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Hydrocarbons in Space and Time

9-10 April 2019

The Geological Society, Burlington House, Piccadilly, London

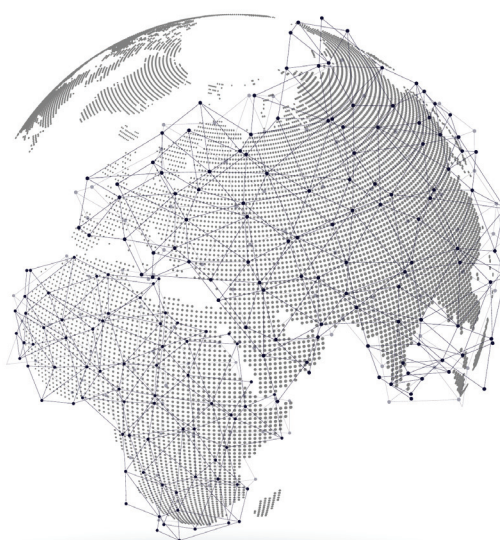**Convenors:**

Owen Sutcliffe
Halliburton

Frans van Buchem
Halliburton

Mark Houchen
Shell

Bruce Levell
Oxford University

Hannah Steaggles
BP

Mike Simmons
Halliburton

PROGRAMME AND ABSTRACT VOLUME

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	Finish

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# Oral Presentation Abstracts
(Presentation order)

Session One:
Exploration Economics

INVITED SPEAKER: Petroleum Group 'Hydrocarbons in Space and Time' Conference: Abstract for oral presentation Conventional oil and gas exploration – five trillion barrels and counting

Dr Andrew Latham,
Vice President Exploration, Wood Mackenzie

Exploration for conventional oil and gas resources has discovered around five trillion barrels over the past century (Figure 1). More recently, since around 2000, the industry has focused on two resource themes commercialised by new production technologies. Offshore, it is now discovering the majority of new volumes in deepwater locations. Onshore, the industry is overwhelmingly drilling in the tight reservoirs and source rocks of the unconventional plays.

Figure 1. Oil and gas volumes by discovery year
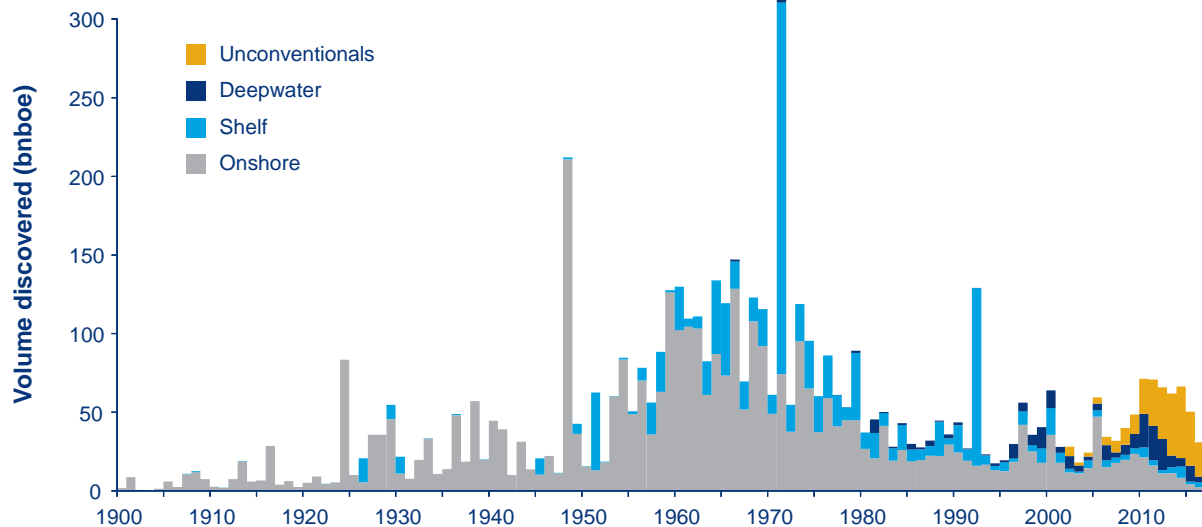
Source: Wood Mackenzie

Conventional explorers are finding the majority of oil and gas discoveries in new plays, including new basins. More than half of all volumes discovered over the past decade has come from new frontier plays yet to produce their first barrels at the date of exploration well completion.

Since 2000, the largest new conventional oil play is the pre-salt of Brazil's Santos Basin. Cumulative discoveries here now exceed 30 billion barrels. Next largest are several new oil plays each holding volumes less than 10 billion barrels so far. Examples include Alaska's Nanushuk sandstone, deepwater Ghana, deepwater Guyana, and the Jurassic Norphlet play in the US Gulf of Mexico.

Three giant new conventional gas plays have each added over ten billion barrels of oil equivalent (bnboe) resource. These are Mozambique's Rovuma Basin, the eastern Mediterranean deepwater biogenic gas play spanning Israel, Egypt and Cyprus, and the deepwater gas play of Mauritania and Senegal.

The importance of new frontiers and early emerging plays makes extrapolation of exploration trends more difficult than is the case in established and mature plays. Whilst the industry will drill many unproven plays each year, only a handful will be successful and these will be impossible to reliably predict in advance of well results. Creaming curve trajectories for newly-proven plays are usually poorly constrained.

Annual conventional oil and gas discovery volumes have declined sharply since the oil price fall in 2014. The industry sharply reduced its exploration investment and has since been finding around 15-20 bnboe each year, versus 25-40 bnboe per year previously. This decline is a consequence of fewer wells drilled. Average volume discovered per exploration well has remained around 25 million barrels of oil equivalent per well.

The industry's future rate of exploration investment will be the primary determinant of yet-to-find volumes. Spending levels have not returned to their pre-2014 levels as oil prices have partially recovered. Capital discipline remains the watchword. Many companies see a diminished role for conventional exploration in the future, with few large players targeting 100% reserve replacement from new conventional discoveries. The Majors typically expect around 50% of new volumes will come from exploration.

At the current discovery rate, the next one trillion boe of conventional resources will take over 50 years to discover. This may be beyond the oil and gas exploration industry, much of which has a watchful eye on the coming energy transition. For explorers, this means much less appetite for very long-term sources of supply, such as the offshore Arctic. It might also mean greater emphasis on gas as a transition fuel.

NOTES:

INVITED SPEAKER: Geologic Variability, a Key Uncertainty in U.S. Oil and Natural Gas Production Projections

Dana Van Wagener and **Margaret Coleman**
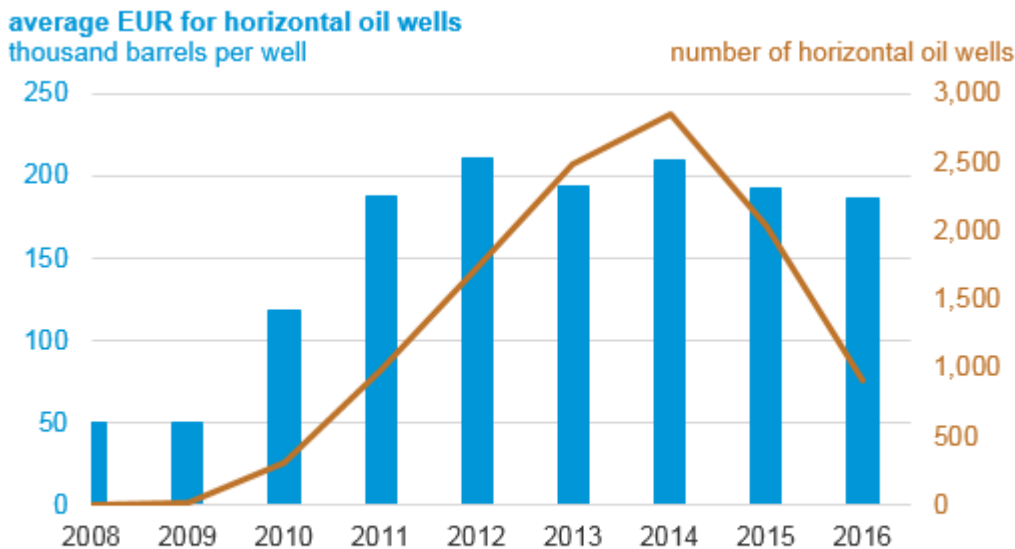*U.S. Energy Information Administration*

The following is an excerpt from the *Annual Energy Outlook 2018* (AEO2018) Issues in Focus article *Oil and Gas Natural Resources Technology*. Future growth in U.S. crude oil and natural gas production is projected to be driven by the development of tight oil and shale gas resources. However, a great deal of uncertainty surrounds this result. In particular, future domestic tight oil and shale gas production depends on the quality of the resources, the evolution of technological and operational improvements to increase productivity per well and to reduce costs, and the market prices determined in a diverse market of producers and consumers, all of which are highly uncertain. This analysis, which includes an example from the Eagle Ford in South Texas, provides background on the key assumptions underlying the projections for oil and natural gas production in the *Annual Energy Outlook 2018* (AEO2018).

Production profiles from currently producing wells provide the basis for calculating existing estimated ultimate recovery per well (EUR) and provide insight about the potential productivity of new wells drilled in the same play. In examining the trend of EURs in a play, the life cycle of development provides a good framework for analyzing the results. Geology, technology, and economic conditions specific to the area being developed also need to be considered. Using the example of the Eagle Ford, the following discussion illustrates the common trends affecting the EUR of a horizontal oil well in a particular play.

The development life cycle of a tight oil or shale gas play consists of four phases: (1) exploration and appraisal, (2) early development, (3) stabilization of production, and (4) maximization of recovery. Even though the play may have many producers with varying lease positions and specific operational objectives, the general pattern of the life cycle of a play follows this pattern. The length of each phase is largely determined by the quality and size of the resource, the availability of infrastructure and experienced personnel, and current market conditions during development.

Development of a play usually begins slowly as producers secure leases and start drilling to determine if oil can be produced from that play given current technology. If the areas of exploration are determined to be economically viable, drilling will speed up quickly. For example, horizontal oil drilling in the Eagle Ford increased rapidly in 2010 when the West Texas Intermediate (WTI) spot oil price averaged slightly less than $90 per barrel (in real 2017 dollars) and continued to increase through 2014 as the WTI spot price remained higher than $97 per barrel (Figure 1). At the same time, the average EUR per horizontal oil well increased from about 50,000 barrels per well in 2008 to more than 200,000 barrels per well in 2014 as producers targeted the most productive counties and improved extraction techniques and operations to increase the productivity of the play.

Figure 1. Average crude oil EUR and number of wells drilled in the Eagle Ford

average EUR for horizontal oil wells
thousand barrels per well

number of horizontal oil wells

Source: U.S. Energy Information Administration analysis of well level monthly production state administrative data provided by Drillinginfo, accessed August 2017.

The range of EURs across counties and within each county can be large. More than 70% of the horizontal oil wells drilled in the Eagle Ford from 2008–2016 were drilled in seven counties with mean EURs ranging from less than 150 to more than 350 thousand barrels per well.

When the WTI spot price dropped to $50 per barrel in the winter of 2014–2015, the number of horizontal oil wells drilled in 2015 and 2016 in the Eagle Ford slowed appreciably. The average EUR decreased slightly because continued drilling in the sweet spots resulted in diminishing returns as wells began to interfere with each other. Producers then reduced drilling in the less productive areas and continued to make operational improvements.

Not surprisingly, for many of the counties in Eagle Ford, the change in EUR over time looks similar to the change in EUR for the whole play. However, the life cycle of a play does not necessarily proceed equally across all counties. Thus, understanding the geology within a county is important to help identify the extent of sweet spots in the county, if any, to better reflect the productive potential as the county is drilled out.

As development of a tight oil or shale gas play continues, the EUR per well decreases. This relationship means that higher prices or significant reduction in costs are needed to spur an additional increase in drilling to maintain constant production levels in a particular play.

NOTES:

INVITED SPEAKER: Utilising a comprehensive E&P database to map historical drilling developments in the Middle East region

Matthew Turner
IHS Markit Global Limited

A large and extensive database was used to analyse drilling patterns in the Middle East. The researching and recording of exploration and production data began in the mid-1950s, data is compiled into separate databases covering North America, Canada and the rest of the world giving complete global coverage. The International Database contains data covering the whole of the globe including some parts of the conterminous United States and Canada. It contains information on nearly 800,000 wells covering over 30,000 fields, extracting hydrocarbons from some 68,000 reservoirs. The database holds information dating back to the first recorded oil well drilled outside the US; the Pechelbronn 1813 well was drilled in France in the Upper Rhine Graben close to the city of Strasbourg. The well was spudded in 1813 and was found to contain oil at a depth of around 100m within Tertiary strata. The longest well in the International Database is the Al Shaheen well which reached a total length of 12,290m making it the longest extended reach well ever drilled. The well was spudded in 2008 and targeted Cretaceous reservoirs. Since the drilling of the first well technological improvements have enabled deeper and longer wells to be drilled in more complex geological settings targeting formations that would have been considered impossible to access 100 years ago. As basins mature and regional knowledge is improved, deeper and deeper hydrocarbon plays are opened up for exploration and exploitation. By using this extensive database it has been possible to visualize the global exploration expansion from the relatively benign and shallow targets to the deeper frontier territories being explored today. Using mapping software such as ArcGIS and Kingdom the database can be used to map the expansion in exploration and development trends on a field, basin and at a regional level as well as giving insight into possible future target horizons. Furthermore this visualisation can show how a basin or region matures over time showing the evolution of production volumes at a formation level from the initial shallowest formations to the gradual targeting of the deeper more extreme formation horizons. Additionally, it is possible to see if and when a basin shifts from conventional exploration and production, to unconventional exploration and production, which is has been a global trend across many basins in recent years.

This paper/presentation concentrates on the development of exploration and production in the Middle East region including the following countries; Turkey, Syria, Lebanon, Israel, Saudi Arabia Jordan, Yemen, Oman, The United Arab Emirates, Qatar, Bahrain, Kuwait, Iraq and Iran. The first well drilled in the Middle East was the Dalika 1 well in Iran, it was spudded in 1892 and turned out to be dry, the first discovery well in the region was spudded in 1904 and resulted in the Chia Surkh Field the well discovered oil, gas and condensate in the Tertiary Upper Fars Formation. Since the drilling of the Dalika 1 well nearly 50,000 wells have been drilled in the Middle East covering some 1,853 fields and targeting a total of 3,538 different formation reservoirs. Up until 1930 the Miocene reservoirs were the main targets for exploration. After 1930 and up to the present day the Cretaceous formations are consistently where the most hydrocarbon finds are made. During the 1940s the first discoveries in Permian formations were made and after 1970 hydrocarbon were discovered in the formations up to and including Cambrian age deposits. The discovery of deeper reservoirs is almost certainly due to improvements in drilling technology and better understanding of the petroleum geology in the region.

The mapping of this information makes it possible to see how hydrocarbon exploitation has evolved across the region. Up to 1930 exploration activities initially targeted the Mesopotamian and the northern Western Arabian Provinces along the Iraq – Iran border. Between 1930 and 1980 the main focus of exploration was in the Gulf region. Since 1980 the Gulf area has still been the main focus of drilling activity however new play fairways are being explored in Oman and the Yemen aswell in the north of the region within Syria, Southern Turkey and Israel. Future targets may see deep drilling in Central Saudi Arabian in the deepest parts of the Rub' Al Khali Province or in Iraq within the Widyan Mesopotamian Province or even within the very deep pre-Unayzah Formations within the Gulf Area.

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Session Two:
Global Patterns

Changes in the Characteristics of Plays and Petroleum Systems through Geological Time

Michael Treloar, Daniel Slidel
Halliburton

The uneven distribution of discovered hydrocarbons, both geographically and temporally, epitomises the importance of subsurface geology in exploration. Understanding the geological factors controlling this observation has long been recognised as a key tool in predicting undiscovered resources. By examining the characteristics of plays and petroleum systems through geological time, a more complete picture of this heterogeneity is revealed. This provides an improved basis for identifying trends to inform future exploration. This evaluation primarily seeks to address changes through time in: the prominence of source rocks, the abundance and characteristics of reservoirs, and the interplay of trapping styles and tectonic evolution.

A global dataset of play and petroleum occurrence information has been analysed in conjunction with an integrated suite of regional geological interpretations. By assessing specific intervals, new insights into key changes in play characteristics through geological time and the control they exerts on hydrocarbon reserves can be gained.

Analysis reveals that source rock and reservoir occurrences generally increase with decreasing stratigraphic age. Within this overall trend, peaks in frequency can be identified at discrete stratigraphic intervals. These include the Late Ordovician, Late Devonian, Oligo-Miocene and most prominently, throughout the Cretaceous. Similarly, the temporal distribution of reservoir occurrences appears heavily weighted towards the Cretaceous at a global scale. An additional peak is noted in the Miocene for clastic reservoirs. However, an assessment of the relative significance of these intervals must also account for the resource endowment and geographical distribution of the petroleum systems. Late Jurassic source rocks are well acknowledged to account for the majority of oil reserves in some of the richest petroleum provinces, including the Middle East, West Siberia and the Gulf of Mexico. Likewise, early Silurian shales source the majority of gas discovered in the Middle East and both oil and gas in many North African basins.

Trends can also be recognised in the types of traps, depositional systems and structural evolution of petroleum systems that dominate the resource profile for different stratigraphic intervals. Some of the most prolific plays in the Cenozoic are those associated with large, clastic deltas in passive tectonic settings, such as the Niger, Congo and Mississippi. Often, the hydrocarbons stored in these systems have been generated, at least in part, by a Mesozoic source rock. Conversely, the prolonged poly-phase burial histories of many older systems introduces risks such as un-roofing and remobilisation but may also be responsible for creating large structural traps and numerous potential reservoir/seal intervals.

This holistic overview of the evolution of play characteristics through geological time provides key insight into the factors controlling the observed distribution of hydrocarbon resources. Understanding these relationships forms the basis for accurately predicting future resources.

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Global Basins Through Time

Kirsty Campbell and John Howell
School of Geosciences, University of Aberdeen

A recent study by Nyberg and Howell (2015) illustrated that only about 18% of the Earth's land surface sits within active sedimentary basins. Furthermore arid basins which comprise c. 25% of the land account for over 60% of the basins. This suggests that any future rock record would be heavily biased to certain climates and also certain tectonic settings.

The present project sets out to study the distribution of the sedimentary basins through the Phanerozoic in a similar way to the modern study. Using the palaeogeographic maps of Ron Blakey (www.deeptimemaps.com) coupled with the palaeo-climatic reconstructions of Christopher Scotese (Scotese, C.R., 2001 Atlas of Earth History, PALEOMAP Project, Arlington, Texas, 52 pp.) the approximate distributions of basins for 26 time steps over the last 540 my have been mapped and quantified.

The results suggest that the area of terrestrial basins has increased over the last 540 million years and whilst the total land area has also increased the proportion of basins has increased from 7 to 17%. Passive continental margins are the most significant basin type (70%), although there is a long term decrease in their relative proportion from 81% to 62%. The proportion of rift and foreland basins has increased through time, although there are significant variations and steps within this trend. The amount of intracratonic basins also shows a slight increase.

There is a long term decrease in the proportion of arid continental basins with the clear exception of the Permian-Triassic which is linked to the assembly of Pangea. There is a long term increase in tropical basins, while the proportion of temperate basins is relatively stable. Significant increases in the proportion of cool temperate and cold basins are clearly linked to major ice-house periods.

The results of this study illustrate the incompleteness of the geological record and show how little of the Earth's surface processes lie within basins and are therefore preserved within sedimentary basins. An improved understanding of the distribution of basins also has important implications for the understanding of the global distribution of hydrocarbon source rocks and reservoirs.

NOTES:

Why do nearly half the world's hydrocarbons overlie one basement terrane type?

Jon Teasdale and Tim Debacker
Geognostics International Limited

Basement geology, in particular its composition, rheology and isostacy, intimately controls the nature and evolution of overlying basins. By studying basement it is possible to understand basins and their hydrocarbon reserves in a holistic way that can lead to more accurate prediction of prospectivity and reduce exploration risk.

The Geognostics Earth Model (GEM) provides a bottom-up view of global geology focussing on basement first. GEM contains an accurate global interpretation of basement terrane type, structures and age, as well as a new interpretation of global basins attributed by basin type and age. As such GEM is the first platform where hydrocarbon reserves, basement terranes and basin type can be correlated.

One of the most significant features in the present day global oceanic domain are large areas of thickened oceanic crust (oceanic plateaux) that formed where mantle plumes interacted with spreading centres. Oceanic plateau crust is generally 12-20km thick, forming large plateaux from a few hundred thousand up to 2 million square kilometres in size. The most obvious modern-day example is Iceland, where new oceanic plateau crust is being formed. The largest example is the Ontong-Java Plateau in the South Pacific. As such oceanic plateaux are 2-3 times normal oceanic crustal thickness, and comprise more differentiated (i.e. more felsic) mantle-derived igneous rocks. Beyond a certain minimum size (yet to be determined), such plateaux will be too buoyant to subduct, therefore will accrete to the continents. The fact that many present plateau have 'jammed' subduction zones is testament to this process.

Once accreted to the continents, oceanic plateau terranes are less buoyant than surrounding continental terranes therefore act as sediment sinks, accumulating thick platformal sequences over long periods of time. They have distinct gravity and magnetic signatures, and unusually flat top-basement surfaces. As they have low internal heat production, they are rheologically strong and resist deformation.

An intriguing result of the correlation between hydrocarbon reserves and GEM basement type is that a significant proportion of the World's hydrocarbon reserves overlie buried oceanic plateaux. According to USGS and IHS figures, approximately 37% of all oil reserves and 47% of all gas reserves overlie oceanic plateau basement terranes. As such oceanic plateau terranes are critically important to hydrocarbon exploration, but why? And how can we leverage this amazing correlation to discover new hydrocarbons?

NOTES:

Integrated Data Unveil the Petroleum Potential of the Conjugate Southern Atlantic Margins

Jean Malan, Peter Webb and Kerri Wilson
Getech Group plc,

Large frontier areas of the conjugate southern Atlantic margins remain sparsely drilled and unexplored. When integrated with third-party seismic profiles and well control, Getech's potential fields data, Global Plate Model, structural coverage and crustal architecture grids provide explorationists with a more complete understanding of the petroleum systems of the Namibian and South African basins and the conjugate Argentinian, Uruguayan and Brazilian basins.

Getech's high-resolution model of the plate kinematics for the southern Atlantic shows a revised pre-rift fit, an adjusted timing for break-up, the extent of flood basalts and the presence of seaward-dipping reflectors (SDRs). Our integrated data set and multidisciplinary approach support a consistent tectonostratigraphic evolution model that allows a direct stratigraphic comparison to be made between the eastern margin (the Walvis, Luderitz, Orange and Cape Basins) and the western margin (the Pelotas, Punta del Este, Salado, Colorado and Rawson Basins; see Figure 1).
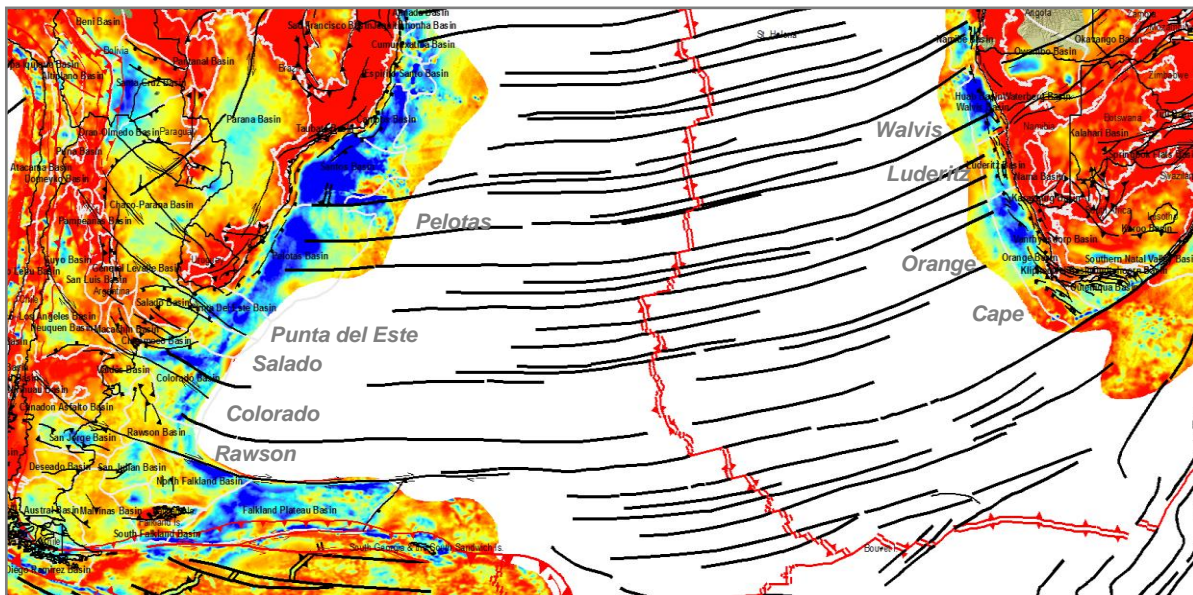

Figure 1: A sediment thickness map for the basins of the conjugate southern Atlantic margins.

An example of the comparative petroleum systems of the South African margin and the conjugate Argentinian margin is the three proven and four potential plays present in the Orange Basin and the five potential plays present in the Colorado Basin. The Orange Basin's oil (the A-J Graben), condensate (Ibhubezi) and gas (Kudu) fields and discoveries are derived from Lower Cretaceous syn-rift lacustrine source rocks and marine Barremian–Aptian early drift to drift source rocks. The Colorado Basin's oil shows (the Cruz del Sur-1 and Estrella-1 Wells) originate from Upper Jurassic–Lower Cretaceous lacustrine source rocks situated within the well-developed syn-rift sequence.

Getech's integrated data have revealed the full extent of the SDRs present along the conjugate southern Atlantic margins, providing explorationists with an opportunity to explore the same untested Barremian volcaniclastic play

along both margins. In the Present Day deep-water areas, the Upper Cretaceous and Paleogene sections of both margins remain undrilled and poorly explored; despite their frontier nature, there are positive indicators of hydrocarbon potential existing within these sections.

Our work on the margin-opposed basins and their syn-rift histories, subsidence characteristics and facies relationships together with our Globe data and extensive knowledge bases offer explorationists a unique insight into the southern Atlantic region, allowing them to make a thorough assessment of exploration risk in these opposing and emerging basins.

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Session Three:
Predictive Palaeoclimate

INVITED SPEAKER: Advances in the use of Plate Models for Regional Exploration in Shell

Cees van Oosterhout[1], Ailsa Higton[2], Karin Warners[2]
[1]*Argo Geological Consultants*
[2]*Shell International Ltd*

In the last decade Shell Global Exploration has revisited many regions such as the Arabian Plate, Gulf of Mexico, South Atlantic, Europe and the Arctic. Although well known areas to Shell, various new plays and hydrocarbon occurrences had to be better defined in space and time when we re-entered these regions. Likewise the plate models to date, as well as the understanding in geodynamics had advanced during our absence and so had the tools, methods and integration of various geoscience disciplines.

Through various consortia: PaleoMAP (Scotese); Geodynamics Module (Halliburton); Geodynamics Gamechanger (Utrecht, Cardiff, Lausanne universities) and IS Source rock (Senter Innovation), geodynamics and regional geology was addressed. Specific tools were built by Rothwell (PaleoGIS and PaleoGlobe) and Earthbyte (GPLATES) allowing the effective distilation of geodynamic data to a wider audience. Internal work to build a global source rock inventory led to a source rock atlas, defined in time and space.

This source rock atlas was illustrated using geodynamic maps which allowed the explorers to:
- o Take a plate model of choice
- o Take a selected Age or Age Range
- o Add age-calibrated exploration information (regional as well as local) and put them on the maps
- o Add their own information and put them on the maps as well
- o Use the information digitally in various workflows for geochemistry, stratigraphy and basin modelling to arrive at a consistent understanding of the basin history.
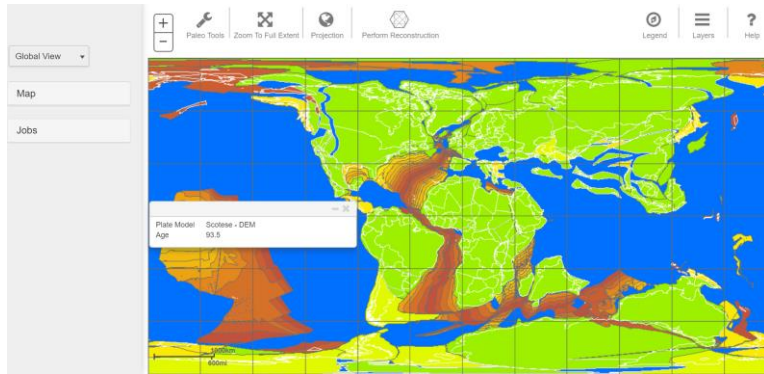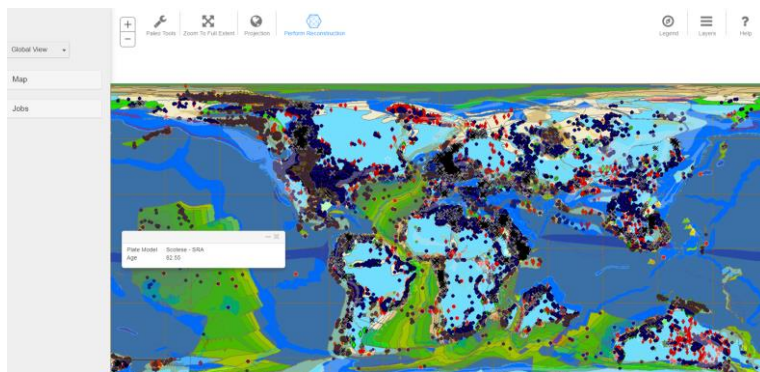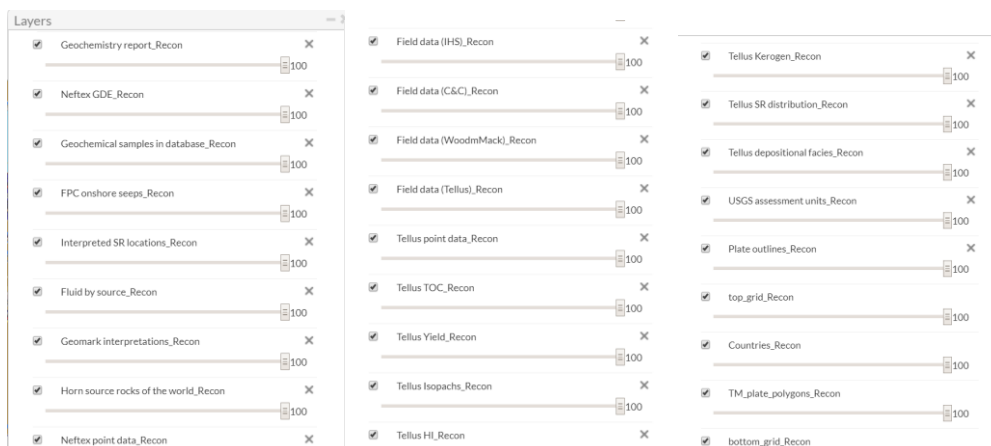

Basic Plate Reconstruction

Colourfull PaleoDEM

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Source Rock Atlas Map

Standard Layers Available

Example shown is Scotese Plate Model ~OAE1 time PaleoDEM and Source Rock Atlas Map can be worked at all scales at all times for which we have stratigraphically calibrated data. Technology has advanced from non-GIS data back in 2000 via ArcGIS desktop PaleoGIS modelled to ArcGIS Server modelled in PaleoGlobe to now *finally* based jobs in support of Basin and Play Analysis engine to capture basin history analysis. Specialist Geodynamic Modelling can be done in GPLATES can use data from the server and can be ported back to feed the Shell Global Plate Model.

In our talk we will demonstrate a history match showing the information known prior to the use of geodynamics, and then how the use of geodynamics has impacted the understanding of the basin history since; specifically the hydrocarbon occurrences within the basin as well as the source rocks that produced the hydrocarbons.

NOTES:

Climatic controls on heterogeneous source rock deposition: a micron- to global-scale investigation of the Kimmeridge Clay Formation

Elizabeth Atar[1], Prof Andrew Aplin[1], Dr Olaf Dellwig[2], Dr Violaine Lamoureux-var[3], Dr Thomas Leslie Leith[4], Prof Daniel Lunt[5], Dr Christian März[6], Dr Bernhard Schnetger[7], and Prof Thomas Wagner[8]
[1]Durham University
[2]Leibniz-Institute for Baltic Sea Research, Marine Geology
 IFP Energies Nouvelles
[4]University of Leeds, Leeds
[5]University of Bristol
[6]Equinor ASA
[7]ICMB, Oldenburg University
[8]Lyell Centre, Heriot-Watt University

Mudstones can exhibit great temporal heterogeneity yet remarkable spatial homogeneity that is evident on micrometre to decimetre scales. They can be correlated across vast distances (100's km) suggesting large scale processes influenced their deposition. Investigating these controls is pertinent to improving source rock quality and quantity predictions but requires multiscale investigation.

Global climate models (GCMs), derived from modern day observations, can be applied to the geological past to reconstruct atmospheric dynamics, which exert a fundamental control on marine sedimentation through variations in precipitation, affecting sediment, nutrient, and fresh water supply to the oceans, and variations in wind strength and direction, affecting ocean currents and upwelling. These large scale models must be validated with observational data but integration of different data resolutions (i.e. micron–kilometre and annual–millennial) requires careful consideration.

The Late Jurassic Kimmeridge Clay Formation (KCF) was deposited across NW Europe in the Laurasian Seaway, which connected the Tethyan and Boreal Oceans. Climate modelling results indicate the southern sector of the seaway experienced intermittently tropical (warm and wet) conditions, comparable to the modern day monsoonal system, due to the poleward migration of the inter tropical convergence zone (ITCZ, Figure 1; From Armstrong et al., 2016).

To further test this hypothesis and to explore the processes controlling sedimentation from mid to sub-polar paleo-latitudes, three time-equivalent Upper Jurassic sections were studied from the Boreal Seaway (Dorset, Yorkshire, and Svalbard). The sections were analysed for major and trace elements, mineralogy, organic carbon, bulk-rock oxygen isotopes, total organic and inorganic carbon, and sedimentological information from petrography/SEM. In addition, two independent climate models, the high resolution HadCM3L atmospheric and the low resolution FOAM coupled atmosphere-ocean, were cross-validated and integrated with geochemical and sedimentological data to better understand the Late Jurassic dynamic depositional environment of the Boreal Seaway where organic carbon enrichment was persistent, but influenced by different climatic processes, throughout the seaway.

The integrated approach using GCM simulations, geochemistry, and petrography, is a powerful tool with which we can constrain source rock presence, particularly in areas with sparse data (e.g. Arctic) and gives insight in to the biogeochemical processes and feedbacks during organic carbon enrichment; hence it is of economic and scientific importance.
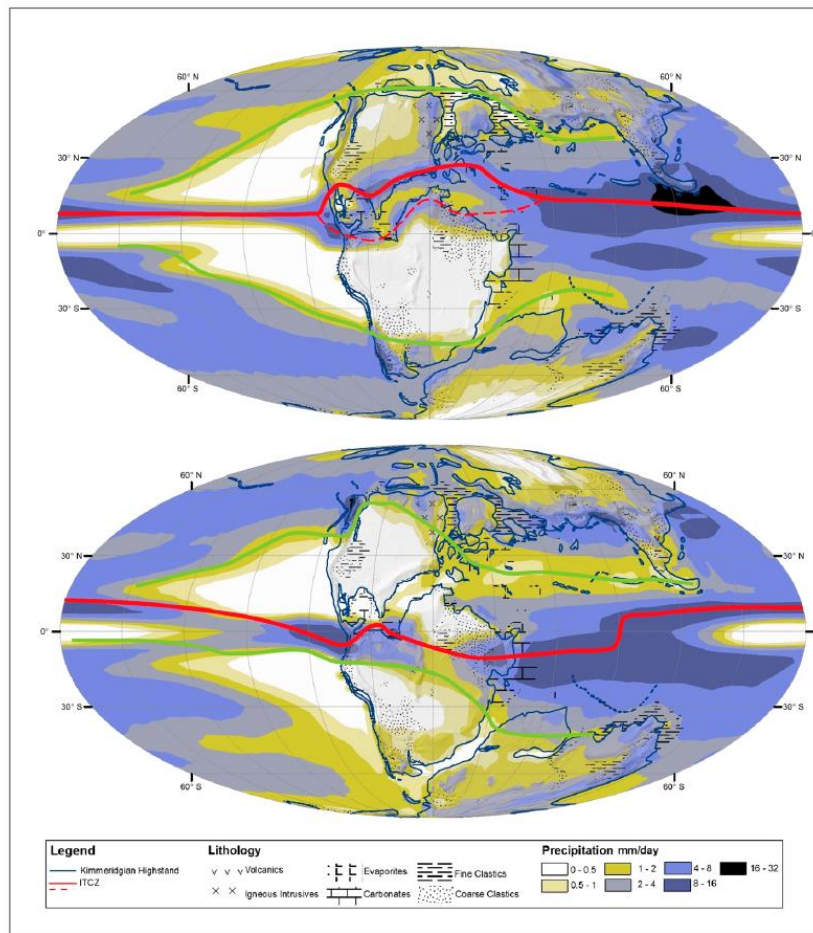
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Figure 1. From Armstrong et al., 2016. Modelled precipitation (contours, mm/d), location of the Intertropical Convergence Zone (ITCZ, red line) during the deposition of the KCF based on HadCM3L model and a paleogeography of the Late Jurassic (155.5 Ma [Getech, 2013]). Upper map is boreal summer (June, July, and August), and lower map is boreal winter (December, January, and February). During boreal summer the ITCZ lies in a more northerly location than at the present day placing the boreal sector of the NW European seaway temporarily under tropical-like conditions. The green line shows the approximate 1 mm/d precipitation contour, whose position is influenced by the location of the descending limb of the Hadley cell and the subtropical jet, as indicated in Figures 3b and 3c.

NOTES:

INVITED SPEAKER: Unraveling Carbonates through Time and Space: Reducing Prospect Uncertainty and Optimizing Reservoir Characterization

Jeroen Kenter[1], Jean Borgomano[1,2], Yannick Donnadieu[2], Alexandre Pohl[2], Julien Michel[2], Alexandre Lettéron[2] and Cyprien Lanteaume[2,3]
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[3]*MODIS Pau*

Though carbonate reservoirs are holding more than 60% of undiscovered reserves, exploration results over the last decade have dampened such expectations and confirm that uncertainties around, for example, identification from seismic have not come down. Similarly, development and characterization of carbonate reservoirs is still more expensive and challenging than sandstone reservoirs. Consider, for example, the lower recovery factors, net to gross, matrix permeability and porosity in carbonates.

To improve exploration results and optimize characterization, several research projects were initiated with academic partners of choice. Two of those are presented here. The first project seeks to utilize deep time paleoclimate modeling to deliver probability maps of carbonate presence through time and space. The second project is to identify the geological attributes (e.g., texture, environment of deposition, diagenetic modification, and heterogeneity) that have a relevant contribution to reservoir models.

An early pilot has demonstrated that current paleoclimate modeling techniques and paleogeographic reconstructions are sufficiently robust to test the distribution of "carbonate factories" (associations of grain types that share a common set of ecological behaviors). In particular, the abundance and quality of information and relevant knowledge in the Cenozoic makes this period an excellent starting point for estimating the probability of occurrence in space and time. In parallel, several relational databases provide and supplement the relevant information for the paleoclimate modeling effort.

Carbonate reservoir characterization is a challenge for several reasons, one of which is the continuously changing quality, abundance and representativity of data. Equally important, however, are the many workflows utilized to integrate geological attributes of significance, such as rock typing, sequence stratigraphic framework and horizon building, geostatistical distribution of properties, validation and dynamic evaluation. To identify which geological attributes have common relevance (influence the distribution – heterogeneity – of petrophysical properties at reservoir scale), static and dynamic models of more than 10 carbonate reservoirs were screened to separate out "noise" caused by workflow variability.

Both approaches, multi-year projects, will deliver first solutions toward reducing uncertainty in the identification of prospects and optimize the way geological attributes are integrated in carbonate reservoir characterization.

NOTES:

Session Four:
The Importance of OAEs

INVITED SPEAKER: Comparing and quantifying the known organic carbon burial with mapped estimates for global burial during two significant Mesozoic oceanic anoxic events

Jeremy D. Owens[1] and Benjamin C. Gill[2]

[1]*Florida State University | National High Magnetic Field Laboratory*
[2]*Virginia Polytechnic Institute and State University*

There were numerous global climatic perturbations to the ocean-atmosphere system during the Mesozoic greenhouse. The best-documented of these climatic events are termed oceanic anoxic events or OAEs. These events resulted in the burial of significant amounts of organic carbon and subsequently the widespread formation hydrocarbon source rocks. Among the OAEs, the Toarcian OAE (~183 Ma) and the Cenomanian-Turonian boundary event (~93.9 Ma), or T-OAE and OAE2, respectively, represent the best studied and are documented in over 80 sections from multiple ocean basins. While the studied and preserved sedimentary record of these two OAEs have a widespread spatial distribution there are still significant geographic regions that are not represented or underrepresented. Notably the expansive Pacific Ocean is under represented for both events. However, the global amount of organic carbon (OC) burial that occurred during these events can be quantified using numerical modeling of the carbon isotope record. While this approach provides quantitative estimates for global OC burial, these solutions non-unique and subsequently yielding a large range of estimates.

These estimates can be compared to those derived from the known stratigraphic and geographic distribution of Toarcian and Cenomanian-Turonian deposits analyzed with modern mapping methodologies (GIS). Specifically, mass accumulation rates (MAR) of OC can be calculated using total organic carbon (TOC) contents of the units and estimates of the sedimentation rates from each locality. Following this, OC burial rates from these locations can be extrapolated to larger geographic areas with similar depositional environments ultimately providing an estimate for the total preserved OC burial for each event. For OAE2 this analysis has highlighted that some of the highest OC MAR are areas with moderate TOC contents, but very high sedimentation rates. These environments are typically understudied as the focus on these events is generally placed on black shale localities with high TOC but are not stratigraphically extensive.

Despite the widespread modern distribution of preserved Toarcian and Cenomanian-Turonian sedimentary deposits, conservative mapping and extrapolation shows these sites only represent a small portion of the ocean, less than 20%. Additionally, they predominantly represent only marginal marine settings. While these documented sites can account for significant OC burial during the OAEs there is still large discrepancies when these mapping derived estimates compared to those derived from the carbon isotope record. These discrepancies implies there may be untapped hydrocarbon resources associated with these events that are present in understudied regions. Potential targets should be underexplored regions that were equatorial and on the eastern margins of the ocean basins since they would will be likely candidates for increased productivity and generally experience lower oxygen conditions in the modern.

NOTES:

Complexity of organic enrichment during Oceanic Anoxic Events: a study of the Cretaceous Western Interior Seaway

Libby Robinson[1], Jessica Whiteside[1], Samantha Gibbs[1], Richard Twitchett[2]
[1]University of Southampton
[2]Natural History Museum, London

Ever since their identification in the 1970s, Oceanic Anoxic Events (OAEs) have become a key component for petroleum geologists in their search for source rocks. Not only do they seem to have global, or at least regional, influence in enhanced organic matter preservation in the geologic record, but evidence for them arguably spans across 100s Myr from the Cambrian to the Cretaceous.

Are OAEs truly the ubiquitous source rocks they seem however? Many sediments deposited during times of OAEs are not effective source rocks – despite substantial thickness and suitable thermal maturity. In addition, each OAE can display significantly different characteristics in the geological record, including severity of anoxia, geographical extent and carbon isotope expression.

The Western Interior Seaway is a highly productive hydrocarbon basin that does not show expected global trends during OAEs. During the mid-Late Cretaceous it spanned the Boreal realm of the Canadian Arctic through to the Tethyan realm of the Gulf of Mexico (Figure 1). A shallow, epicontinental basin, it was highly influenced by changing eustasy, tectonics and climate, and full transgression from north to south occurred intermittently.
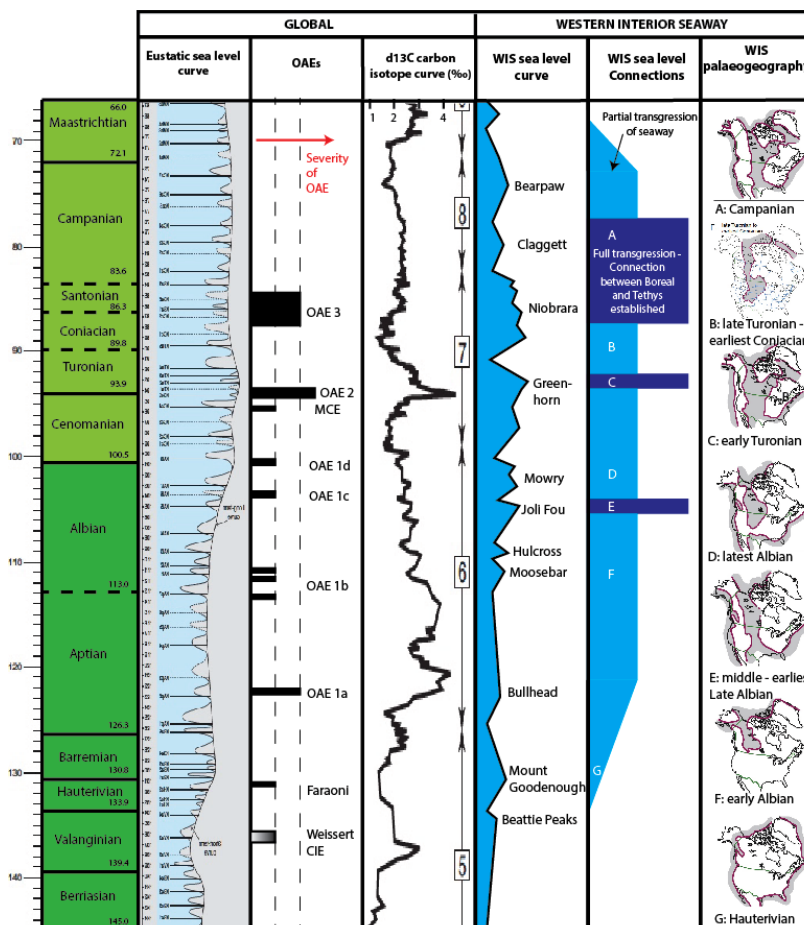

Figure 1: Western Interior Seaway sea-level changes against global trends and events. a) 3rd order transgressive and regressive eustatic sea level cycles of Haq (2014) b) Oceanic Anoxic Events; c) d13C carbonate isotope curve (Robinson, 2017 and sources therein); d) Sea level-curve of the Western Interior Seaway (Kauffman and Caldwell, 1993; Schroder-Adams, 2014); e) Marine connections across the Western Interior Seaway (Schroder-Adams, 2014); f) Western Interior Seaway paleogeography across the Cretaceous (Schroder-Adams, 2014)

As part of this study an extensive database of published organic geochemical data has been compiled for the Cretaceous Western Interior Seaway (Figure 2). This dataset illustrates enhanced organic matter in sediments deposited during the 2nd order transgressions associated with the major OAEs in the Niobrara and Greenhorn cycles. However, when looking at a higher-resolution many authors have found that anoxia is diachronous with the true timing of the OAE, and actually present evidence for increased oxygenation at this time (e.g. Arthur and Sageman, 1994; Leckie et al., 1998, Lowery et al., 2017). These findings raise questions as to the true drivers behind anoxia and subsequent organic enrichment in the WIS, and suggest significantly locally-driven factors.
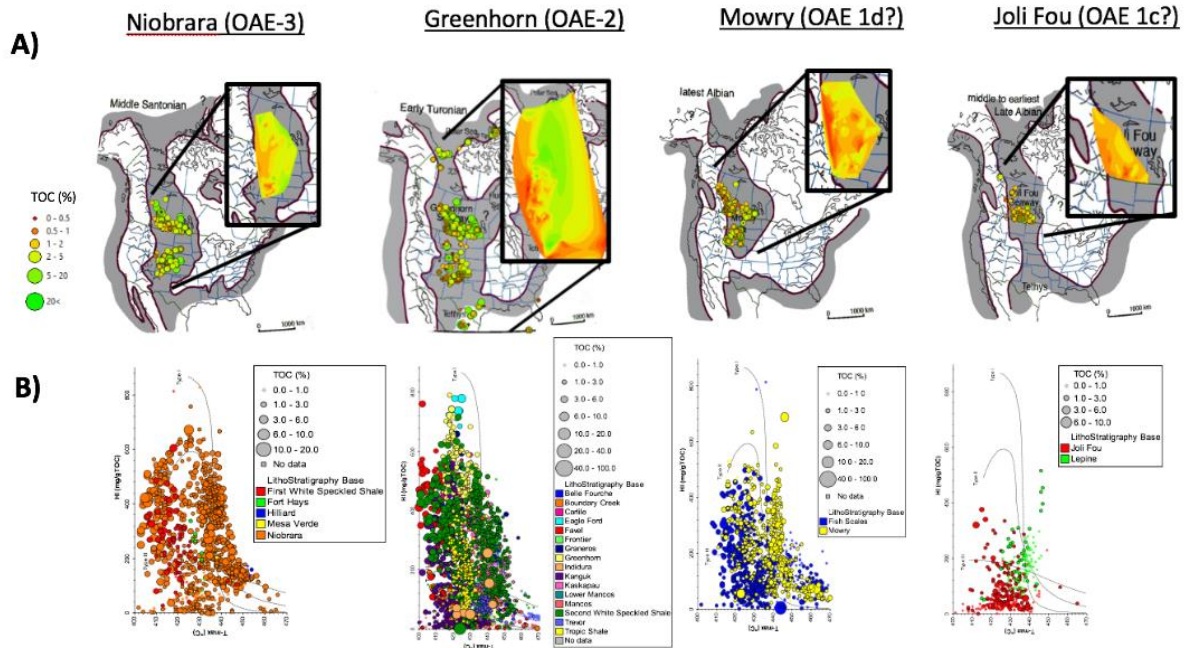
Figure 2: Rock-Eval data for four main transgressions in the Cretaceous Western Interior Seaway: A) Total Organic Carbon data displayed spatially as data points and interpolated from these values; B) HI vs Tmax parameters displayed with different lithostratigraphic units highlighted.

This study investigates Cenomanian – Turonian sediments at a high resolution along an E-W transect in the WIS. Lipid biomarkers and their isotopic composition will be used to study the physical and biogeochemical evolution during the mid-Cretaceous by reconstructing variations in water column oxygenation, stratification, sea surface temperatures and organic matter provenance. Objectives are to investigate: a) changing sea-level and presence of differing water masses on anoxia in the basin b) the role of precipitation and salinity stratification as drivers for ocean deoxygenation; c) the role of productivity and changing ecology on ocean deoxygenation and black shale formation; and d) potential diachroneity between anoxic conditions, black shale deposition and carbon isotope excursions.

The study of the Cretaceous Western Interior Seaway not only allows more accurate prediction of organic-rich facies within the basin itself, but also facilitates greater understanding of organic matter deposition in epicontinental settings during Ocean Anoxic Events.

NOTES:

Global, regional and local controls on lateral and vertical heterogeneity of the Eagle Ford Group Mudrocks, Texas, USA

Eldrett, J.S[1]., Bergman, S.C[2,3]., Minisini, D[2]

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[3] *SCB Geosciences*

The Late Cretaceous Epoch was characterized by sustained global warming, emplacement of several large igneous provinces (LIPs), global extinctions, and global sea-level high-stands leading to the marine flooding of several epicontinental seaways. These global mechanisms, combined with major global perturbations in the carbon cycle, favoured the widespread deposition and preservation of organic rich source rocks. One such example is the Eagle Ford Group (Gr.) located at the southern entrance to the North American Cretaceous Western Interior Seaway (KWIS), encompassing the Cenomanian to Turonian stages. Compared to time equivalent strata in the central and northern parts of the KWIS, the Eagle Ford Gr. is a more prolific source rock and intensive shale gas and liquid rich unconventional play. Furthermore, within the Eagle Ford play there are geographically constrained "sweet-spots" characterized by top quartile producing wells (measured in barrels of Oil Equivalent; BOE). Therefore, although favoured by global processes characterizing the Late Cretaceous Greenhouse world, the deposition and preservation of organic-rich sediment in the KWIS and in particular southern Texas was strongly modulated and ultimately dependent on local and regional processes including the foreland basin plate tectonics behind an active magmatic arc, paleo-topography/bathymetry, regional ocean circulation, basin restriction, water stratification, bottom currents, and sediment input domains.

Shell International Exploration and Production conducted research on road cuts along US Highway 90, and natural outcrops in the vicinity of Big Bend National Park, Del Rio and Austin, Texas that provide excellent exposures of the Buda, Eagle Ford (locally known as Boquillas Fm.) and the Austin Chalk. In addition, Shell has drilled two shallow cores, Shell Iona-1 and Shell Innes-1, behind these outcrops, recovering continuous core of the entire Eagle Ford stratigraphy and parts of the adjacent formations, the Austin Chalk and Buda Limestone. Key scientific aspects of this research have been published in peer-reviewed journals, so here we provide a new synthesis of the main local and regional controls on the lateral and vertical heterogeneity within and across the Eagle Ford Gr. Furthermore, using our high precision astrochronological framework, we place the Eagle Ford Gr. into a supra-regional context by comparing with correlative sections from the across the Cretaceous WIS and Equatorial Atlantic. These learnings may be applicable to other Unconventional Gas/Liquid-Rich Shale plays, where the ability to rapidly identify which parts contain the thickest, most organic-rich stratigraphic sections of reservoir with the highest porosity and hydrocarbon saturation, is essential for enabling early access to the most prospective acreage. Following acreage acquisition, assessment of subsurface variability is required to enable optimal well spacing and placement.

NOTES:

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Session Five:
Organic-Rich Facies

INVITED SPEAKER: Source Rocks in Time and Space: a Quantitative Description of Source Rock Organofacies, Expulsion Potential, Expelled Fluid Composition and Properties - with examples from some of the world's major Conventional and Unconventional Petroleum Systems

Andrew Pepper[1], Elizabeth Roller[1,3], Jean-Marie Laigle[2], Laure Philippe[2], Chris Yarbrough[2]
[1] *This is Petroleum Systems LLC*
[2] *Belmont Technology Inc.*
[3] *CGG*

The Petroleum System is a machine driven by petroleum fluid volume creation in the source bed. Rates of expulsion from Organic Matter (OM) are vanishingly slow and these rates ultimately control all migration rates, determining the progression of the lateral or vertical charge fronts in the basin; and limiting the rates of reservoir charging and leakage. The two factors limiting the mass of petroleum expelled from the OM in the source bed are: 1) its initial expulsion potential (mass and composition); and 2) the cumulative fraction of its potential expelled up to its maximum state of maturation.

The four most important parameters determining initial expulsion potential are: thickness, organic carbon (Corg), Hydrogen Index (HI) and Organofacies. In its most simple form, composition can be modeled as the proportions of two petroleum carbon (PC) fractions: PC1-5 "gas" and PC6+ "oil". This mass ratio can then be converted to "oilfield" volumetric equivalents and related to subsurface physical properties such as density and viscosity at the ambient pressure and temperature conditions.

HI is the most important in determining composition, since it governs the ratio of reactive to inert carbon in the OM and thereby controls the mass of generated PC6+ ("oil") that can be expelled from the organic matrix, once its sorption capacity is exceeded. Un-expelled oil is cracked and is added to the PC1-5 mass expelled from the gas-generating kerogen portion of the OM, increasing significantly the expelled gas-oil ratio. Note: HI is largely independent of Organofacies, since oxidation can reduce the preserved HI irrespective of its biological origin. In the classical Tissot scheme, Type III OM with low HI is not necessarily terrigenous in origin! Organofacies control the kinetics of generation of the PC1-5 ("gas") and PC6+ ("oil") components and the increasing temperature (from A to F) required to generate PC6+ sufficient to exceed the sorption capacity of the OM. Terrigenous organic matter (Organofacies D to F) has increasingly high oil generation temperatures which increasingly overlap with oil-to-gas cracking; this compounds their tendency to have low HI / low expulsion efficiency, explaining why these Organofacies are associated typically with high GOR through dry gas systems. Thickness and Corg are scalar factors that largely influence gross mass / volume rather than composition. Note: they are often negatively correlated; there are few thick and organic-rich source rocks!

Rather than "starting with the end in mind", many Petroleum Systems analyses continue to overlook this all-important step in establishing Source Potential in time and space. Terms such as "world class source rock" have been so over-used that they constitute little more than a cheap advertising slogan: buyer beware! Many modern basin modeling packages still proliferate the problem by requiring a single number per cell, as input to the kinetic model calculation of generated and expelled masses and volumes – essentially a hang-over from the low computing power of the 1980's when kinetic modeling originated. Present-day computing power now allows us to model the effects of "real" vertical, lateral and temporal changes in source rock Organofacies, richness and quality arising from the conditions under which organic matter was developed and preserved. In turn, this now behooves us to go "back to the source" to revise / develop new workflows in mapping and quantifying the raw material from which the Petroleum System originates. Therefore, to evaluate the initial expulsion potential quantitatively, we introduce a workflow to estimate the Ultimate Expellable Potential (UEP), which represents the cumulative mass of oil and gas that can be expelled upon complete maturation of the source rock. For use in resource estimation, these masses can be converted to surface volumes of oil and gas per unit area (UEO in mmstb/km2 and UEG in bscf/km2 or mmboe/km2, respectively). UEO, UEG and UEP can be mapped across the depositional extent of the source bed, just as a reservoir depositional system can be mapped. We show global examples of such maps for aquatic source

rocks in the Arabian, West Siberian, Bohai, Williston and Zagros Basins. The source beds that drive the world's significant petroleum systems have 10's of mmboe/km2; with the world's most prolific source beds reaching 100mmboe/km2 or more. Constructing UEP logs, plotted in the time rather than the depth dimension, it also becomes apparent that there are many global coincidences in the times at which source rock potential "Acmes" were deposited, providing a feedback loop into the causal mechanisms of the originating OM depositional events.

The last decade or so of exploitation of organic-rich "shale" reservoirs has created large volumes of detailed geochemical and petrophysical data on source rocks, that were rarely available in the often sparsely-sampled conventional exploration world. Here, it has become easier to see how changes in organic matter properties result in differences in "shale" reservoir fluid properties such as GOR and viscosity and in some cases the storage characteristics of the reservoir rock itself.

NOTES:

Global Climate, the Dawn of Life and the World's Oldest Petroleum Systems.

Jonathan Craig and Andrea Cozzi
Eni Upstream & Technical Services

Organic carbon productivity and formation of hydrocarbon source rocks during the Early Precambrian was almost exclusively the product of the growth of microbial mats. Eukaryotic steranes (biomarker for eukaryotic cells and, therefore, evolved forms of life) are present in the geological record from about 2.7 Ga, but they are not abundant or diverse within Archaean communities, which tend to be dominated by Archaea isoprenoids. Some hydrocarbons have been generated and migrated from Archaean organic-rich shales, but they were probably not of sufficient volume to be of commercial interest. The world's oldest significant hydrocarbon source rocks are Palaeoproterozoic in age and include the shungite deposits (2.0 Ma) in the Lake Onega region of Arctic Russia.

There is strong evidence of a global biospheric oxygenation event at c.1300-1250 Ma (Mesoproterozoic), in conjunction with a first-order positive shift in the marine carbon isotope record. The oxygenation event probably played a significant role in supporting the emergence of the more diverse eukaryotic communities preserved in the Neoproterozoic molecular record that provided the volume of organic material required to generate commercial volumes of hydrocarbons. Hydrocarbon source rocks of late Mesoproterozoic and Early Neoproterozoic age are widespread and include highly organic-rich shales deposited in restricted basinal settings adjacent to stromatolitic carbonate banks. By c.850 Ma, the Neoproterozoic molecular record is dominated by hopanes derived from cyanobacteria and a significant abundance and diversity of eukaryotic steranes, including those of multicellular eukaryotes (red and green algae), as well as molecular evidence for heterotrophic protists. The most widespread Precambrian hydrocarbon source rocks are black shales deposited during a global-scale Oceanic Anoxic Event associated with the emplacement of Large Igneous Provinces during the Mesoproterozoic (c. 1380 Ma) and commonly transgressive organic-rich black shales associated with inter-glacial and post-glacial phases of the Neoproterozoic global scale glaciations (c. 700-600 Ma). The relative dominance of microbial mats in the contribution of organic matter as a source of hydrocarbons probably decreased significantly during the late Neoproterozoic and earliest Cambrian, perhaps due to the rapid growth of grazing metazoan communities or possibly due to changes in sea water chemistry and/or nutrient supply.

Precambrian petroleum systems are relatively abundant and widespread. The oldest live oil recovered to date is sourced from Mesoproterozoic rocks within the Velkerri Formation (Roper Group) of the McArthur Basin of northern Australia, dated at 1361 ±21 Ma and 1417 ±29 Ma (Re-Os dates) with at least the initial phase of oil generation and migration having taken place before 1280 Ma. However, the geologically oldest commercial production is currently from the Late Mesoproterozoic to Early Neoproterozoic (Middle to Late Riphean) and Late Neoproterozoic (Vendian) petroleum systems in East Siberia, the Late Neoproterozoic (Sinian) petroleum systems of the Doushantao and the Dengying formations in southern China and from the latest Neoproterozoic to Early Cambrian Huqf Supergroup (including the Al Shomou Silicilyte and 'carbonate stringer' plays) in Oman. Other, potentially commercial, Precambrian petroleum systems have been identified on the Colorado Plateau in the southwest United States, the Nagaur-Ganganagar and Vindhyan basins in India, the Taoudenni Basin in West Africa, the Owambo Basin in Namibia and in the North China Craton. Despite long held scepticism about the hydrocarbon potential of Precambrian rocks, based on the assumption that there are simply not enough rocks of this age preserved and those which are preserved do not contain enough organic matter, it is becoming increasingly evident that potential hydrocarbon source rocks of Precambrian age are both abundant and geographically widespread and have charged a variety of clastic and carbonate reservoirs of Precambrian and Palaeozoic age. Permeability enhancement as a

result of subaerial exposure and associated karst development is a particular feature of many Precambrian carbonate reservoirs, most notably in Siberia and in south China.

The deposition, maturation and preservation of organic-rich hydrocarbon source rocks in the Precambrian sedimentary record is closely and complexly interrelated with the evolution of life, of the Earth's atmosphere and of the associated marine and terrestrial environments. The volume, nature and mix of the organic components that contributed to the hydrocarbon source rocks evolved progressively and, at times, dramatically during the Precambrian, together with changes in water/atmospheric chemistry and probably depositional extension into deeper-water environments. From the earliest evidence of organic molecules in the sedimentary record, to the diverse biosphere after the Cambrian revolution, these changes can be traced through the evolving palaeobiology and geochemistry of the Precambrian source rocks and of the hydrocarbons generated from them. Relatively high abundances of monomethylalkanes, alkylcyclohexanes and methylalkylcyclohexanes, and very low abundances of acyclic isoprenoids, including pristane and phytane are typical of many Proterozoic source rock extracts and oils, indicating that cyanobacteria were the dominant source of organic matter at least during the early and mid-Proterozoic. Before this time, the relative dominance of anaerobic Archaea might have prevented sizeable accumulation of hydrocarbons, while afterwards with the continuous availability of oxygen, a broad mix of eukaryotes contributed to the composition and relatively widespread abundance of hydrocarbons.

There is still much to learn about the palaeobiology and geochemistry of Precambrian hydrocarbon source rocks and their associated petroleum systems. It is becoming increasingly apparent that they have the potential to generate commercially significant volumes of oil and gas. This can then be trapped within the source rocks as 'unconventional' resources and/or migrated into 'conventional' structural and stratigraphic traps. If generation, migration and trapping occurs at an early stage, however, then the continued preservation of the commercially-viable volumes of hydrocarbons in 'conventional' traps requires conditions of relative tectonic stability and, typically, the presence of a salt super-seal.

Further research is needed to understand better what controls the spatial and temporal variations the quantity, quality and maturity of Precambrian hydrocarbon source rocks, the distribution of biofacies, the origin, distribution and kinetics of the kerogen and relationship between biomarkers and particular biota. As these studies progress, our increasing knowledge will inevitably focus greater attention on Precambrian petroleum systems as a target for future exploration and exploitation.

NOTES:

A Multi-Proxy Palaeoenvironmental Analysis During Deposition of the Mahogany Oil Shale Interval of the Green River Formation, Utah

Amy L. Elson[1], Megan Rohrssen[2], John Marshall[1], Jessica H. Whiteside[1]
[1]*Ocean and Earth Science, National Oceanography Centre Southampton*
[2]*Geology and Environmental Sciences, Central Michigan University*

The Lower Eocene Green River Formation of Utah and Colorado documents a ~15 million-year record of unusually large lakes that spans the Early Eocene Climatic Optimum, a time when global temperatures were ~5-10°C warmer than present. During this period, one of the world's largest petroleum resources developed with an estimated 750 billion barrels of oil equivalent in the oil shales of the Green River Formation. Several drill cores and outcrop sections forming a transect through the basin margin and centre of the Mahogany Oil Shale Zone offer an excellent opportunity to construct high-resolution records of terrestrial conditions during the Early Eocene Climatic Optimum and peak oil shale deposition.

Recent studies indicate that climate in continental interiors during hothouse periods varied differently than previously presumed and may be far more complex. In this study, mid-latitude hydrological change during rapid warming is investigated through compound-specific hydrogen isotopic analyses of n-alkanes and isoprenoids extracted from the Mahogany Oil Shale Zone of the Uinta basin, Utah. Variation in the hydrological cycle through the transition out of the Early Eocene Climatic Optimum can be tracked through the hydrogen isotopic signal preserved in leaf waxes and chlorophyll-derived compounds. Comparison of this novel record with high-resolution sedimentary logs, SEM data and other biomarkers such as steranes and hopanes allows the differentiation of hydrological change from broader ecosystem change during the Early Eocene Climatic Optimum. This study seeks to merge a multitude of scales, from field outcrops to microscopic imaging to molecular analysis, to bridge novel proxies with traditional methods in answering fundamental questions about organic matter production and preservation coupled with regional climate.

Disentangling the factors controlling deposition and preservation of organic matter in the Green River Formation through a combination of geochemical and sedimentological tools will lead to greater understanding and predictability of the organic-rich layers in the oil shale. This will help improve modelling of lacustrine source rocks and could have implications for the development of the U.S unconventional hydrocarbon industry, energy security and petroleum independence in the region.

NOTES:

Session Six:
Carbonate Systems

INVITED SPEAKER: The stratigraphic record of the Middle-Late Jurassic Transition events on the peri-Tethyan carbonate platforms

Raphaël Bourillot[1*], Mehdi Carmeille[1], Pierre Pellenard[2], Marie-Françoise Brunet[3] and Philippe Razin[1]
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[2]*UMR CNRS 6282 Biogéosciences, Univ. Bourgogne Franche-Comté*
[3]*Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, iSTeP*

The Middle and Upper Jurassic peri-Tethyan carbonate platforms host some of the largest hydrocarbon reserves in the world. Over the past decades, extensive research has led to the construction of high-resolution stratigraphic frameworks on the northwestern (e.g., Paris Basin) and southern (e.g., Arabian Platform) Tethyan margins. These studies and others show that although being a period of elevated carbonate production, the Callovian-Oxfordian interval is marked by major changes in carbonate production and platform architecture, stratigraphic gaps and condensed series. These changes have commonly been linked to regional to global climatic and tectonic events associated with the so-called Middle-Late Jurassic Transition (MLJT).

The stratigraphy of the northern Tethyan margin (Central Asia) was comparatively less documented. A vast carbonate platform developing on the northern margin of the Amu Darya Basin was recently investigated. A high-resolution stratigraphic framework of the platform was built based on facies analyses, sequence stratigraphy, chemostratigraphy and biostratigraphy.

This presentation reviews the key stratigraphic features of the Callovian-Oxfordian carbonate platforms in several areas of the northern, western and southern Tethyan margins. Our comparison shows striking similarities in the stratigraphic records of carbonate platforms which developed at the periphery of the Tethys, several thousands of kilometers apart and reinforce the hypothesis that global-scale events strongly affected the shallow water domain of the Jurassic ocean. The impact of climate, tectonics and major paleoenvironmental events, e.g. the Upper Callovian-Lower Oxfordian cold episode, the sea level fall possibly linked to glacio-eustatism and the tectonic events are finally discussed.

NOTES:

INVITED SPEAKER: Global Stratigraphic Exploration Concepts for the Cretaceous

Frans van Buchem, David Ray, Andy Davies, Gareth Carroll, Benjamin Greselle, Owen Sutcliffe, and Mike Simmons
Neftex Exploration Insights

The identification of time-specific global exploration concepts can help reduce geological subsurface uncertainty and guide strategy. How this can be applied to the Cretaceous is demonstrated by establishing global sedimentary patterns that can be linked to specific controlling parameters. Compared to previous endeavors to capture global geological patterns, this effort is different because it is based on a global temporal framework of third-order sequences and has a specific focus on the following three parameters, the frequency and magnitude of relative sea-level change, global sediment volume trends, and climate modelling.

The third-order global depositional framework is based on the systematic analysis of thousands of stratigraphic sections, from which gross depositional environment (GDE) maps have been constructed and projected on plate tectonic reconstructions. This insight in the general litho-facies and paleogeography is further complemented by geometrical information from 2D and 3D seismic and outcrop studies, as well as faunal assemblages of carbonate systems, which add further stratigraphic architecture detail. Finally, mineralogical and (organic) geochemical information completes this picture to provide essential information regarding the presence and quality of reservoir, source rock, and seal.

Based on a literature review, the presence of four periods with distinct trends in the magnitude of high-frequency sea level variations is demonstrated, which have a direct impact on stratigraphic patterns. In the Early Cretaceous, Phase I (Berriasian to earliest Hauterivian) and Phase II (late Hauterivian to Aptian) both have a similar upward trend of increasing magnitude of sea level fluctuations. They both terminate with a major eustatic sea level drop, causing carbonate platform exposure and siliciclastic bypass, followed by transgressive backfill of incised valley systems. In the Late Cretaceous, Phase III (Albian to Coniacian) coincides with the Cretaceous thermal optimum and is characterized by a gradual, large scale sea level rise, with a relatively low magnitude of high frequency sea level fluctuations, and typically punctuated by global oceanic anoxic events. Phase IV (Santonian – Maastrichtian) is characterized by a gradual increase in the magnitude of sea level fluctuations.

Because climatically driven eustasy is the likely cause of short-term sea-level change, an assessment of the characteristic upper magnitude limits of the principal climatic drivers (thermo-, acquifer- and glacio- eustasy) has been made. Such a comparison argues that glacio-eustasy is the driver of significant short-term sea-level change. Additionally, climate proxy data demonstrates that the Valanginian, Aptian, Albian and Maastrichtian are intervals of cooling within the Cretaceous. In-house climate modeling supports the link between significant magnitudes and glacio-eustasy.

The combination of GDE maps, sediment volumes, and an improved understanding of critical drivers, such as high-frequency sea level fluctuations, helped recognize and define trends in the Cretaceous stratigraphic record. A similar approach can be applied to other periods in the stratigraphic record, and is likely to reveal the existence of several time specific patterns that can qualify as exploration concepts.

NOTES:

INVITED SPEAKER: Variations in carbonate reservoir quality through time

Jo Garland and Andy Horbury
Cambridge Carbonates Ltd

A key characteristic of carbonate reservoirs is that the biological components constituting the sediment have evolved through geological time. This is a function not only of evolution, but also of 1st and 2nd order eustatic sea level variations, which is closely tied to climate and the chemistry of the seas (aragonite/calcite). As a result, Precambrian carbonates are considerably different to their modern counterparts, not only in facies, but also in their early diagenesis, reservoir stacking and pore systems.

Carbonate sediments are highly susceptible to diagenesis, which can modify a reservoir at any stage of its burial/uplift history. Diagenetic modification is not always negative for reservoir quality, with karstification (both meteoric and hypogenic), dolomitisation and fracturing creating dual and sometimes triple porosity systems for hydrocarbons to migrate into. Despite the almost ubiquitous propensity for diagenesis to modify the pore system in carbonates, temporal trends in reservoir quality can still be recognised.

Precambrian and Palaeozoic carbonate reservoirs occur mainly in Central Europe, the Former Soviet Union, Barents Sea, China and North America. Whilst the reservoirs typically have a reefal character (i.e. the Devonian build-ups of Western Canada), most of these reservoirs rely on later diagenesis (karstification, fracturing, hydrothermal/burial dolomitisation) to generate reservoir quality.

Permian and Triassic carbonate reservoirs have both organic and inorganic origins. For example, the reefal reservoirs of the Permian Basin in the USA are well-known, having been produced for many years. However, on the other side of the world, Permian to Early Triassic oolitic grainstones and dolomites are the reservoir to the largest gas field in the world, namely South Pars/North Field (on the Iran/Qatar border). Despite this, Permian and in particular, Triassic, reservoirs commonly have poor reservoir quality compared to some of their younger counterparts.

Jurassic carbonate reservoirs, and the Upper Jurassic in particular, are often world-class. These are distributed primarily in the Middle East/North Africa, Mexico/southern USA and to some extent Europe and Canada. Although Jurassic reefal reservoir systems do occur, the majority of reservoirs are characterised by laterally extensive and vertically stacked grainstones (oolitic/peloidal). Dolomitisation, and often late dissolution, commonly enhance reservoir quality.

The Cretaceous was a prolific geological period for carbonate deposition. The evolution and dominance of rudist reefal communities, and the shear diversity of platform types during this period, resulted in a vast array of carbonate reservoir types. These range from
- Shallow-water platformal reservoirs (prolific in Latin America/southern USA, and the Middle East and North Africa), where meteoric diagenesis is a common factor in the resultant reservoir quality
- Deep-water fractured carbonate reservoirs (Mexico, Middle East, southern Europe), which may have no effective matrix porosity, but produce through fractures
- Cretaceous chalks of the European North Sea (microporous fractured reservoirs)
- "Sub-salt" reservoirs of the South Atlantic margins.

Finally, Palaeogene and Neogene carbonate reservoirs predominate in SE Asia and the Middle East. These reservoirs are typically reefal in nature (i.e. Oligo-Miocene pinnacle reefs of Indonesia and Malaysia), and frequently these reservoirs can have very good matrix reservoir properties.

It is clear that reservoirs, of course, form only one element of the "reservoir-source-seal-trap-migration" story that is necessary for successful trapping of hydrocarbons. Early migration of hydrocarbons is often a key component in halting burial diagenesis (and thus preserving reservoir quality), and the close temporal association to world-class source rocks is often key to the success of carbonate reservoirs.

NOTES:

Session Seven:
Stratigraphic Architecture

5 Years Exploring Offshore Newfoundland and Labrador: Insight from Forward Stratigraphic Modeling to Petroleum System Assessment

Erwan Le Guerroué[1], **Paul Jermannaud**[1], Marie Callies[1], Alcide Thebault[1]Thebault[1], Emerson Marfisi[1].
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Since 2010, under new Scheduled Land Tenure System, the Canada-Newfoundland and Labrador Offshore Petroleum Board (CNLOPB) and Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) announced several calls for bids and block definition in the Eastern Canada region which includes the Jeanne d'Arc, Orphan, Scotian and Laurentian basins. Nalcor Energy, the Provincial Energy Corporation for Newfoundland and Labrador and the Offshore Energy Research Association of Nova Scotia (OERA) lead with Beicip-Franlab independent resource assessments of the different areas ahead of the calls for bids. Such projects aimed at conducting a basin analysis, play risk analysis and resource assessment based on available geological and geophysical data.

In petroleum exploration, understanding the lithological and stratigraphic basin architecture is a key component of a successful assessment. Such detailed 4D evaluation can only be possible with the use of Forward Stratigraphic Modeling (FSM) as a fundamental step of the workflow. FSM allows defining and characterizing reservoir, seal and source rock distribution and their fine heterogeneity in time and space, by assessing the complex interaction between accommodation space, sediment supply and transport through a combined simulation of sedimentary processes (continental to marine siliciclastics, carbonates). This numerical approach is at the very base of the recognition and definition of the different play systems in the Eastern Canada margin that concluded to repeated successful bid rounds.
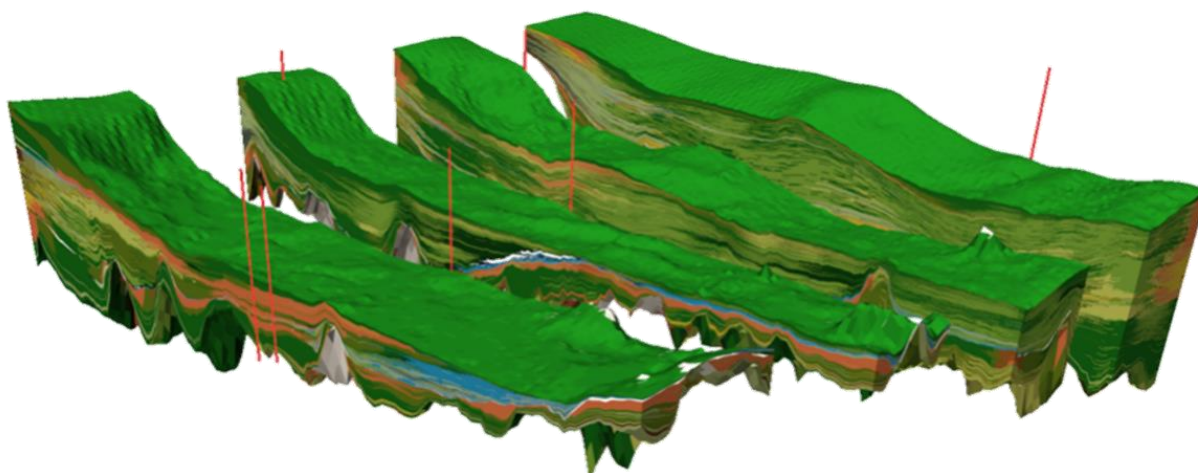
Figure 1: Orphan Basin DionisosFlow™ model. 3D fence diagram.

Backed-up by a sound geological and geophysical work consisting in sequence stratigraphic analysis and GDE mapping, this technology ultimately provides a geocube with various environmental properties such as lithologies (volume of sand, shale or carbonate) but also water energy, bathymetry, etc. Calibrated to well and seismic data, the model allows testing hypotheses on depositional environment, structural accommodation history, sedimentary source dynamics, pathways and sedimentary object styles. From the geocube, facies are interpreted as a function of their environmental properties allowing lateral and vertical extension of main sediment packages and geobodies to be addressed. Additionally, based on specifics environment conditions such as sedimentation and organic matter degradation rate within the substratum, source rock deposition and preservation can be modeled.

We present case studies from the exploration of the Eastern Canada margin where FSM was performed using DionisosFlow™ software. Sampling syn-rift to post-rift stratigraphy, clastic to carbonated to evaporitic systems, with facies ranging from shoreface to deep water turbidites, these studies showcase the added-value of FSM for oil & gas exploration with (some example presented in Figure 1 and 2):

- An optimal outline of the petroleum play definition based on the 4D distribution of main organic-prone sediments, reservoir and seal with respect to the stratigraphic framework;
- A detailed lithological understanding of the area ready for petroleum system modeling to further test hydrocarbon generation/expulsion/migration & entrapment modelling;
- A better assessment of the geological risk (Common Risk Segment mapping), by considering reservoir/seal presence and effectiveness.
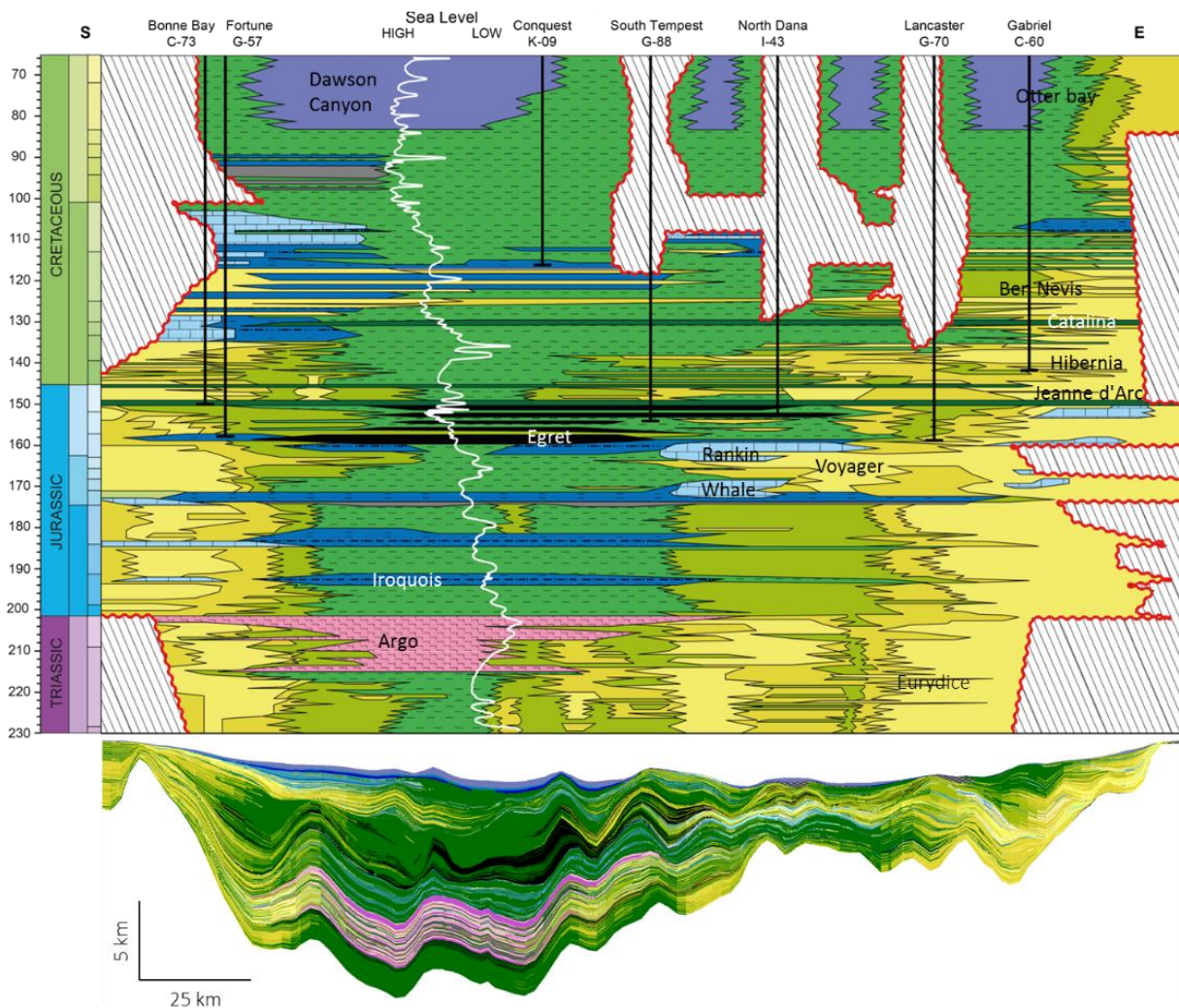
Figure 2: Eastern Jeanne d'Arc basin DionisosFlow™ model. Wheeler diagram and structural section.

NOTES:

Stratigraphic, early diagenetic and seismic forward modelling applied to the Natih Formation carbonates in Oman – an integrated approach to reduce uncertainty

Didier Granjeon[1]., Frans van Buchem[2]., Emerson Marfisi[3], Chris Gravestock[2]

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[2] *Halliburton, Abingdon*
[3] *Beicip-Franlab, Rueil-Malmaison*

The prediction of carbonate rock types in subsurface datasets is a major challenge in exploration and production. The combination of different consecutive processes, including the primary depositional environment, the stratigraphic and structural context, and different phases of diagenetic overprint and deformation processes, result in very heterogeneous petrophysical and petroacoustic characteristics causing a challenge for seismic imaging and interpretation. An integrated solution has been developed to reduce this uncertainty using stratigraphic and seismic forward modelling constrained by regional context and applied to one of the most prolific carbonate-dominated intervals of the Middle East, the Natih Formation in Oman.

The challenge of this study was to develop a fast and accurate workflow combining wireline log and outcrop interpretation, regional geological knowledge, and detailed sedimentological and diagenetic studies with deterministic stratigraphic forward and synthetic seismic modelling of a carbonate reservoir at an appraisal scale. A review of thickness and gross depositional environment maps extracted from the Neftex® Insights database allowed the definition of stratigraphic parameters such as accommodation space, carbonate production rates, and sediment transport parameters. A series of numerical simulations were performed using the DionisosFlow stratigraphic model to simulate sedimentological and diagenetic processes through geological time. The simulation results were used to estimate petroacoustic properties. Convolution of this rock property model with a synthetic wavelet made it possible to compare simulation results to seismic data. Finally, sensitivity analysis was performed to evaluate the impact of stratigraphic and diagenetic processes on the seismic signal.

This workflow has been applied to the Upper Cretaceous (Cenomanian, Turonian) Natih Formation in Oman at the appraisal scale (average thickness of about 200 m, simulated area about 40,000 km²). The carbonate system comprises rudist-dominated ramp and platform geometries bordering an organic-rich intrashelf basin. It is organised in three 3rd order depositional sequences which have been recognised across the Arabian Plate. The first two are mostly eustatically driven, whereas the third has a clear tectonic component. Subaerial exposure, incised valleys, and karstification are typically found associated with the 3rd order sequence boundaries and influenced reservoir properties. This overall sequence stratigraphic pattern can be applied as an exploration model at the scale of the NeoTethys Ocean.

By combining the Neftex Insight geological data base and the DionisosFlow stratigraphic forward model, the capability of this integrated geological and numerical workflow is shown to assist in the population of an earth model representation of the subsurface. The combination of geological knowledge and sedimentary process simulation provides 3D stratigraphic insight into white space outside of data control, which is a critical input for basin modelling and for the prediction of petroleum system elements.

NOTES:

Spatial and temporal prediction of shoreline–shelf depositional process regimes: Insights from palaeotidal modelling

Daniel S. Collins[1], Alexandros Avdis[1], Martin H. Wells[2], Andrew J. Mitchell[1], Peter A. Allison[1], Howard D. Johnson[1], Gary H. Hampson[1], Jon Hill[3], Christopher D. Dean[1], Matthew D. Piggott[1], Gerard J. Gorman[1], and Christopher C. Pain[1]

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Summary

Understanding tides is fundamental to predictive models of ancient shoreline–shelf process regimes. These models principally relate ancient tidal potential to shelf width (c. 10–100 km) and shoreline geometry (c. 1–10 km) but do not fully consider larger-scale basin physiography (100–1000 km) or variability in tidal influence with changing shoreline geometry. A refined predictive decision tree for ancient shoreline–shelf process regimes is presented based on a review of modern shoreline–shelf processes and several palaeotidal modelling studies. Modern depositional shorelines are overwhelmingly wave-dominated, suggesting the first-order control of wave fetch and meteorological conditions on shoreline–shelf processes. Palaeotidal models highlight the following separate controls: (1) 100–1000 km-scale physiography on tidal inflow versus outflow; (2) 10–100 km-scale shelf physiography on shelf tidal resonance potential; (3) tidal amplification (funnelling and shoaling) versus frictional effects in shoreline embayments (1–10 km scale); and (4) palaeogeographic uncertainty. The refined decision tree considers the influence of accommodation and sediment supply (A/S) ratio in terms of shoreline geometry. In addition, it considers the effects of basin physiography, shelf width and shoreline morphology on wave, tide and fluvial processes separately. Resulting predictions of process regime are limited to primary and secondary processes, due to uncertainty in the process classifications of modern shorelines and ambiguity in interpreting ancient mixed-process shoreline–shelf deposits. The result is an improved tool for predicting shoreline–shelf processes at exploration scale, including spatial–temporal changes in process regime which can be corroborated by the preserved sedimentary record.

Background

Seminal classification models of clastic shoreline–shelf processes regimes related the geomorphology of present-day deltas to the relative influence of wave, tidal and fluvial process (Coleman & Wright, 1975; Galloway, 1975). This ternary process classification was expanded by Boyd et al. (1992) to include a wider range of major depositional settings, including non-deltaic shorelines, and predictive evolutionary relationships linked to the rates of sediment supply versus relative sea level change (shoreline transgression vs. regression). Ainsworth et al. (2011) built upon these process-based models by developing the following: (1) a semi-quantitative classification based on the relative importance of primary, secondary, and tertiary processes (Fig. 1A); and (2) a predictive decision tree for spatial and temporal changes in shoreline–shelf process regimes (Fig. 1B). The decision tree integrated the effects of basin physiography (c. 100–1000 km scale) and shelf width (c. 10–100 km scale), fluvial versus wave effectiveness, A/S ratio, and shoreline morphology (c. 1–10 km scale) (Fig. 1B). In this model, basin-scale tidal potential is the first-order control and is principally controlled by shelf resonance potential, which is empirically correlated to shelf width. However, the effect of additional basin physiographic effects, especially the number, configuration, dimensions and bathymetry of ocean inflow and outflow connections, are not fully considered. Relatively local-scale tidal potential is related to shoreline geometry and highly embayed shorelines are predicted to be exclusively tide dominated (Fig. 2B). However, variations in the balance of tidal amplification versus frictional effects result in significant variability in tidal dominance in present-day shoreline embayments (e.g. Dalrymple et al., 1992; Collins et al., 2018; cf. Nyberg & Howell, 2016).
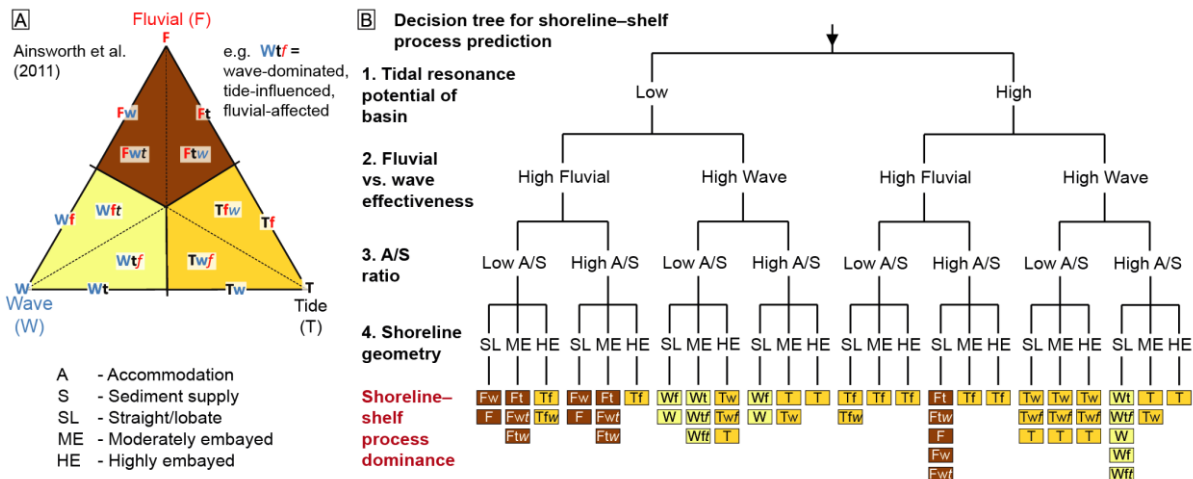
Figure 1. (A) Quantitative, process-based classification for shoreline–shelf systems. (B) Predictive decision tree for shoreline–shelf process regimes. After Ainsworth et al. (2011).

Key findings

1) Quantitative process classification of modern global shorelines suggests that wave processes (including storms), which are controlled principally by wave fetch and meteorological conditions, are the first-order control on shoreline processes and should be considered separately from fluvial processes (Nyberg & Howell, 2016).

2) Palaeotidal models and modern global tides highlight the following separate controls. First, in semi-enclosed basins (e.g. present-day South China Sea, North Sea), regional-scale (100–1000 km) physiography controls tidal inflow versus outflow; open-ocean systems are assumed to have a relatively high basin tidal potential. Second, although present-day tidal resonance potential increases with shelf width, this relationship also depends on shelf break geometry, the absolute ranges in shelf width, the dominant tidal constituent and frictional effects. Third, the balance between tidal amplification (funnelling and shoaling) and frictional effects in shoreline embayments (1–10 km scale) is highly variable: not all highly-embayed shorelines are tide dominated. Lastly, modelled palaeotides are highly sensitive to palaeogeographic uncertainty.

3) The A/S ratio is difficult to estimate and apply practically (Ainsworth et al., 2008; Ainsworth et al. 2011). Instead, the interpreted effect of the A/S ratio on depositional process regime (Ainsworth et al., 2011) can be applied in terms of shoreline geometry.

4) Classification of modern and ancient process regime is limited to primary and secondary processes due to uncertainty in the process classifications of modern shorelines and ambiguity in interpreting ancient mixed-process shoreline–shelf deposits.

NOTES:

Session Eight:
Local Integration

Invited Speaker: From Abu Madi to Zohr : reinassance of hydrocarbon exploration in the Eastern Mediterranean (Nile, Levantine) and role and perspectives of Biogenic Systems.

Fabio Lottaroli[1], Lorenzo Meciani[1] & Luigi Gugliotti[2]
[1] *Eni Upstream and Technical Services (Milano)*
[2] *Eni Var Energy (Stavanger)*

Summary

The area of the Eastern Mediterranean (Nile Delta Cone, Levantine and Herodotus Basins and the Eratosthenes Seamount) should be regarded, from a petroleum geology perspective, as a large, single Province. Its 60+ years of exploration history are marked by six major breakthrough rejuvenations, when new exploration plays were successfully opened. The first to be unraveled was the Messinian Play and the last the Cretaceous Carbonate play (2015, Zohr).

The exploration history of the Province is a unique example of how a basin perceived as mature can be rejuvenated by the development of new exploration concepts, with the largest discoveries made in the most recent past by the opening of new plays. Eni was a forerunner and main actor throughout the entire exploration history of the province. Zhor and Leviathan along with other discoveries worldwide have made biogenic gas plays stand out for their potential to deliver giant gas discoveries. This call for a re-thinking of the global relevance of biogenic plays, along with the need to establish new paradigms on biogenic gas potential.

Petroleum Geology Overview

Above a relic of the Late Paleozoic to Early Mesozoic Neo-Tethys rifting the area underwent significant subsidence for more than 100 m.y., resulting in basement buried under up to 14 km of Mesozoic and Cenozoic rocks.
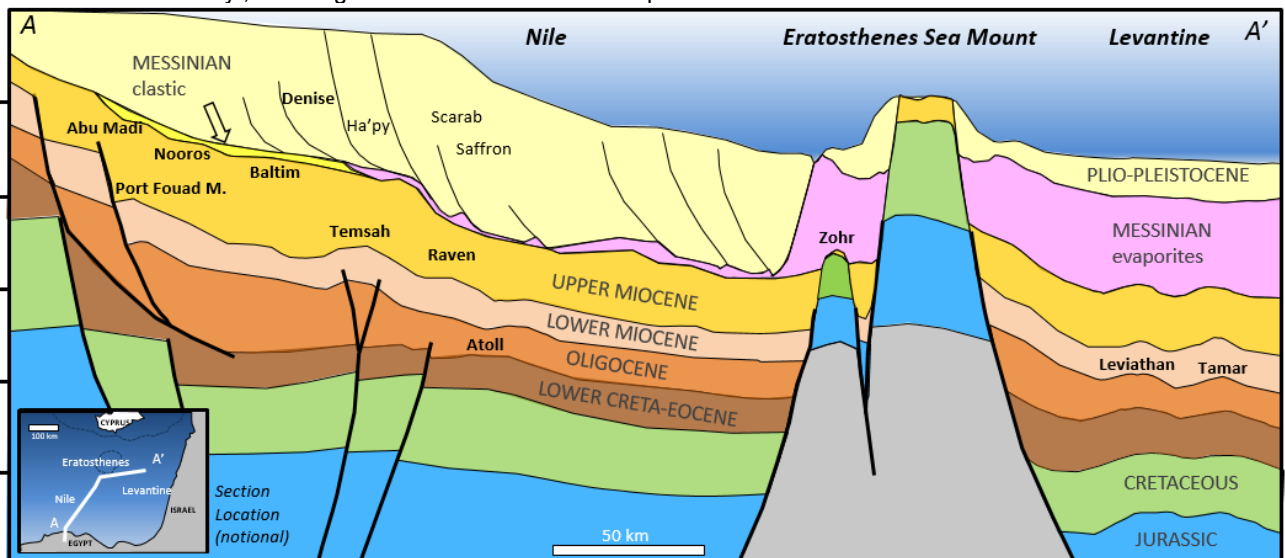
Fig. 1. Schematic geosection with the main exploratory plays and main discoveries stratigraphic position.

The articulated sedimentary sequence contains a variety of reservoirs, seal and source rocks (fig. 1) mostly hosted within pre-Messinian sequence. Several structural and stratigraphic elements characterize the province: the Nile Delta system and its submarine cone (Oligocene to Present); the Messinian evaporites, exceeding 2,000 m thickness in the depocenter; the pre-Messinian sequences. The Mesozoic succession, tested on the basin margins and on the Eratosthenes Sea Mount, a huge elevated structure, separating the Nile Delta/Levantine province from Cyprus thrust Zone to the North.

Exploration History

About 620 exploratory (New Field Wildcats) wells have been drilled in the area, discovering in excess of 20 Bnboe of recoverable resources/reserves (mostly gas) distributed in 215 discoveries, six of which can be classified as giant. The basin historical creaming curve (figure 2) represents several flat time-intervals indicating maturity of the plays explored until that moment. Interestingly, the largest discoveries (Zohr, Leviathan and Tamar, all in c. 1500 m WD) were made in the past 10 years, indicating that the understanding of the full basin potential was a long process.

The Six Exploration Play Openings - Breakthroughs
- Messinian Play (Abu Madi, 1967), with two important rejuvenation moments, Baltim in 1993 and Nooros in 2015. Amplitude/DHI supported play. Pioneers: Agip/Eni
- "Miocene" (pre-Messinian) Play. Tortonian-Serravallian structural-stratigraphic themes first (Temsah and Port Fouad Marine), then play rejuvenation with stratigraphic themes (Raven, 2004). Pioneers: Agip/Eni, then Bp.
- The DHI supported Plio-Pleistocene Play. Structural themes on the Eastern delta first (Denise), then stratigraphic development in the Western-distal section (Scarab, Saffron). Agip/Eni, then Bg, Bp.
- The Oligo-Miocene in the Levantine. Sub salt, deep water structural exploration on distal turbidites. (Leviathan, Tamar), almost 40 Tcf rec. res. Pioneer: Noble.
- The HP/HT Oligocene Play, still only marginally explored due to operational challenges and high costs (Atoll). Pioneer: Bp.
- The Carbonate Play (Zohr). Sub Salt, deep water structural exploration on Cretaceous carbonate platforms. Largest discovery in the basin (Zohr), 20+ Tcf rec. Pioneer: Eni.
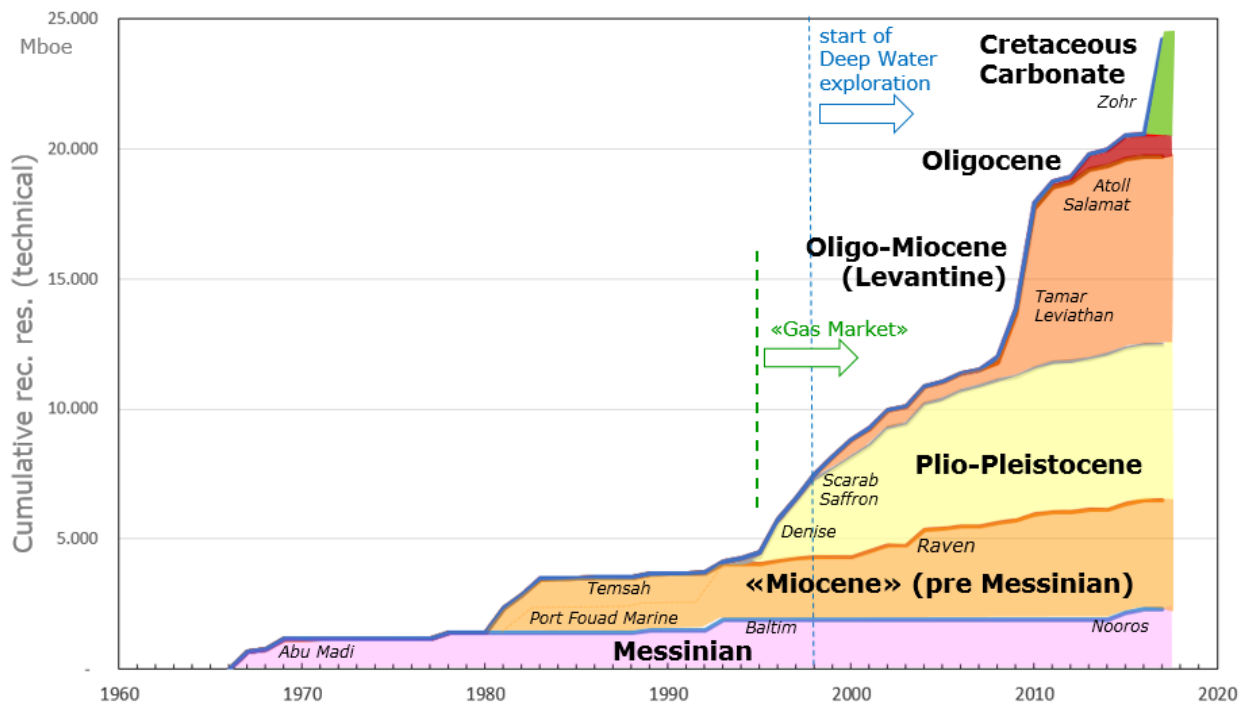
Fig. 2. Historical basin creaming curve, with the contribution of the various plays.

Biogenic Systems
The vast majority of the gas discovered in the East Mediterranean is of biogenic origin, and globally the last decade has seen a sharp increase of biogenic gas discovered in deep water. Eastern Med accounts for more than 80% of the Biogenic Gas discovered since 2007. The peculiar geological evolution of East Med (Messinian Salinity Crisis onset) is the key reason for this outstanding gas potential.

NOTES:

Understanding reservoir distribution in the Central North Sea: how much do we understand; how can we improve?

Thomas Harris Uist, Håkan Ledje & Trond Ødegård
Point Resources AS, Grenseveien 6, 4313 Sandnes Norway

The North Sea is a well explored basin, with reservoir (and non-reservoir) distribution well studied and documented. But to what extent is all of this knowledge used? Can we improve our exploration success?

Jurassic marine and paralic reservoirs can be understood using a sequence stratigraphic framework incorporating major tectonic episodes (e.g. Partington 1993; Rattey & Hayward, 1993; de Graciansky et al., 1998). Forcing a model to predict reservoir distribution can be problematic; but as a method of describing reservoir distribution, sequence stratigraphy can be powerful (Burgess et al., 2016).

Permo-Triassic arid continental reservoirs have been poorly understood until recently (Triassic mudstones group, Aberdeen University; McKie & Williams, 2009, Dorenbal & Stevensen (eds.), 2010). Extensive information has been published on the Southern Permian Basin (SPB) but little on reservoir development in the Northern Permian Basin (NPB). Recent exploration successes (and failures) have advanced our understanding of Permian-Traissic reservoirs in the NPB (e.g.Edvard Grieg, Luno II, Lupin).

Paleocene deep-water systems continue to be an exploration target along their pinch-out edge. They often have a predictable relationship between total sediment package thickness and sand presence. However, understanding the behavior of low-density and high-density turbidite systems and how they fill accommodation (e.g. Annot basin), as well as the behavior of the top of the Chalk/Shetland Group prior to the first sand ingression into the basin (Maureen/Ty Fm.), is vital in order to verify or disprove this relationship.

We present 3 examples where we attempt to understand reservoir distribution in space and time in the Central North Sea:
- Jurassic shallow-marine example: west flank of the Utsira High (Block 25/7)
- Permian arid-continental example: Ling Graben (Block 16/8)
- Paleocene deep-marine example: southern flank of the Utsira High (Block 16/7)

In all of these examples, appropriate tools (data) and methods are needed to unravel reservoir distribution. Accurate lithological, sedimentological and chronostratigraphic data from wells and cores is essential and needs to be integrated with broadband seismic data. An holistic approach, that integrates data over local and regional scales and uses well-documented theories and frameworks but isn't constrained by them, is needed to make predictions of reservoir distribution in both space and time.

Poor understanding of reservoir distribution has led to many 'bad' wells which were drilled in positions where good quality reservoir is highly unlikely to have been developed. These dry wells are often attributed to failure of source and migration, when in fact reservoir is the primary failure reason for the well.

Open data has been implemented in the North Sea (NPD, OGA) and if used unlocks huge amounts of information. An holistic approach looking at both new and old data allows us to make better predictions of reservoir distribution, which will ultimately improve our exploration success.

NOTES:

Session Nine:
21st Century Exploration

INVITED SPEAKER: Advances in prediction of lithology before drilling through seismic geomorphology and seismic stratigraphy analyses

Henry W. Posamentier
Posamentier Geosciences LLC

As worldwide exploration has expanded to progressively higher risk opportunities, the ability to manage and reduce risk through better prediction of lithology has become an essential component to business success. Direct imaging of depositional elements from 3D seismic data through the application of seismic geomorphology coupled with seismic stratigraphy has become an essential tool in this effort. With efficient and creative workflows geoscientists identify geologically significant patterns in both section – stratigraphy - and map views – geomorphology, and then populate these patterns with appropriate lithologies. This approach has been made possible through advances in computer hardware and software in recent years as well as through improvements in geophysical data acquisition and processing. Successful application of seismic stratigraphy and seismic geomorphology depends upon the following key workflows designed to extract maximum stratigraphic value from 3D seismic data: 1) Rapid reconnaissance and screening of seismic data through analysis of inlines, crosslines, and time/depth. 2) Continued reconnaissance and screening through analysis of optical stacks in the time/depth domain, 3) flattening volumes at or near target stratigraphic interval and evaluate horizon/stratal slices. Where no horizons stratigraphically close to target level are available upon which to flatten, "creative datuming" techniques should be employed. 4) Focusing on key horizons and extracting interval and horizon attributes. The role of illumination direction will be highlighted. These analyses should be applied to all available data such as full stack amplitude volumes, near/middle/far offset stack volumes, inversion volumes, spectral decomposition volumes, etc. The emphasis is on uncovering patterns that can lead directly to lithology prediction.

This presentation will review workflows and analytical techniques pertinent to seismic stratigraphy and seismic geomorphology. Emphasis will be placed on the need for iteration between section and plan views as a means of integrating stratigraphy and geomorphology. Examples of patterns observed from a broad range of depositional settings, both common as well as unusual, will be shown. Pitfalls as well as opportunities will be addressed.

NOTES:

Predicting Hydrocarbons in Space and Time with Artificial Intelligence and Modern Data Science Practices: Case examples from the Norwegian Continental Shelf

Eirik Larsen, Steve Purves, Arne Klepp Kvalheim, Jean Baptiste Bonas
Earth Science Analytics AS

Exploration and production history show that predicting the distribution of hydrocarbons is hard, although experience tells us that some stratigraphic and structural trends are more hydrocarbon prone than others. We know this as a result of the vast volumes of seismic-, well- and production-data acquired over many decades, and we have derived our knowledge from this data through collaboration and data-integration in multidisciplinary teams. The ever-increasing volume and modality of subsurface data is however exposing exploration geoscientists to a formidable challenge; how to extract the right intelligence from the data, and how to use this to make better decisions?

We are now in the midst of the data-science renaissance. It is timely to consider how we can leverage modern data-driven predictive analytics and artificial intelligence (AI) to enhance our understanding of the distribution of hydrocarbons in time and space. In this talk we will discuss; i) what we can predict today using (AI) technology, ii) what new insights we can gain, and iii) how this technology can be used to improve hydrocarbon exploration and production success.

AI, and more specifically machine-learning (ML), is now being used, across multiple domains; to reveal hidden relationships in data, and to predict properties as nonlinear functions of measured data. The technology is said to mitigate human biases through models derived directly from data, whose accuracy can be measured by blind testing against the data itself.

So, how does ML work, and what can these models learn directly from the data we use in hydrocarbon exploration and production? ML can be used to; i) identify inherent structure in data using unsupervised learning, ii) learn, transfer functions that maps an input to an output based on many examples of input-output pairs (supervised learning) iii) learn to model complex phenomena and create new examples of them (generative learning). Unsupervised learning has long been used by; petrophysicists in electrofacies analysis; and geophysicists for multi-attribute analysis. Supervised learning has also been used to infer rock properties from wireline logs and to segment seismic facies from 3D volumes. However, the variety, sophistication and power of these approaches have grown significantly alongside maturing of approaches such as generative learning that are new to geosciences. These methods, and others which we will illustrate, are transforming subsurface workflows across many sub-disciplines of petroleum geoscience. We will review the application of data science practice and artificial intelligence using case examples from the Norwegian Continental Shelf, on both regional and local scales.

On a regional scale we have trained supervised ML models with well-log data (as features) and data from core, and/or from physics models (as target labels). We have conditioned wireline logs across several 100 wells in order to enable prediction of rock and fluid properties across the entire drilled stratigraphy. We have measured prediction accuracies using a cross-validation approach with blind testing against all wells in the dataset. The data-types we have predicted includes porosity, permeability, lithology, sedimentary facies, source rock properties, and fluid saturation among others.

On a local scale we have trained supervised ML models with partial-stack seismic data (features) and rock- and fluid-property data from wells (labels). Deep convolutional neural networks were used to predict rock- and fluid property cubes based on upscaled version of the inferred property logs. Wells within the bounds of 3D surveys were used for blind cross validation allowing network hyperparameters to be tuned and model performance to be assessed.

In order to provide stratigraphic and structural context to the predicted rock and fluid property data we have used automated seismic interpretation techniques to interpret stratigraphic units and faults from seismic data. We used

fully convolutional deep networks for fault interpretation, and deep encoder-decoder networks such as SegNet for stratigraphic interpretation. These techniques classify 3D seismic post stack datasets achieving a high level of consistency based on a relatively small number of expert labelled regions.

Since geological interpretation and prediction is typically based on sparse and low-resolution data and is inherently uncertain, we apply methods such as Bayesian neural networks to determine model uncertainty for automatic seismic interpretation. We efficiently integrate scenario analysis with ML modelling to construct multiple models based on variations of the input data. So, in addition to applying a data-driven approach we aim to make uncertainty analysis fundamental to everything that geoscientists do.

The incredibly rich subsurface data and metadata available in national data repositories and company databases can, and is starting to, serve as rich resources for training machine learning models at scale. When we can use machine-learning technology to build models at scale, using well and seismic data, we can start to piece together the data-driven puzzle needed to define and characterize known and potential hydrocarbon accumulations. We can now begin to; i) leverage machine learning in play screening, using all the available log, core and seismic data, ii) apply machine learning models to reveal missed pay intervals, which frequently have been the inception of successful discoveries, and iii) identify and characterize prospects, discoveries and fields. These tasks typically require use of multiple ML models to be applied to multiple data types, and that we use technology to achieve true data-driven integration.

ML technology paired with solid data science practice; i) facilitates integration of data and disciplines, ii) enables geoscientists to exceed current best practice with the ML tools available today, and iii) paves the way to the "new" best practice which is integrated data science and geoscience. What the future holds is more automation and more reliable data analytics platforms. Geo/data scientists will spend less time on hands on data science, needed to make systems run, and more time on being creative, searching for and characterizing opportunities to build the basis for successful data-driven exploration and production decisions.

NOTES:

INVITED SPEAKER: Towards One Technology-Driven Earth Science: the role of technology and digitalization in driving hydrocarbon exploration and exploitation

Ole J. Martinsen
Equinor

The development of geophysical technology and geological methodology have been closely interlinked since the 1950s. Technology has allowed for mapping and seeing relationships between geological features and driven the development predictive geological techniques such as time stratigraphy, seismic and sequence stratigraphy, 3D and 4D seismic mapping techniques, remote sensing studies and Google Earth, and not least source-to-sink (S2S) methodology. In all respects, these geological breakthroughs have resulted from a digital journey from early basic mapping techniques to the current digital revolution. Increased scales of acquisition, processing and resolution of geophysical data from seismic to remote sensing have been critical to these advances. In many respects, these advances are in the spirit of William Smith, because geological mapping is the technique still critical to handle. Nevertheless, the content, complexity and components of the maps have obviously changed through time, and not least our abilities to analyze them.

In more detail, the developments from time stratigraphy through seismic and sequence stratigraphy to S2S, is a journey of increasing predictability from surface mapping of stratigraphy onshore through a two-dimensional representation of basin stratigraphy to a three- and four-dimensional (time included) insight into how basins fill. Nevertheless, scale is a fundamental component, and computer processing power has allowed to create high-resolution, margin-scale overviews on onshore (remote sensing) and offshore (seismic) stratigraphic development. While previous techniques have concentrated either on the onshore or offshore parts of basins, S2S combines the two main segments and allow for a complete understanding of sediment erosion, generation, transport and deposition. This integration considerably increases confidence in prediction and allows for basin ranking at a different level than previously, both for reservoir and source prediction.

New capabilities introduced by the new wave of digitalization, such as artificial intelligence and machine learning provide possibilities not conceivable only a few years back. Now there is ability to scan through vast and even left-behind databases. Still, the outcome is to see geological relationships in map format, naturally in a more advanced way than William Smith's map that changed the world, and particularly those that the human brain cannot process. However, to allow for this to create material results for the identification of hydrocarbons, the new digital tools created need to be formed with that result in mind. The potential is there to create a new large breakthrough in geology like the previous ones, but probably even better founded in relevant data examples identified through the new digital techniques. The product will likely also drive initially separate earth science fields towards One Earth Science.
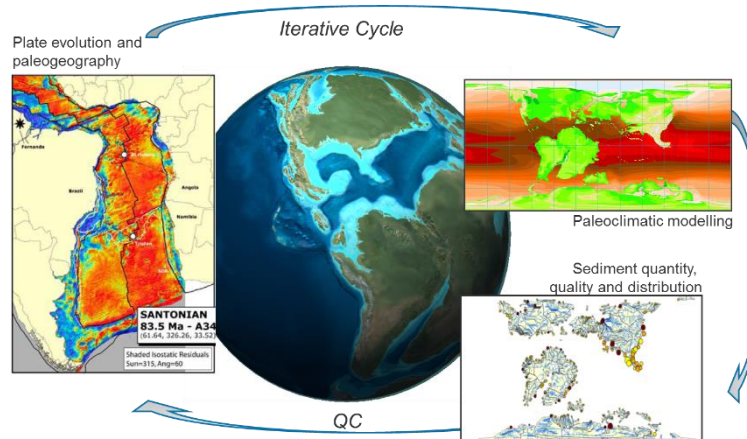

Figure 1: Digitalization allows for combined Earth models to be built with increasing resolution

NOTES:

Gsl Code of Conduct for meetings and other events

Introduction

The Geological Society of London is a professional and learned society, which, through its members, has a duty in the public interest to provide a safe, productive and welcoming environment for all participants and attendees of our meetings, workshops, and events regardless of age, gender, sexual orientation, gender identity, race, ethnicity, religion, disability, physical appearance, or career level.

This Code of Conduct applies to all participants in Society related activities, including, but not limited to, attendees, speakers, volunteers, exhibitors, representatives to outside bodies, and applies in all GSL activities, including ancillary meetings, events and social gatherings.

It also applies to members of the Society attending externally organised events, wherever the venue.

Behaviour

The Society values participation by all attendees at its events and wants to ensure that your experience is as constructive and professionally stimulating as possible.

Whilst the debate of scientific ideas is encouraged, participants are expected to behave in a respectful and professional manner - harassment and, or, sexist, racist, or exclusionary comments or jokes are not appropriate and will not be tolerated.

Harassment includes sustained disruption of talks or other events, inappropriate physical contact, sexual attention or innuendo, deliberate intimidation, stalking, and intrusive photography or recording of an individual without consent. It also includes discrimination or offensive comments related to age, gender identity, sexual orientation, disability, physical appearance, language, citizenship, ethnic origin, race or religion.

The Geological Society expects and requires all participants to abide by and uphold the principles of this Code of Conduct and transgressions or violations will not be tolerated.

Breach of the Code of Conduct

The Society considers it unprofessional, unethical and totally unacceptable to engage in or condone any kind of discrimination or harassment, or to disregard complaints of harassment from colleagues or staff.

If an incident of proscribed conduct occurs either within or outside the Society's premises during an event, then the aggrieved person or witness to the proscribed conduct is encouraged to report it promptly to a member of staff or the event's principal organiser.

Once the Society is notified, staff or a senior organiser of the meeting will discuss the details first with the individual making the complaint, then any witnesses who have been identified, and then the alleged offender, before determining an appropriate course of action. Confidentiality will be maintained to the extent that it does not compromise the rights of others. The Society will co-operate fully with any criminal or civil investigation arising from incidents that occur during Society events.

Burlington House Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshal on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
> Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre
> Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance
> Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society. Event organizers should report as soon as possible to the nearest Fire Marshal on whether all event participants have been safely evacuated.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

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

ROYAL ACADEMY
COURTYARD

MUSTER POINT
(outside Royal
Astronomical
Society)

EXIT

CLOAKROOM

GENTS

LECTURE THEATRE

GENTS

LADIES
DOWN

MAIN
RECEPTION

EXIT

EXIT

EXIT

STAFF
ONLY

LOWER LIBRARY

MAIN
RECEPTION

MAIN ENTRANCE
TO GEOLOGICAL
SOCIETY

Entrance to
Royal Academy

PICCADILLY

The Geological Society

serving science, profession & society

Registration Open

**Celebrating the life of
Chris Cornford (1948-2017)**

Petroleum Systems Analysis 'Science or Art?'

24-25 April 2019

The Geological Society, Burlington House, London

Approaches to tackling the scientific and practical questions in the fields of Petroleum Geochemistry and Petroleum Systems Analysis range from the entirely theoretical to the empirical. Chris Cornford embraced both in his working life. The integrated approach he espoused will form the basis of the technical programme for the Conference covering two themes:

- Recent developments in the use of data including integration of models and (big) data; use of visualisation and data exploration or mining techniques.
- Topical issues & controversies ranging from mass balance approaches, petroleum migration to specific modelling studies and practical applications.

The Conference will be inspired by Chris' ethos of innovation, encouragement of youth and challenging received wisdom.

For further information please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Tel: +44 (0)20 7434 9944 or email: sarah.woodcock@geolsoc.org.uk

Convenors:

Steve Lawrence
Subsurface Resource Consulting

Dan Cornford
IGI Ltd

Elin Rein
Equinor

David Gardiner
IGI Ltd

Abhen Pather
RPS Energy

Mark Groves Gidney
Energetical

Richard Bray
Subsurface Resource Consulting

John Argent
Sound Energy

Mark Osborne
BP

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Call for Abstracts

Capturing Geoscience in Geomodels

26-27 June 2019

Robert Gordon University, Aberdeen
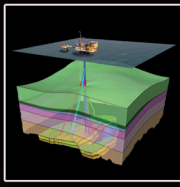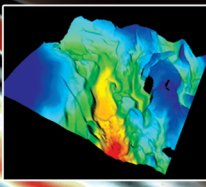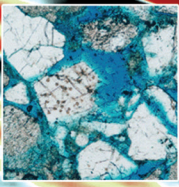
Convenors:

Matt Jameson
Glencore

Gwilym Lynn
Shell

Leigh Truelove
Schlumberger

Ingrid Demaerschalk
Tullow

Alun Griffiths
Rockhopper

Catherine Tonge
Shell

David Hulme
Equinor

Tom Marsh
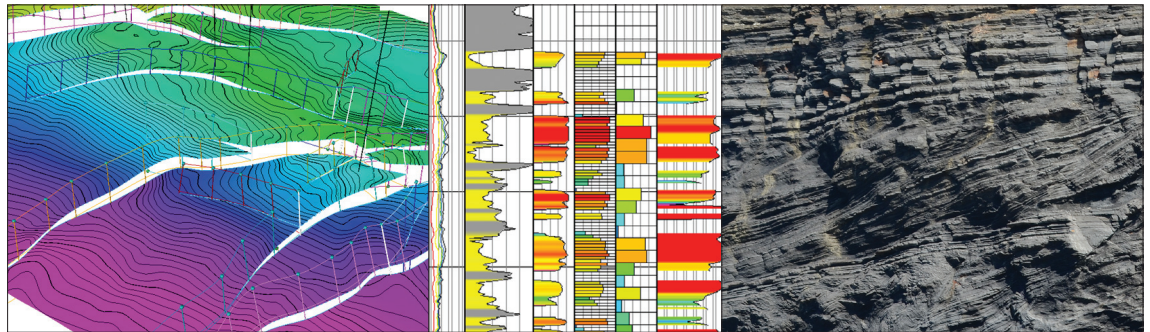Rock Flow Dynamics

James Aguas
Halliburton

Over recent years the construction of 3D static and dynamic reservoir models has become increasingly complex. With the availability of extensive tools and technology it is important not to forget the objective of the modelling process.

As we develop our hydrocarbon fields it is essential that 3D Static Models be built with fit-for-purpose geological models, honouring the geological, geophysical and petrophysical data that they are created from.

This two-day conference will explore how geoscience information should be used to best effect, and how to identify when geoscience data may no longer add value. Sessions will include the following themes:

- Data integration: seismic, well log, sedimentological, core dynamic data and beyond
- Capturing conceptual geology in reservoir modelling for different settings and depositional environments
- Scale: geology vs model vs data
- Uncertainty: dealing with geological uncertainty in modelling and understanding its benefits and limitations
- Embracing new modelling technology and approaches.
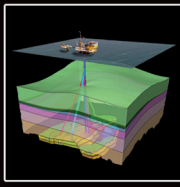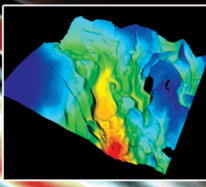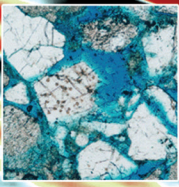
For further information please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Tel: +44 (0)20 7434 9944 Web: https://www.geolsoc.org.uk/PG-Geomodels

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Registration Now Open

Petroleum Geology of Mexico and the Northern Caribbean

14-16 May 2019

The Geological Society, Burlington House, Piccadilly, London

2017 Zama Discovery
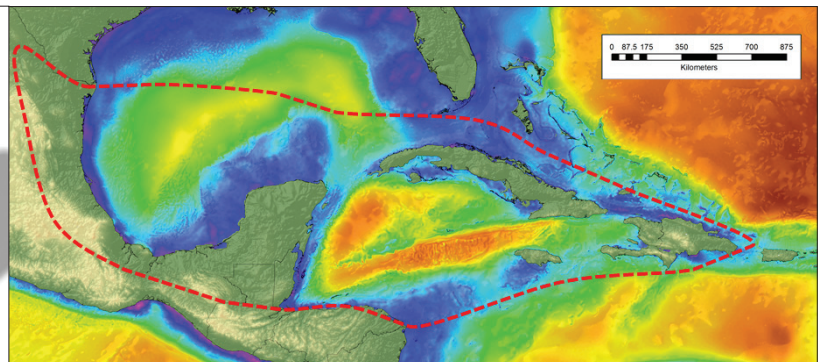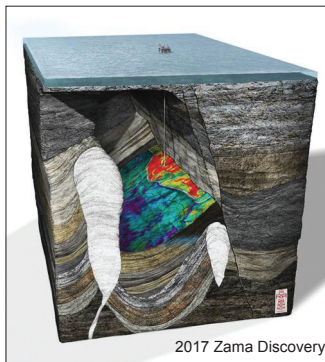
The Gulf of Mexico is a world class prolific hydrocarbon system. As a result of recent energy reform the Mexican sector of this basin has been open to international companies for the first time through a series of competitive licence rounds. The first phase of drilling on these newly awarded permits has resulted in the discovery of giant hydrocarbon accumulations in the Mexican offshore sector. Geologically, the offshore and onshore basins of Mexico offer a diverse range of play types with multiple source / reservoir pairs and are characterised by complex tectonic evolution with associated halokinesis and shale tectonics.

More widely within the Northern Caribbean region, exploration activities are ongoing in several countries targeting both proven and frontier petroleum systems. Some of these play elements are potential extensions of the proven systems in Mexico. While geologically complex, these areas have the potential to emerge as major hydrocarbon basins.

An excellent series of abstracts have been submitted for the conference which have been arranged into the following themed sessions – Mexico Regional Tectonics, Mexican Basins - Sureste, Campeche, Burgos, Perdido Basins, Onshore Basins, Northern Caribbean Regional Tectonics, Northern Caribbean Basins Reservoir Distribution, Petroleum Systems and Salt Tectonics with the following Keynote Presenters:

- *Elisa Fitz-Diaz, Instituto de Geología, Universidad Nacional Autónoma de México*
- *Iain MacEwen, Premier Oil*
- *Chris Matchette Downes, CaribX Limited*
- *Jim Pindell, Tectonic Analysis Ltd*
- *Mark Rowan, Mark Rowan Consulting*
- *John Snedden, The University of Texas*

Registration is now open and the full conference program is available on the Geological Society Website: https://www.geolsoc.org.uk/petroleum

Poster submissions are still being accepted until 15th March 2019 and the committee would encourage further submissions for this category.

For further information please contact:

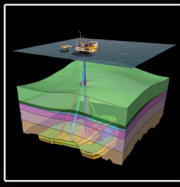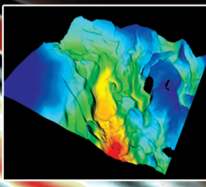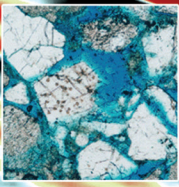Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Tel: +44 (0)20 7434 9944

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www.geolsoc.org.uk/petroleum
#PGMexico19

Convenors:

James Hammerstein
Royal Holloway
University of London

Jürgen Adam
Royal Holloway
University of London

Clare Bond
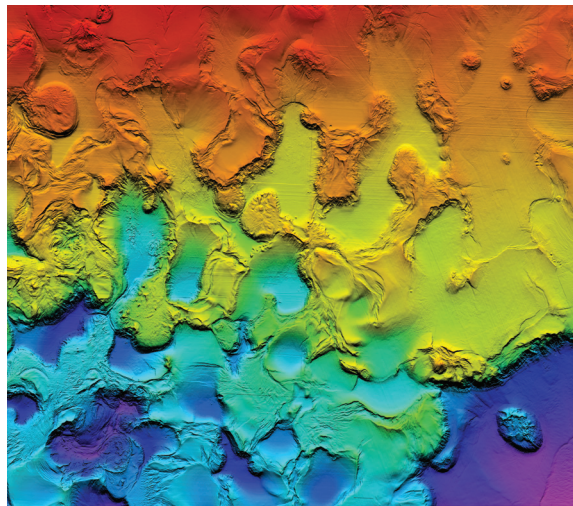University of Aberdeen
and Tectonic Studies
Group

Christina Von Nicolai
BP

Call for Abstracts – Deadline: 31 May 2019

Salt Tectonics:
Understanding Rocks that Flow

29-31 October 2019

The Geological Society, Burlington House, Piccadilly, London

The complex behavioural and rheological characteristics of salt can strongly influence the structural and stratigraphic evolution of a basin. With many of the largest hydrocarbon provinces existing within salt-related basins understanding of the processes involved in salt tectonics has important scientific and economic implications for geological research and hydrocarbon exploration.

Modern high-resolution 3D seismic data with improved imaging of salt structures in combination with more advanced physical and numerical modelling techniques revolutionises the way we see salt tectonics and the role of salt structures.

This three-day international conference aims to bring together leading academic and industry geoscientists to discuss new techniques and case studies, and to capture an up to date assessment of our understanding of salt tectonic processes including:

- Geographical case studies; e.g. North Sea, Gulf of Mexico, Persian Gulf, Campos Basin
- Salt tectonics in extensional and contractional settings
- Halokinetic sequence stratigraphy
- Analytical methods of interpreting salt in seismic data
- Physical and numerical modelling of salt tectonics
- Implications of salt tectonics for hydrocarbon exploration.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 31 May 2019.

For further information please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Tel: +44 (0)20 7434 9944

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Conferences and Abstract Deadlines

Petroleum Systems Analysis 'Science as Art'?

24-25 April 2019
Registration Open
The Geological Society, London
www.geolsoc.org.uk/PG-Celebrating-the-life-of-Chris-Cornford

Petroleum Geology of Mexico and the Northern Caribbean

14-16 May 2019
Registration Open
The Geological Society, London
www.geolsoc.org.uk/PG-Mexico-and-Northern-Caribbean

Capturing Geoscience in Geomodels

26-27 June 2019
Call for Abstracts: Deadline 12 April 2019
Robert Gordon University, Aberdeen
www.geolsoc.org.uk/PG-Geomodels

Salt Tectonics: Understanding Rocks that Flow

29-31 October 2019
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The Geological Society, London
www.geolsoc.org.uk/PG-Salt-Tectonics

Image: Laminated sandstones on Gullane beach © Milena Farajewicz