Source Rocks: Character, Prediction and Value

12-13 September 2011

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Monday 12th September

Predicting Source Occurrence, Character, and Distribution in Frontier Settings using Paleo-Environmental Factors: The SourceRER Modeling System (Source Retrodiction & Environmental Reconstruction)

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Overview: 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. 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 character, generation timing and hydrocarbon yields.

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.

Understanding 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.

Description of 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. 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 Earth’s 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.

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Source Rock Petrophysics: Some Thoughts in a Changing World

Andrew C. Aplin, *School of Civil Engineering and Geoscience, Newcastle University, UK*

Historically, source rock research has focussed almost uniquely on the preservation of organic matter and the generation and expulsion of petroleum. Petrophysical properties were largely ignored, with the exception of log-based methods of determining organic matter. Times have changed; over the last decade, as source rocks have been reborn as gas reservoirs, the need to quantify and thus predict the storage, flow and mechanical properties of organic-rich sediments has become clear. It is also clear – and exciting - that we are dealing with a genuinely complex set of rocks with variable physical properties which are difficult to measure.

Consider the simplest parameter, porosity. Publicly available measured data are relatively sparse. Different measurement techniques (e.g. water content, He pycnometry, Archimedes methods, mercury injection, CO_2 sorption) give different results and also depend on the techniques used to prepare samples. Some methods see all the porosity whilst others only see connected porosity or pores of a certain size. This is particularly important for organic-rich sediments, where a significant fraction of the porosity may be unconnected or contained within pores smaller than 10 nm.

Standard log-based methods of porosity estimation need to be applied carefully to organic-rich sediments. Methods based on the sonic log require a matrix transit time which is affected by organic matter and which cannot be assumed to be the same as that commonly used for organic-lean shales. Furthermore, many organic-rich sediments contain substantial volumes of biogenic silica, carbonate and clay minerals, all of which recrystallise during diagenesis, resulting in a stiffening of the sediment matrix and a likely – but poorly constrained - change in velocity, independent of porosity.

Density-based porosity methods require a skeletal density which varies not only as a function of organic matter content but also the common presence of dense minerals such as pyrite and siderite. The density of the organic matter also varies as a function of maturity and Hydrogen Index, increasing from 1100 to 1400kgm^{-3} through the oil window. Log-based estimates of porosity thus require a multi-faceted approach which requires resolution of organic matter content and preferably mineralogy prior to an accurate assessment of porosity.

The general lack of porosity data, especially on lithologically characterised organic-rich sediments, means that the rate at which source rocks compact as a function of effective stress and temperature remains poorly constrained. The quantitative effects on compaction of (a) organic matter, (b) biogenic silica and (c) carbonate contents, both individually and collectively, remain to be determined. Data from the Kimmeridge Clay Formation in the North Sea suggest that compaction continues through the oil window, despite the conversion of solid kerogen to fluid. Recent data suggest that gas generation at temperatures above 150°C may form pores within organic matter, possibly increasing porosity.

Fluid transport depends on the nature of connected pore network. Mercury injection (MICP) data give information about the dimensions of pore throats and can be used as a way to estimate permeability. Data for the Kimmeridge Clay Formation and Posidonia shale show pore throat dimensions typically less than 20 nm, with modal throat sizes of 10 nm or less. Calculated permeabilities are in the nanoDarcy range; high quality measurements on well characterised sediments are rare. CO_2 sorption techniques point to significant porosity in the <1 nm range. Recent technological developments such as Focussed Ion Bean-Scanning Electron Microscopy are allowing us to image pores and to consider their topology and connectivity, so that it is becoming possible to relate physical measurements of pores to visual data. In addition to pores between mineral grains, pores are also seen in organic matter, possibly related to gas generation at high maturities. It is interesting to speculate about the wetting state of the pore systems and thus the nature of fluid flow and fluid trapping. Within the organic phase, it seems very likely that the pores are hydrophobic and may be gas-filled, thus allowing the flow of petroleum without the need to overcome a capillary entry pressure. Within the mineral matrix, pores may be water filled and may be water-wet, although the partitioning of water soluble organic compounds from oil to water and then to mineral surfaces may alter the wetting state of those pores. If the pores *are* water wet, then the capillary pressures which the non-wetting phase needs to overcome are on the order of megaPascals. These considerations, plus observed heterogeneity of storage and flow properties on the nano- to micro- to macro-scale, reminds us that current models of petroleum expulsion, retention and flow are simplistic and potentially inappropriate.

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Source Rock from Seismic – From Rock Properties to Basin Modelling

Helge Løseth, Lars Wensaas, Marita Gading, Michal Springer, Kenneth Duffaut, Jorunn Johannesen, Per Inge Espedal,Richard Tøndel, *Statoil ASA, Norway.*

The ability to identify a source rock in the subsurface and quantify its parameters has a significant impact on prospect risking assessment of a petroleum play. Traditionally, the risking is based on geochemical analyses of hydrocarbons or source rock samples. Here we present results from a multi-disciplinary research group with backgrounds in geology, petrology, geophysics, geochemistry and petrophysics that has studied relationships between organic content, rock properties and seismic responses. This led to a new way of identifying, characterizing and mapping spatial distributions and variations of thick source rocks based on seismic data. The proprietary method has been used on datasets worldwide with success over a number of years.

The relationship between organic content and rock properties of shale source rocks has been studied in fully cored scientific boreholes and in numerous exploration wells. The results show that bulk density (Rhob) is linearly reduced, while the compression velocity (Vp) and shear velocity (Vs) are non-linearly reduced with increasing organic content. Consequently, acoustic impedance (Zp) is reduced non-linearly while the Vp/Vs-ratio increases with increasing organic content. Forward modelling of reflectivity and amplitude versus offset (AVO) behaviour suggests that the top of a source rock interval on zero-phase data with normal polarity is characterized by a drop in impedance that produces a negative reflection coefficient or a ‘soft’ response (Figure 1). This negative normal incident reflection decreases from near to far offset, i.e., class 4 AVO response. The seismic responses at the top and base of source rock intervals will depend upon factors such as layer thickness and variations in richness. Our models suggest that source rock shale intervals can be identified on seismic data if their total organic content (TOC) is larger than 3-4% and their thickness is more than 15 m. Not only the amount of total organic carbon, but also the vertical distribution of the organic material, a parameter we term the ‘TOC profile’, influences the seismic expression of the organic rich claystones. Consequently, the presence, thickness and basin wide spatial distribution of a source rock can be mapped based on seismic data.

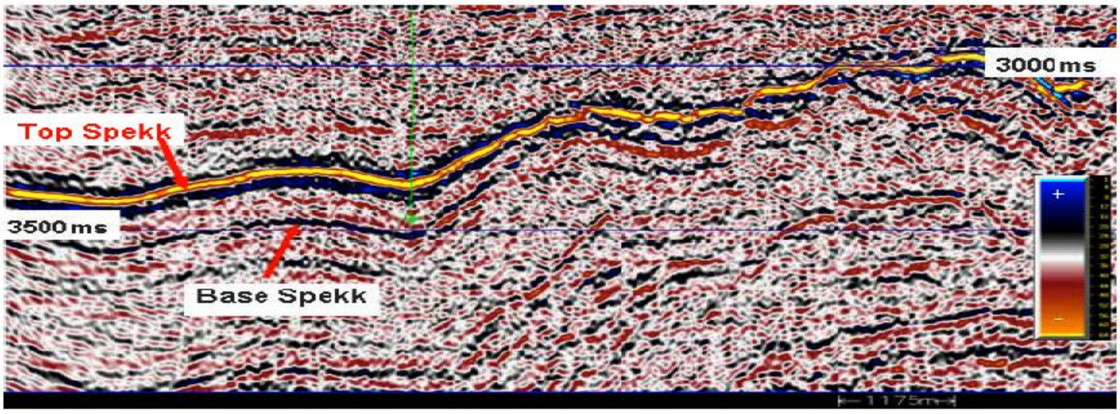

Figure 1. Typical seismic response at top of hydrocarbon source rock. Strong yellow reflection represents top of source rock layer.

In a case study from the Norwegian Sea we illustrate how source rock properties extracted from seismic data can be utilised directly in hydrocarbon generation modelling. Several oil and gas fields prove a working petroleum system. A 3D seismic survey with near and far offset stacks and a standard suite of well logs and organic geochemical data from two exploration wells within the seismic area and three wells outside the area were used. Extent, thickness and richness of the source rock were interpreted from the seismic amplitudes and the resulting maps were input to hydrocarbon generation modelling. We compare results from traditional basin modelling (parameters predicted from interpolated well data) with two scenarios taking seismic derived parameters into account; 1) seismically derived thickness of the source rock and organic content derived from interpolated well data and 2) seismically derived thickness and organic content (Figure 2). The traditional basin modelling gave significantly larger generated hydrocarbon volumes than the models using seismically derived source rock parameters.

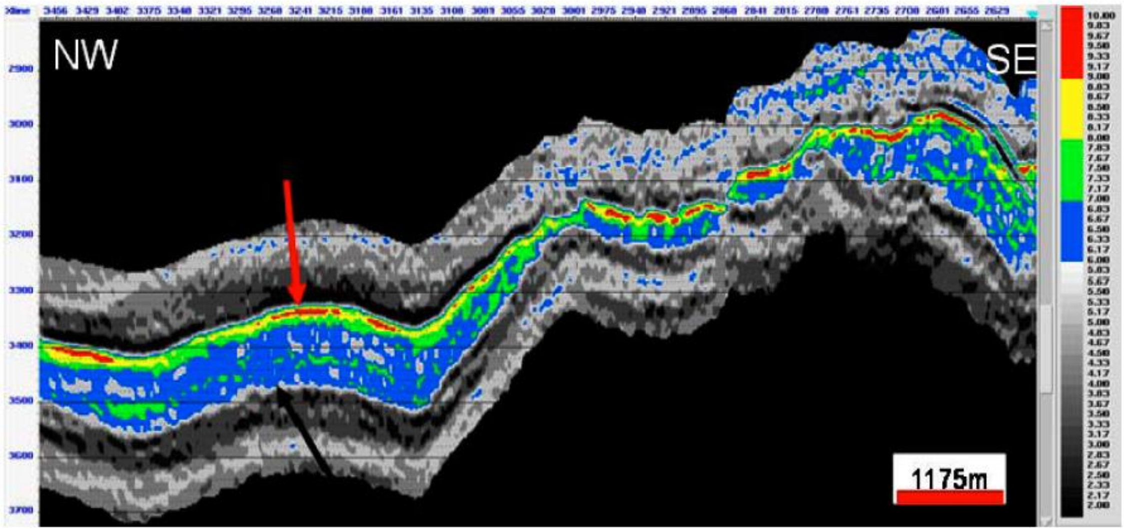

Figure 2. Seismic section where the source rock interval is converted to TOC content. Blue: 6-7%, green: 7-8%, yellow: 8-9% and red 9-10 % TOC. Red and black arrows indicate top and base source rock layer, respectively.

We conclude that seismically derived source rock parameters are better constrained than parameters traditionally used in basin modelling and thus give more realistic modelling results. The results presented here will change the way basin analysis is done because the source rock, which is the first and foremost element of the geological system required to produce a petroleum play, now can be mapped based on seismic data.

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The Role of Hadley Cell Dynamics on Cretaceous Black Shale Sedimentation in the Low Latitude Atlantic Ocean

Thomas Wagner, *School of Civil Engineering and Geosciences, Newcastle University, U.K*

A central question for understanding and predicting marine black shale distribution and quality in the low latitude Mesozoic ocean other than by fluctuations in ocean currents and long term geological processes, including volcanism and the opening or closure of ocean gateways is the linkage between marine productivity, redox conditions and Hadley Cell dynamics in the subtropical-tropical climate zone. The Hadley Cells north and south of the thermal equator are major components of the global atmospheric circulation that exert control on continental climate via the trade wind and monsoonal systems and ocean processes. The critical role of ITCZ dynamics on tropical continental hydrology and evolution of watersheds, marine productivity and marine organic carbon burial has been shown in numerous studies from modern and Quaternary climate to the Mesozoic greenhouse, and further back in time.

Extensive black shale sedimentation in the tropical Atlantic occurred throughout the Cretaceous super greenhouse period when sea surface temperatures in the equatorial region ranged between 30° and possibly up to 40°C. Black shale formation however ceased when the equatorial Atlantic gateway was sufficiently opened to establish a meridional oceanic circulation system with unrestricted exchange of well oxygenated shallow and deep water masses between the Central and South Atlantic lead to a progressive cooling of the Atlantic since the Campanian.

Fundamental consequences of a superheated tropical zone are a vigorous atmospheric circulation associated with latitudinal heat transport and an intensified hydrological cycle in equatorial regions. The critical role of this land-ocean connection has been shown to be instrumental in the temporal formation of oil-prone black shale off tropical Africa where nutrient, (clay) mineral and freshwater from continental run off led to short periods of oxygen deficiency and exceptionally enhanced organic carbon storage. Millennial scale marine proxy records and climate modeling identified a cascade of processes that lead to the deposition of thick black shale units in the Deep Ivorian Basin (DIB) off the Ivory Coast during Coniacian to Santonian times. In this region black shale formation was forced by the orbital precession that paced regional strength of the monsoonal system which itself triggered the discharge of nutrient and clay-mineral loaded freshwater to the Central Atlantic, kick starting a series of processes that resulted in euxinic depositional conditions and black oil-prone source rock formation.

The mode of black shale formation off tropical West Africa emphasizes the importance of an accelerated hydrological cycle and continental climate processes as one critical driver of black shale formation. Fluctuations of the ITCZ and the Headley Cells, however, also control marine upwelling processes via the trade winds on the subtropical limbs of both Headley Cells, adding a second equally powerful mechanism to force anoxia and enhanced organic carbon burial in the tropical ocean. Since both mechanisms are directly linked via the position of the ITCZ upwelling and runoff processes force black shale formation in different areas of the tropical ocean either in phase or out of phase. Understanding these large scale and temporal relationships is of central interest to better predict depositional conditions and the occurrence of oil prone source rocks in areas where no direct evidence from well data exist.

The impact of ITCZ and Hadley Cell dynamics on black shale formation on both sides of the tropical Cretaceous Atlantic is investigated. Combining conceptual ideas with geological evidence from different critical time intervals of the Cretaceous and results from modeling will be used to evaluate the mechanistic and temporal relationships of black shale formation on both sides of the Equatorial Atlantic as primarily driven by large scale tropical atmospheric processes.

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Palaeoenvironmental and Geodynamic Controls on Global Source Rock Intervals

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Major intervals of source rock deposition punctuate the rock record. Klemme and Ulmishek (1991) described these in detail while discussing the contribution of each identified source rock to global petroleum reserves. Understanding the temporal and spatial distribution of organic facies within a palinspastically restored and sequence stratigraphically constrained global environmental framework allows us to predict source rock deposition in frontier regions away from good data control.

Source rock deposition occurs when a sedimentary facies can accumulate above-average quantities of organic carbon of a quality which can, if following the right burial and maturity pathway, generate hydrocarbons. On a global scale this occurs when production and subsequent preservation of organic matter interact in a suitable manner. At a very broad scale the overriding controls on organic matter production and preservation are environmental setting, tectonics, and climate.

Using data we can establish, with confidence, gross depositional environment maps for biostratigraphically defined surfaces. Published data allow us to define areas of organic enrichment within our gross depositional framework. Taking these maps drawn for specific time horizons and using a global geodynamic model we can restore sedimentary basins to their syn-depositional configuration.

Having the ability to examine the distribution of organic-rich facies in a global setting permits us to detail major controls such as structural silling, upwelling, climate, fluvial discharge and other key factors. From these we can start to reconstruct global palaeoclimate belts and oceanic current distribution improving understanding of how organic-rich facies may have been developed in frontier areas with low data density.

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Characterising Palaeoredox in Marine Organic-Rich Environments

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The elevated organic carbon contents that typify hydrocarbon source rocks require high organic carbon accumulation rates, which indicates that the depositional conditions that gave rise to these lithologies were somewhat unusual. In the past, the debate has frequently polarized into a question of whether high organic carbon contents implied enhanced productivity or preservation, but such an analysis is clearly an oversimplification of the problem. It much more likely that a combination of a range of environmental factors (such as local and global climate; nutrient supply; oceanographic setting and conditions; the state of the hydrological cycle on land and the delivery of terrigenous matter to the oceans) together enabled unusually high amounts of organic carbon to accumulate locally, and sometimes globally.

In this presentation, we will review recent research that enables us to characterise and understand how and why seawater redox conditions have varied over both time and space. While most geochemical proxies for seawater redox provide information that pertains to the local conditions at or near the point of sediment accumulation, the Molybdenum (Mo) isotope system has the potential, under certain circumstances, to reflect an average value for global seawater redox. For example, recent results centered on Mo-isotope data (Pearce et al., *Geology*, 2008) are consistent with a significant expansion of reducing conditions in the oceans during the Toarcian (Early Jurassic) Oceanic Anoxic Event (OAE). The lateral extent of reducing conditions fluctuated during the OAE in line with orbitally-driven fluctuations in the global carbon cycle (Kemp et al., *Nature*, 2005), whilst the entire process appears to have been initiated by abrupt global warming. High resolution field observations have allowed us to relate these changes to contemporaneous variations in macrofossil abundance, size and diversity.

A similar study on samples from the Upper Jurassic Kimmeridge Clay Formation (KCF) in the Wessex Basin, U.K. (Pearce et al., *Paleoceanography*, 2010) found that marine redox conditions and total organic carbon levels again responded to changes in sealevel, although the areal extent of reducing conditions, even at its most extensive, appears to have been smaller than it was during the Toarcian OAE. New Mo-isotope data for samples spanning the Paleocene Eocene Thermal Maximum (PETM), some 55.8 Ma ago, indicate that seawater anoxia was extensive within the Arctic basin after the initial stages of the PETM (Dickson et al., *under review*, 2011), despite the basin being open to global circulation at that time. Additionally, the data suggest that the extent of marine anoxia after the initial stages of the PETM was never as great as it had been during the Toarcian OAE.

In the past, certain discrete time intervals were more conducive to the accumulation of organic carbon than others because of the fortuitous combination of a variety of environmental factors. These intervals can be characterized and their origins understood through high-resolution geochemical, isotopic and biotic analysis of well-preserved sedimentary sections. Taken together, this information has the potential to provide us with a better understanding of the environmental conditions that lead to the formation of hydrocarbon source rocks.

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Is it all About TOC? A Biological Approach to Shale Gas Prospectivity in the UK

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With European shale gas candidate plays being developed in the near future, a substantial amount of research is required in the identification of depositional ‘sweet spots’ in organic-rich mudstones. Recent investigations of mudstone successions have indicated that the heterogeneity and variability in chemical composition and texture profoundly affect the shale gas potential of these systems. This study evaluates the sedimentological and biological controls on the abundance, distribution and composition of organic matter in the Upper Mississippian Bowland Shale Formation, a proven oil and gas source rock in Central England. These factors have a significant impact on the amount and quality of the associated gas. The research undertaken in the project will test the hypothesis that the distribution, type and concentration of organic matter in mudstones, and hence the location of prospective shale gas, relates to changes in biological productivity and palaeoenvironment.

The Upper Bowland Shale Formation was deposited during the Serpukhovian (Namurian) over a wide epicontinental area of shallow carbonate platform highs and linked relatively deep water sub-basins of the Central Pennine Basin. Established concepts of the depositional environment in the sub-basins, e.g. the Widmerpool Gulf and the North Staffordshire Basin interpret background hemipelagic mud deposition with frequent influxes of distal pro-delta turbidity currents. The repeated occurrence of (a) thin but widespread goniatite-bearing and organic-rich ‘marine bands’ and (b) (partly calcareous) silt- and sandstones and thick successions of clay-rich to silty mudstones reflects high amplitude and high frequency sea-level changes. Previous studies have noticed systematic differences in the type and origin of organic matter and have attributed these to variations in salinity during the deposition of the marine bands and the intervening sediments.

Initial observation of thin sections of samples from a borehole in the Widmerpool Gulf in Derbyshire, UK indicate a wide range of mudstone facies (including bioturbated clay-dominated mudstones, graded silt-bearing mudstones, thin-bedded pellet-rich mudstones and shell debris-bearing calcareous mudstones) interbedded with thin quartz-rich siltstone and fine sandstone layers. This suggests great variety of dynamic changes in depositional processes; in addition evidence for different bioturbation intensities suggest that conditions at the seabed would have significant affected the amount of preserved organic material. In fact, levels of organic carbon vary between 1.5 and 12%. Allied studies of carbon isotope geochemistry and palynology indicate high abundances of amorphous organic material (AOM) throughout the succession in comparison to time equivalent intervals in the northern parts of the Central Pennine Basin. The origin of the AOM is unclear but algal remains and degraded plant tissues are both potential precursors. This question of AOM origin will be addressed in the ongoing investigations because the two candidates have very different implications for potential gas generation and storage in the mudstones.

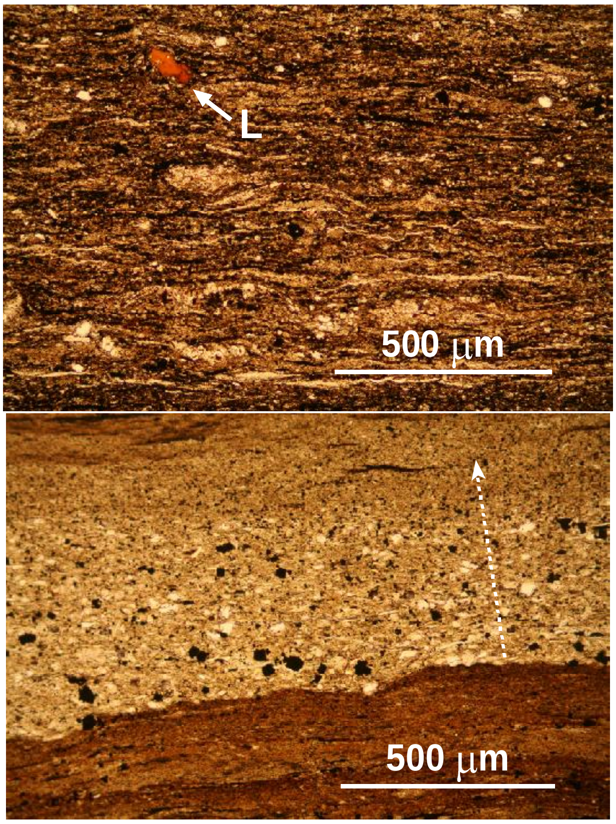

Figure 1: Photomicrographs of selected thin sections: (left) calcareous mudstone in parallel/wavy bedding, rich in organic matter and some distinct liptinite clasts [L]; (right) graded siltstone bed with erosive base on top of clay-dominated pelleted mudstone, angular silt-sized quartz grains and pyrite framboids.

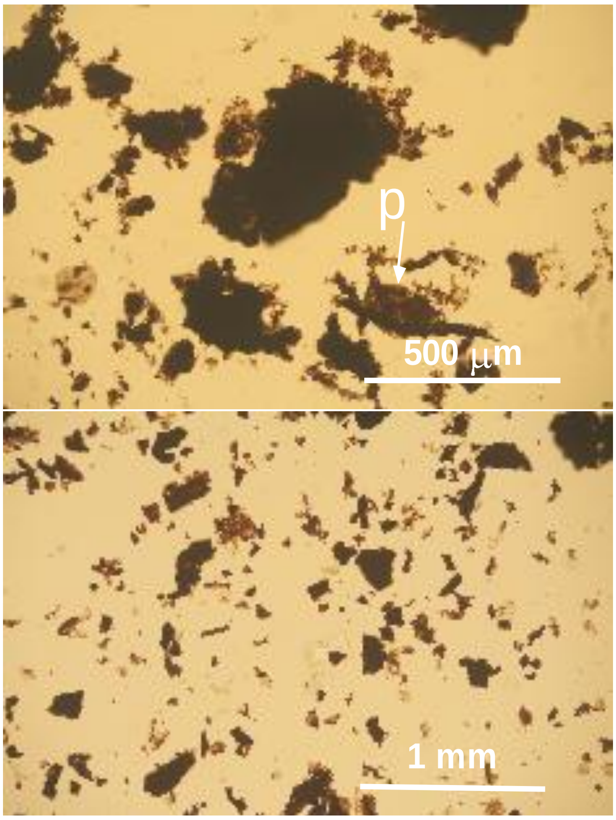

Figure 2: Photomicrographs of isolated kerogen: (left) organic matter dominated by large coherent particles of black AOM with fuzzy outlines, pollen grain (p); (right) organic mixture made up of brown and black AOM, phytoclasts and few palynomorphs.

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Source Facies Prediction: Boundary Conditions, Uncertainties, History and Future

Paul Markwick, *GETECH Group plc., Elmete Hall, Elmete Lane, Leeds, LS8 2LJ, United Kingdom*

Source rocks are fundamental to any petroleum system: no source rock, no hydrocarbons. Therefore, a critical first step in New Ventures exploration is to determine if a source rock is, or ever was, present in an area of interest. Unfortunately, data is usually sparse in frontier areas; not least because few exploration wells intentionally penetrate the source rock horizons. This places a great emphasis on source rock prediction.

In this talk I will concentrate on the prediction of source rock facies, which relates to the deposition and early burial history of a source rock system, but which does not include any treatment of kinetics, expulsion, etc., (for discussion of this aspect, see Pepper and Corvi, 1995a; Pepper and Corvi, 1995b; Pepper and Dodd, 1995). The talk will include a brief outline of the history of source facies modelling, but the focus will be on the uncertainties involved in defining the processes (production, transport and preservation) and boundary conditions (viz., palaeogeography, palaeoelevation, tectonics, Earth System modelling).

Most source facies prediction models are process-based, either through the use of analogues and/or by directly modelling the processes believed to be responsible for organic carbon accumulation. Today, predictive source facies models take two broad forms:

1. 2-D, 3-D and 4-D global models, in which predictions of the spatial presence or absence of source facies are generated by the representation of processes using Earth System modelling and palaeogeography (the subject of the SEPM-GSL Snowbird conference in 2006). Examples include:
    a. Fugro-Robertson's "Merlin" (Harris et al., 2006) and its predecessor (Burggraf et al., 2006);
    b. "SourceRocker", which is part of the "Gandolph" project of Scotese and GeoMark (Scotese, 2006);
    c. The source rock retrodiction model of Bohacs et al., (2008; US Patent application 2/601895);
    d. Lithofacies prediction models of Markwick (2008).
2. 1-D and 2-D Basin-scale or box-type predictive forward models such as:
    a. Sintef's OF-Mod software (Mann and Zweigel, 2003, 2008), which simulates the source rock type and quality variations for input into basin modeling.
    b. Schwarzkopf (1993) probabilistic source facies model

Early predictive models were based on empirical or semi-quantitative climate models applied to global palaeogeographies (these maps were relatively course scale, and often only defined the land-sea distributions). They largely focussed on the identification of areas of high primary productivity in the past, indicated by the former distribution of ocean upwelling (Parrish, 1982; Parrish and Curtis, 1982; Scotese and Summerhayes, 1986). The link between areas of ocean upwelling and enhanced productivity was already well known by the 1970's through the fishing industry (Cushing, 1971). Sampling of the seafloor in shelfal areas revealed concomitant high organic carbon concentrations in many of these high productivity areas, although not all (Demaison and Moore, 1980; Premuzic, 1980; Premuzic et al., 1982). By the mid-1980's quantitative models were also being applied to the prediction of upwelling (Barron, 1985; Kruijs and Barron, 1990) and a substantial literature on the significance of upwelling to source rocks had built up (Suess and Thiede, 1983; Thiede and Suess, 1983). But, deep sea drilling, notably by the DSDP, demonstrated during this same period (1960's – 1980's) that organic-rich sediments extended beyond the shelf and onto the slopes and abyssal plains. The DSDP also revealed that organic-rich rocks were not homogenously distributed through time. This led Schlanger and Jenkyns (1976) and Demaison and Moore (1980) to postulate the role of anoxia in the past in facilitating organic matter preservation (anoxia being at one end of a range of levels of oxygen deficiency). The presence of widespread, temporally discrete organic-rich horizons was interpreted as indicating occasional regional to global oceanic anoxic events (OAEs). The resulting controversy between the advocates of preservation over production or production over preservation, usurped much of the source rock debate during the 1980-1990s.

The problem therefore faced by explorationists was to develop models that took all these processes into account within a single tool, whilst accounting for uncertainties. This became the goal of many exploration groups through the late 1980s and 1990's, resulting in models such SORCER at Shell (Westrich et al., 1993) and Schwarzkopf's probabilistic organic carbon prediction model at BP (Schwarzkopf, 1993) amongst others. Of these, the Schwarzkopf model is significant historically in that it established paradigms adopted by later models:

1. Organic matter is treated as particles;
2. The processes leading to organic carbon accumulation are broken into three groups, which were largely treated independently: carbon production, sedimentation rate and preservation (oxygen conditions are included within a "Burial Efficiency" term);
3. A probabilistic treatment of input values using Monte Carlo statistical techniques.

The 2D version of OF-Mod follows the Schwarzkopf approach most closely, although it is more deterministic than its predecessor. But, like Schwarzkopf, OF-Mod focuses on marine organic matter and nutrient sources, and does not account for the consequences of horizontal transport of either nutrients or organic matter, as some of the more recent global spatial models attempt to do. Tyson (2001) compiled a large database of modern sediment data to explore statistically the controls on TOC, which resulted in his unpublished model RVTOC. Again, this work treated organic matter as particulate, following Schwarzkopf and also broke the problem into production, sedimentation rate and preservation. The precept of organic matter as particles was also fundamental to the philosophy behind "Merlin" as well as the lithofacies models of Markwick (Markwick et al., 2008; Markwick et al., 2006; Markwick and Valdes, 2007), who modified the tripartite process division into "Production – Transport – Preservation" in his lithofacies prediction models; this included not only source facies prediction, but also the prediction of siliciclastics in general.

The development of the current array of models during the late 1990's reflected a number of innovations, not least a better understanding of the processes responsible for source facies deposition, but especially the availability of Earth System models and detailed global palaeogeographies to provide the boundary conditions. But all of these elements include inherent uncertainties and the definition of these, and more especially their relevance to exploration risking, is key. Thus the sorts of questions that need addressing include:

- How wrong can reconstructions of palaeoelevation be before they impact exploration related processes?
- What are the consequences for exploration risk of using different plate models with different plate configurations for the same time interval?

- What is the affect of different modelled ocean temperatures for source facies prediction?
- How sensitive are upwelling predictions to changes in boundary conditions (atmospheric chemistry such as CO_2 or palaeogeography) or errors in the model?

What has been found from these sorts of sensitivity experiments is that some model uncertainties have a greater impact on the prediction of source facies than others; it is these that must be understood and quantified in order to improve the veracity of results.

What is also clear is that we can improve the representation of many of the processes being modelled through testing of results and the wider literature now available, but also by how existing models parameterize different processes and their consequences. This is well illustrated by the treatment of upwelling systems in different models. In the early models of Parrish and Barron upwelling predictions were largely a question of their presence or absence. In contrast, models such as those of Schwarzkopf or OF-Mod allocate production values based on analogy with present day ranges of values for similar settings. In the Merlin model, areas of upwelling are identified using coupled ocean-atmosphere model results, but only included in calculations if upwelling is present in an area for more than a set number of months. In the models of Markwick, upwelling is again extracted directly from the climate models, but then, like OF-Mod, values of productivity are assigned to that upwelling based on modern day values. The problem with all of these models is that in reality, the relation of upwelling to enhanced productivity and then on to export carbon production, is not simple. Export carbon production depends on, amongst other factors, seasonality in the upwelling system, such that there are periods when the biological system (phytoplankton-zooplankton) is not in equilibrium (Berger and Wefer, 1990). Interestingly, modelling experiments suggest that this seasonality may be susceptible to changes in climate model boundary conditions such as atmospheric CO_2 concentrations (Valdes and Markwick, 2006). Other factors that need to be considered include: the depth from which upwelled water is sourced, since this must be from below the photic zone; upwelling velocity, because the rate of flow of nutrients through the system can exceed the ability of the biological system to take up those nutrients (eg. NW African upwelling system); the bathymetric geometry, which can result in bottom currents that either disperse and/or redistribute organic matter away from the area of maximum productivity (as seen on the margin of Peru and also SW Africa). These can now be dealt with systematically in models.

The future? The inclusion of a stratigraphic forward model in OF-Mod, and the development of a 3D OF-Mod solution, marks a step towards convergence between the two different modelling approaches. But, there is still a long way to go. Other developments that are required include the following:

- Integration of models that look at the whole system, not just source facies, and incorporating tectonics, landscape and drainage (source to sink relationships) and depositional systems.
- A better understanding of boundary conditions and the variability of input values
- A quantitative assessment of uncertainty to define which are significant for exploration and need to be addressed, and which are not.
- Further investigate and refine what we know about the underlying processes and better represent these within our models
- Ensure that models remain transparent; a black box is of no value to understanding any natural system.

But, perhaps the most important question to answer is “do these predictive models get us any further forward in the exploration risking process?” This can only be done through systematic testing with on the ground observations. At the end of the day, it must always be remembered that source facies prediction is driven by the needs of explorationists and not just academic curiosity. Thus the aim is to provide a risk reduction tool not the definitive source facies depositional model.

NOTES

Comparing Equations to Calculate Total Organic Carbon Content and Primary Productivity

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Equations describing the amount of organic carbon in sedimentary deposits range from multivariate regressions on the relevant input parameters, to equations made up of equations describing the processes leading to the deposits. Relevant input parameters are normally primary productivity, water depth, sedimentation rate, dry bulk density, and sometimes oxygen concentration. These input variables may also be used as input for the processes (carbon flux and burial efficiency of the deposited organic carbon). Some of the equations describing organic carbon deposition and burial have also been used to back-calculate primary productivity from values measured in deposits (commonly in cores).

These empirical equations are derived from fits to modern data sets. Multiple equations exist for each process, derived by different authors from different data sets (although older data sets are commonly included in newer derivations). What remains unclear is how much variation in the computed values results from the inherent variability in the input parameters and how this is propagated through the (various combinations of) different equations, and thus how applicable the different equations are for predicting total organic carbon (TOC) values or back-calculating primary productivity values.

Here a comparison is made with different methods for calculating TOC, using different carbon flux and burial efficiency equations. A similar comparison is made for primary productivity back-calculations. The results are compared with present-day measured values. These measurements cover a large range of depositional environments, e.g. shallow to deep water, oxic to anoxic conditions, etc. The results for both TOC and primary productivity calculations show large variation with many outliers, and some consistent over- or under-prediction of computed values compared with the measured values. Uncritical use of such equations may thus lead to incorrect predictions of deposit characteristics or environmental reconstructions.

NOTES

Insights into Organic Carbon Source Fractions and Depositional Environment from Geochemical Bulk Parameters

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The organic carbon content of sedimentary deposits is derived from several different sources commonly classified as marine, terrestrial, or, when the original source cannot be identified due to degradation, residual carbon. The mixture of these different fractions determines the characteristics of the organic part of the deposit. Knowing the relative amounts of such fractions can aid in understanding and reconstructing the environment in which the deposit formed. This understanding is in turn important for determining the input for any mathematical model of organic carbon deposition, be it calculations for a well or for basin studies. For such models, primary productivity values need to be known rather than the marine organic carbon fraction. These values can be back-calculated once the marine fraction has been determined. Primary productivity is of course also a more direct environment indicator than the marine organic carbon fraction.

One way of determining the characteristics of the organic deposits is by doing a careful microscopic examination of samples, in order to identify the different fractions visually. Other, chemical, methods like pyrolysis GC or biomarker analyses are also suitable for organic matter typing. However, all these methods are time and money consuming, and may lead to inconsistent results. Here a method is presented where three fractions (marine, terrestrial, residual) are calculated from bulk parameters TOC, HI, and $\delta^{13}C$. The method uses an end-member mixing model for HI and $\delta^{13}C$. This requires the setting of end-member values for the different fractions, which can be difficult especially for $\delta^{13}C$ as these depend on the particular environment. Nonetheless, a good fit can be obtained, so that the three different fractions can be determined.

Once the marine fraction is known, primary productivity can be determined using similar methodology as used in the organic facies modelling tool OF-Mod 3D (Mann & Zweigel, 2008). The methodology has been implemented in a new tool, provisionally called OF-Mod 1D.

NOTES

Relationship between Sea Level Changes and Organic Carbon Deposition Simulated with Organic Facies Modelling (OF-MOD).

Eliza Mathia[1], Justin Fadipe[1], Maarten Felix[2], Thomas Wagner[1]

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There has been much contention regarding the parameters considered most influential on the deposition and preservation of organic-rich sediments in the marine realm. Much of the debate has focussed on the effects of primary productivity and water-column/sediment anoxia, to explain the spatial variability of organic-rich sediments in the ocean. To explain the temporal variability of these sediments variations in TOC richness have been related to different stages of the sea level, especially sea level highs and lows. Constraining the correlation between sea level and organic carbon burial has broad implications for petroleum exploration as it allows prediction of both the temporal and spatial distribution and quality of organic-rich marine rocks, which are critical input variables for basin modelling studies.

This study further explores the function of sea level changes as a primary control on sedimentation rates and organic carbon burial. Extreme levels of sedimentation rate were linked to sea level high and low stands, representing - for example - interglacial and glacial conditions respectively, with sedimentation rate maxima being linked to the low stands.

Several scenarios of organic carbon deposition were tested using the organic facies modelling programme, OF-MOD (Mann and Zweigel, 2008, *International Association of Sedimentologists, Special Publications*, **40**, 239-274). The model was calibrated using geochemical data from ODP Leg 175 drilled along the western continental margin of Southern Africa, covering prominent high productivity areas such as the Benguela Upwelling System. The Miller *et al.* (2005, *Science,* **310**, 1293-1298) sea level curve was selected to capture sea level variations during the glacial and interglacial periods of the past 400.000 years.

The model results show that variable sedimentation rate is needed to fit the modelled to the measured TOC results. For example, the positive impact of low sedimentation rate on organic carbon deposition is confirmed for high stand deposits, due to minimal dilution and best preservation. However, sedimentation rate changes alone cannot account for the measured variability of organic carbon contents in the Benguela sediments, and additional mechanisms are required to explain the variation. To test this, we also modified primary productivity and preservation. The outcomes of these models show that high primary productivity has a decisive role in enhancing organic richness and quality in low stand sediment sequences whereas high preservation outweighs the negative impact of excessive dilution.

Overall, the results from this study suggest that the correlation between sea level changes and TOC and HI measured in the Benguela sediments is moderate and reliant on several factors, including primary productivity, preservation condition and sedimentation rate. The results thus challenge the notion that the deposition of organic rich sediments can be placed at sea level highs, and emphasize the importance of other, external, factors. The modelling outcomes offer great promise with regard to the possibility of predicting the source rocks variability in other poorly drilled continental margin areas.

NOTES

Techniques for the Prediction and Evaluation of the Distribution and Quality of Organic-Rich Rocks in Europe

Fivos Spathopoulos, Mark Sephton, *Imperial College London*

Successful exploration for petroleum in Europe depends on the ability to detect good quality, thick, organic-rich rocks, with significant yields of oil and gas. The distribution of these rocks was governed by paleogeographic, paleoclimatic and paleoceanographic factors. However, although these factors have a regional extent, local parameters can cause a significant variation in lithology and geochemical quality of the sediments. The main depositional periods of organic-rich sediments onshore Europe were studied, in order to explain and predict the accumulation of such rocks. It was found that simple paleogeographical and paleoclimatic models can explain sufficiently both the distribution and local variation of organic-rich rocks in the European basins. During the Cambro-Ordovician the Baltic Sea was an enclosed marine basin, where the Alum Shales accumulated. In the Silurian, organic-rich graptolite beds were deposited at the northern continental shelf of Gondwana, which was located at the South Pole, whereas a different type of marine black shales accumulated at the Baltica continent that lied at the Tropics. The Lower Carboniferous black shales were deposited within an elongated trough that existed in northern Europe, which at that time was still in the Tropical zone, with significant variations in their properties from one basin to another. Following the Variscan orogeny, intramontane lakes were formed along a SW-NE trend in Central Europe, where extremely rich lacustrine black shales were deposited during the Early Permian.

During the Triassic, no major organic-rich rocks were deposited in Europe, except for the Black Limestones in south-eastern Europe. At the beginning of the Jurassic, extensive rifting started to break-up the Pangea continent and the Tethys Ocean became a topographic “cul-de-sac”. Southern Europe was located at about 25°-30° N, at a geographical location conducive to monsoons. Rich Lower Jurassic black shales were deposited in the rift basins. A continuous series of black marls and shales accumulated throughout the Late Jurassic and Cretaceous in southern Europe, at the western edge of Tethys. Finally, within the Oligocene Paratethys Ocean, thick black shales were deposited as a result of isolated basin anoxia.

Geochemical studies of the most important organic-rich rocks in Europe were carried out and revealed a significant lateral variation in lithology and source rock quality of time-equivalent formations. Paleozoic and Mesozoic black shales show important changes from one location to another, indicating that detailed studies of these rocks are necessary to decipher the most pro

The yield of gas from black shales in Europe, as well as their content in sulphur were also studied in order to further determine their unconventional petroleum prospectivity. The highest yields of shale-gas were found in lacustrine black shales, with Type I kerogen.

Further modelling of the depositional conditions of European black shales can reveal the detailed areal extent and the kerogen type of the organic-rich sediments, as well as their European-wide correlation.

NOTES

Tuesday 13th September

Organic Carbon in Cenozoic Arctic Ocean Sediments: Origin, Paleoenvironment, Burial, and Source-Rock Potential

Ruediger Stein, *Alfred Wegener Institute for Polar and Marine Research, 27568 Bremerhaven, Germany*

In the modern (Quaternary to Neogene) „glacial“ Arctic Ocean organic-carbon (OC) accumulation is predominantly controlled by terrigenous (riverine, sea-ice- and current-controlled) input whereas increased primary production or increased preservation under oxygen-deficient conditions are of secondary/local significance. On the basis of sediment thickness obtained from acoustic profiles, AMS^{14}C-dated sediment cores and OC data, Stein and Macdonald (2004) put together a first-order estimate of OC burial in the Arctic marginal seas and the central Arctic Ocean for the Holocene time interval (Fig. 1; for data sources and references as well as background and limitations of estimates see Stein and Macdonald, 2004). The average Holocene OC burial rates vary widely between the different marginal seas and the central Arctic Ocean. In total, about 11 x 10^6 t y^{-1} of OC have been buried annually in the entire Arctic Ocean. Based on the origin of the OC, the OC burial rates can be divided into terrigenous and marine proportions. Whereas terrigenous OC is predominant in the sediments from the Beaufort, East Siberian, Laptev and Kara seas as well as the central Arctic Ocean, marine OC is much more important in the Chukchi Sea and, especially, the Barents Sea. These differences are related to different environmental situations, i.e., differences in river discharge, sea-ice cover, warm-water inflow, and primary production (Fig. 1; Stein and Macdonald, 2004; Stein, 2008).

In the (late Cretaceous to) Paleogene „preglacial“ central Arctic Ocean, OC accumulation was controlled by very different processes, as known from recent studies of the 430 m thick sequence of upper Cretaceous to Quaternary sediments that has been drilled in the central Arctic Ocean on Lomonosov Ridge near 88°N during the Integrated Ocean Drilling Program (IODP) Expedition 302 or „Arctic Coring Expedition (ACEX) (Fig. 2; Backman, Moran et al., 2006). The lower 230 m of the ACEX sequence consist of unique, very dark gray biosiliceous oozes and mudstones (“black shales“ in a broader sense) of Campanian and Paleogene (late Paleocene to middle Eocene) age, which are distinctly enriched in organic carbon reaching values of about 1 to 14% (Fig. 3; Stein et al., 2006; Stein, 2007). Significant amounts of the organic matter preserved in these sediments is of algae-type origin and accumulated under anoxic/euxinic conditions in an ocean basin relatively isolated from the world ocean at that time (Fig.2). During the middle Eocene, OC accumulation rates were an order of magnitude higher than those determined for modern central Arctic Ocean sediments.

Detailed data on the source-rock potential of these black shales indicate that most of the Eocene sediments have a (fair to) good source-rock potential, prone to generate a gas/oil mixture (Fig. 3). The source-rock potential of the Campanian and upper Paleocene sediments, on the other hand, is rather low. The presence of oil or gas already generated in-situ from the Campanian and Paleogene ACEX sediments at this part of Lomonosov Ridge, however, can be ruled out due to the immaturity of the ACEX sediments. If these sediments are buried more deeply, however, in-situ hydrocarbon formation is possible. This situation might occur in the more southern part of Lomonosov Ridge closer to the Eurasian continental margin, where sedimentation rates are significantly higher. The results of this study does also not mean that in the underlying deeper (Mesozoic) sedimentary rocks from the Lomonosov Ridge belonging to the rifted continental crustal block of the Eurasian continental margin, hydrocarbons could not have been generated (Stein, 2007, 2008 and references therein).

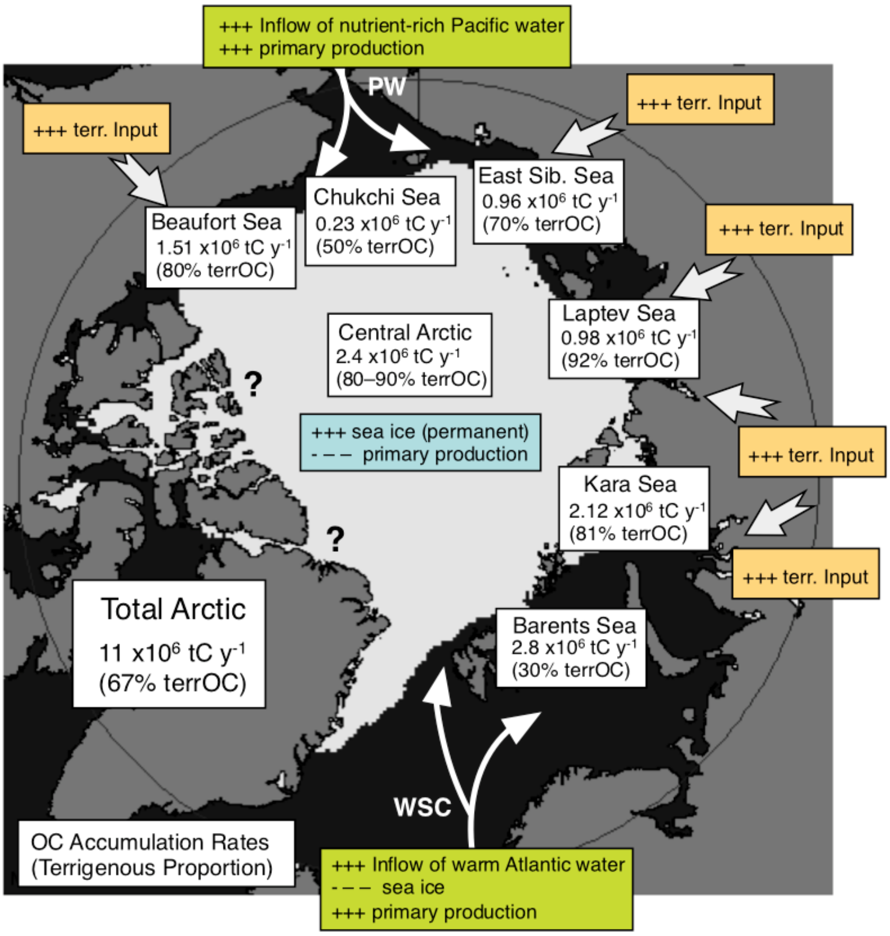

Fig. 1. Average Holocene burial rates (10^6 t y^{-1}) of organic carbon (OC) and proportions of terrigenous OC over the marginal seas and basins of the Arctic Ocean (based on Stein and Macdonald, 2004). Base map with average sea-ice cover (September 1979-2004) according to Maurer (2007; http://nsidc.org/data/atlas/). Figure from Stein (2008).

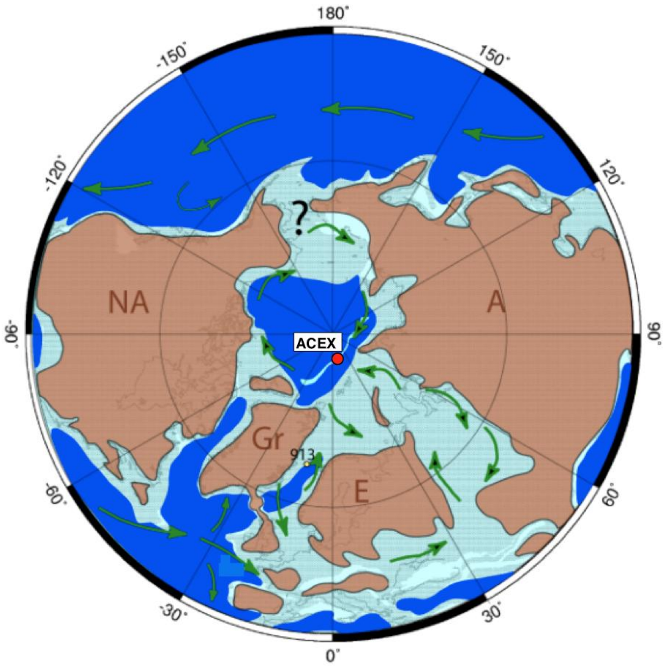

Fig. 2. Map showing a paleogeographic reconstruction of the High Northern Latitudes around 50 Ma and the location of the ACEX drill site on Lomonosov Ridge (from Backman, Moran, et al., 2006).

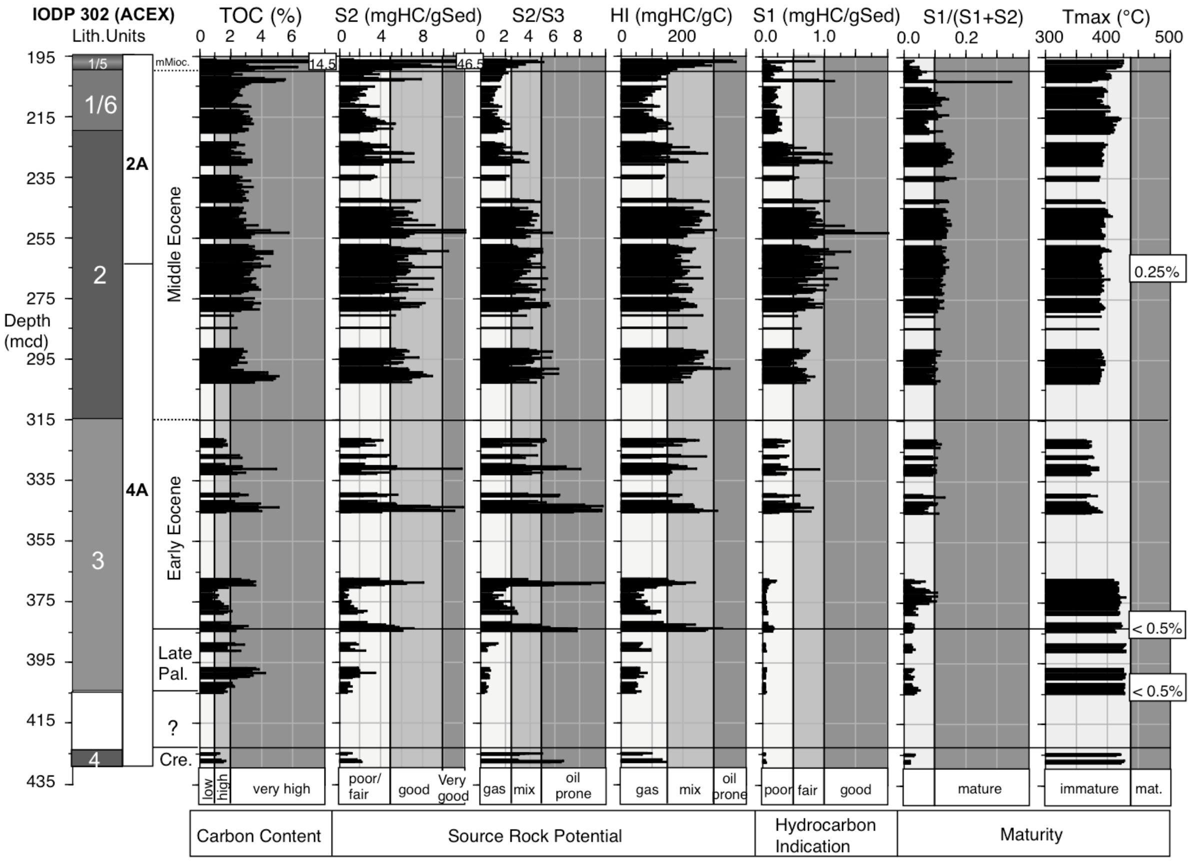

Fig. 3. Total organic carbon (TOC) content and Rock-Eval parameters S1, S2, S3, S2/S3, S1/(S1+S2), hydrogen index (HI), and T_{max} determined in lower 230 m of the ACEX drill site, and interpretation in terms of source-rock potential, hydrocarbon indication, and maturity according to Peters (1986). Numbers in the Tmax record are vitrinite reflectance values. Left, the stratigraphy and the lithological units are shown (Backman, Moran, et al., 2006). Figure from Stein (2007).

NOTES

Petroleum Generation Geochronology and Oil Fingerprinting Using Platinum, Palladium, Osmium and Rhenium: Implications for Petroleum System Modelling

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The past decade has shown that the rhenium-osmium (Re-Os) geochronometer in organic-rich marine and lacustrine sedimentary rocks can provide, not only depositional ages, but also the osmium isotope ($^{187}Os/^{188}Os$) composition of the water column depositing the sediment. These studies have shown that the Re-Os organic-rich sedimentary rock system remains undisturbed by the effects of hydrocarbon maturation and low-grade metamorphism, and therefore the Re-Os geochronometer can be applied to organic-rich sedimentary units through the entire geological rock record. Rhenium and Os are organophilic and are preferentially bound within the kerogen fraction of the organic matter in sedimentary rocks and within the asphaltene fraction of oil. The Re and Os isotopic compositions of asphaltene have also been used to determine the timing of petroleum generation from a source rock. The $^{187}Os/^{188}Os$ composition of petroleum at the time of generation (Os_g) reflects that of the source rock. In addition to the enrichment of Re and Os in petroleum, Platinum (Pt) and Palladium (Pd) are also abundant and combined with the Os_g of petroleum provide a novel inorganic technique to identify the source rock. We demonstrate the applicability of this method in the well-understood United Kingdom Atlantic Margin (UKAM) petroleum system and the West Canadian Oil Sands (WCOS), for which the source is highly debated.

The UKAM oils are found in a series Devonian to Miocene rift basins situated between the West Shetland Platform and Faroe Islands. Petroleum reservoirs are found in Devonian / Carboniferous, Jurassic and Paleogene sediments as well as fractured, weathered basement. The known major petroleum source within the UKAM is an Upper Jurassic marine shale (Kimmeridge Clay Fm. equivalent). Rhenium-Os petroleum geochronology within the UKAM yields an age of 68 ± 13 Ma, which is indistinguishable from published basin models and Ar-Ar dating. Furthermore, the Os_g and Pt/Pd values of these oils are indistinguishable from those of the known Upper Jurassic source rock demonstrating that Os_g and Pt/Pd values can be used to identify oil source units.

At present there is no consensus on the source of the WCOS, however, the Upper Devonian Duvernay, Devonian / Mississippian Exshaw and Lower Jurassic Gordondale Fms. have all been proposed as possible source units. Comparison of the Pt/Pd and Os_g values of the WCOS with the three potential source units suggests that the dominant source unit is the Jurassic Gordondale Fm. with only minor inputs from the Devonian-Mississippian Exshaw Fm. Unlike traditional organic geochemistry, Pt/Pd and Os_g fingerprinting is not rendered ineffective by high-levels of biodegradation, allowing oil source correlation in previously unsuitable petroleum systems and the deduction of migration pathways. Thus, combining Re-Os geochronology, Os_g and Pt/Pd permits the establishment of both the spatial and temporal constraints on petroleum systems and therefore provides a significant new tool for petroleum system exploration, development and research.

NOTES

Beyond Orgas- BP's New Predictive Model for Biogenic and Thermogenic Gas Expulsion from Source Rocks

Mark Osborne, Tony Barwise, *BP Exploration, Sunbury, UK.*

BP's 'Orgas' kinetic scheme, was created in the 1980's-early 1990's to predict the oil and gas volume expelled from different source rock organofacies[1,2,3]. The global kinetic model assigned kinetic parameters based on gross depositional environment and stratigraphic age- very useful in areas of low geochemical knowledge including frontier exploration. The published scheme has been implemented in most commercially available basin modelling tools, becoming widely used throughout the petroleum industry to the present day.

Recent production from unconventional gas plays and integrated technical studies have provided a flood of new information and insights about source rocks and petroleum expulsion. In light of this data, BP has made improvements to the Orgas scheme to provide enhanced pre-drill predictions of the volume, composition and physical properties of expelled petroleum fluids. This information is important for understanding the likely quality, value and volume of petroleum fluid that may be present in a basin or prospect, for both conventional or unconventional play types.

With reference to the modelling of gas expulsion, the modifications to our proprietary scheme fall into three main categories:

1) Modelling of both biogenic (bacterial) and thermogenic gas generation and expulsion. Biogenic and thermogenic gas should not be modelled separately- they are part of the continuum of fluid types that are generated during burial of most source rocks (Fig 1).
2) A revised model for gas adsorption and retention. The new model is critical for the correct evaluation of gas in place in shale gas plays.
3) Prediction of the isotopic composition of the expelled gases. As biogenic and then thermogenic gas is generated and becomes mixed in the source, the expelled gas isotopic composition systematically evolves in a predictable manner (Fig 2).

Collectively these three modifications produce more realistic assessments of gas expelled from (and retained within) source rocks

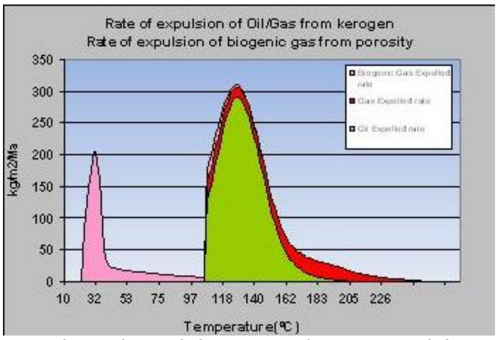

Fig. 1. Biogenic and thermogenic gas expulsion rates versus source rock thermal stress

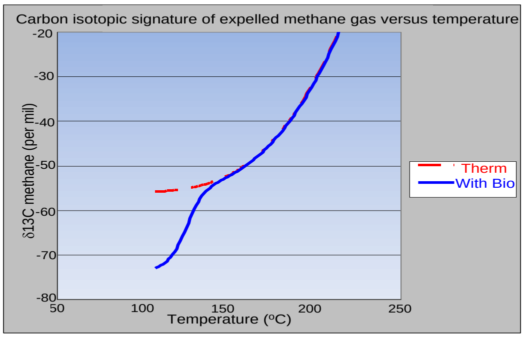

Fig. 2. Methane carbon isotopic signature versus source rock thermal stress

NOTES

Fundamental Controls on Oil Generation from Cretaceous–Tertiary Coaly Source Rocks

Richard Sykes, *GNS Science, New Zealand*

Coaly (or terrestrial) source rocks are generally considered gas-prone, yet humic coals and coaly mudstones have sourced medium–large (10^7–10^9 bbls) black oil accumulations in several Cretaceous-Tertiary basins of Australasia and Southeast Asia. Coaly organofacies are more heterogeneous than their marine and lacustrine counterparts; the paleoecological controls on their gas:oil ratios are more diverse; and their maturation characteristics are fundamentally different. These differences have not always been fully appreciated and, as a result, methods and guidelines developed in the main for marine and lacustrine source rocks commonly produce misleading or erroneous results for coaly source rocks. On the other hand, a more customised approach to research of coaly source rocks in New Zealand basins over the past 20 years has led to a much improved understanding of the underlying controls on their oil generation characteristics and, with it, wider industry acceptance of oil potential in basins that have hitherto been frequently dismissed as too gas-prone.

Oil generation from New Zealand Cretaceous-Tertiary coaly source rocks is controlled by multiple bio- and geo-chemical factors. To identify the more influential and their respective effects on oil generation, a comprehensive research approach was adopted in which (1) all samples were lithology-based and positioned within a robust framework of geological rank [provided primarily by the Suggate rank scale, Rank(S_r)]; (2) organic petrography was integrated with bulk and molecular geochemistry (e.g., Rock-Eval and thermal extraction-pyrolysis-gas chromatography); and (3) the compositions and properties of correlative crude oils, which are typically waxy and highly paraffinic, were also taken into account.

New Zealand coaly source rocks comprise a continuum of organic carbon contents from <1% to c. 85%, and which, for practical purposes, can be divided into three broad lithologies: coaly mudstones (TOC <20%), shaly coals (TOC 20–50%) and coals (TOC >50%). All parts of the continuum above TOC ~3% have good to excellent petroleum potential (i.e., S2 >5 mg HC/g rock). Coals, shaly coals and coaly mudstones each contribute to the petroleum potential of kitchen areas in proportion to their respective genetic potentials (S1+S2) and net volumes, and therefore all three lithologies should be included in source rock assessments.

The three coaly lithologies display similar ranges of hydrogen index (HI) of c. 200–450 mg HC/g TOC near the onset of oil expulsion (see below). This reflects broadly similar, mixed gas- and oil-prone to oil-prone kerogen throughout the source rock continuum, but with important variation related to peat mire facies and synsedimentary marine influence. Maceral assemblages typically comprise >80% vitrinite, with small to moderate amounts of inertinite and liptinite. However, non-volatile paraffinic oil (nC_{15+}) potentials of all three lithologies correlate most strongly with the abundance of leaf-derived liptinites (i.e., cutinite and cutinite-derived liptodetrinite), despite these typically constituting <25% of the total organic matter. Leaf biomass and hence paraffinic oil potential tend to be greatest in thin, planar mire coals and their associated coaly mudstones, the formation of which is favoured by high rates of accommodation increase, such as in syn-rift sequences. In contrast, raised mire coals tend to be more gas condensate-prone owing to their generally lower contents of leaf biomass.

Stratigraphic variations in coal sulphur content (and other marginal marine indicators) indicate widespread and ever-changing synsedimentary marine influence within New Zealand coal-bearing sequences. Brackish conditions within the peat-forming environment significantly enhance kerogen quality, increasing HI by as much as 100 mg HC/g TOC. However, they do not exert a major, direct control on paraffinic oil potential, other than facilitating the expulsion of paraffinic oil by increasing the HI.

The generation of non-volatile paraffinic oil (nC_{15+}) commences at c. Rank(S_r) 9 (R_o 0.55%, T_{max} 425°C), whereas the generation of volatile paraffinic oil (nC_6–nC_{14}) commences slightly later at c. Rank(S_r) 10 (R_o 0.65%, T_{max} 425°C). Oil generation kinetics are also affected by kerogen type, with modelling results at geological heating rates showing that abundant leaf biomass and strong marine influence can each reduce the temperatures required for oil generation by up to c. 20°C, resulting in significantly earlier and shallower expulsion of oil. Micro-scale sealed vessel pyrolysis of representative coals showed they were generally capable of expelling undersaturated black oil up to at least 70% kerogen transformation. Thus, black oil prospectivity should be enhanced where kitchen area maturities are constrained to below about 70% transformation, limiting secondary cracking and the total volumes of later gas charge. Paraffinic oil potential is largely exhausted by Rank(S_r) 16 (R_o 1.6%, T_{max} 490°C), signifying the base of the oil window.

The New Zealand Coal Band displays a pronounced, rank-related increase in HI, typically of up to 110–150 mg HC/g TOC, from lignites [Rank(S_r) <4] to about the onset of oil expulsion (Fig. 1). This increase (like those of other coal bands) is attributed to structural rearrangement of the coal macromolecular matrix related to aromatisation, which also results in the formation of new higher energy bonds. The implications are problematic in that the established guideline of selecting immature samples for analysis would result in low values of HI, indicating almost entirely gas-prone kerogen. Moreover, kinetics-based predictions of oil generation would be too early or too shallow. Instead, samples of rank near the onset of oil expulsion are more appropriate in that they provide the effective HI values (for assessing kerogen quality and expulsion efficiency) and kinetic parameters relevant to the critical threshold of expulsion.

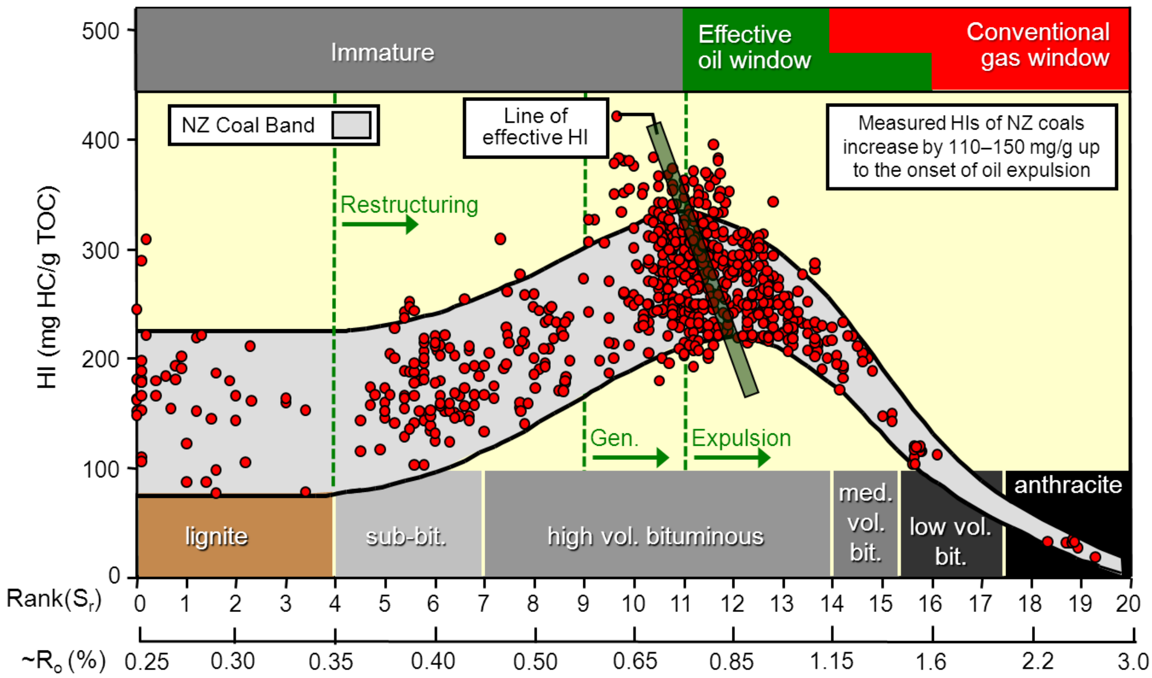

Figure 1. The maturation pathway of the New Zealand Coal Band shown with respect to changes in Hydrogen Index (HI) with increasing Suggate coal rank [Rank(S_r)], vitrinite reflectance (R_o) and ASTM rank.

Recent application of these methods and concepts to Miocene coaly source rocks of the Kutei Basin, Indonesia, suggests they are likely to be relevant to many Cretaceous-

Tertiary terrestrial-sourced basins of the Australasia-Southeast Asia region, albeit probably with local variations and differences.

NOTES

Quantitative Evaluation of TOC, Porosity and Residual Gas Content in a Gas Shale Play Using Petroleum System Modelling

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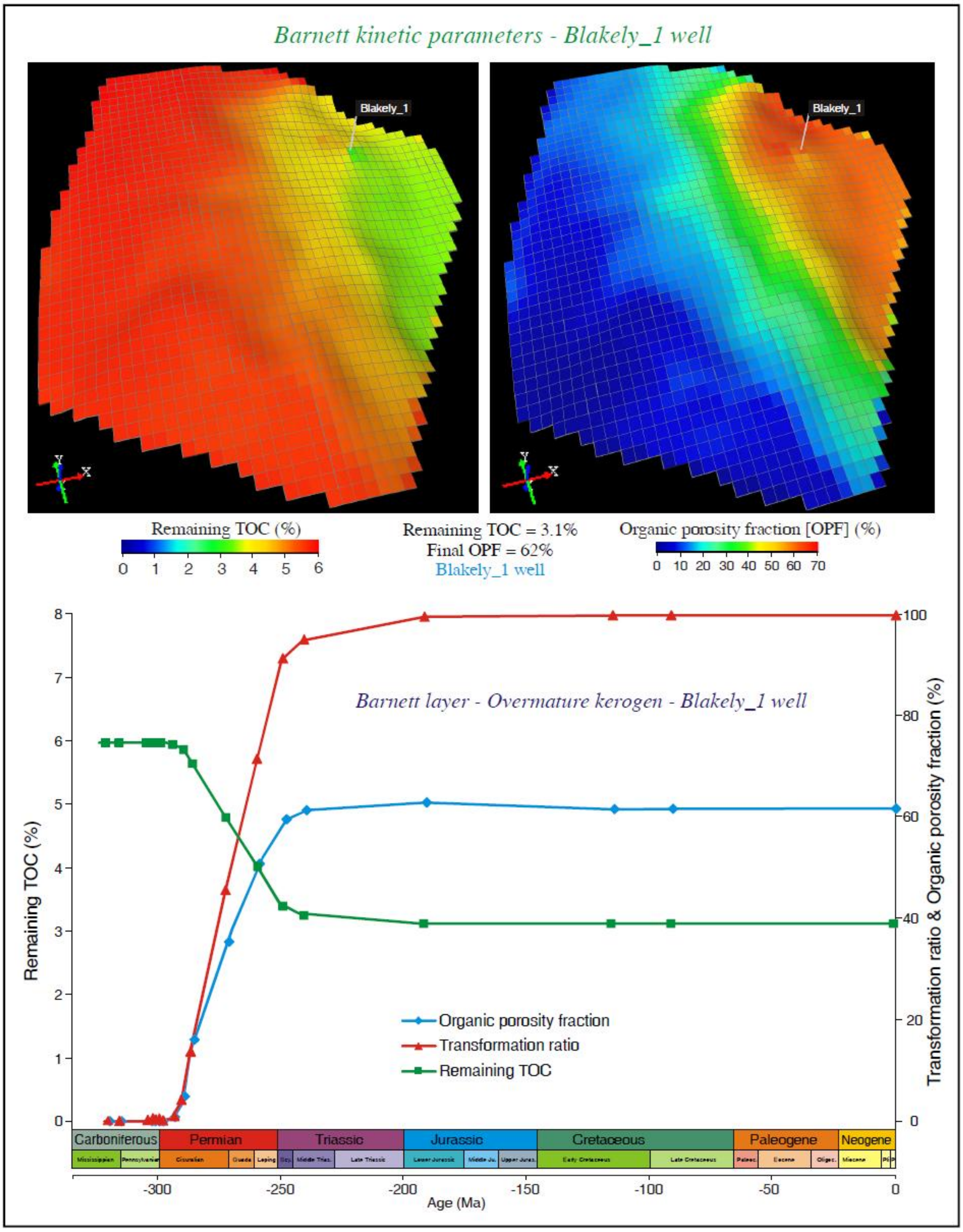
Estimation of Total Organic Carbon (TOC) content at both present-day and prior to thermal maturation is a key-issue in gas shale play evaluation. The distribution of the original organic carbon content has indeed a direct impact on the potential volume of gas generated within the rock at a given thermal maturation level. This parameter also has a significant contribution to the gas-in-place volume, as the conversion of organic matter into hydrocarbons creates additional porosity in the shale where residual gas can be stored. Present-day TOC distribution, which results from both original TOC and thermal maturity distributions, is therefore an important criteria for the estimation of free vs. adsorbed gas, which is part of the decision scheme for the gas production design.

The close relationships between original TOC, present-day TOC, shale porosity and residual gas yield were quantitatively investigated by means of petroleum system modelling. Accordingly, a 3D basin model of the Mississippian Barnett Shales in Texas (USA) was build and calibrated for thermal maturity on Rock-Eval and vitrinite reflectance data. A specific compositional kinetic approach was used to simulate both hydrocarbon generation and cracking, and ensure a complete organic carbon balance within the shaly source rock formation. Furthermore the model was able to compute both TOC variations and organic contributions to porosity through time, as a result of both thermal cracking and rock property changes. Based on observed TOC values from various wells, a distribution map of original TOC was performed by inversion of basin simulations results. We found that depositional TOC from 5 to 8 % were consistent with observed TOC values and maturity distributions in the Barnett shale. In addition, the contribution of organic matter cracking to the shale porosity varied from 0 % in immature zones of the basin, to nearly 65 % in mature zones (Fig. 1). So more than 2/3 of the shale porosity would be from organic origin in productive areas of the gas shale play.

Fig. 1: Remaining TOC and organic porosity fraction distributions in the Barnett shale.



NOTES

Source Rocks as Petroleum Reservoirs: Lessons from the North America Shale Experience

Harris Cander, *BP America, Houston, Texas*

The explosion of shale source rock plays in North America has provided several insights into our fundamental understanding of source rocks. Although many shales have been tested, the most successful plays are usually associated with periods of widespread source rock deposition across multiple continents. These were periods of relatively warm global conditions with sluggish ocean bottom water circulation, including the mid to late Devonian (cf. Marcellus, Woodford, Muskwa-Duvernay), the Kimmeridgian (Haynesville), and the Cenomanian-Turonian (Eagle Ford). The most prolific fairways in these formations often overlie or are associated with carbonate environments that are distal to major delta systems. These environments have relatively low dilution by terrigenous clastic material, resulting in a clay-poor, brittle, and TOC-rich rock.

Perhaps the most important lesson from the North America shale experience is that many source rocks retain (i.e. *trap*) large volumes of petroleum, leaving comparatively less petroleum available for migration out of the source rock. Prior to the shale revolution, many of the existing kinetic models did not fully take into account the three sites of petroleum occurrence in a source rock: adsorption sites in the organic matter, porosity in the organic matrix, and porosity in the inorganic matrix (see abstract by Osborne and Barwise, this conference). Data from commercial source rock plays show that petroleum saturations are often greater than 60% when *initial* TOC exceeds 4% (i.e. residual TOC > 2%). Given typical porosities of 5-10% and thicknesses of 50 meters, volumes of petroleum retained in the source rocks often exceed 7 mmboe per square kilometer. These volumes represent a significant proportion (>20%) of total generated and expelled petroleum calculated from commercial kinetic models. A corollary to this concept is that substantial migration losses occur within the source rock as retained petroleum, with correspondingly smaller migration losses in the overburden.

Existing kinetic models of petroleum generation have proved quite useful for predicting changes in fluid composition, phase, and product value in source rock plays. Fluid compositions can be predicted given knowledge of the thermal stress state of the source rock in many of the plays, including the Marcellus, Woodford, Barnett, and Eagle Ford plays. Boundaries between fairways of viscous oil, volatile oil, wet gas, and dry gas are often sharp and parallel to contour lines of thermal stress (often measured by vitrinite reflectance). Isotopic compositions of methane in gas fairways and GOR in liquid-rich fairways can be correlated with thermal stress. In cases where fluid composition is out of equilibrium with the thermal stress state of the source rock, the reason can sometimes be traced to production from overlying or underlying units that contain migrated petroleum.

The correlation between thermal stress and fluid composition in source rocks has several important implications. First, the majority of the petroleum retained in the source rocks was generated *in situ* with limited lateral migration in the source rocks. Secondly, the source rocks are their own trap and structural or geometric closures are often not necessary. Once generation stops, petroleum is no longer pushed from the source rock and the trapping mechanisms are adsorption/absorption forces and micro-stratigraphic traps resulting from highly variable capillary entry pressures in heterolithic, low-permeability rocks. The trapping mechanism can be as effective in synclines as in structural traps. Petroleum saturations are more often a function of TOC and maturity rather than structural position such that synclines can be as saturated as structural highs. As a consequence of the previous points, the composition of retained petroleum in source rocks is usually closer to an instantaneous product over a narrow thermal stress range rather than a cumulative product from expulsion and migration over a large range of thermal stress.

The predictability of fluid composition coupled with the abrupt phase boundaries has important implications for acreage capture strategies. Companies seeking dry gas fairways can be less precise in acreage capture than companies seeking low viscosity oil or high yield gas. Dry gas fairways span a large range of thermal stress (Ro 1.5 – 3.0%) and thus wide swaths of acreage can be captured in which there is comparatively little variation in composition, fluid viscosity, and BTU content (i.e. value!). In contrast, petroleum fluid properties change rapidly over the vitrinite reflectance range of 0.8% to 1.3% that brackets low viscosity oil and high yield gas. Companies in search of low viscosity, high GOR oils or high yield gas must be far more surgical in their acreage capture. Sudden and large changes in fluid viscosity and composition and commerciality of wells should be expected over relatively short distances.

Over-pressure is a critical component for commerciality of some, but not all, source rock plays (ex: Haynesville and Eagle Ford shales). High over-pressure benefits production in both gas and liquid plays, although some of the commercial benefit is offset by higher drilling and completion costs. In gas fairways, over-pressure increases the volume of gas per unit rock. In oil plays, high reservoir pressure maintains gas in solution and provides reservoir pressure support during depletion. As well, over-pressure reduces effective stress and preserves permeability and porosity.

Several authors have attributed the origin of over-pressure in source rocks purely to petroleum generation, expulsion, and cracking (cf. Meissner, 1974; Law, 1984). However, the widespread occurrence of over-pressure both above and below many of the North American shale source rock intervals strongly suggests that petroleum generation and expulsion are not the main cause of over-pressure in these basins.

Basin modeling performed for the Anadarko and Arkoma basins of the U.S. mid-continent, and the Maverick Basin in Texas reveals that much of the regional over-pressure resulted from disequilibrium compaction during rapid burial associated with foreland subsidence (Late Paleozoic in the mid-continent and Cretaceous-Tertiary in the Maverick). The top of over-pressure in these basins is often in the TOC-poor, clay-rich strata far above the main source rock.

Because it is the foreland phase of subsidence and burial that triggers both disequilibrium compaction and source rock maturation, generation of over-pressure and petroleum are often coincident and their effects on total over-pressure, effective stress, and rock mechanics can be difficult to differentiate. Natural fractures and veins are common in some of the North American source rocks but their origin may have less to do with petroleum generation, expulsion, and cracking and more to do with regional stresses or large changes in effective stress that accompany burial and exhumation.

NOTES

Carboniferous Mudstone Variability and Implications for Shale Gas Targets

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Fine grained successions enriched in organic matter (>1% TOC) are common in the subsurface. In the US, Carboniferous shale gas plays, such as the Barnett Shale in Texas, are the focus of significant economic activity but exploration in the UK is still in the earliest phases, despite a number of prospective intervals in Carboniferous successions. Understanding the fundamental controls on sedimentation and the preservation of organic matter has significant implications for effectively exploring for unconventional shale gas plays and conventional source rocks, in particular identifying the spatial and temporal distribution of organic matter. This research uses a multidisciplinary approach; thin section analysis (optical and electron optical) and whole rock geochemical methods (XRF, XRD and Total Organic Carbon) to identify the mudstone lithofacies and interpret the range of processes delivering sediment to the basin.

Spatial variations in lithofacies are examined on a local and a regional scale. Measuring multiple sections through one exposure documents the local spatial changes over distances of tens of metres. Time equivalent successions, containing a key biostratigraphic marker horizon, are traced along a 'proximal' to 'distal' transect from north to south in the Pennine Basin, UK over a total distance of 170km.

A comprehensive analysis of a 'distal' succession (Oakamoor in North Staffordshire) revealed four main lithofacies present in three 3 m-thick sections; (1) homogeneous, (2) pelleted, (3) carbonate-rich and goniatite-bearing, and (4) carbonate-rich and bedded mudstones (Figure 1). Lithofacies are organised into packages of 10-80cm in thickness and most extend, with variations in thickness, across adjacent sections over distances of 45 m. However, the lithofacies packages can only be identified from thin section analysis and, in this location neither a systematic organisation or repeated pattern of lithofacies is observed. The lithofacies suggest different transport and depositional processes, for example the pelleted and homogeneous lithofacies indicate deposition from suspension settling, whereas some of the bioclast-bearing and bedded mudstones are interpreted as the products of turbulent flows which transported sand and silt-sized grains and larger bioclasts.

Tens of kilometres north of the distal succession, at a location in Yorkshire, muds were deposited closer to the supply of siliciclastic sediment and therefore the mudstones contain a higher proportion of silt-sized quartz and feldspar. There are lithofacies common to the locations in Staffordshire and Yorkshire, in particular the homogeneous and pelleted mudstone lithofacies. The northern most section, near Brough in Cumbria, has a much higher carbonate content and initial observations show that homogeneous lithofacies dominate. Changes in the dominance of lithofacies in different parts of the basin clearly result from the relative importance of different physical sediment transport processes delivering and dispersing sediment, such as an increased presence of bedded sediments where flows are actively bringing sediment into the basin.

Organic carbon abundances vary between lithofacies and location. Three of the main lithofacies observed at Oakamoor have high Total Organic Carbon (TOC) abundances; carbonate-rich and goniatite-bearing mudstone (4.5-5% TOC); pelleted mudstones (1-5% TOC); and carbonate-rich and bedded mudstones (2-8.5% TOC). The lowest TOC is observed in the homogeneous lithofacies (0.2-2% TOC). At Pule Hill, TOC is highest in the pelleted mudstones (2-6.5% TOC), and lower in both the homogeneous (1.5-4.5% TOC) and bedded (1.5-2.5% TOC) mudstones. Overall, higher TOC would be expected in the more distal locations where there is less dilution by siliciclastic material and higher productivity would be predicted However, the pelleted mudstone lithofacies have similar TOC abundances in proximal and distal settings. Ongoing research is investigating the reasons for these spatial and temporal changes and the significance of the variations observed in the distribution and preservation of organic matter.

As interest in shale gas targets continues to grow, understanding the transport and depositional mechanisms of fine grained sediment and characterising the lithofacies variability (reflecting the different processes and depositional environments) becomes increasingly important for predicting the location and abundance of prospective successions.

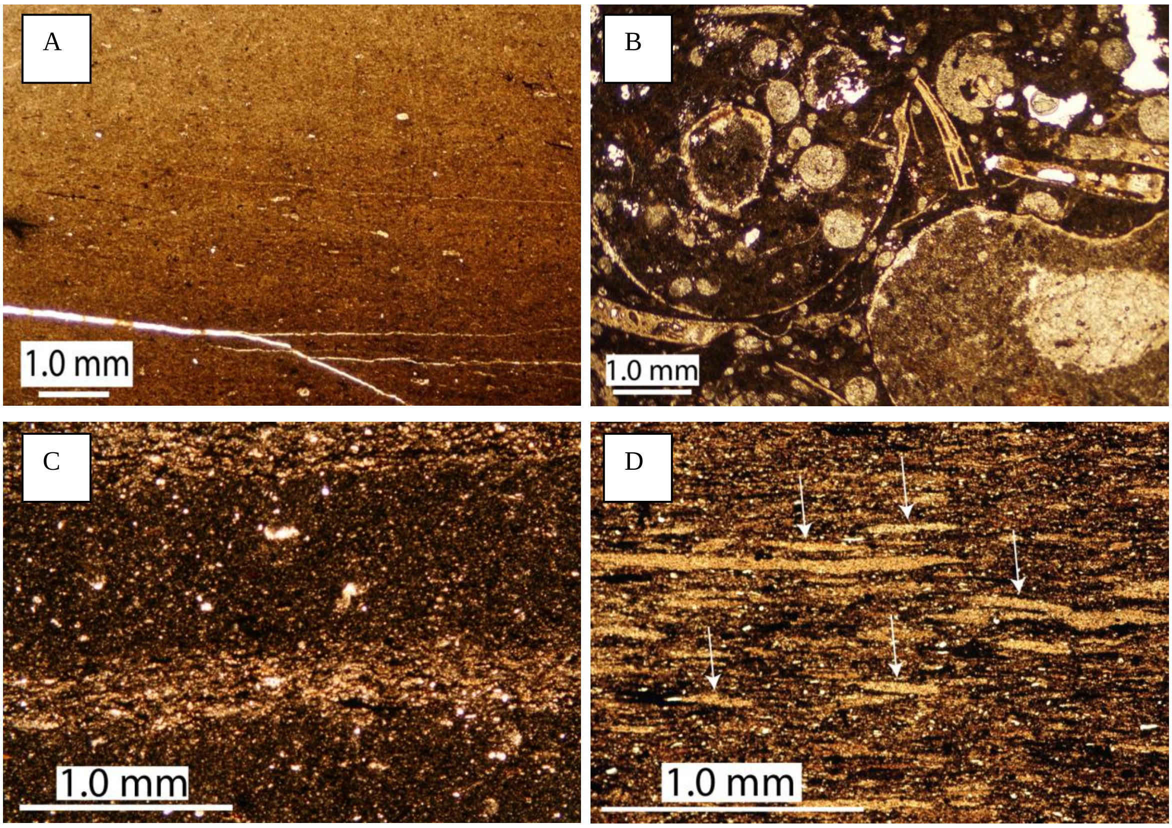

Figure 1: Examples of the different lithofacies present at Oakamoor, Staffordshire. A: Homogeneous. B: Carbonate-rich and goniatite-bearing. C: Carbonate-rich and bedded. D: Pelleted.

NOTES

Source Rock Mapping in Time and Space: The Silurian 'Hot Shales' of North Africa and Arabia

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Silurian organic-rich shales were the source of large amounts of hydrocarbons in northern Gondwana, including supergiant and giant fields in the Middle East and North Africa. They are generally enriched in uranium and can be identified easily in gamma-ray logs through their characteristic gamma-ray peaks. While these “hot shales” contain up to 17% TOC, their organic-richness and thickness vary strongly across the region. Detailed case studies in North Africa and Jordan have allowed compiling an integrated regional depositional model for the Silurian across North Africa and Arabia. Sedimentary events are similar in the two regions and exhibit clear proximal-to-distal trends.

Generally, two organically enriched horizons occur in the Silurian, termed the “lower hot shale” and the “upper hot shale”. The lower hot shale has been deposited during the early Llandovery during a major second-order sea-level rise following the melting of the late Ordovician glacial ice. The thickest and organically richest source rocks were generally deposited in palaeodepressional areas (Lüning et al. 2000a). Early Silurian palaeohighs lack the “lower hot shale” and instead were dominated by non-deposition or deposition of shallow marine/continental siltstones and sandstones.

Sedimentation of the “upper hot shale” occurred around peak sea level during the late Llandoverian and/or early Wenlockian and was limited to the distal parts of the shelf, in front of the prograding silty-sandy deltaic front (Lüning et al 2003, Lüning et al 2005). Additional organic rich horizons of Late Silurian age occur in the most distal parts of the northern Gondwanan shelf, e.g. in parts of Morocco and Turkey (Lüning et al 2000b).

A chronostratigraphic and sequence stratigraphic model was developed for the Silurian of region that allows improved predictions of source rock availability and quality. The model may be used to explain the various different facies stacking patterns and may help with facies trend identification.

NOTES

Stratification in Black Shales: Lamination or Thin-Bedding?

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Black shales are organic matter-rich, fine-grained sedimentary rocks. They are typically characterised by a ubiquitous, macroscopic stratification which, without further optical magnification or enhancement, appears as thin, parallel layering in hand samples.

In sedimentary rocks, a distinction between layering, i.e. stratification, produced by continuous vertical aggradation of sedimentary particles of varying composition and characteristics—lamination—and layering produced by sedimentation events separated by periods of erosion and/or nondeposition—bedding—can be made. Several definitions have been proposed throughout the years for 'lamination' and 'bedding'. Irrespective of the definition used, it is important to identify the type of layering because this reflects which depositional processes led to the development of layering in black shales. This information has important implications for interpretations of environments of black shale deposition and, therefore, for source rock prediction.

A petrographic study was carried out using Posidonia Shale Formation (Lower Toarcian) black shale samples from two wells located offshore The Netherlands in the Dutch Central Graben. These black shales exhibit a variety of depositional fabrics, sedimentary structures and textures that indicate dynamical energetic conditions at the time of deposition. They appear to have been deposited by bottom currents rather than settling from suspension. The studied black shales are characterised by normally graded thin-beds (< 10 mm thick) with erosional bases wherein cross-lamination is very common. The top of the thin-beds is often bioturbated.

These observations are in contrast with the traditional interpretation of the deposition of these black shales as having taken place under a stagnant, anoxic water column by suspension settling. The results highlight the need for more detailed sedimentological studies of black shales and underline the importance of multidisciplinary investigation of these lithologies.

NOTES

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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly