Source Rocks: Global and Regional Control on Organic Matter Accumulation: Middle East Examples*

A-Y. Huc[1]

Search and Discovery Article #30456 (2016)**
Posted June 27, 2016

*Adapted from extended abstract prepared in relation to oral presentation at AAPG Geosciences Technology Workshop, “Source Rocks of the Middle East,” Abu Dhabi, UAE, January 25-26, 2016

[1] Institut des Sciences de la Terre, UPMC (Université Pierre et Marie Curie), Paris, France (alainyveshuc@gmail.com)

Introductory Comments

Most source rocks in the Middle East (Sharland et al., 2001; Alsharhan, and Nairn, 2003) belong to secular world-wide Paleozoic and Mesozoic time intervals recognized to be prone to accumulate sedimentary organic matter (Huc et al., 2005) (Figure 1). They include:

- Neoproterozoic - Early Cambrian: e.g., Huqf Supergroup (inter alia Nafun Group, Athel Formation) in Oman
- Silurian: e.g., Qusaiba Formation in Saudi Arabia and Oman, Jordan and Iraq
- Upper Jurassic: e.g., Tuwaiq Mountain Formation - Hanifa Formation in Saudi Arabia, Najmah Formation in Kuwait, Diyab Formation in UAE
- Mid-Cretaceous: e.g., Kazdhumi Formation in Iran, Shilaif Formation in UAE, Natih Formation in Oman.

As far as the geological context is concerned, the Neoproterozoic - Early Cambrian source rocks were deposited in a rift system; the Lower Silurian source rocks were deposited during a period of sea-level rise and accumulated mainly in depressions of the paleo-topography resulting from Late Ordovician glacial erosion (e.g., glacial valleys, fluvial incisions), and depressions inherited from Early Paleozoic tectonic features. Mesozoic source rocks accumulated within shallow carbonate intra-shelf basins (ISB) along the southern rim of the Tethys Ocean, in an arid rain-shadow climatic regime.

With the major exception of the Silurian source rocks (Type II), the marine carbonate/evaporitic environments of the infra-Cambrian rift system and of the Mesozoic ISB’s, when associated with anoxic conditions (and when depleted in iron-bearing minerals, often connected with clay clastic input), led to the widespread occurrence of sulfur-rich sedimentary organic matter (Type IS, e.g., Athel Formation, and Type IIS).

Main Controlling Factors in Accumulation of Organic Matter

The main controlling factors favoring the accumulation of organic matter in a basin are:

1. Level of organic productivity driven by the availability of nutrients in the euphotic zone, which is dependent on external input and/or effective water mixing (local impact of global and regional paleoclimate).
2. Minimized residence time of the organic detritus in the water column, which reduces the exposure time to external bio-scavenging and intra-microbial activity. For the sake of a sufficient ballast effect, the organic detritus which is exported toward the sea bottom need to be embedded within organo-mineral aggregates, such as bio-aggregates or fecal pellets. The residence time in the water column is a function of the sinking rate of the aggregates (size and density of which increase according to the primary productivity itself) and the extent of the water depth. In this respect the shallow-water conditions of the carbonate intra-shelf basins played a beneficial role for source-rock deposition.
3. Occurrence of anoxic bottom water, which results in a less efficient microbial degradation of the organic matter and which does not allow meso-benthic life, preventing the detrimental effect of borrowing. Anoxia is triggered by increasing the oxygen demand (mainly derived from increasing organic rain) and/or decreasing the oxygen renewal (e.g., basin physiography, water-column properties). The latter situation can be considered to be relevant in Middle East carbonate intra-shelf basins with limited access to the open ocean (Kendall et al., 2014).

Due to their very fragile assemblage and their hosted microbial activity, bio-aggregates and fecal pellets are short-term live bodies and are rapidly dismantled on the sea bottom. However, the organic particles can contract association with fine-grained minerals in order to generate organo-mineral flocculates. Flocculates are intimate organo-mineral associations. They provide an efficient protection against further extensive biodegradation of the organics on the sea floor. Moreover, these flocs exhibit a low density due to their constitutive organic part. These flocculates are considered to be the main vehicles of organic material for lateral transport by advection, resuspension and horizontal flux along the Bottom Boundary Layer. This lateral transport of low-density flocs is driven by the gradient of water energy. Finally, when reaching a sufficiently low bed-shear stress, the organic matter is delivered to its final resting place where it will be buried. At this stage the sedimentation rate can be instrumental for the ultimate organic content of a source rock. In marine environment during the early burial, the occurrence of sulfates in the pore water sustains the activity of sulfate-reducing bacteria which progressively oxidize the fossilizing organic matter. At very shallow depth in the sediment, these sulfates, which are subsequently depleted, can be replenished by additional sulfates, diffusing from overlying sea water, implying for the organic matter an increasing exposure time to sulfate-reducing process. In this respect, increasing sedimentation rate exports more rapidly the organic matter out of this oxidizing zone and improves its preservation (higher TOC). However, if the sedimentation rate becomes too high, the higher mineral input initiates a dilution effect, which will consequently decrease the organic content (lower TOC).

Specific Middle East Source Rocks

These different factors can be considered as instrumental when considering specific Middle East source rocks.

1. According to Droste (1990) and Carrigan et al. (1995) the deposition of the Upper Jurassic source rocks in Saudi Arabia (Callovian Tuwaiq Mountain Formation and Oxfordian Hanifa Formation) are separated by a lack of organic deposits. This lack actually corresponds to a dramatic cooling episode of the Surface Sea Temperature (SST) documented by an incursion of boreal ammonites in

the Tethys Ocean (Dromard et al., 2003). This cooling event is indicated by $\delta^{18}O$ of belemnites and shark teeth of northeastern and western Europe, by land plant biomarkers, suggesting a substantial change in the continental vegetation, and by geochemical proxies from IODP site 511 on the Falkland Plateau. It can tentatively be inferred that this paleoclimate episode might have affected the organic factory in the intra-shelf basins. High SST is known to favor high surface wind velocity and subsequently intensive water stirring, promoting nutrient delivery from bottom water toward the photic zone, a situation which is likely to initiate a high organic productivity. A substantial drop of the SST, as occurred at the Callovian-Oxfordian transition, might have temporarily shut off this blooming condition and interrupted the organic accumulation (Figure 2).

2. On the Arabian platform, the depocenters of the Silurian Qusaiba Member are indeed localized in the depressions of the Ordovician paleo-topography; however, the organic-richest source rock facies have been identified by Jones and Stump (1999) to occur on the margins of the depocenters, not in the depocenters themselves. A situation which is comparable to the upper slope organic “belts” described offshore Namibia by Inthorn et al. (2006) and rationalized at the parasequence scale by Guthrie and Bohacs (2009) for the Chimney Rock Formation in the Carboniferous Paradox basin, USA. Accordingly, the Qusaiba organic-richest facies probably correspond to what would be expected in a water-energy-driven mechanism as previously discussed.
3. High resolution stratigraphy study of the Natih Formation in Oman (Van Buchem et al., 2005) emphasizes the role of mineral dilution in a quasi-binary system (carbonate and organic matter). The organic–richest section (source rock) belongs to the transgression phase, when the sea-level rise promotes the building of the carbonate platform and keeps the produced carbonate mineral within the landward-shifting platform. Early during the following regression, to keep pace with the sea level change, the carbonate platform starts to prograde, generating bioclastic grainstone clinoforms on the rim of the basin, reducing the area of organic-rich facies in the center of the basin and likely diluting organic matter by carbonate mud, up to the point that the sediment loses its source-rock character.

In the last decade enormous progress has been achieved in identifying and quantifying the processes implied in the accumulation of fossilized sedimentary organic matter. However, the multiple interplaying factors resulting in the deposition and distribution of regional source rocks and the difficulties to encompass their respective role in a given petroleum system paves the way to the development of approaches taking advantage of the integrating power of numerical modelling. Several research or in-house models are currently used and developed for this purpose. They serve to integrate field data, to test hypothesis and scenario, and ultimately to tentatively populate basin models with realistic source-rock distribution and attributes. In this respect, Forward Stratigraphic Models are well fitted to accommodate Source Rock modules. As an example, based on previous geological model, it is possible to model the main specificities of the Natih Formation with a numerical stratigraphic model (Figure 3). This model (Granjeon et Joseph, 1999; Chauveau et al., 2012, 2015), which takes into account inorganic and organic sediment transport and deposition, allows testing several organic-matter depositional scenarios.

References Cited

Alsharhan, A.S. and C.G.St.C.Kendall, 1986, Precambrian to Jurassic rocks of the Arabian gulf and adjacent areas: their facies, depositional setting and hydrocarbon habitat: AAPG Bulletin, v. 70, p. 977-1002.

Alsharhan, A.S. and A.E.M. Nairn, 2003 Sedimentary Basins and Petroleum Geology of the Middle East: Elsevier Science B.V., Amsterdam, The Netherlands, 843p.

Ayers, M.G., M. Bilal, L.R.W. Jones, W. Slenz, M. Tartir and A.O. Wilson, 1982, Hydrocarbon habitat in main producing areas, Saudi Arabia: AAPG Bulletin, v. 66, p. 1-9.

Carrigan W.J., G.A. Cole., E.L. Colling and P.J. Jones, 1995, Geochemistry of the Upper Jurassic Tuwaiq Mountain and Hanifa Formation petroleum source rocks of eastern Saudi Arabia, in B. Katz, editor, Petroleum Source Rocks: Springer Verlag, p. 67- 87.

Chauveau, B., D. Grangeon and A.Y. Huc, 2012, Depositional model of marine organic matter coupled with a stratigraphic forward numerical model: Application to the Devonian Marcellus Formation: AAPG Hedberg Conference, "Petroleum Systems: Modelling the Past, Planning the Future," 1-5 October 2012, Nice, France.

Chauveau, B., D. Grangeon, P. Michel, A. Pujol and M.N. Woillez, 2015, Simulation du dépôt de la matière organique à l'échelle bassin dans un modèle numérique stratigraphique: SGF conference, "Les roches mères pétrolières," 26-27 novembre 2015, Paris.

Dromart, G., J-P. Garcia, F. Gaumet , S. Picard, M. Rousseau, F. Atrops, C. Lecuyer and S.M.F. Sheppard, 2003, Perturbation of the carbon cycle at the Middle/Late Jurassic transition: Geological and geochemical evidence. American Journal of Science, v. 303, p. 667-707.

Droste, H., 1990, Depositional cycles and source rock development in an epeiric intra-platform basin: The Hanifa Formation of the Arabian Peninsula: Sedimentary Geology, v. 69, p. 281-296.

Granjeon, D. and P. Joseph, 1999, Concepts and applications of a 3-D multiple lithology, diffusive model in stratigraphic modeling. Numerical experiments in stratigraphy: Recent advances in stratigraphic and sedimentologic computer simulations: SEPM Special Publication 62, p. 197–210.

Guthrie, J.M. and K.M. Bohacs, 2009, Spatial variability of source rocks: A critical element for defining the petroleum system of Pennsylvanian carbonate reservoirs of the Paradox Basin, S.E. Utah, in The Paradox Basin Revisited – New Developments in Petroleum systems and Basin analysis: RMAG Special Publication, p. 95-130.

Huc, A.Y., F.S.P. Van Buchem and B. Colletta, 2005, Stratigraphic control on source rock distribution: First and second order scale, *in* N.B. Harris and B. Pradier, editors, The Deposition of Organic rich Sediments: Models, Mechanisms and Consequences: SEPM Special Publication 82, p. 225-242.

Inthorn, M., T. Wagner, G. Scheeder and M. Zabel, 2006, Lateral transport controls distribution, quality and burial of organic matter along continental slopes in high-productivity areas: Geology, v. 34/3, p. 205-208.

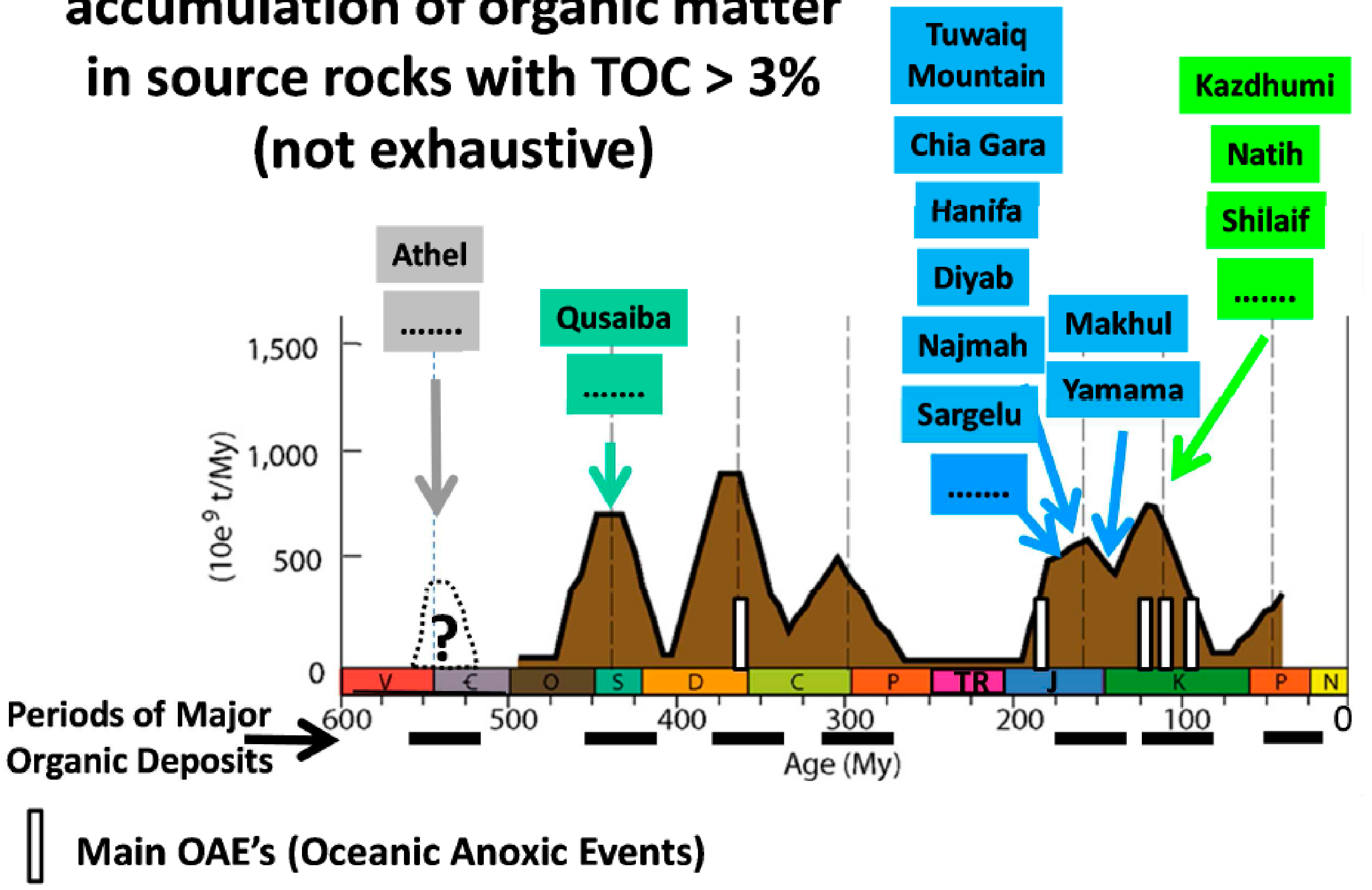
Jones, P.J. and T.E. Stump, 1999, Depositional and tectonic setting of the Lower Silurian hydrocarbon source rock facies, central Saudi Arabia: AAPG Bulletin, v. 83, p. 314-332.

Kendall, C.G., P. Moore, E. Viparelli, A.S. Alsharhan, T. De Keyser and C. Kloot, 2014, Analysis of sequence stratigraphic models for the Jurassic Cretaceous sedimentary fill of the eastern margin the Arabian Plate: Search and Discovery Article #30326 (2014). Website accessed June 21, 2016, http://www.searchanddiscovery.com/documents/2014/30326kendall/ndx_kendall.pdf.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons, 2001, Arabian Plate Sequence Stratigraphy: GeoArabia Special Publication 2, 371p.

Van Buchem, F.S.P., A-Y. Huc, B. Pradier and M. Stefani, 2005, Stratigraphic patterns in carbonate source rock distribution: 2th to 4th order control and sediment flux, *in* N.B. Harris and B. Pradier, editors, The Deposition of Organic rich Sediments: Models, Mechanisms and Consequences: SEPM Special Publication 82, p. 191-224.

Middle East source rocks compared to world-wide massive accumulation of organic matter in source rocks with TOC > 3% (not exhaustive)



Curve: Huc et al 2005

Figure 1. Secular distribution of some of the major source rocks of the Middle East (Huc et al., 2005).

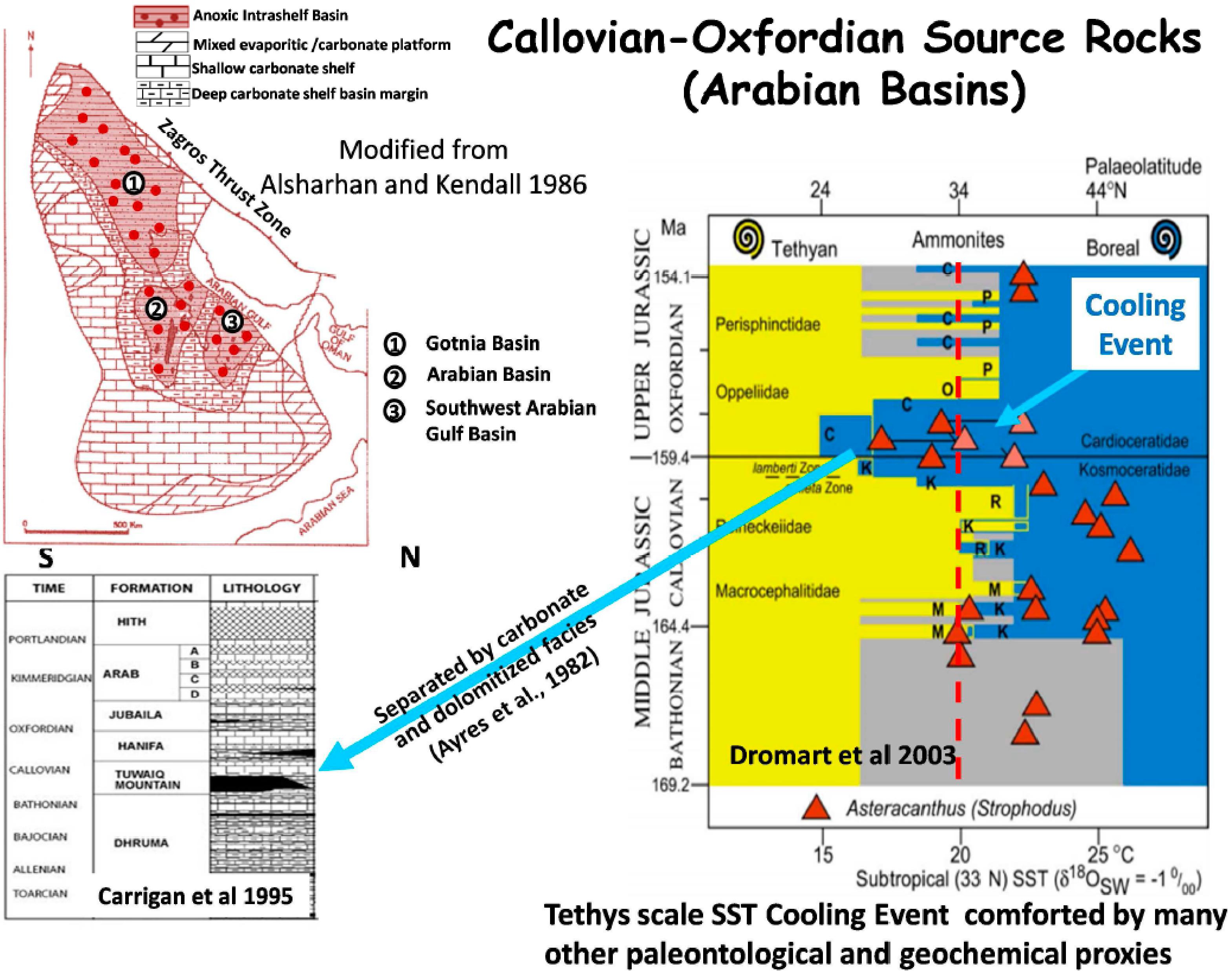
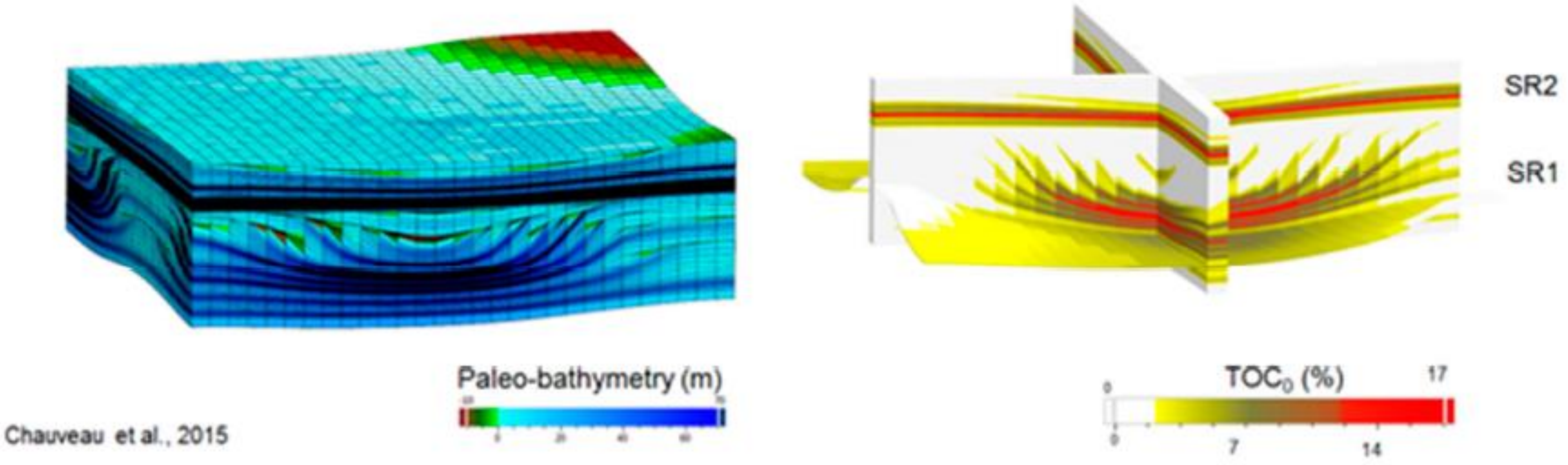


Figure 2. Tentative scenario accounting for the impact of productivity responding to Sea Surface Temperature (SST) change (Carrigan et al., 1995; Alsharhan and Kendall, 1986; Ayres et al., 1982).



Chauveau et al., 2015

Figure 3. Numerical simulation of organic deposition in an intra-shelf carbonate basin, inspired by the Natih Formation in Oman (Chauveau et al., 2015).