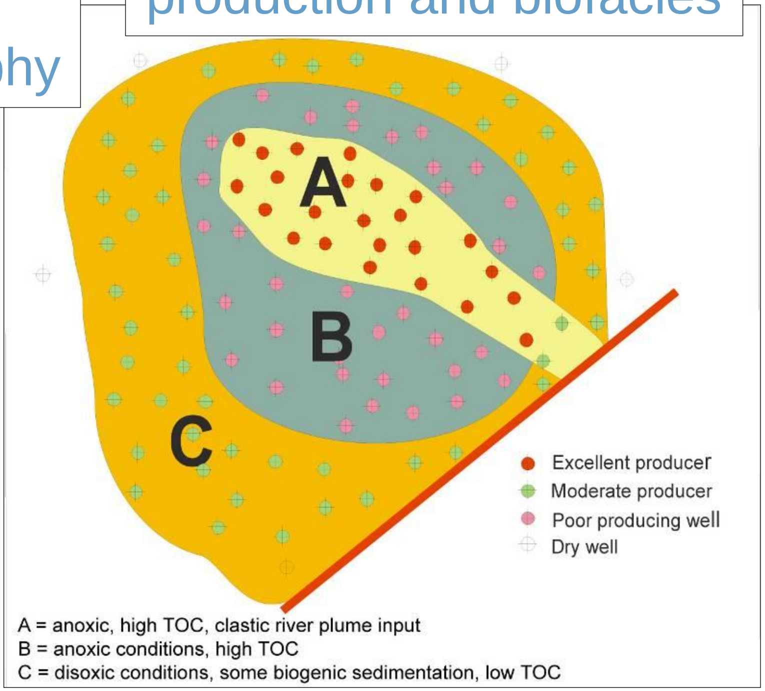
Warm and dry climate
Normal marine conditions


For shale gas exploration it is important to identify “sweet spots” and “pay zones”



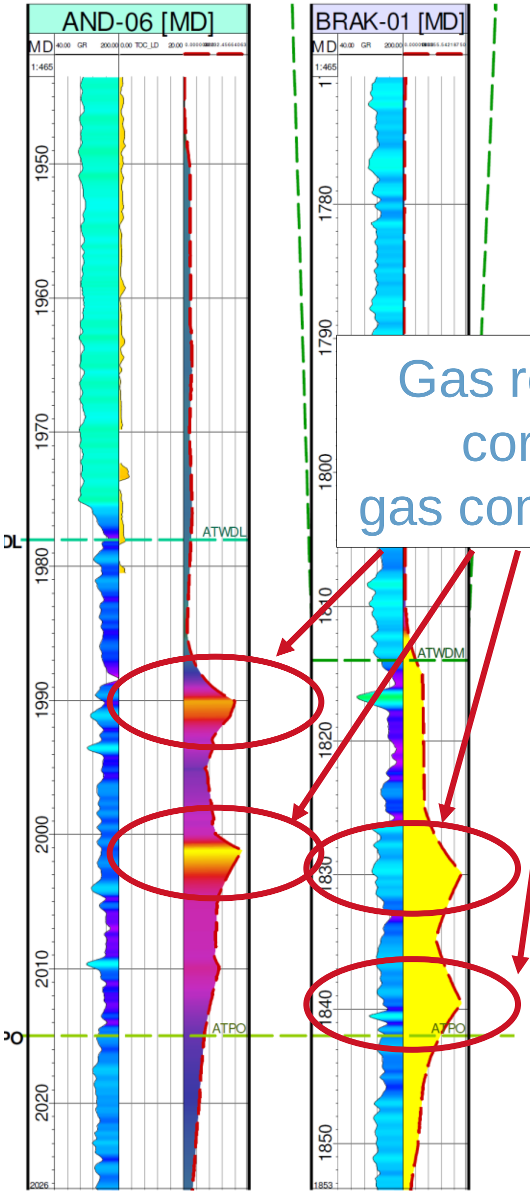
Gas readings in mud log: correlation between gas content and stratigraphy

Biofacies map: correlation between production and biofacies



A = anoxic, high TOC, clastic river plume input
B = anoxic conditions, high TOC
C = disoxic conditions, some biogenic sedimentation, low TOC

For shale gas exploration it is important to identify "sweet spots" and "pay zones"



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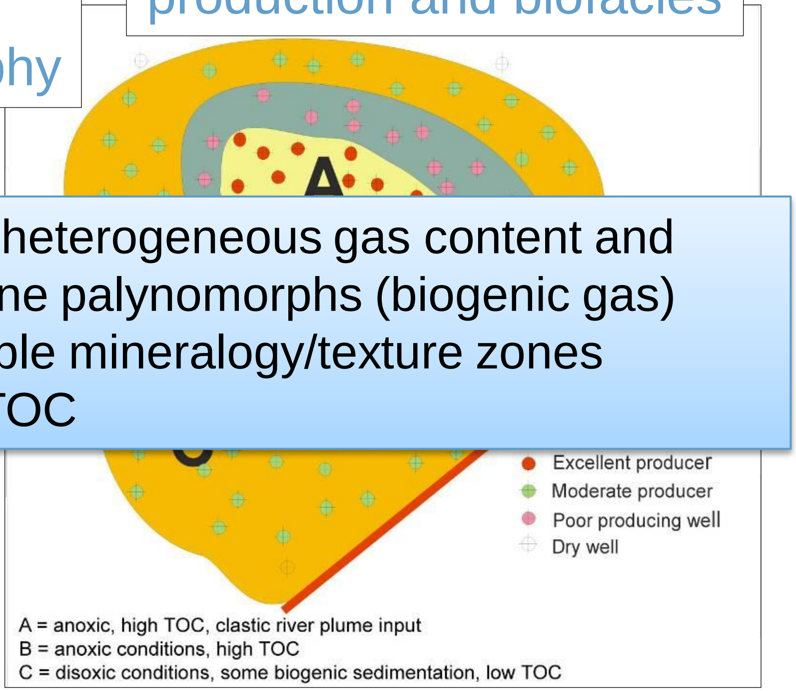

A = anoxic, high TOC, clastic river plume input
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C = disoxic conditions, some biogenic sedimentation, low TOC

Link between heterogeneous gas content and

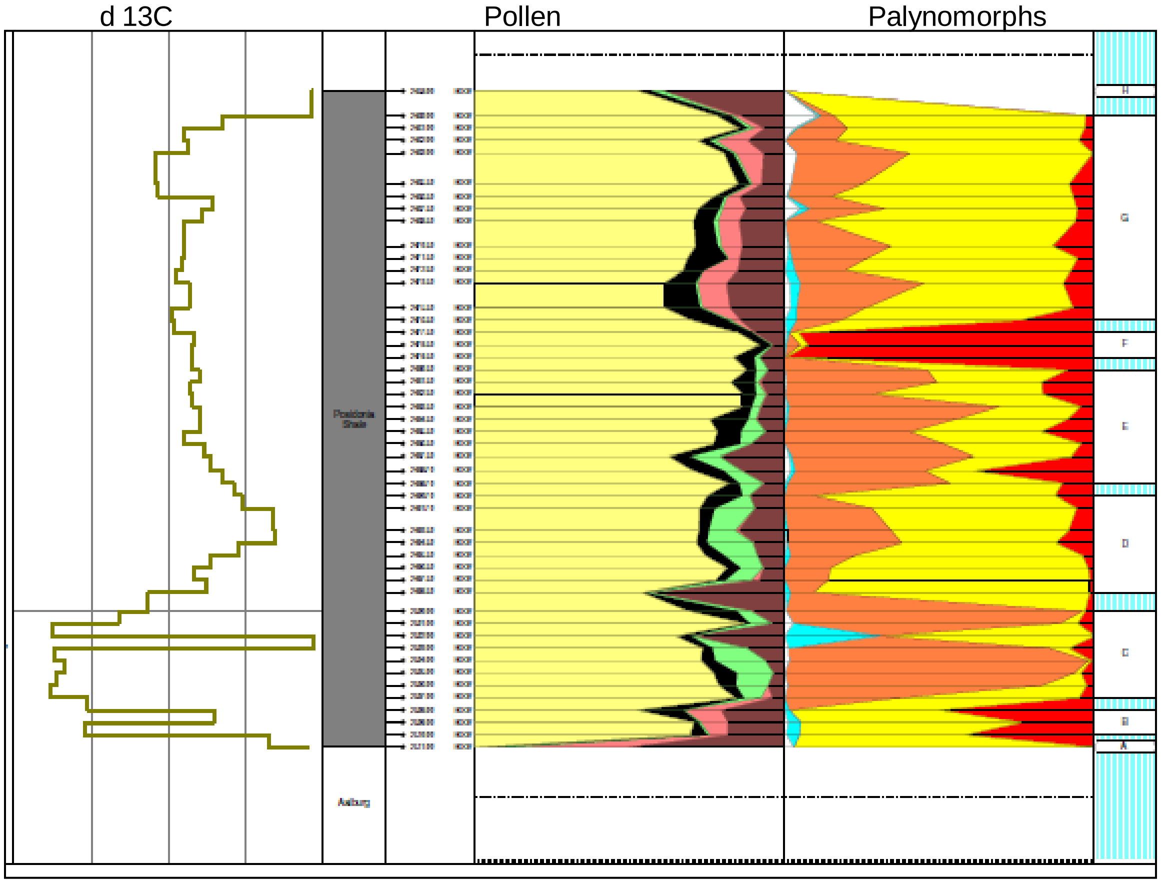
?

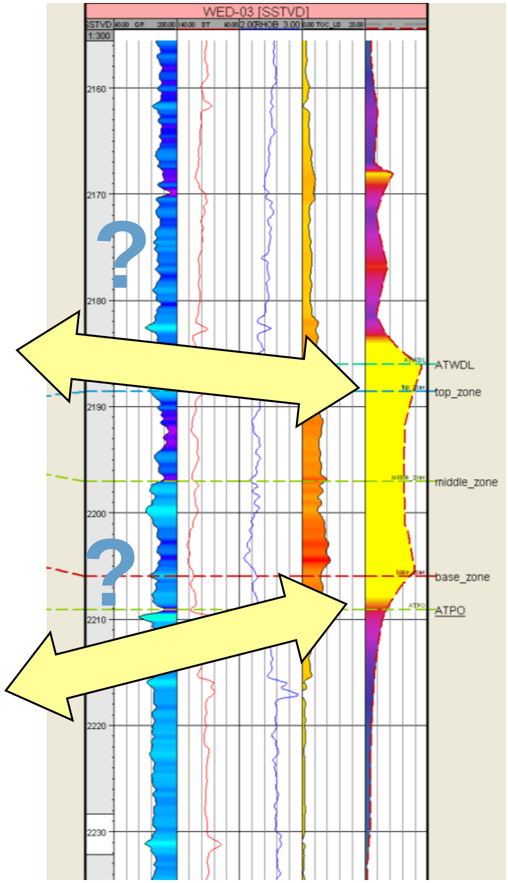
- gas-prone palynomorphs (biogenic gas)
- favourable mineralogy/texture zones
- higher TOC

Sweet spot identification ?

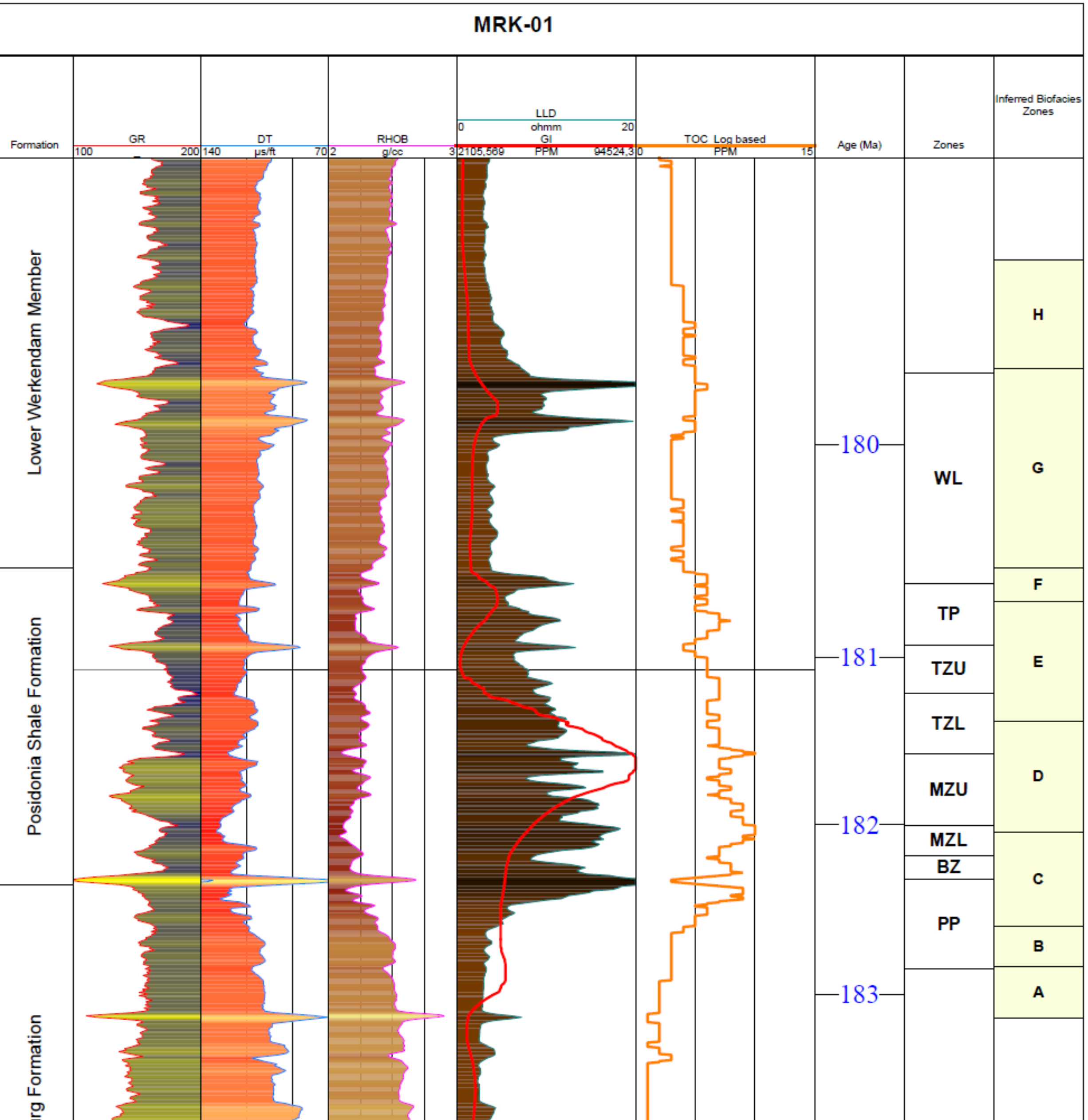
A possible link between heterogeneous occurrences of high gas content and

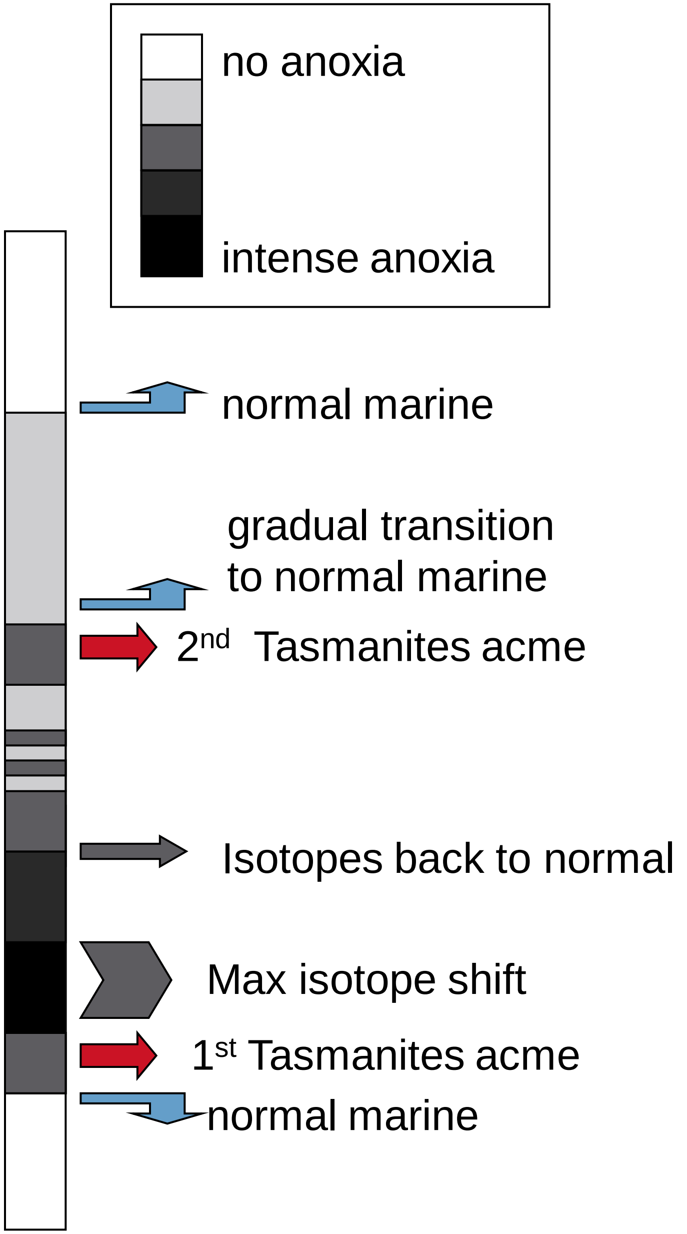
- gas-prone palynomorphs (biogenic gas)
- favourable mineralogy/texture zones with high fracturing potential
- higher TOC






Log zonation and biofacies zonation





☐ no anoxia

■ intense anoxia

normal marine

gradual transition to normal marine

2nd Tasmanites acme

Isotopes back to normal

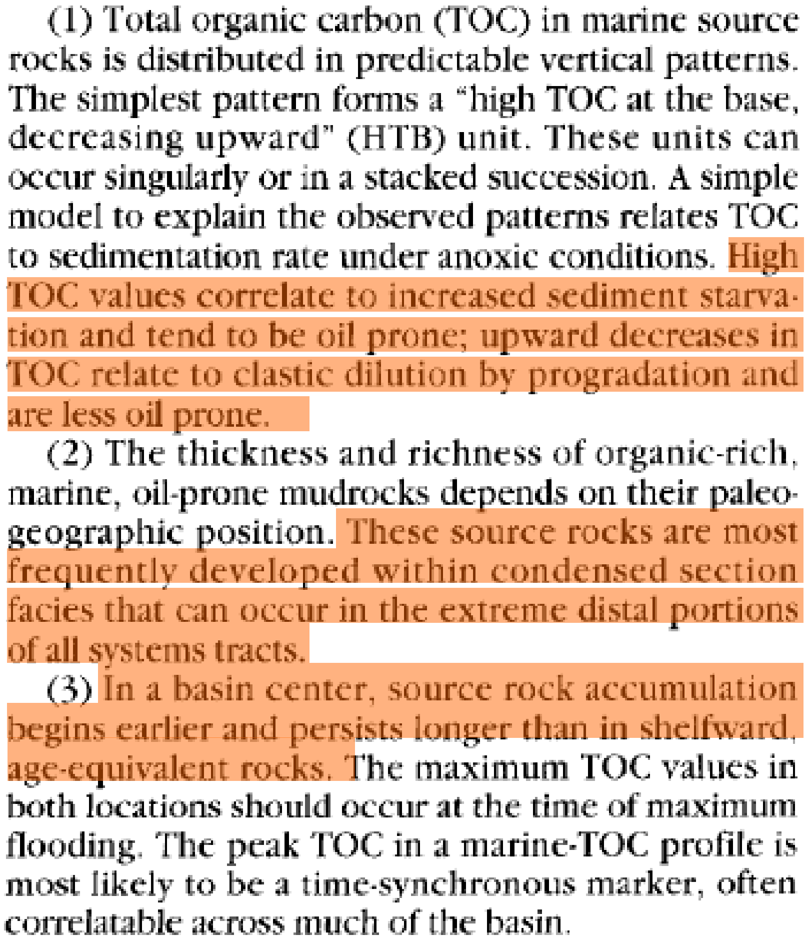
Max isotope shift

1st Tasmanites acme

normal marine

Shale reservoirs within a seq-strat framework

Creaney & Passey, 1993, AAPG Bull:

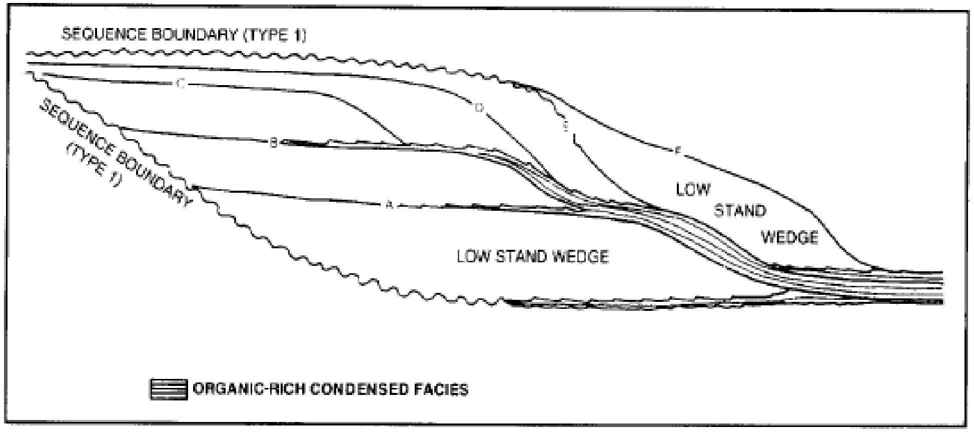


(1) Total organic carbon (TOC) in marine source rocks is distributed in predictable vertical patterns. The simplest pattern forms a "high TOC at the base, decreasing upward" (HTB) unit. These units can occur singularly or in a stacked succession. A simple model to explain the observed patterns relates TOC to sedimentation rate under anoxic conditions. High TOC values correlate to increased sediment starvation and tend to be oil prone; upward decreases in TOC relate to clastic dilution by progradation and are less oil prone.

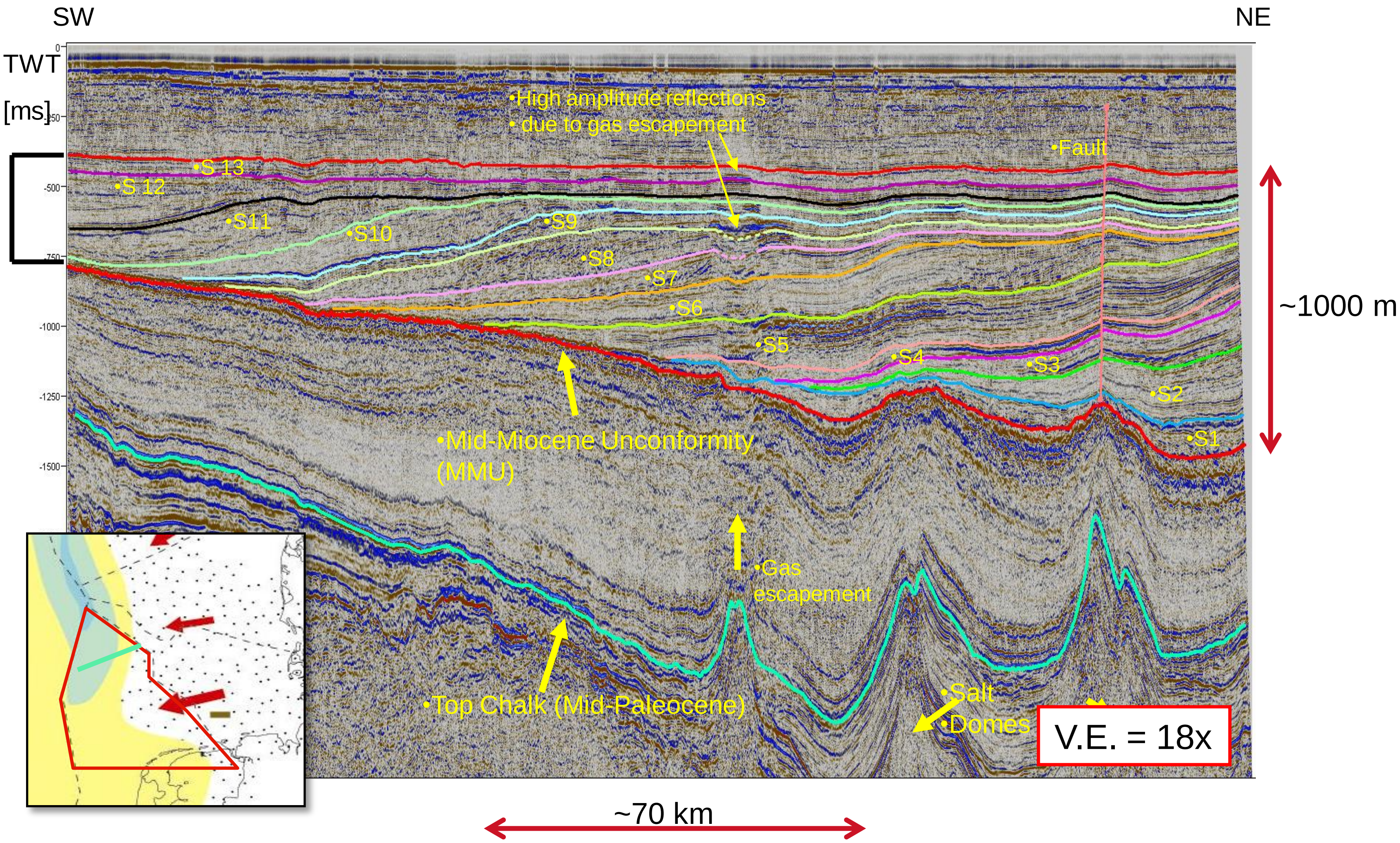
(2) The thickness and richness of organic-rich, marine, oil-prone mudrocks depends on their paleogeographic position. These source rocks are most frequently developed within condensed section facies that can occur in the extreme distal portions of all systems tracts.

(3) In a basin center, source rock accumulation begins earlier and persists longer than in shelfward, age-equivalent rocks. The maximum TOC values in both locations should occur at the time of maximum flooding. The peak TOC in a marine-TOC profile is most likely to be a time-synchronous marker, often correlatable across much of the basin.

Vertical and lateral dilution trends

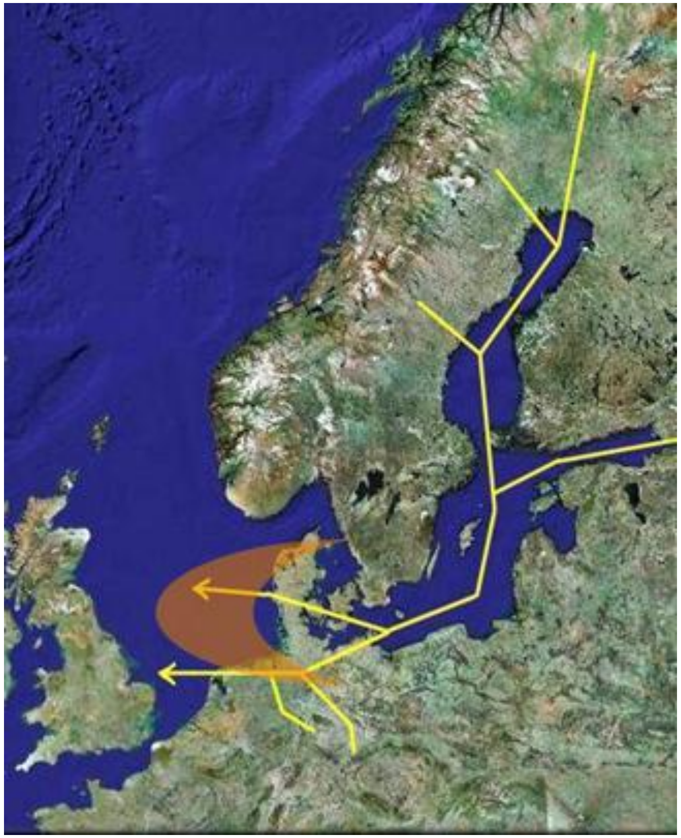


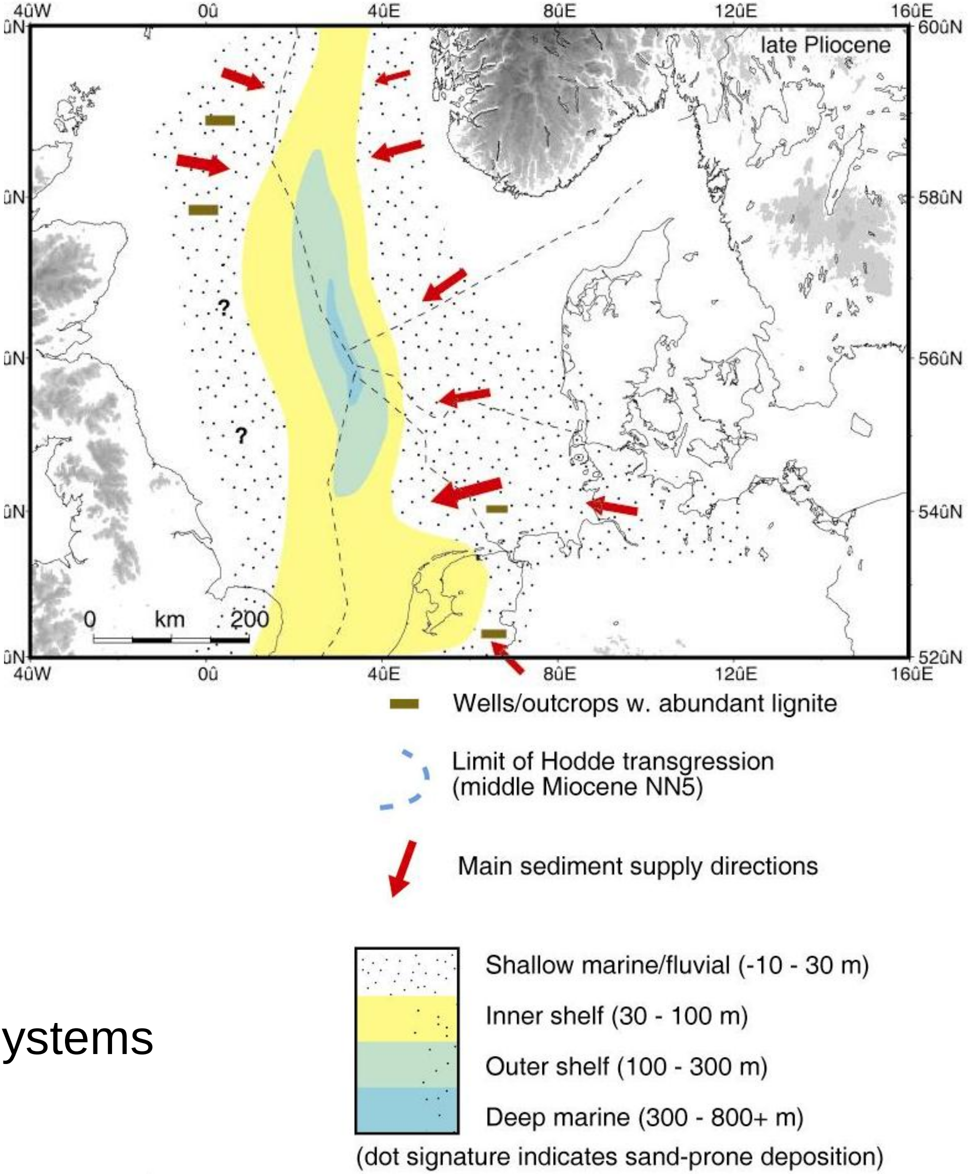
Eridanos mud-dominated clastic wedge
13 NE→SW parasequences (L. Miocene– E. Pleistocene)



Alternation of organic-rich silt and grey mud

The Eridanos delta

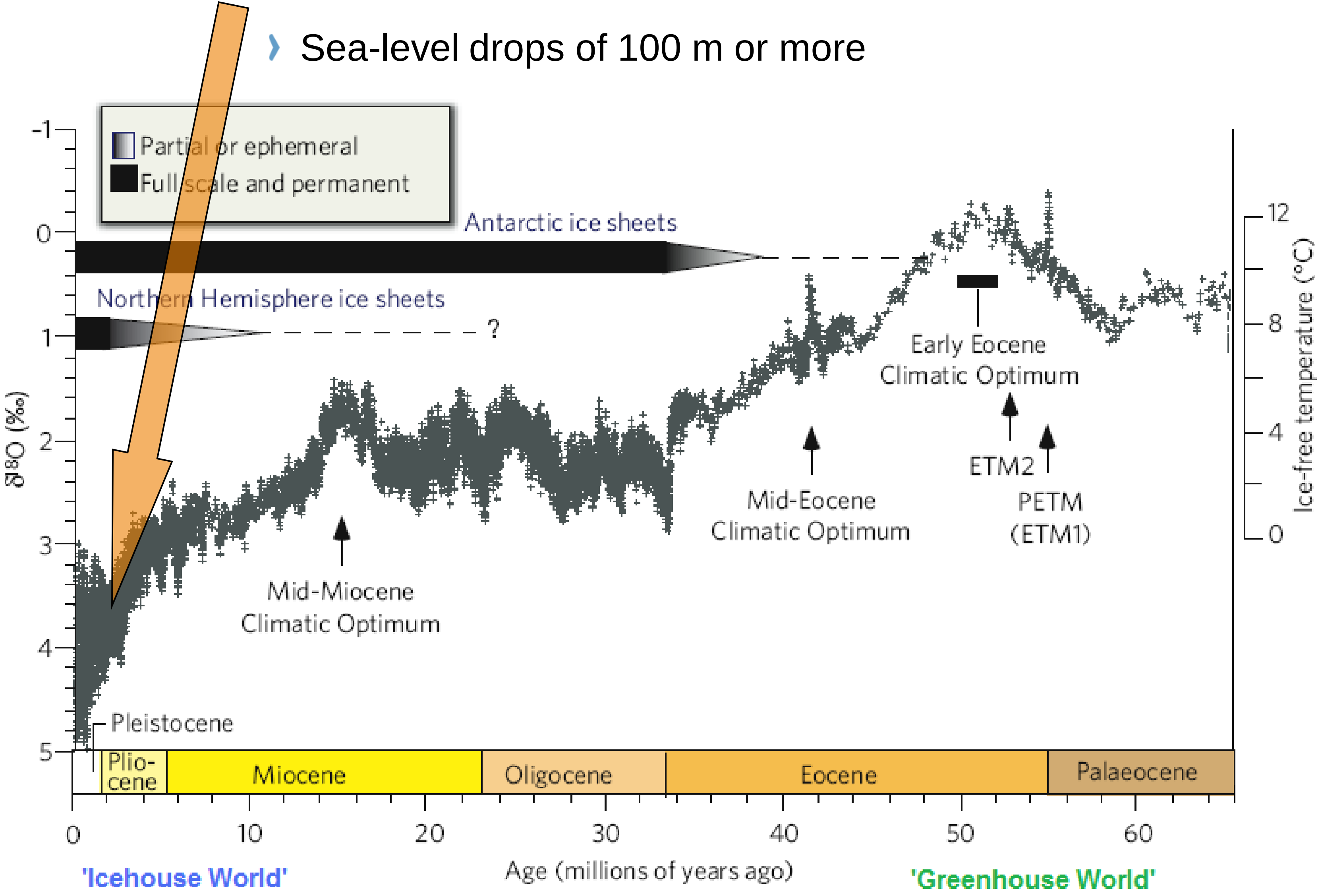




- Oligocene – Pleistocene river-delta systems
- In NL: Late Miocene - Pleistocene

Eridanos (or SNS) delta on a world scale

- Repeated glacial advance during Gelasian
- Sea-level drops of 100 m or more



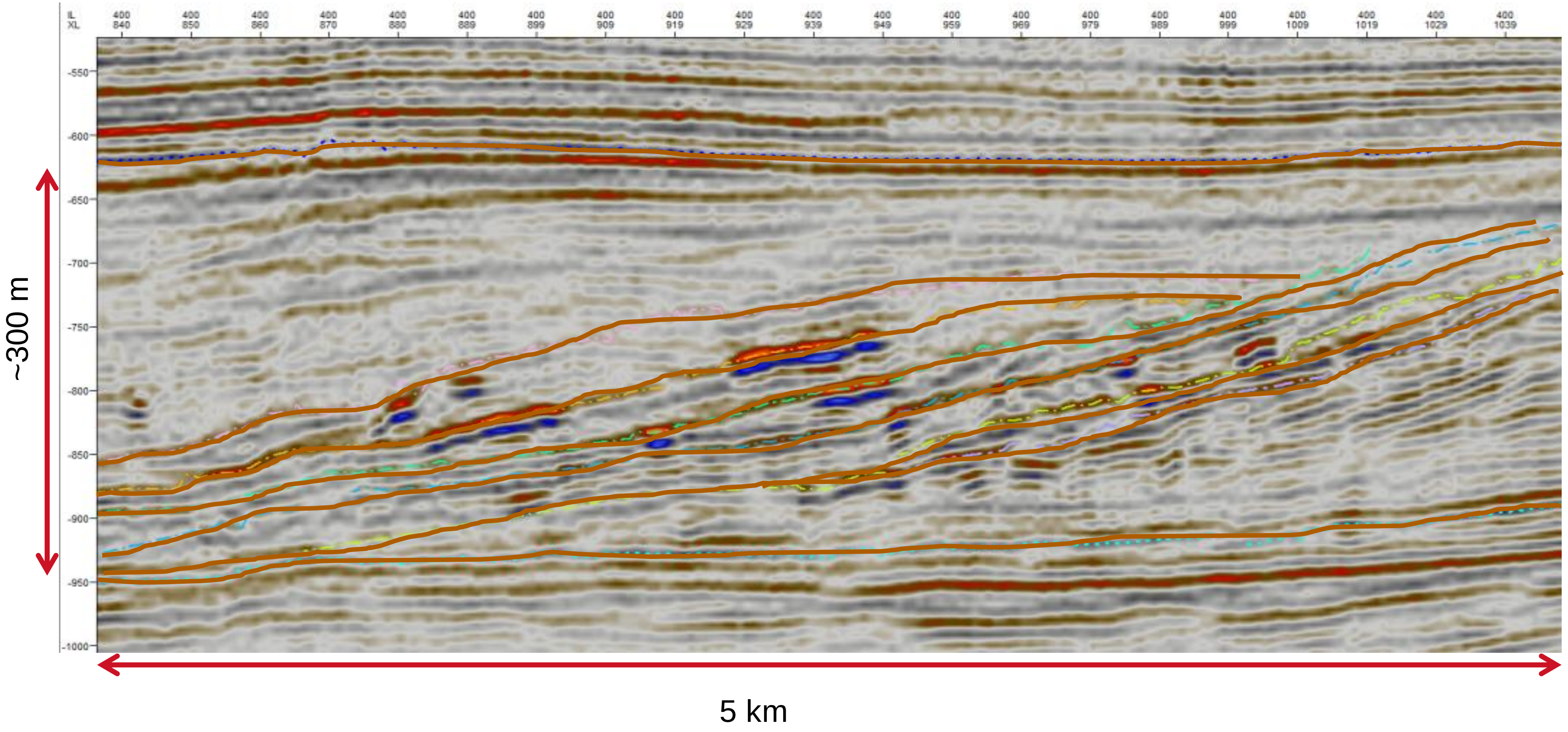
Pleistocene (Gelasian) climate and deposition

- The Gelasian climate was characterized by repeated glacial advance
- At glacials, sea-level drops of 100 m or more occurred

GLACIAL INTERGLACIAL

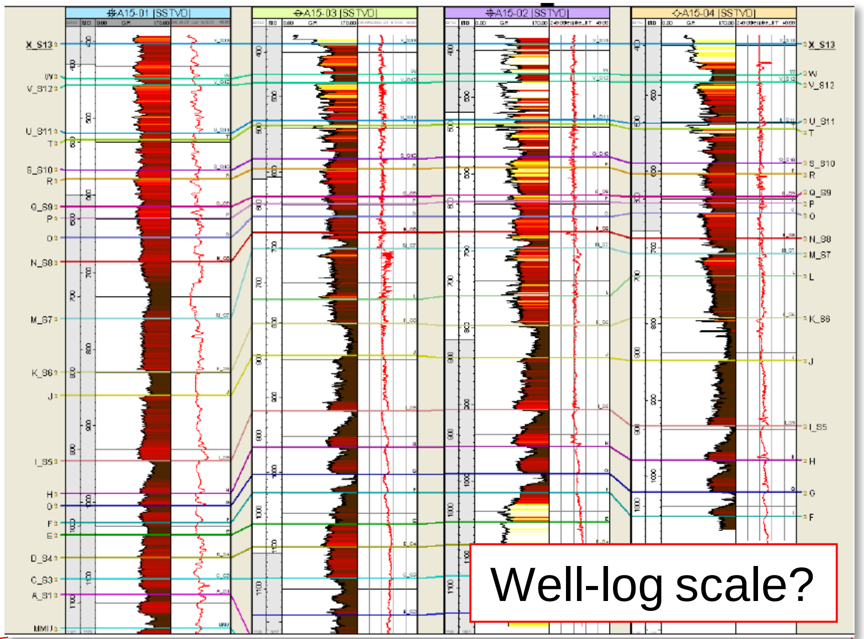
- IG: Strong progradation without iceberg scours
- IG: Progradation accompanied by failure (Sed. supply >> Accommodation)
- G: Progradation culminated in shelf erosion (incised valleys)
- G: Iceberg scouring on aggrading shelf

Recoverable depositional geometry?

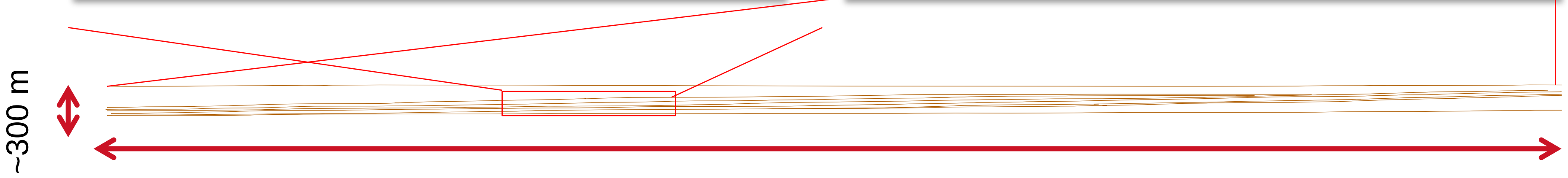



Recoverable depositional geometry?


Outcrop scale?

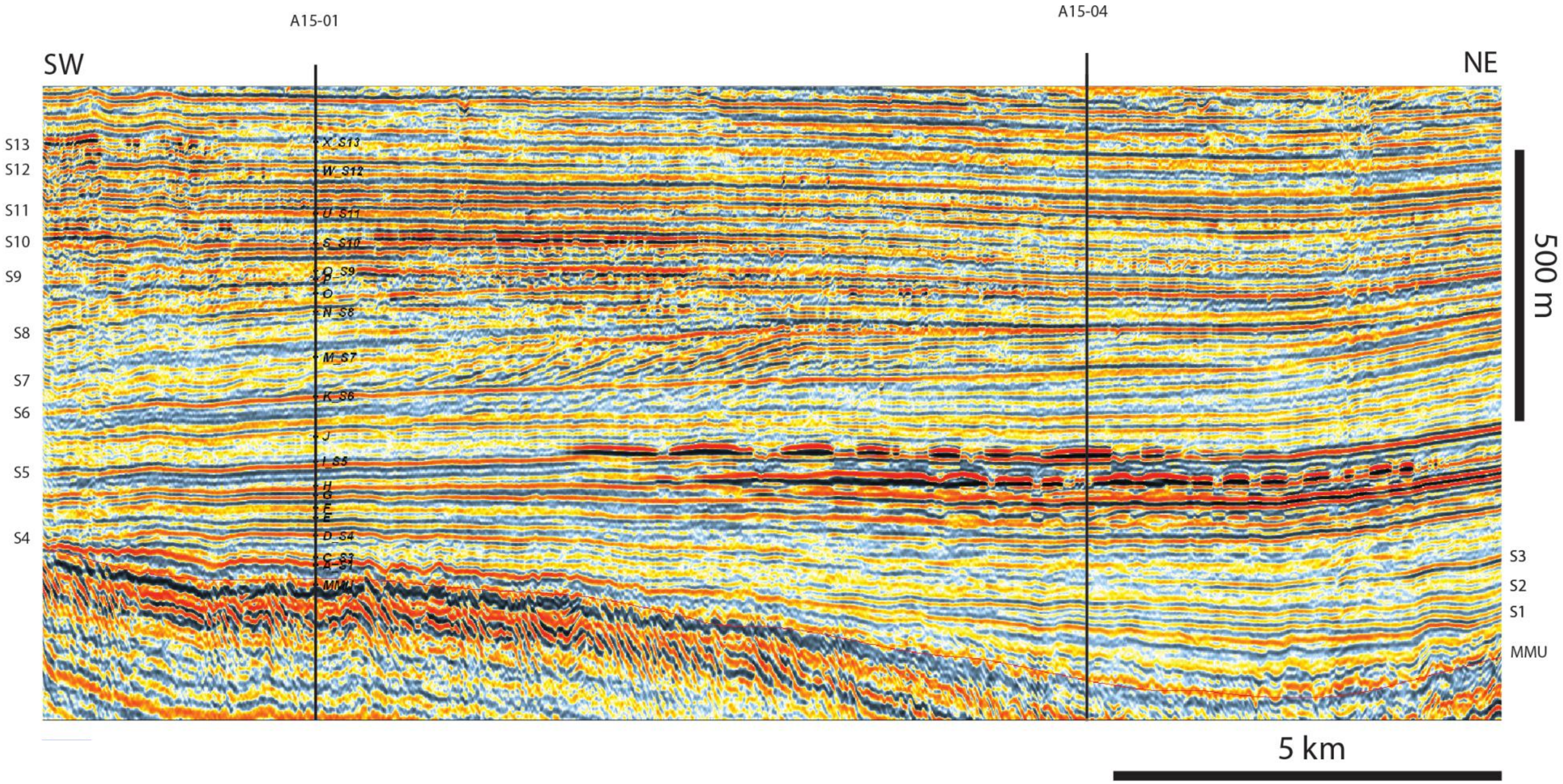


Well-log scale?



5 km

Basin scale


A15-01
A15-04
SW
NE
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
X_S13
W_S12
U_S11
S_S10
Q_S9
P
O
N_S8
M_S7
K_S6
J
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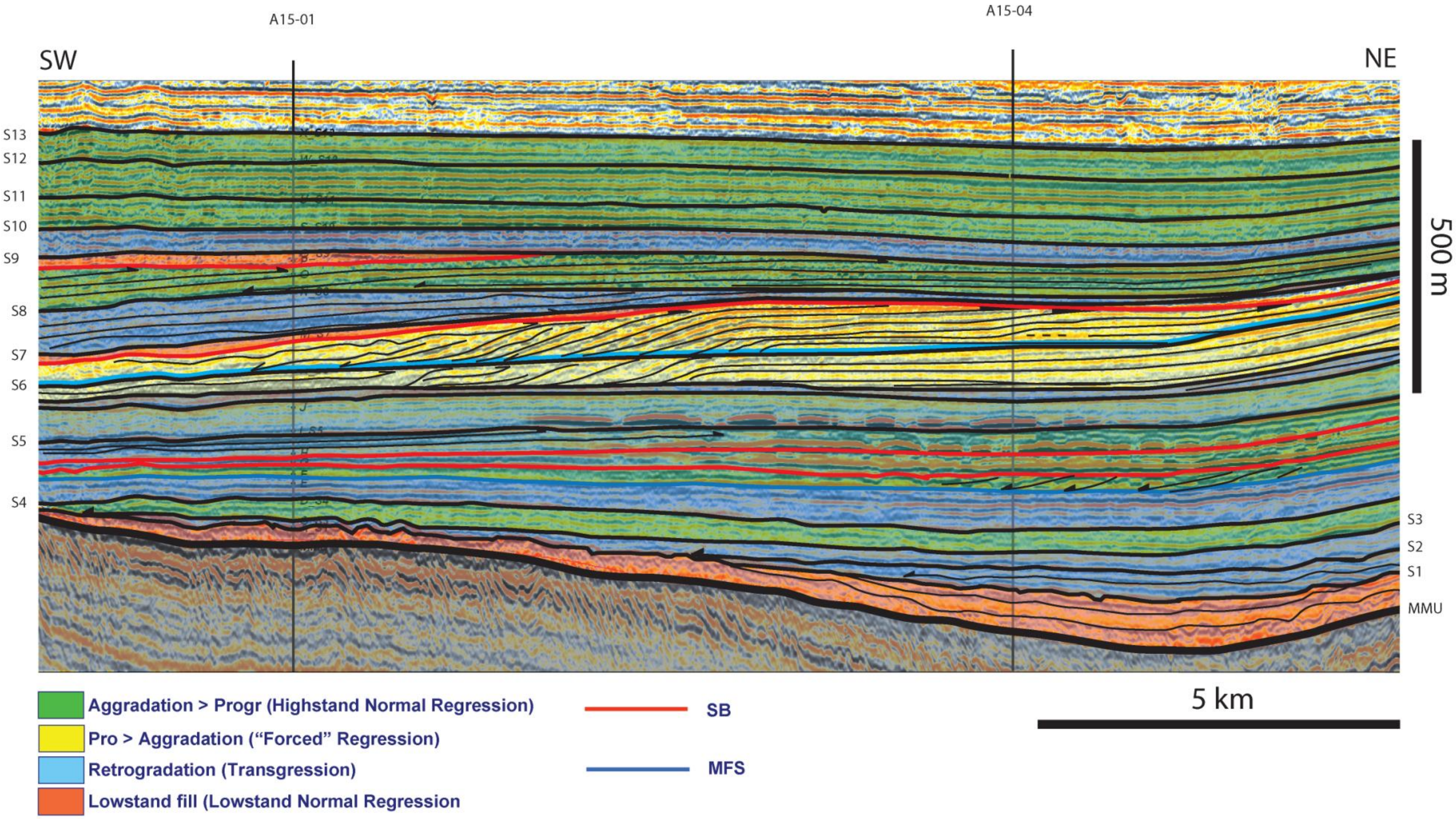
S3
S2
S1
MMU
5 km


A15-01
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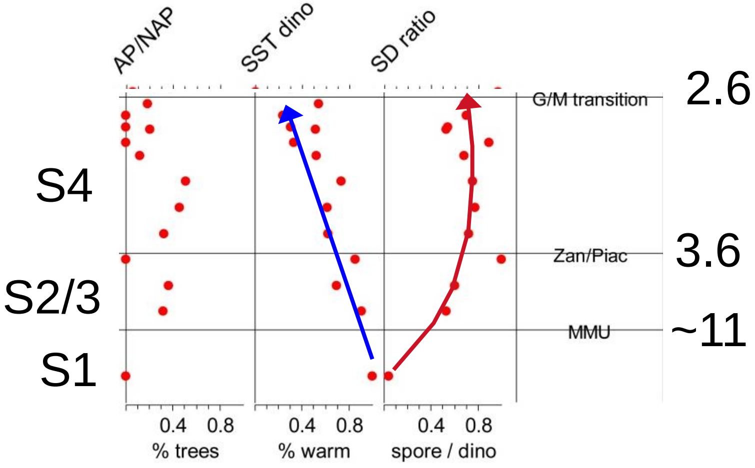
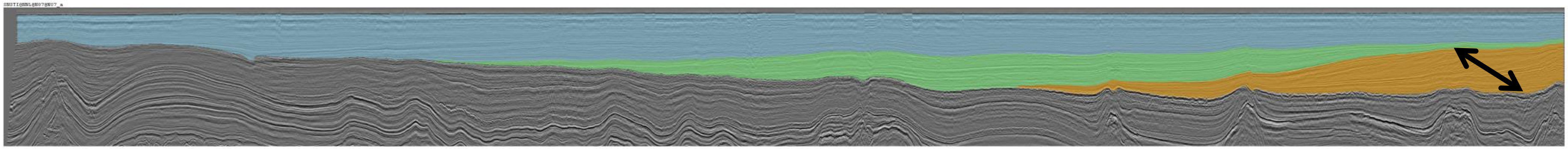
S7
S6
S5
S4
S3
S2
S1
MMU
500 m
5 km
🟩 Aggradation > Progr (Highstand Normal Regression)
🟨 Pro > Aggradation (“Forced” Regression)
🟦 Retrogradation (Transgression)
🟧 Lowstand fill (Lowstand Normal Regression
SB
MFS

Temperate Climate Shallowing Sequence (MMU-Pliocene)

- Base - deep water (MMU)
- Top - shallow marine / fluvial
- Strong contour currents
- Steep-dipping, high-relief clinoforms at top
- Supply-driven system, sea-level fluctuations higher order cycles

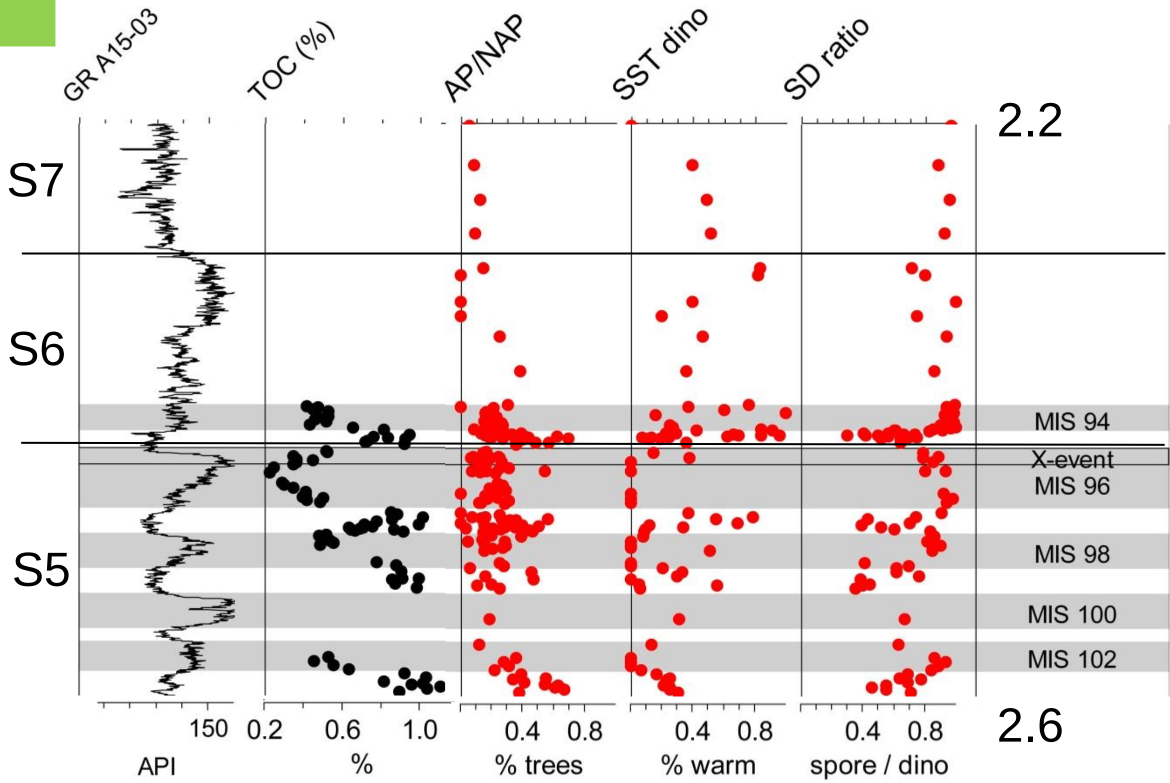


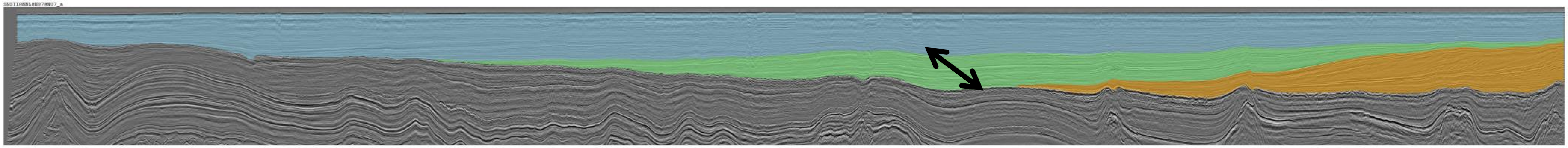
Long-term cooling (SST), many trees (AP)
Shallowing, but continuously marine (SD)



Alternation of Warm and Cold Periods (S5-S7)

- Alternation of glacial and Interglacial periods
- Climate controls sediment quantity and type
- Glacial plough marks
- Sealing clays
- TOC variations

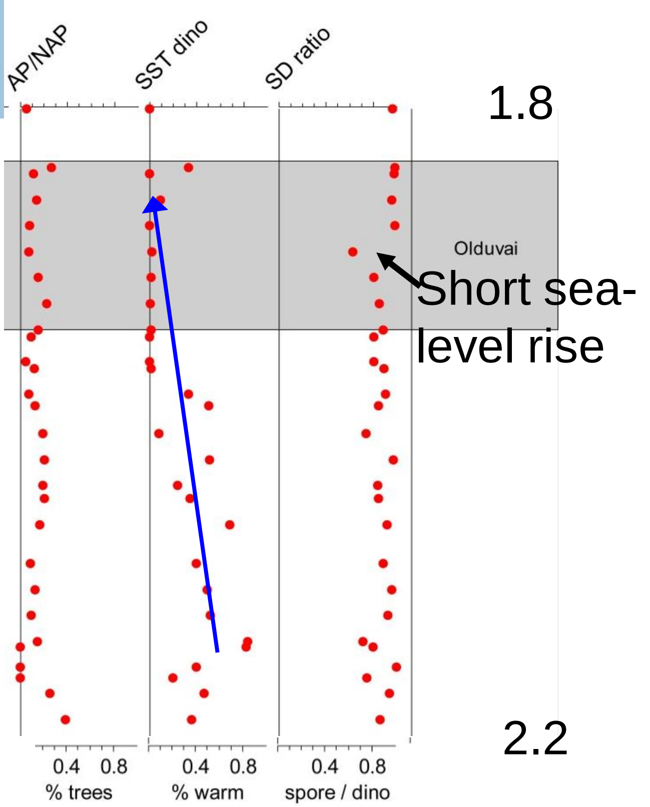




Cycles in clays, depth (SD) and temperature (SST/AP)

Arctic Infill
(S8-S13, 2.2 – 1.8 Ma)

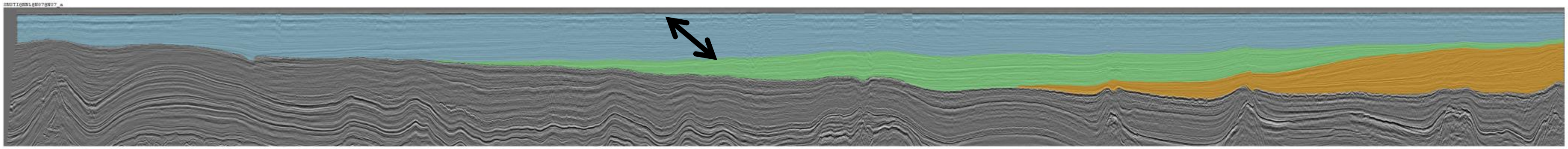
- Shallow sea (compared present) under arctic conditions with sea ice cover.
- periods with an open vegetation during warm climatic pulses with open marine conditions.
- low relief, low-angle progradations.
- Hiatuses



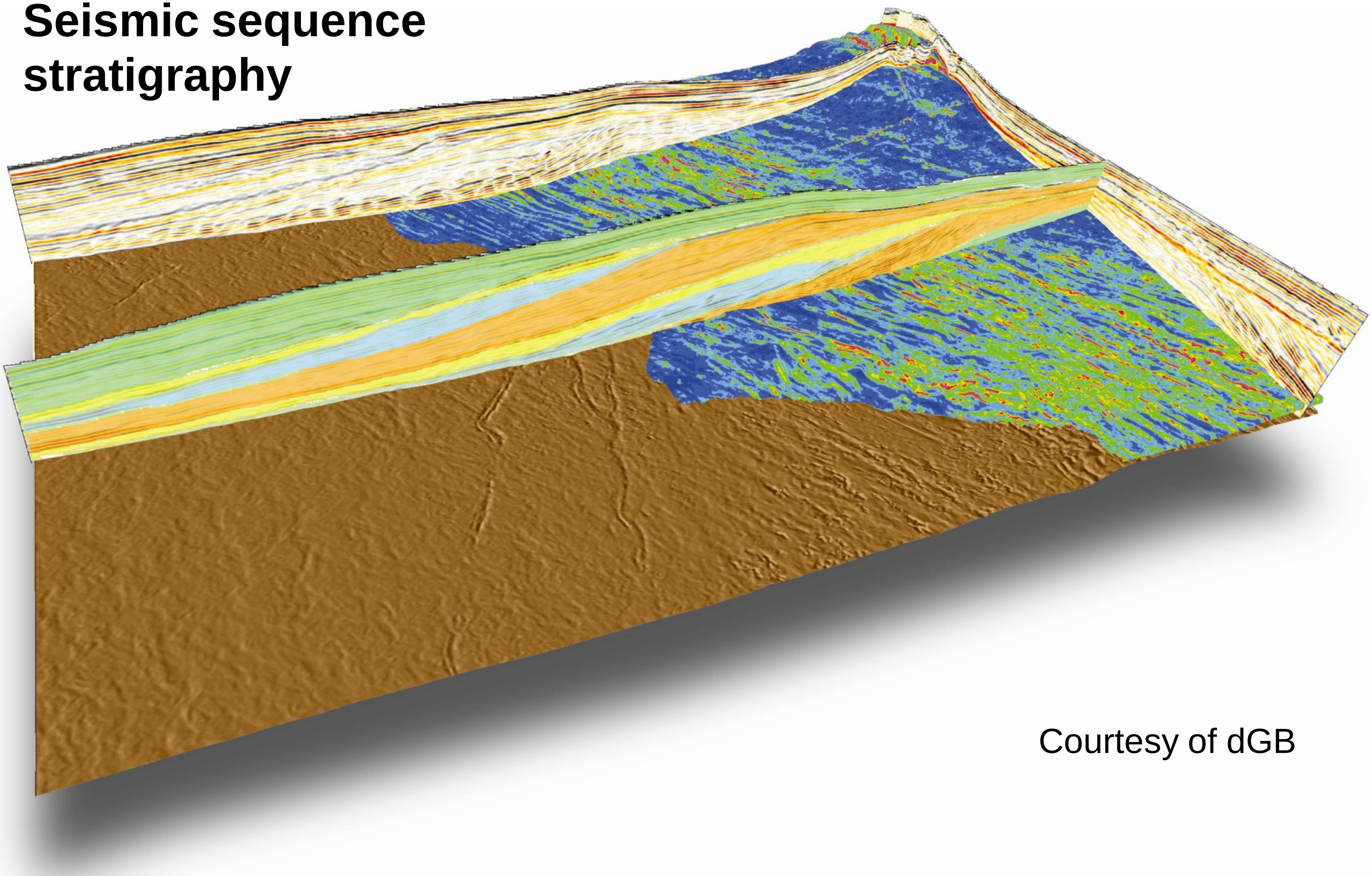
1.8

Short sea-level rise

2.2

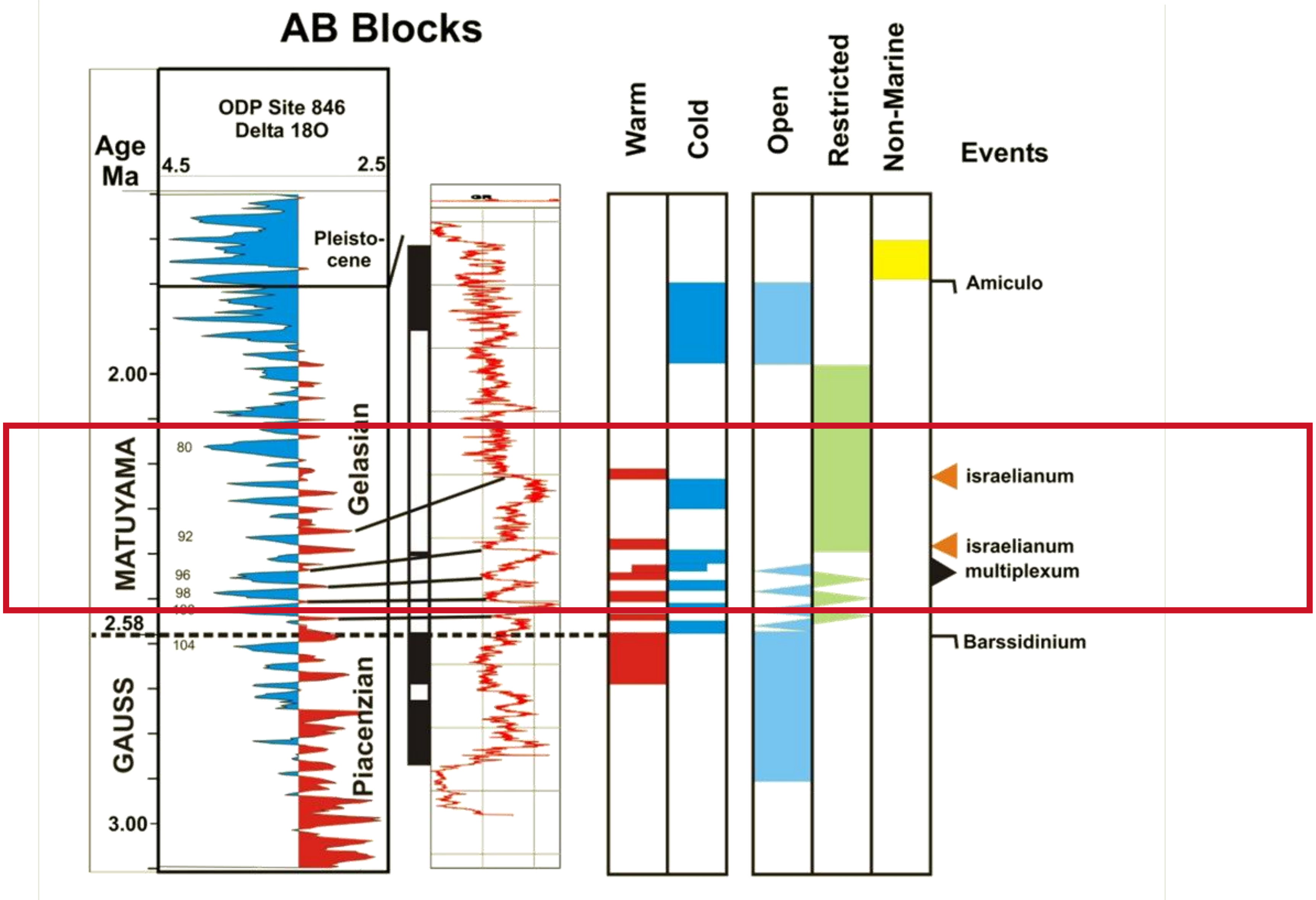


Seismic sequence stratigraphy

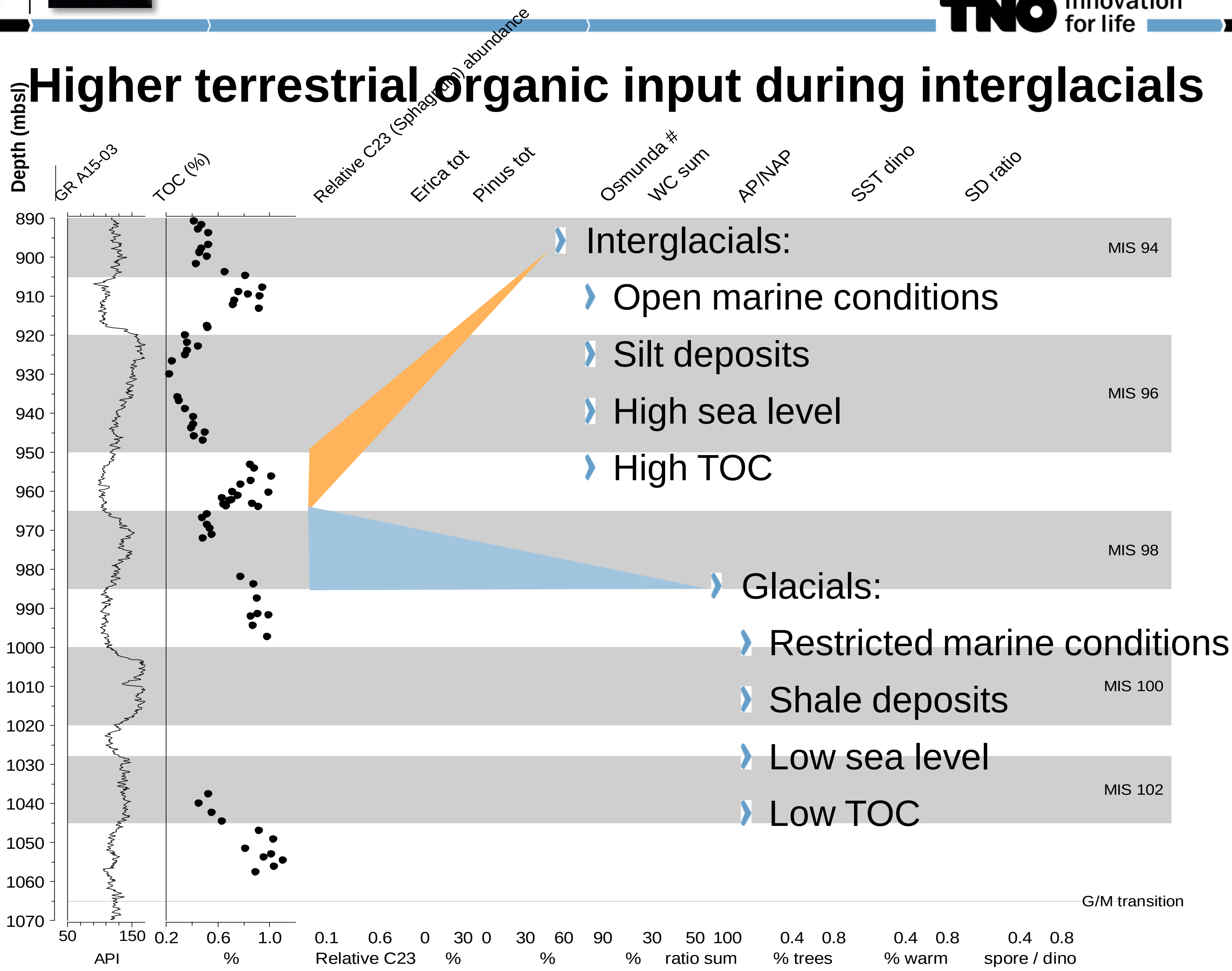


Courtesy of dGB

Depositional model: coupling climate to (bio)facies

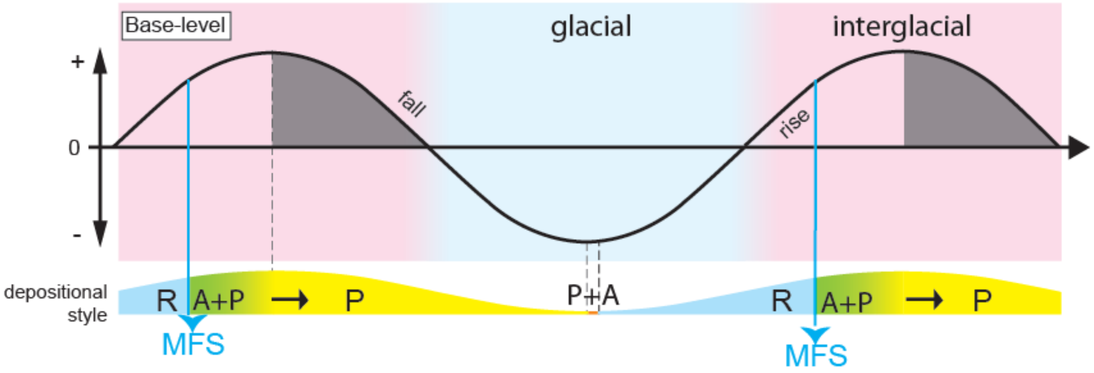


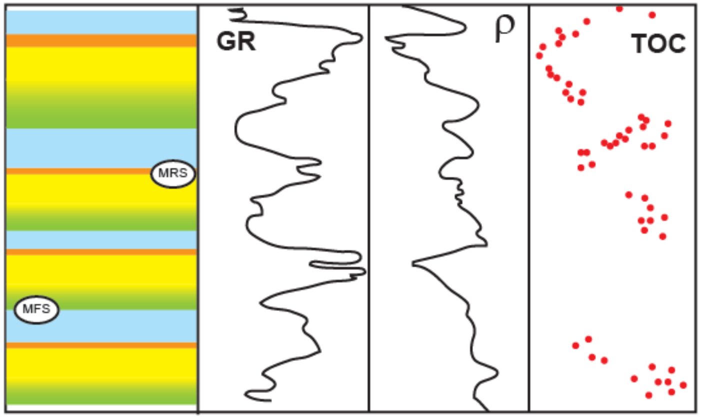
Higher terrestrial organic input during interglacials



- Interglacials:
  - Open marine conditions
  - Silt deposits
  - High sea level
  - High TOC
- Glacials:
  - Restricted marine conditions
  - Shale deposits
  - Low sea level
  - Low TOC

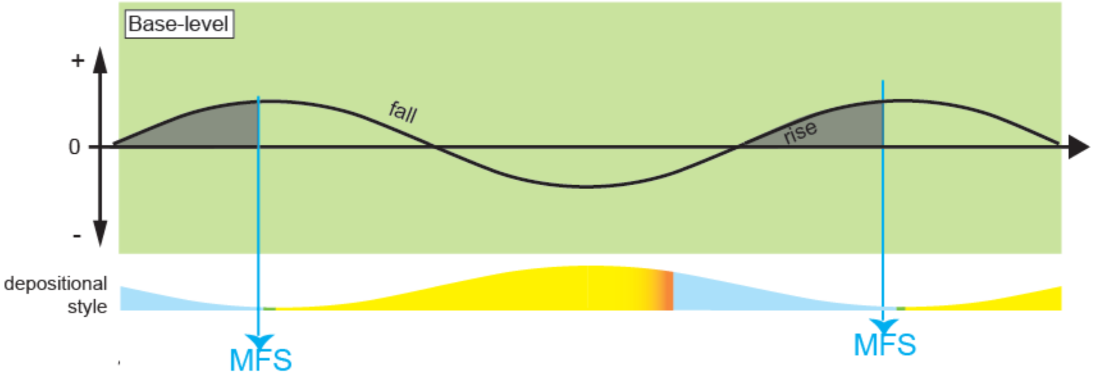
Icehouse world model

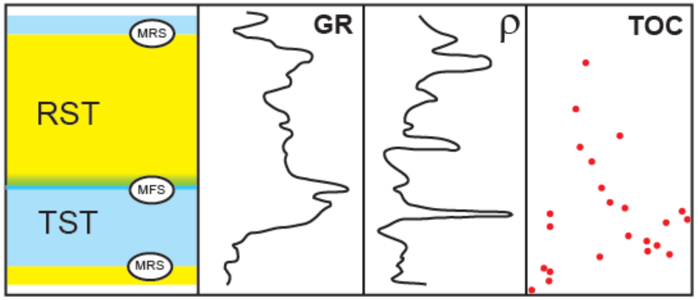




Based on Cenozoic, Eridanos Δ, this study

Greenhouse world model





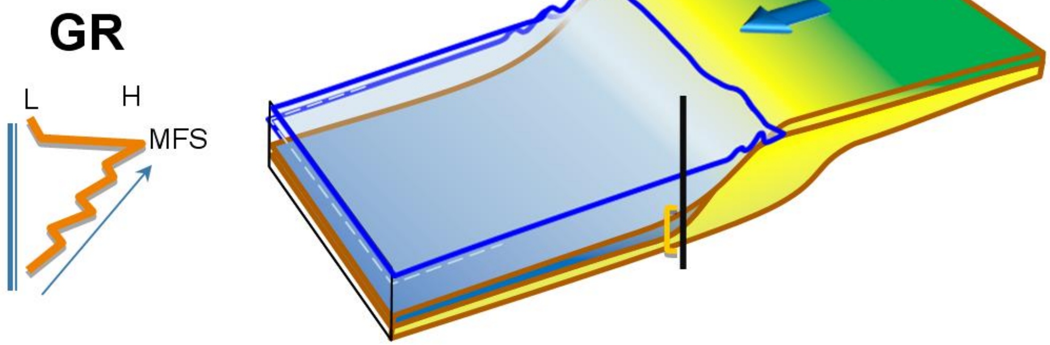
Based on Union Spring Mbr, Lash & Engelder, 2011

- 🟩 **Aggradation > Progr (Highstand Normal Regression)**
- 🟨 **Pro > Aggradation (“Forced” Regression)**
- 🟦 **Retrogradation (Transgression)**
- 🟧 **Lowstand fill (Lowstand Normal Regression**

ICEHOUSE vs GREENHOUSE

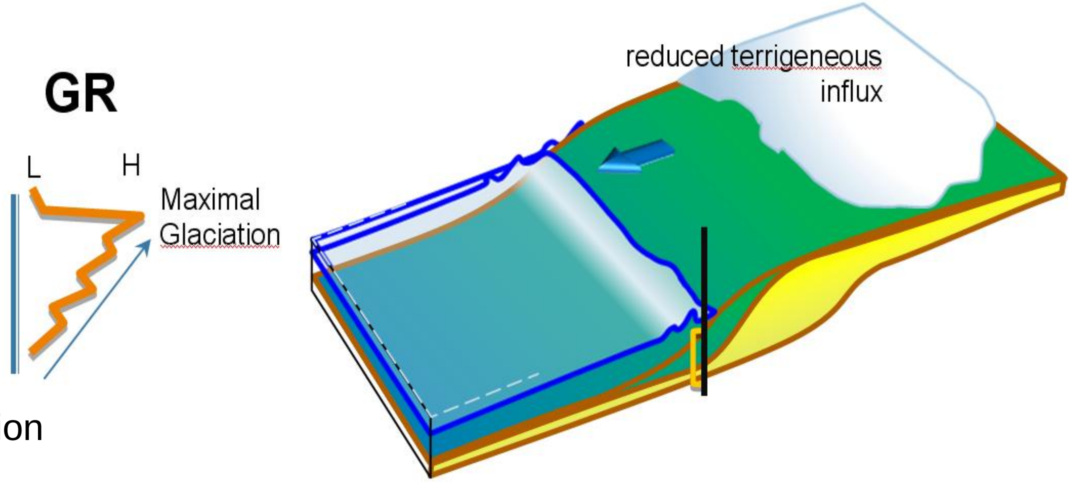
(classical) Greenhouse Transgression

- Constant clastic influx
- High clay content (flooding)
- GR peak = maximum flooding
- High TOC at MFS



Icehouse Regression

- Reduced clastic/nutrients influx
- Higher clay content/no organics
- GR peak = maximum glaciation
- High TOC during highstand progradation



Concluding remarks

- In greenhouse world high TOC zone (GR peaks) might correlate with TST and MFS
- Effects of climate-induced nutrient input and water column should be considered
- In icehouse worlds peaks in TOC/GR correlate with max glaciation (LST)
- More work, thoughts and input to support concepts are needed

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