Source Rock: The Organic Factory, Facts and Modelling*

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Abstract

E&P of fossil fuels require understanding, assessing and predicting source rock attributes. These attributes include occurrence, organic-richness, organo-facies, type, kinetic parameters, impact on the nature of generated fluids, stratigraphic and lateral distribution, architecture at the regional and local scale, and lithology. These attributes are essential for conventional petroleum system exploration, specifically for populating 3D basin models, and they are mandatory for optimal exploitation of unconventional plays such as Shale plays (Shale oil/gas, underground kerogen shale retorting) and Coal Seams (Coal Bed Methane, Underground Coal Gasification).

Accumulation of organic matter in sediment relies on an organic factory which is controlled by three main drivers (Huc, 2013), including: (1) a sufficient primary production of biomass, which is controlled in marine domain by the availability of nutrients within the euphotic zone (e.g. riverine input, coastal upwelling, transient eddies). In continental domain, water budget and climate are the main controlling factors; (2) the level of alteration, (a) during the settling of organic detritus through the water column, from the production site to the sediment floor. The sinking of the organic material proceeds thanks to the ballast effect provided by associated mineral grains (e.g. fecal pellets, aggregates), (b) then eventually, as organo-mineral flocs, during their transfer along the Benthic Boundary Layer, following the water energy gradient and the minimum bed shear stress toward the delivery site where organic remains are finally buried; and (3) the condition of fossilization within the sediment, where organics are subjected to degradation by foraging biological communities during early burial and even on a longer time term by the deep-biosphere microbes. At this stage the impact of Redox reactions, following a decreasing energy yield sequence (e.g. O_2, SO_4^{--}, CO_2 reduction) dependent on the concentration of available electron acceptors, and which is linked to sedimentation rate, is instrumental. The actual occurrence and properties of the resulting source rocks are consequently the sequel of the amount and nature of the living biomass precursors, the process of sedimentation and the environment of deposition.

The major impact of the secular change in biotic communities has to be considered when contemplating the organic and bio-mineral attributes of a source rock. This biological evolution includes, inter alia:

a) The large contribution of microbial organisms during the Precambrian and InfraCambrian,

b) The rise of phytoplankton with cellulosic cell wall at the end of Neoproteozoic and dawn of phanerozoic (Brocks, 2017), and

c) The rise of siliceous organisms during the Cambrian (Conley, 2017),

d) The instrumental rise of vascular plants in Mid-Devonian followed around 100 Ma latter by the rise of lignin-degrading white rot fungi together with the rise of resin producing gymnosperms (pinaceae) as a defense mechanism against infestation of fungi into tree (Hower et al., 2010), the earliest wood feeder common ancestor of termites dating to the Late-Jurassic (Bourgignon et al., 2014), the rise of Angiosperms during the Late Cretaceous, producing β-amirine (precursor of Oleanane) as a defense against insects, fungi and various microbial invaders, the rise of dipterocarps (Dammar-resin prolific angiosperms highly resistant to parasitic attack) during the Eocene on the Indian Plate and subsequently radiating into Southeast Asia (Dutta et al., 2011),

e) The rise of calcareous plankton during the Early Mesozoic, following a platform and reefs dominated era (Monteiro et al., 2016),

f) The major rise of marine diatoms in the Late Cretaceous, flourishing during the Cenozoic, leading to an ocean dominated by biosilicification (Conley et al., 2017).

For operational purposes, and in order to rationalize the different natures of sedimentary organic matter/kerogen, two complementary classifications are currently used:

1) “Organo-facies”, richness and quality owing to the conditions under which organic matter was developed and preserved (Pepper and Corvi, 1995), and

2) “Types”, based on the initial elemental composition/petroleum potential of a kerogen (Tissot and Welte, 1984)

Current knowledge on the fate of organics from source to sink, associated with advances and ongoing developments in stratigraphic forward models (e.g. DionisosFlowTM) provide the opportunity to simulate the distribution and quality of organic matter in specific sedimentary systems such as marine environments and terrestrial influenced environments. In the marine domain (Grangeon and Chauveau, 2014), the computing components take into account are:

• The primary productivity by estimating the nutrient supply or by importing external library data (maps, analogues), an input which can be eventually adjusted by inversion.

• The degradation of the organic detritus through the water column relying on an equation providing the organic flux as function of depth and primary productivity in the euphotic zone.

• The transport of organo-mineral flocs along the Benthic Boundary Layer using diffusion equations.

• The Redox conditions in the water column derived from water mixing and oxygen demand (consumption by organic matter degradation).

• The burial efficiency which is taken as a proxy encompassing the Redox conditions in the bottom water and the sedimentation rate.

In coastal plain/wetland domain, in addition to the primary productivity of the terrestrial plants, the "in-situ" accumulation/preservation of organic matter is assumed to rely on the water saturation of the sediment, which is dependent on the groundwater dynamics (piezometric surface) and on the soil lithology (Chauveau et al., 2017a). Simulation of terrestrial land plant-derived organics deposited downslope in the marine domain by mass transport is built upon organic supply by river flow, degradation in the water column, transport and burial efficiency (Chauveau et al., 2018).

Current computing experience encompasses:

• Organic facies B and A (respectively Type II and IIS). They are exemplified by the epicontinental Lower Jurassic formations of Northwestern Europe (Bruneau et al., 2017) and intrashelf basins (ISB) exemplified by Upper Devonian Duvernay Formation in the Western Canada Sedimentary Basin (Chauveau et al., 2017b) and the Cretaceous Natih Formation in Oman (Chauveau et al., 2016).

• Organic facies D/E "ever-wet" (Type III/III-H) and F (Type III/IV) terrestrial coastal plains/wetland domain are exemplified by the Cretaceous Mannville Group in Canada (Chauveau et al., 2017a), as well as organic facies D/E/F mass transported in open marine setting exemplified by the modern deep-sea fan of the Congo River (Chauveau et al., 2018).

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Advancing the World of Petroleum Geosciences

Source Rock:

Organic factory, Facts and Modelling

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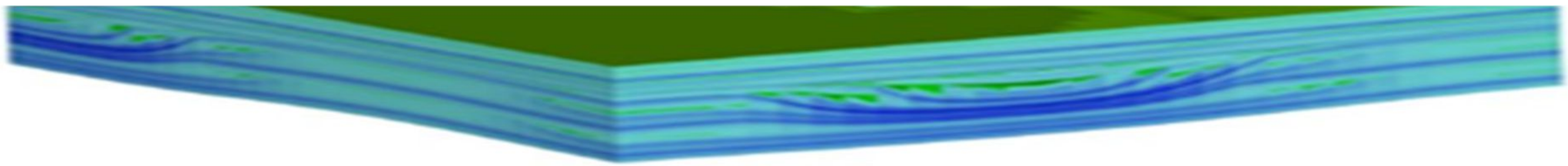
IFP Energies nouvelles

Source rock initial attributes:

Occurrence, Organic-Richness, Type/Organo-facies, Kinetic Parameters, Potential Nature of Generated Fluids, Lateral / Stratigraphic distribution, Architecture at the regional and local scale, Lithology



Understanding, assessing and predicting these attributes

- Is essential for Conventional Petroleum Systems exploration (e.g. Populating numerical basin models)
- Is mandatory for Unconventional Plays
  - Shale targets: Shale Oil/Gas, kerogen shale retorting…..
  - Coal Seams: CBM, Underground Coal Gasification projects….

OUTLINE

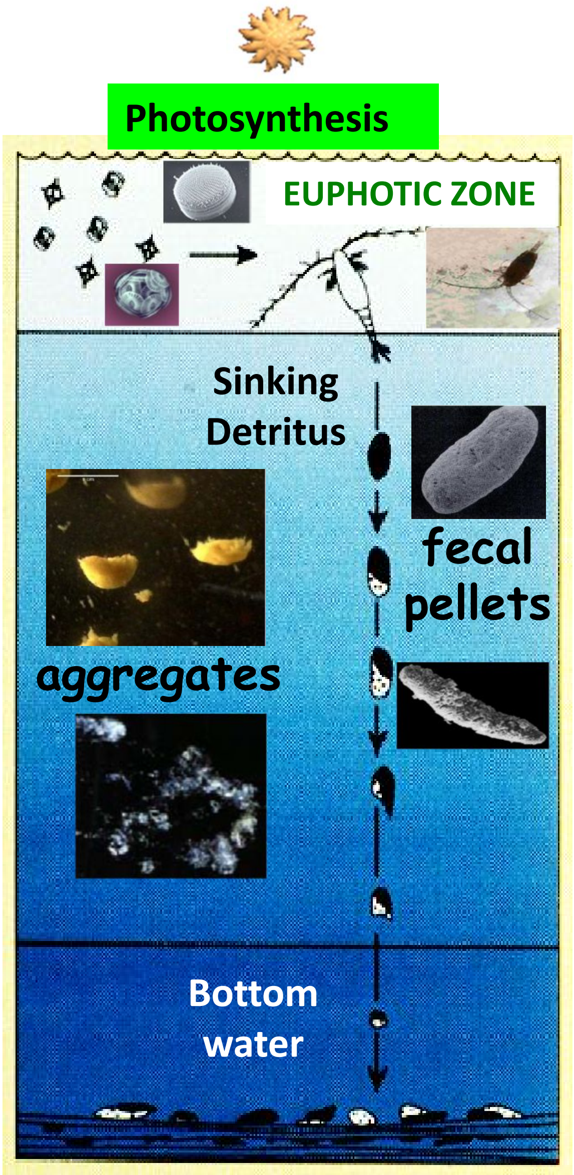
SOURCE ROCKS

Facts: The Source Rock Factory Trilogy

- Biomass production and organic preservation
- Sedimentary transfer
- Burial and fossilization

Modelling: An Integrating Approach

- Formalizing the processes
- Selected examples



Organic Factory

Aquatic Domain

1. **Primary organic productivity**=
   f(nutrients)

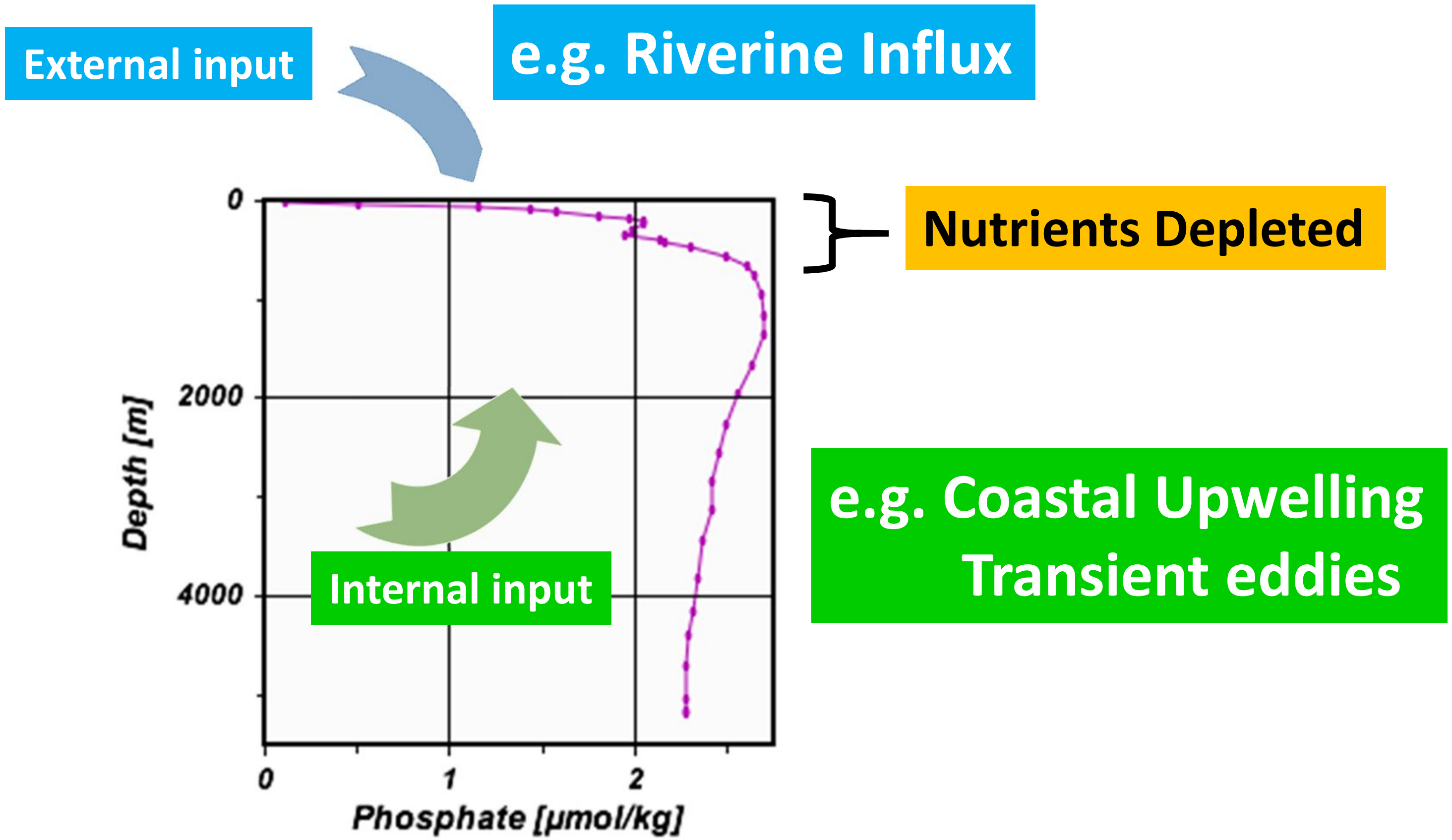
2. **Residence time of organic detritus in water column**=
   f(water depth, sinking rate of organic detritus, which are biologically associated with minerals for ballast effect: aggregates, fecal pellets)
   note: Sinking rate=f(primary productivity)

3. **Redox condition of bottom water**
   f(oxygen demand, oxygen renewal)
   Oxygen demand=f(organic rain: 1 + 2)
   Oxygen renewal=f(water mixing: basin physiography, water circulation and properties)

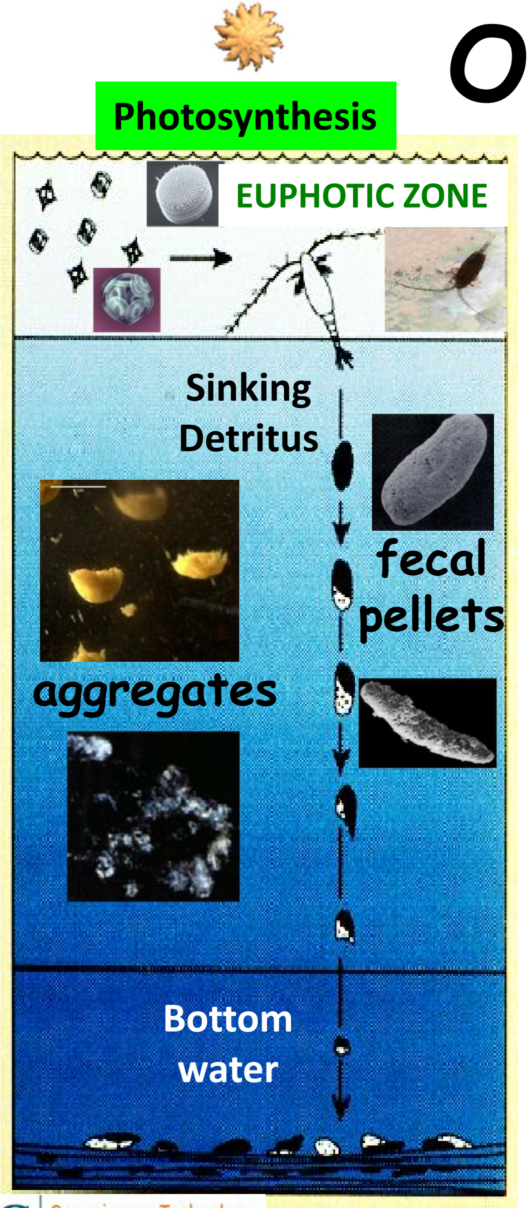
Organic Factory

Aquatic Domain

1. Primary organic productivity=f(nutrients)



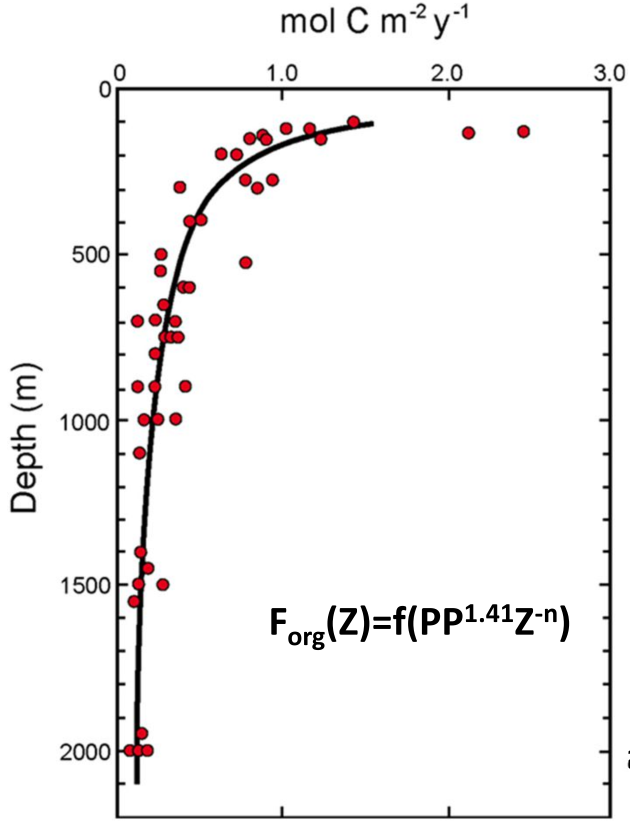
Organic Factory



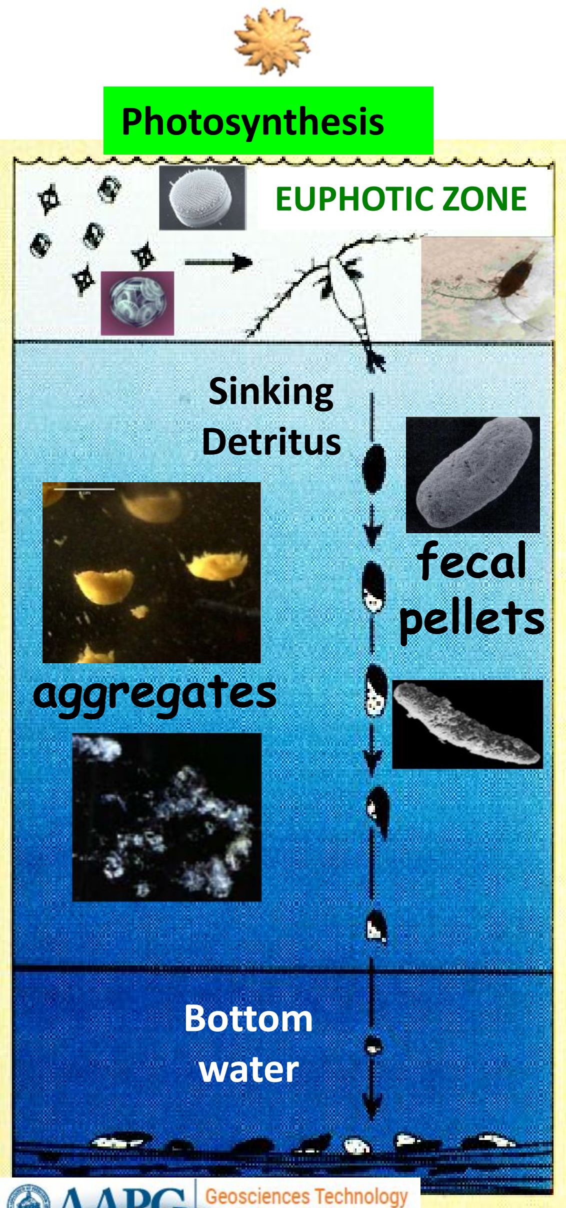
2. Residence time in water column=

f(water depth, sinking rate)

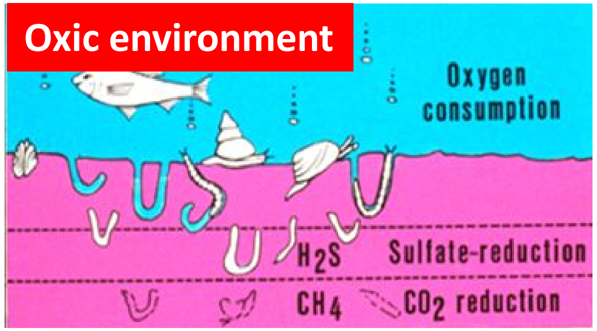
Sinking rate=f(primary productivity)



after Martin et al 1987

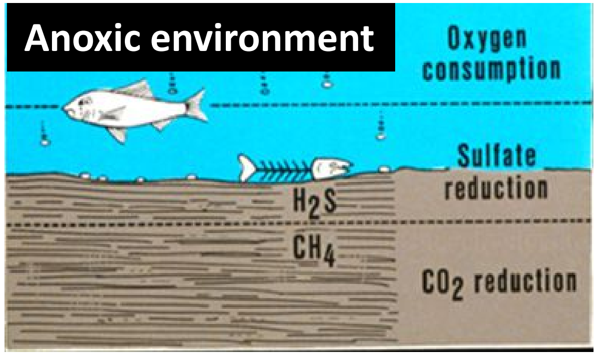


Organic Factory



More efficient microbial activity

Bioturbation



Less efficient microbial activity

No bioturbation

Mixing Rate coef

$$\frac{dOx_z(z)}{dt} = A_z(z) \times Ox_{REF} - D_z \times Ox_z(z)$$

Oxygen consumption

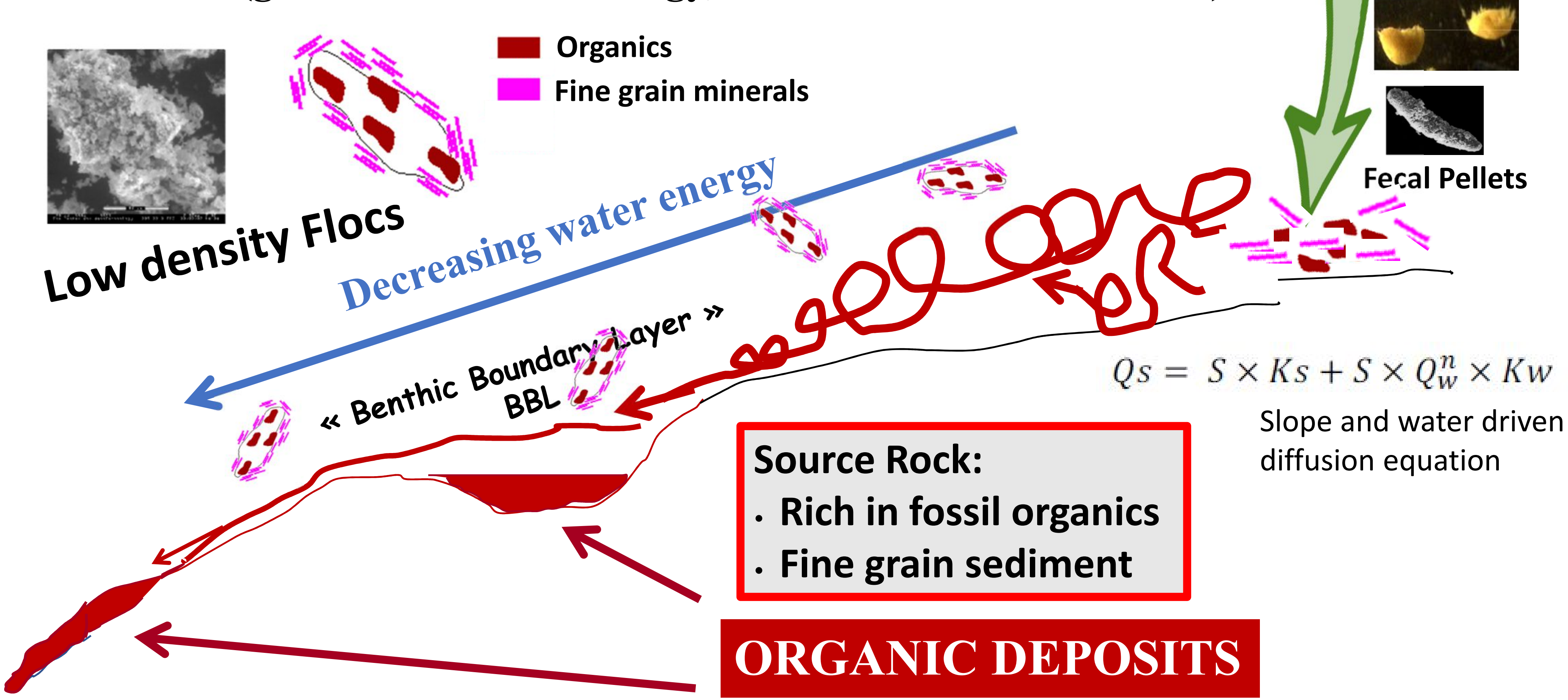
3. Redox condition of bottom water

f(oxygen demand, oxygen renewal)
Oxygen demand=f(organic rain: 1 + 2)
Oxygen renewal=f(water mixing:
basin physiography,water circulation, water properties)

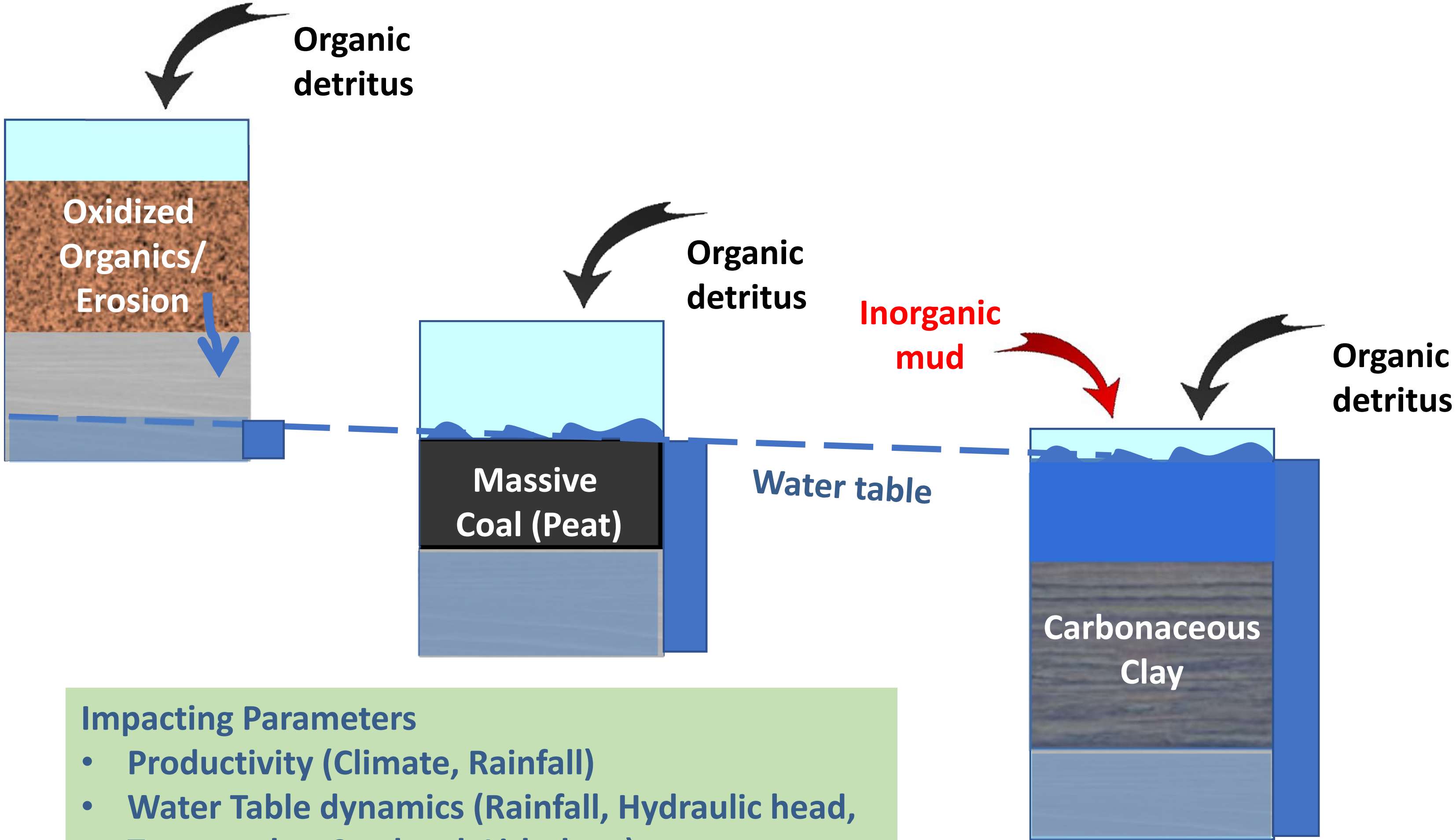
Lateral transport of Organo-Mineral Flocs

Advection, resuspension, horizontal flux….

f(gradient of water energy, minimum bed shear stress)



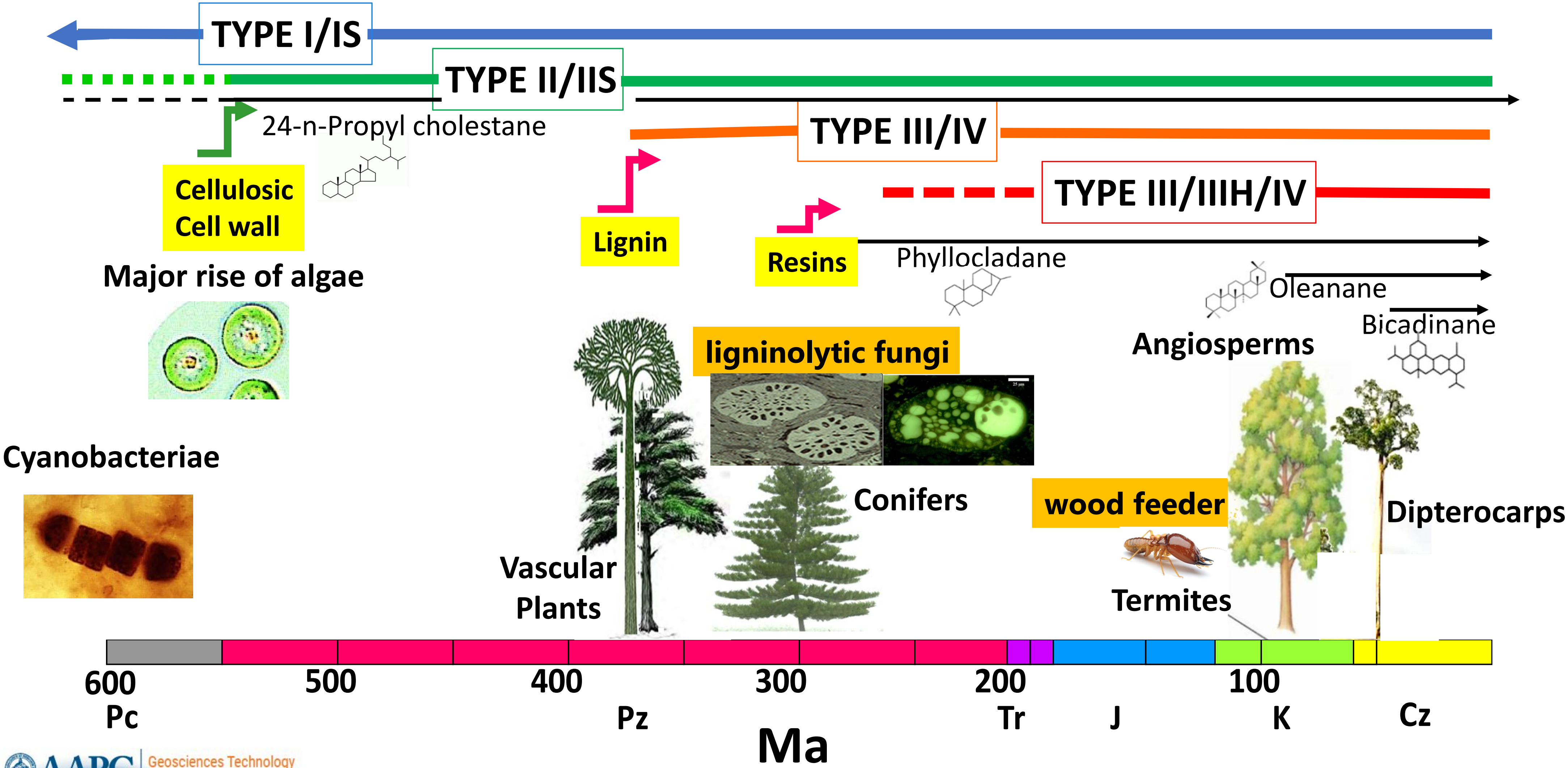
In situ accumulation in wetland domain

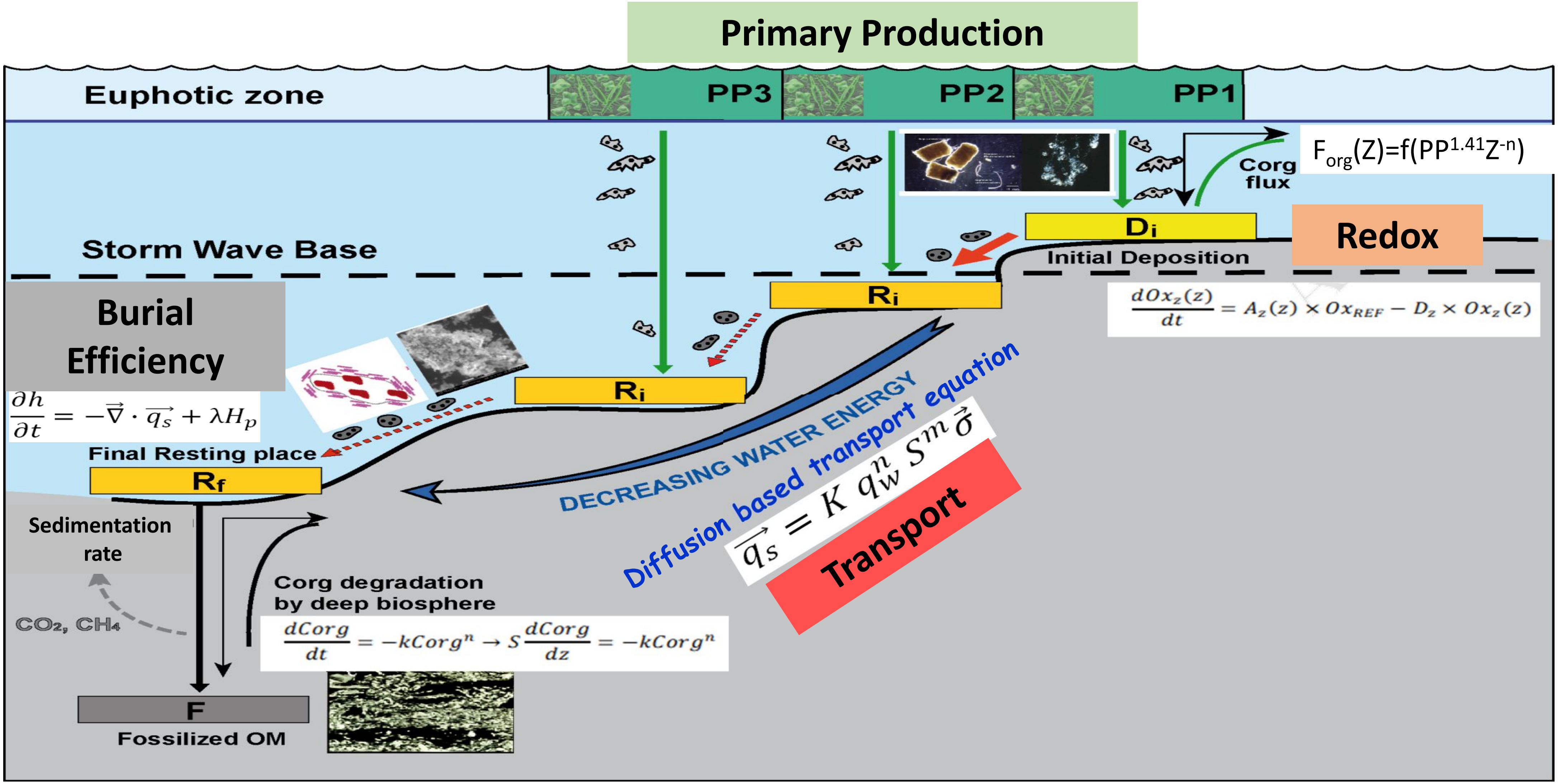


Impacting Parameters

- Productivity (Climate, Rainfall)
- Water Table dynamics (Rainfall, Hydraulic head, Topography, Sea level, Lithology)
- Accommodation vs Organic Production

Impact of Biological Evolution on Kerogen



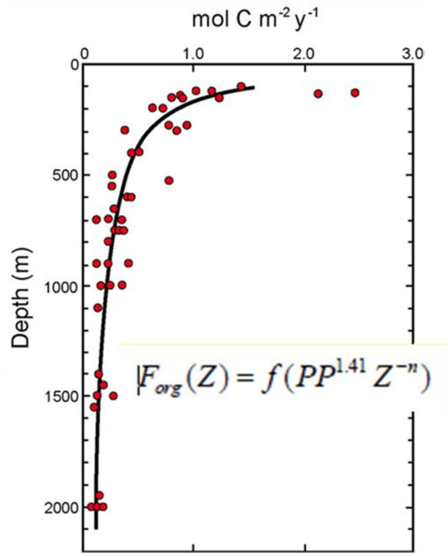

Primary Production
Euphotic zone
PP3
PP2
PP1
$F_{org}(Z)=f(PP^{1.41}Z^{-n})$
Corg flux
Di
Redox
Initial Deposition
Storm Wave Base
$\frac{dOx_z(z)}{dt} = A_z(z) \times Ox_{REF} - D_z \times Ox_z(z)$
Ri
Ri
Burial Efficiency
$\frac{\partial h}{\partial t} = -\vec{\nabla} \cdot \vec{q_s} + \lambda H_p$
Final Resting place
Rf
DECREASING WATER ENERGY
Diffusion based transport equation
$\vec{q_s} = K\, q_w^n\, S^m \vec{\sigma}$
Transport
Sedimentation rate
CO_2, CH_4
Corg degradation by deep biosphere
$\frac{dCorg}{dt} = -kCorg^n \rightarrow S\frac{dCorg}{dz} = -kCorg^n$
F
Fossilized OM

Modelling: Basic Elements

Primary Productivity

Distance to shore
Nutrient input
Bathymetry
Wind stress
External library/maps

Exported Organic Carbon Flux

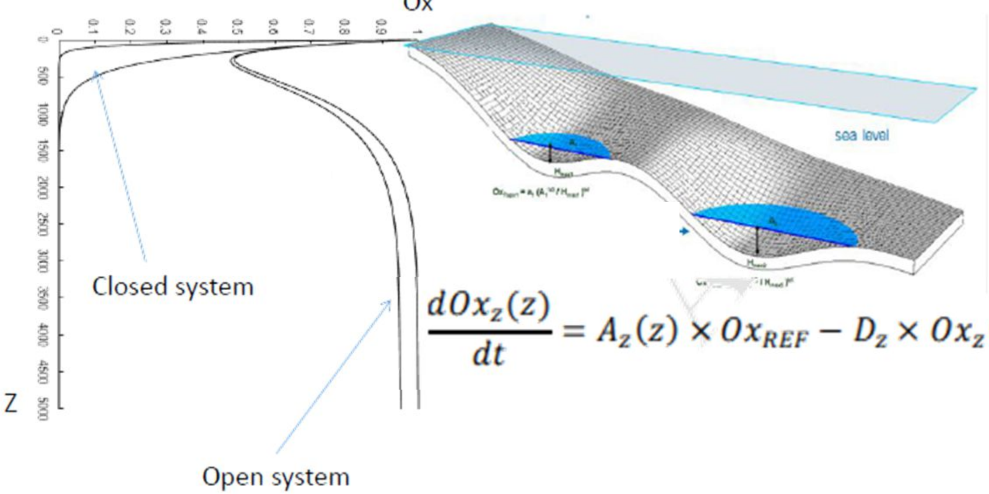


$$F_{org}(Z) = f(PP^{1.41} Z^{-n})$$

REDOX condition, Water column

Oxygen demand (organic oxidation)
Oxygen renewal (water mixing)
Basin Closeness and physiography

$$Qs = S \times Ks + S \times Q_w^n \times Kw$$



$$\frac{dOx_z(z)}{dt} = A_z(z) \times Ox_{REF} - D_z \times Ox_z(z)$$

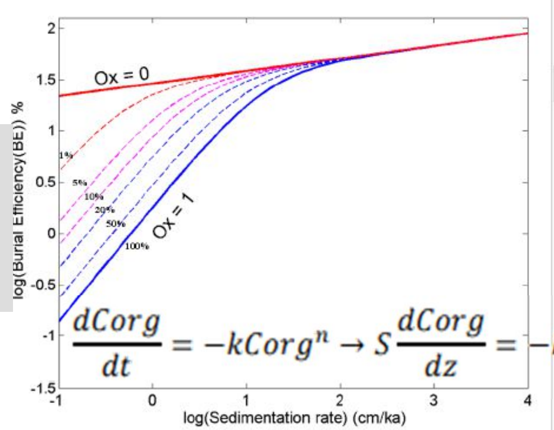
Transport

$$\overrightarrow{q_s} = K\, q_w^n\, S^m \vec{\sigma}$$

Burial Efficiency

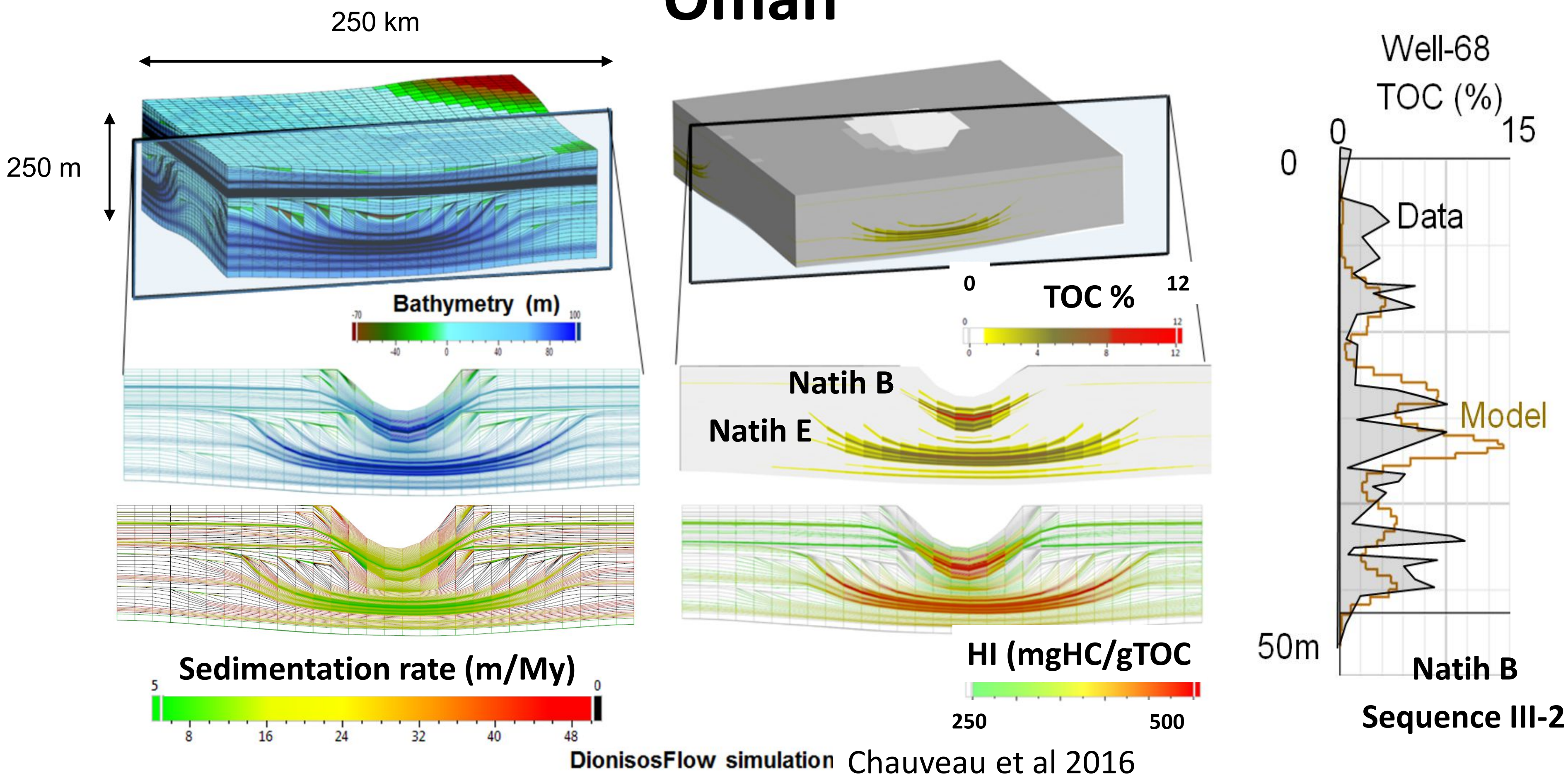
Sediment Redox condition
Sedimentation rate

$$\frac{\partial h}{\partial t} = -\vec{\nabla} \cdot \overrightarrow{q_s} + \lambda H_p$$



$$\frac{dCorg}{dt} = -kCorg^n \rightarrow S\frac{dCorg}{dz} = -kCorg^n$$

Albian-Cenomanian Natih Formation, Oman



Chauveau et al 2016

CONCLUSIONS

- Occurrence of a source rock at the basin scale is the result of the efficiency of the « Organic Factory »:
  - Primary organic productivity
  - Residence time of organics in the water column
  - Redox condition of bottom water
- The distribution, lateral variation, and stratigraphic architecture of a source rock in a sedimentary basin is controlled by:
  - Regional efficiency of the « organic factory »
  - Mode of transport processes
  - Local sedimentation rate at final burial site

CONCLUSIONS

- **Involved biological, chemical and physical processes are tentatively simulated by empirical equations (e.g. Martin's equation, Oxygen level, Diffusion equation, Burial Efficiency….)**
- **Conceptual models and numerical 3D Stratigraphic Forward Modeling devoted to organic matter sedimentology (e.g. DiomisosFlow) contribute to predict source rocks occurrence, quality and distribution.**
- **They help in populating numerical Basin Models with source rock attributes in an educated way**
- **They contribute at directing Unconventional Exploitation at the regional scale**