Application of the SourceRER Modeling System (Source Retrodiction & Environmental Reconstruction) to Unconventional Reservoirs: Estimating Mudstone Character and Distribution using Paleo-Environmental Factors*

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Overview

Source rocks are the essential foundation to all hydrocarbon systems and most ‘shale’ reservoir units are, or are closely associated with, source rocks. The potential of these rocks are a strong function of their content of biogenic and organic matter. The Source Retrodiction+ & Environmental Reconstruction (SourceRER) modeling system uses many aspects of the depositional environment of organic-matter-rich rocks (ORRs) as input to make quantitative reconstructions of the key proximate controls of Production, Destruction, and Dilution and of the consequent source-rock quality. These inputs include key states of the ocean and atmosphere as well as such geological contingencies as geological age, paleogeographic setting, and climate mode (Figure 1). A Bayesian network is used to model this system, honoring various non-linear interactions among natural controls, mechanisms, processes, and contingencies, and tracking their probabilistic relations. The output parameters quantifying source-rock quality comprise both ORR character and source rock potential attributes. SourceRER analyses have been conducted on 37 time horizons spanning the Phanerozoic (based on ExxonMobil global paleogeographic reconstructions). The analyses accurately match > 88% of calibration data, with significant mismatches for only a few time slices (3 of 37). Potential users include: explorers evaluating source adequacy and play-element distribution, explorers and assessors estimating risk of source presence and adequacy, and basin modelers addressing source and reservoir character, generation timing, hydrocarbon yields, and unconventional reservoirs.

The processes that control source-rock occurrence have been well studied and documented for decades. Many of these studies are locale specific, although a number of recent studies have attempted to describe underlying principles and provide a framework for source-rock prediction. If the characteristics of a particular source occurrence are known, it is possible, in theory, to relate those characteristics to the inferred paleoenvironment of their deposition. Sophisticated tools are currently available to forward model many aspects of the Earth’s paleoenvironmental processes (climatic, biotic, oceanographic); however, few methods or workflows exist that combine all these aspects to predict source rocks. Those workflows that do exist are generally linear, ‘if-then’ conditional type constructions-- these do not attempt to determine fully a dependent probability of source-rock presence and character that accounts for inherent uncertainty of input factors and non-linear feedbacks. SourceRER was developed to provide a framework for robust and systematic prediction of likelihood of source presence and character based on fundamental processes and contingencies, expert opinion, and observations. This system does not require detailed quantitative input (e.g., paleoclimate estimates from a GCM) and is not a traditional forward model. SourceRER is a tool for modeling fundamental relations that combine to result in source-rock deposition.

Fundamental Controls on Source Presence and Quality

The accumulation of organic matter in depositional environments is controlled by complex, nonlinear interactions of three main variables: rates of production, destruction, and dilution. Significant accumulations of organic-matter-rich sediments can arise from many combinations of these factors. Although a few organic accumulations are dominated by one or another of these factors, most organic-matter-rich sediments and rocks record a variety of optimized interactions of all variables. Conceptually, organic-matter enrichment can be expressed as an overall simple relation that is quite complex in detail because of the interdependencies of the variables:

Organic-matter enrichment = Production – (Destruction + Dilution)

Where:
Production = *f*(Insolation, Nutrient supply, & Water supply),
Destruction = *f*(Consumer population growth as a *f*(Production)) + *f*(Consumer access (=*f*(Eh, pH, rheology))) + *f*(Oxidant exposure time) + *f*(Sedimentation rate < burial-efficiency threshold), and
Dilution = *f*(Clastic sedimentation rate > burial-efficiency threshold) + *f*(Production of biogenic silica, carbonate, or charcoal).

Significant enrichment of organic matter occurs where organic-matter production is maximized, destruction is minimized, and dilution by clastic or biogenic material is optimized. Hence, there are various depositional settings in which source rocks accumulate. The existence of the multiple possible pathways to organic-matter enrichment requires a modeling system that evaluates the complex nonlinear interactions of the controls and highlights propitious combinations.

Our modeling approach uses process-based relations and observation-constrained expert opinion to determine the likelihood that suitable interactions of various geologic conditions existed and to establish the probability that a particular source presence, quality, and distribution resulted. Whereas other methods have proven moderately successful using a single linear combination of conditional statements or spatial queries, SourceRER is the only model, to our knowledge, that uses a contingent process-based probabilistic approach (through Bayesian Belief Networks) to quantitatively predict the presence, quality, and quantity of the full range of potential source facies that would have been likely to have occurred under a particular set of geologic conditions.

The Model

The *Source Retrodiction and Environmental Reconstruction* system links the factors that control source deposition in a basin in a contingently nonlinear and holistic manner that more accurately represents the behavior of natural systems than the simple linear conditional statements or filters approach (Figure 2). At the highest level, these factors include plate tectonic, solar, and biologic characteristics of the particular age under investigation. Other influences are combinations of these first-order controls and include climate, oceanography, sea level, and geography. We explicitly include paralic and continental realms throughout the Phanerozoic, detailed physiographic settings, and the influence of changing flora and fauna character and distribution not included in commercially available models. Each of these input parameters is estimated from a normal exploration workflow (either at specific points or within polygons derived from spatial analysis and queries) and then processed through a Bayesian Belief Network that combines cause-and-effect-process relations into a logic network that propagates probabilities of various results. The outputs of the model are the probabilities that sources with specific character, distribution, and volume occurred given the input controls. A range of outputs can arise from the same initial inputs because a variety of paths within the logic network explores the full range of possible outputs by evaluating contingent dependencies and accounting for nonlinear interactions.

SourceRER has the additional advantage of being able to assist in paleoenvironmental characterization if the presence of a source rock is known – utilizing the model in an 'inverse' sense. This is an advantage inherent in the use of a BBN. For example, if the paleogeography of a basin is assumed to be known, existence of a source is confirmed, and other characteristics are also well constrained, then one parameter such as climate, can be systematically inferred based on the interdependencies in the BBN. Additionally, in an exploration setting, if the model yields a low probability of source occurrence, the model can highlight the input parameters to which the system is most sensitive. Subsequent work can then focus on better characterizing the most critical parameters that, if changed, would result in a higher probability of source occurrence.

Application to Unconventional Reservoirs

This type of modeling is also quite helpful for some unconventional reservoirs: Most currently producing 'shale' reservoirs are mature to overmature oil-prone source rocks. Commercial production from mudstones can result from various combinations of rock and hydrocarbon properties, effectively spanning 'conventional' tight oil to 'shale' reservoir matrix production from:

1)'Conventional' tight—non associated, through 2) Interbedded/Hybrid and
3) Porous 'shale' to 4) Fractured 'shale'.

SourceRER modeling helps address dominantly fine-grained 'shale' reservoir types ("Porous Shale" and "Fractured Shale" classes) that comprise 'shale oil' reservoirs at lower thermal maturities and pressure-temperature (P-T) conditions to 'shale-gas' reservoirs at higher maturities and P-T conditions. Both contain a variety of pore types: intergranular, intragranular, intra-kerogen, and intra-bitumen-- the last two, 'organic-associated' types, are better developed and connected at higher maturities.

Shale oil reservoirs share many attributes with shale gas reservoirs, but they also have some distinct differences. Key additional dimensions include fluid properties; over geological time, fluid density and phase control fluid saturation in the matrix, and in the short term, viscosity and phase affect flow and production rates.

The higher thermal maturities of 'shale-gas' reservoirs result in some contrasts with 'shale-oil' reservoirs; they tend to have less smectite (interlayer water) due to illitization, but they develop significant porosity associated with kerogen and bitumen. SEM images of ion-beam-milled samples reveal development of a distinct separate nanoporosity system contained within the organic matter, in some cases comprising >50% of the total porosity, and these pores tend to be hydrocarbon-wet, at least during most of the thermal maturation process.

Thus it can be seen that integrating estimations of the occurrence, distribution, and character of biogenic/organic-matter-rich rocks into models of burial and P-T history addresses many aspects of evaluating unconventional 'shale' reservoirs.

Selected References

Bohacs, K.M., G.J. Grabowski, Jr., A.R. Carroll, P.J. Mankiewicz, K.J. Miskell-Gerhardt, J.R. Schwalbach, M.B. Wegner, and J.A. Simo, 2005, Production, Destruction, Dilution, and Accommodation— the many paths to source-rock development, *in* N. Harris (ed.), The deposition of organic carbon-rich sediments: Mechanisms, Models and Consequences, SEPM Special Publication 82, p. 61-101.

Bohacs, K.M., B.P. West, and G.J. Grabowski, Jr., 2010, Retrodicting Source-Rock Quality and Paleoenvironmental Conditions. United States Patent Application 20100175886.

+Retrodict is defined as: "to infer a past state of affairs from present observational data" (Webster's Third New International Dictionary, 1986). Retrodiction is the act of making such an inference. A common synonym in the geological and hydrocarbon exploration literature is 'prediction', used in the sense of making an inference about a state of affairs before observational data is obtained, rather than before the occurrence of that particular state of affairs.

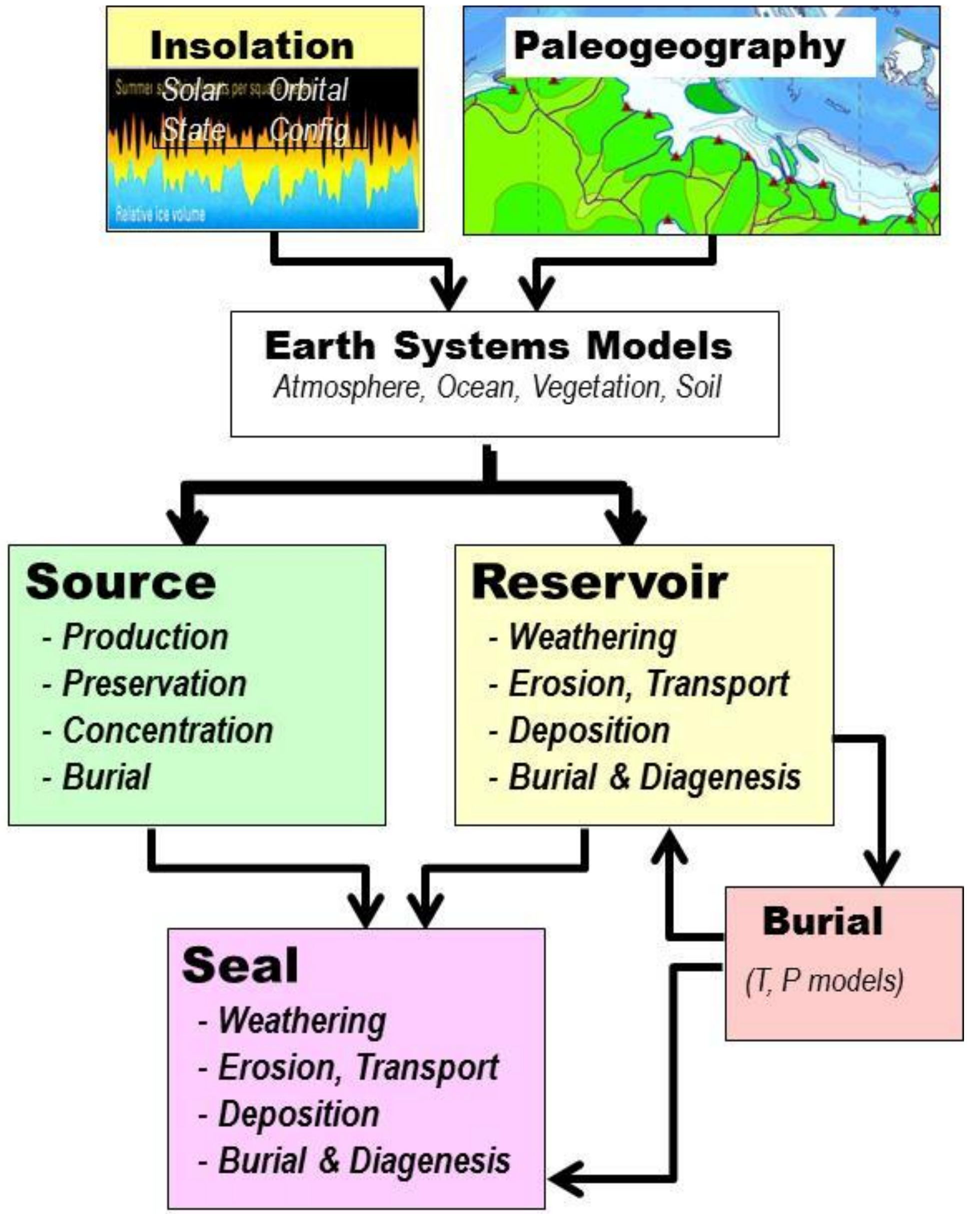

Figure 1. Inputs and contingencies used by the Source Retrodiction & Environmental Reconstruction modeling system.

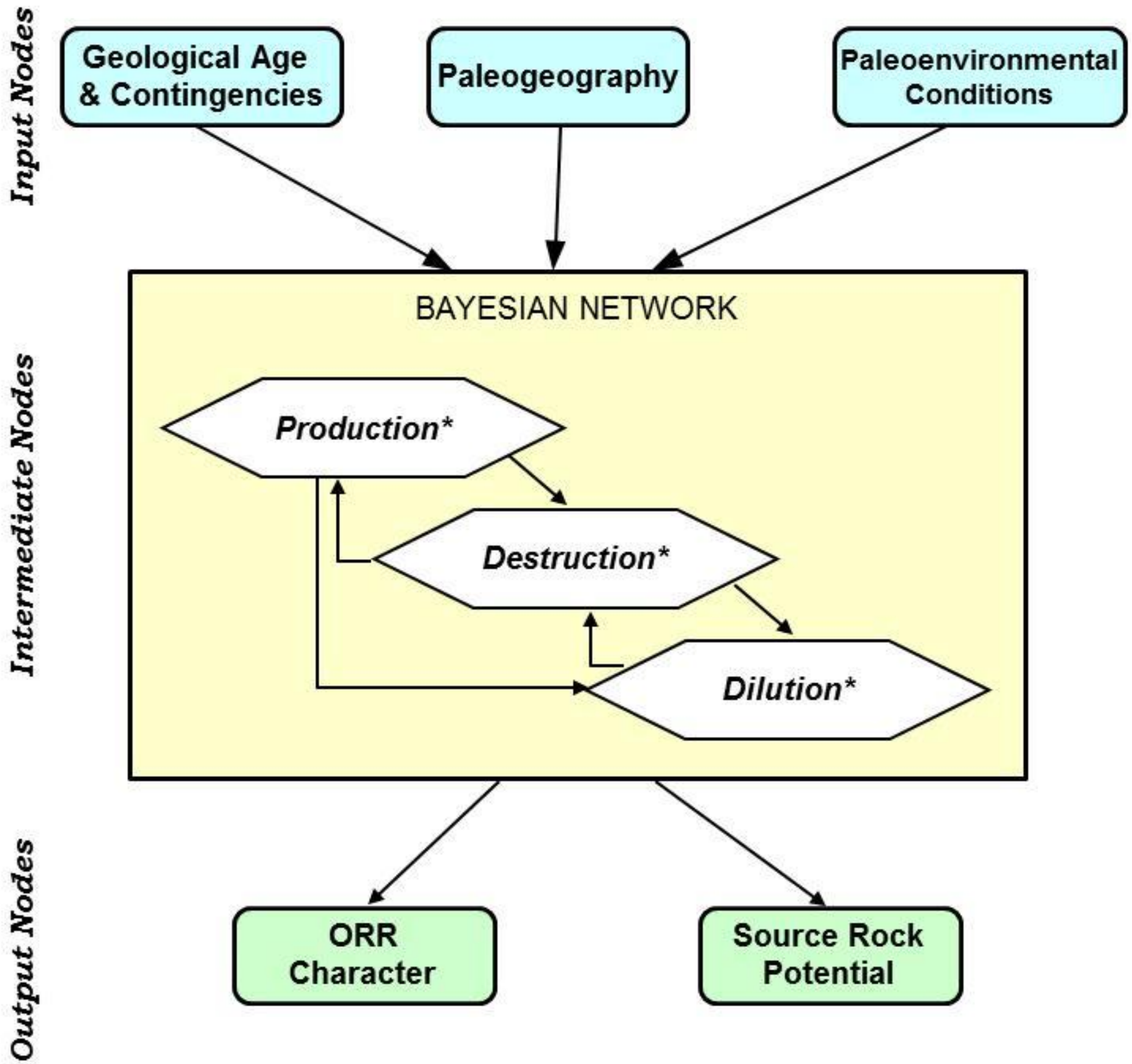

Figure 2. Links and nodes comprising SourceRER.