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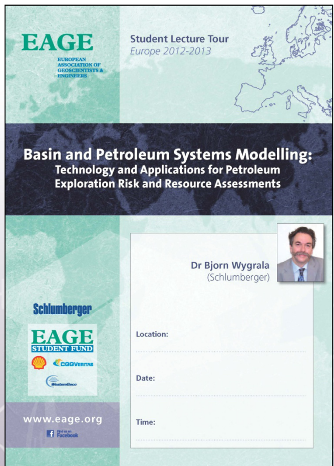

Basin and Petroleum Systems Modelling:
Technology and Applications for Petroleum Exploration Risk and Resource Assessments

By Dr Bjorn Wygrala
Schlumberger

EAGE

EAGE Student Lecture Tour 2012-2013

Basin and Petroleum Systems Modeling: Technology and Applications for Petroleum Exploration Risk and Resource Assessments

Course Note

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Introduction

Foreword

These **Lecture Notes** describe the general content of the lecture, however they are not copies of the presentations, as most of the lecture will be live software presentations of applications. The intent is also to give the audience an opportunity to obtain information in advance, to follow the lecture without being distracted, and to enable the lectures to be customized to specific requirements and updated if necessary.

Abstract

The stage will be set with general information about **petroleum exploration and production (E&P)** and how the industry operates. The goal is to give the audience a feeling for the scope of the task as well as of the scale, costs and risks of the operations and of the investments and decisions that have to be made.

Basin and Petroleum Systems Modeling will then be introduced, starting with the rationale for models and process modeling in the geosciences, and followed by an introduction to the data types, workflows and goals of typical applications. Rather than just showing these points in theory, a case study will be used in a live software presentation to illustrate all of these points. Audience participation and questions will be encouraged in order to ensure that the key issues are understood. This part will conclude with a summary of the roles of the various geoscientific disciplines and show that the technology is integrative and can only be successfully applied with a truly interdisciplinary approach.

The **technology** itself will then be introduced in more detail. What are the controlling factors for the development of oil and gas resources, and how can these be simulated with geological process modeling in order to at first understand petroleum distributions and properties, and then to predict them. As petroleum generation is primarily a function of temperature and geologic time, thermal history modeling is the first step. As distributions of oil and gas and in particular their phase are controlled by temperatures and pressures, pressure history modeling is then introduced. This is followed by a review of the methods that are available to simulate the entire process of petroleum generation, expulsion, migration, accumulation and loss in petroleum systems, and a discussion of special technical challenges such as geomechanics.

Applications of the technology will then be presented, with options ranging from frontier exploration in which large areas with only sparse data are screened, to petroleum resource assessments of yet-to-find oil and gas, to detailed assessments of exploration risks in structurally complex areas, as well as applications for unconventional oil and gas exploration.

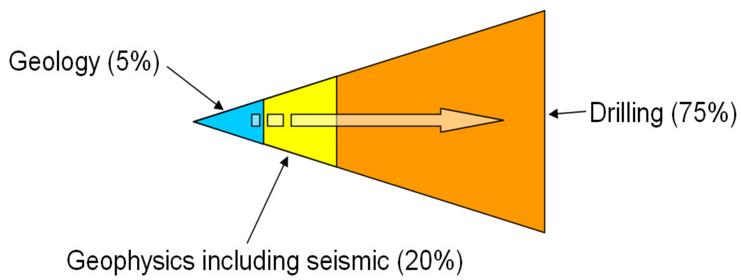
The lecture will conclude with some key references and recommended reading, as well as a review of academic and professional opportunities to show possible next steps that can be taken by the students to develop their careers.

Oil and Gas Resources and Exploration

Global Energy Resources and Petroleum Exploration

Energy is the most important single resource to enable the essential functions of human society to be performed at present and in the future. The acquisition and management of all other resources are primarily controlled by the availability of energy. At present, fossil fuels and especially petroleum (oil and gas) are the most important source of energy and this will remain so for many decades. The value of these energy resources is substantial and enormous financial resources are required to find, produce, and distribute petroleum and petroleum products. It is therefore not surprising that the Petroleum Exploration and Production (E&P) industry is one of the largest global industries. The risks and the required resources are particularly high in **petroleum exploration**, and examples will be shown to demonstrate the scale, costs and risks that the E&P industry has to address.

The lecture will address the Geoscience component of petroleum exploration which is only responsible for a relatively small part of the total cost of exploration, but which has a critical effect on the other significantly more expensive components.



Conventional and Unconventional Resources

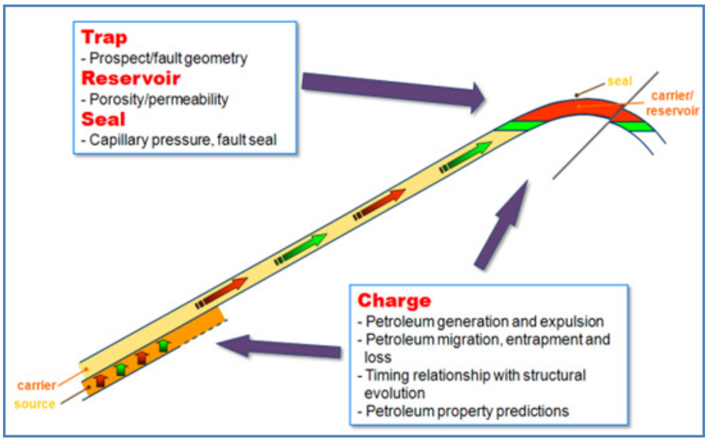
Oil and gas is the result of the thermal maturation of organic material that was deposited in sediments (**source rocks**) and then subjected to increasing temperatures through geologic time as the rocks were buried by overlying sediments. The original organic material is converted to oil and gas as a function of temperature, time and the type of organic material. It can then be **expelled** from the source rocks and migrate through a basin until it is trapped by a favourable combination of structural, reservoir and seal properties. This process results in **conventional** oil and gas which is defined as petroleum occurring as discrete accumulations or fields, and which has been the principle target of exploration since the first oil well was drilled more than 150 years ago.

However, generated oil and gas in source rocks can also be partially **retained** in the source rocks, and major technical breakthroughs which were initially developed in the 1990s now enable gas (and increasingly oil) to be directly produced from the source rocks. These shale gas and shale oil plays are commonly described as '**unconventional'** as opposed to conventional oil and gas occurrences. However, these are not the only new, unconventional resources: for example gas hydrates also have potential to be major energy sources in the future. Both conventional and unconventional hydrocarbon resources will be addressed and examples will be shown in the lecture.

Geological Risk Factors in Exploration

In petroleum exploration, the main geologic uncertainties and therefore the principle risk factors are related to the 'essential elements' which are needed for a petroleum accumulation to exist. These essential elements are always the same in any exploration risk assessment, regardless of whether it is being performed on a basin, play or prospect scale. They are:

- the **Trap** (geometry, reservoir, seal)
- the **Hydrocarbon Charge** (the amount of hydrocarbons which can reach the trap)
- the **Timing** relationship between the Charge and the formation of the Trap.



The term '**petroleum system'** is used in petroleum exploration to describe the geological elements and processes that need to be in place for a petroleum accumulation to occur (Leslie B. Magoon and Wallace G. Dow, AAPG Memoir 60). These **essential elements** are the source, reservoir, seal and overburden rocks, and the **essential processes** are petroleum generation, migration and accumulation, as well as the timing relationship with the structural evolution of the trap and its properties. The same geological principles apply in both conventionals and unconventionals: in conventionals, exploration is directed at the expelled and migrated hydrocarbons, while in unconventionals the retained hydrocarbons are of interest.

There are some fundamental issues which must be taken into account:

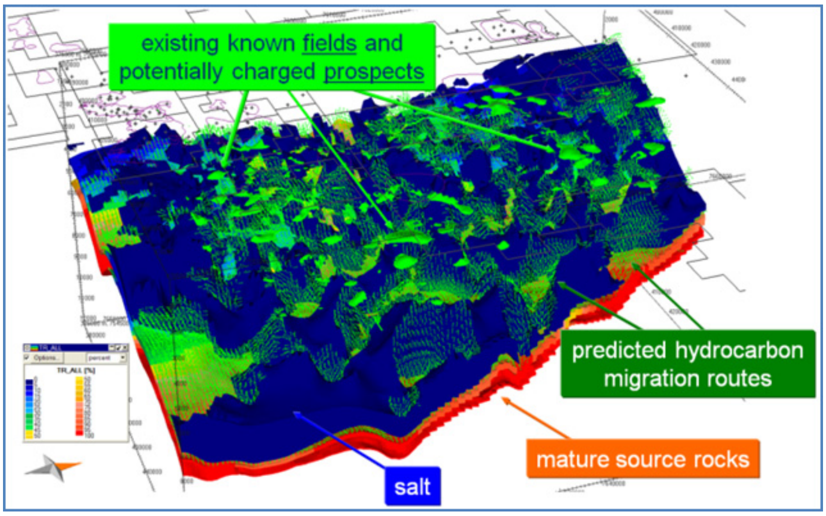
- The principle of the **'weakest link'** applies, i.e. if one of the essential elements Trap Geometry, Reservoir, Seal, Hydrocarbon Charge or Timing is missing, a prospect will not be viable.
- All geoscience data has **uncertainties**, most of which are significant. This applies to every type of geophysical and geological data, as most data cannot be obtained directly and quantifications are mostly subjected to scaling issues. Uncertainties are an inherent part of every geoscientists work: their job is to make decisions based on uncertain data and for this they need to be able to assess the effects of the uncertainties on their assessments.
- As petroleum occurrences are the result of geological processes, **deterministic** analyses are essential. However, uncertainties necessitate **statistical** analyses in order to understand their effects. Both approaches are therefore required.

Basin and Petroleum Systems Modeling

Models are an essential part of any analysis. When we construct a geologic cross-section from outcrop studies, we are constructing a model which represents our understanding of the geology. Even if we have no data, we can construct conceptual models, for example based on analogues. Models are never unique and never 'correct', but they are nonetheless essential to structure, perform and communicate our analyses and they always evolve as additional data is acquired and our understanding improves.

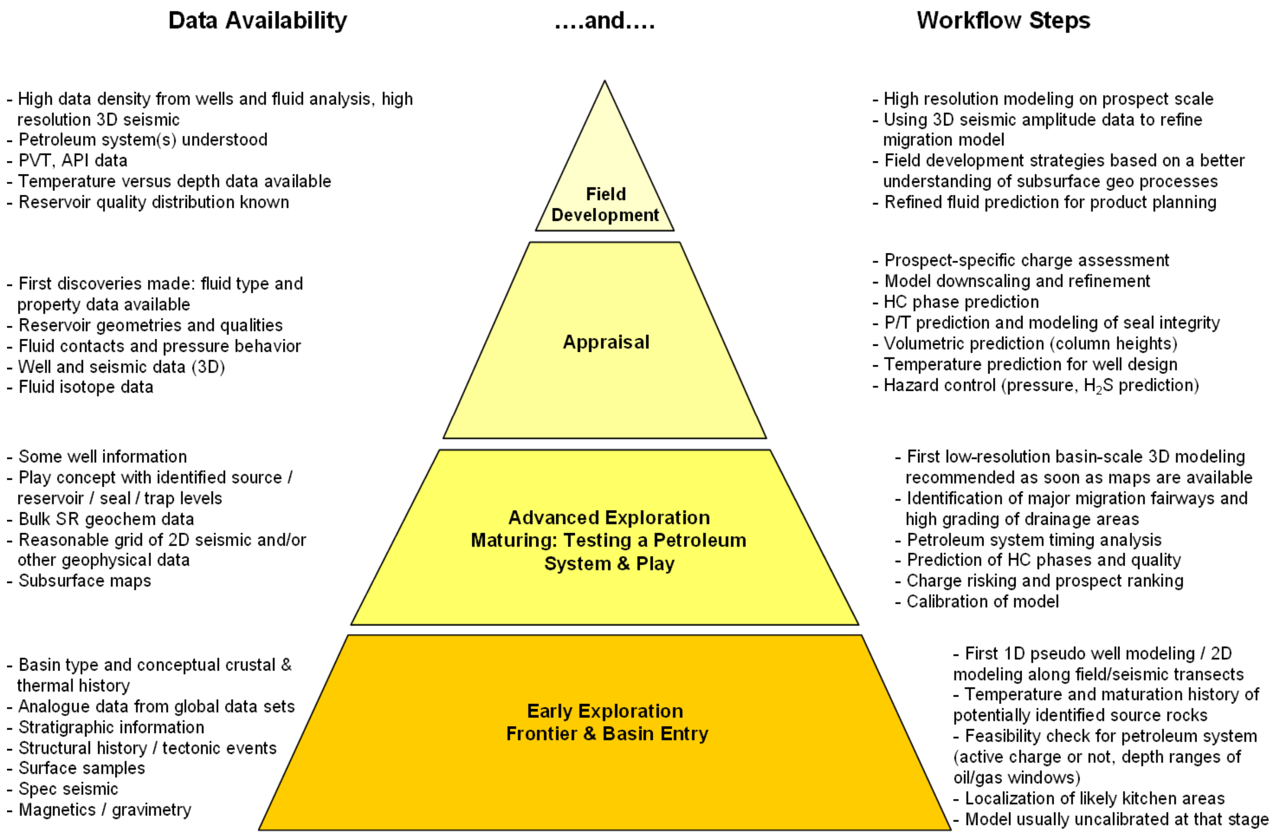
A **Petroleum Systems Model** is a digital data model of a petroleum system in which the interrelated processes and their results can be simulated in order to understand and predict them. A Petroleum Systems Model is a preferably 3D representation of geological data in an area of interest, which can range from a single charge or drainage area to an entire basin. A Petroleum Systems Model is dynamic which means that Petroleum Systems Modeling provides a complete and unique record of the generation, expulsion vs. retention, migration, accumulation and loss of oil and gas in a petroleum system through geologic time!

Petroleum systems modeling is used to process geological data models in conventional and unconventional petroleum systems in order to obtain information on parameters and processes which control the generation and accumulation of oil and gas. They are used to improve our understanding and then to enable better predictions to be made.



The technology originated in the mid 1970s when researchers in geochemistry, after realizing that hydrocarbon generation was determined by temperature and geologic time, developed and published the first usable chemical kinetics. The name **'basin modeling'** was then used to describe the first generation of tools but has gradually been replaced by the term **'Petroleum Systems Modeling'**. This was due to the definition and propagation of the Petroleum Systems methodology, the increasingly widespread use of the term in the industry, and the close match of the methodology and the modeling technology after the introduction of petroleum migration modeling capabilities.

Petroleum systems modeling is now widely applied to address many aspects of the E&P processes from early exploration to field development, as shown in the following diagram (Dietrich Welte and Harald Karg).



Petroleum Systems Modeling Technology

Thermal History Modeling

As **petroleum generation** is a function of temperature and time, thermal history modeling is the primary goal of petroleum systems modeling and temperature predictions are a key application result.

Temperature distributions within a basin are the result of **heat flowing** into the base of the sedimentary sequence and then being conducted through the sediments to their surface. The controlling physical parameter is the bulk thermal conductivity of the rocks which is a function of their matrix conductivity (which depends on mineral types and shapes) and the conductivity of the pore fluids, and therefore of the porosity.

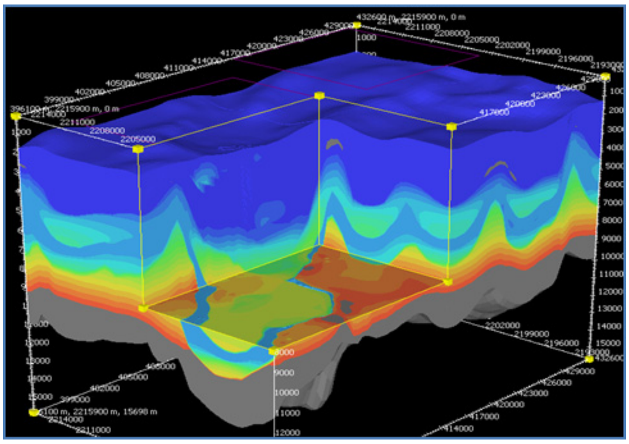
As sediments compact with increasing depths, their porosities and the amount of pore fluids are reduced, so that their bulk thermal properties change. The thermal properties of a specific stratigraphic unit will therefore change with increasing burial through geologic time. The **thermal gradient** shows the temperature increase within a specific unit, and is a result of the bulk thermal conductivity of the unit and the heat flow. High thermal conductivities (e.g. in sandstones) will enable more effective heat transfer and the resulting temperature increase will be lower. Low thermal conductivities (e.g. in shales) will retard heat transfer and result in higher temperatures with the same heat flow input; this is often described as a 'thermal blanketing' effect by sediments such as shales. Thermal gradients will therefore change in each rock unit and through geologic time. This means that using an overall or average thermal gradient for an entire sedimentary column and through geologic time is neither geologically nor physically meaningful. Additional complications in temperature calculations arise from non-steady state conditions when burial rates are high and temperature increases cannot 'keep up' with increasing burial rates, but most modern thermal simulators can take these into account.

There can be other factors which need to be taken into account for accurate temperature predictions. Heat flow is predominantly a vertical process, but rock units with differing thermal properties such as salt domes (salt has very high thermal conductivities) will lead to lateral distortions of the temperature field which can only be simulated with full 2D or even better with full 3D thermal simulators. In some basins, convection processes, for example due to regional aquifer flow systems, can distort the normal temperature distributions as convection is an effective heat transfer process.

Basic thermal modeling tools use 1D or multi-1D thermal calculations which are sufficient for first-pass calculations, but which can deliver insufficiently accurate results if geologic conditions are more difficult as described in the preceding section. Full 2D or better 3D and non-steady state thermal modeling solutions therefore always ensure the most accurate possible calculations. Petroleum systems experts are therefore able to routinely predict temperatures at great depths and with difficult geological conditions with a very high level of accuracy.

Pore Pressure Prediction

Pore pressure and overpressure modeling is an inherent function of petroleum systems modeling simulators in order to determine compaction behaviour, and they are therefore widely used for pore pressure predictions. They are especially effective when used together with seismic pore pressure prediction methods, as the strengths and weaknesses of the methods can complement each other.



Overpressures are mainly the result of a combination of high sedimentation rates and low permeabilities in specific stratigraphic units. Due to these factors, pore fluids cannot escape quickly enough and overpressures result. Modeling these processes in a multi-dimensional model which simulates processes through geologic time is exactly what advanced petroleum systems modeling simulators do. Overpressure modeling can be done with 2D petroleum systems modeling tools, but is much more accurate in 3D, as property distributions can be taken into account more accurately and all lateral effects can be taken into account. The image shows modeled overpressure distributions in a Gulf of Mexico model.

Additional factors which can lead to overpressures can also be modeled. These include the generation and expulsion of oil and gas within and from source rocks, the effects of hydrocarbon phase changes, aquathermal pressuring and others.

Petroleum Generation and Expulsion

Petroleum (oil and gas) generation occurs when organic material in source rocks is exposed to sufficient temperatures and time. The original organic material (**kerogen**) is cracked to oil and gas as the thermal 'load' increases. Both temperature and time have an effect: lower temperatures over a longer period can have the same effect as higher temperatures during a shorter geologic time span. Oil generation can start at depths of between 3000m or even slightly less if the thermal conditions are right, but it can also occur at depths of up to 10,000m in basins with very rapid recent burial such as the South Caspian.

The process of oil and gas generation from kerogen can be modeled by using **chemical kinetics** to determine the dependency of the process on temperature and time. The kinetic parameters and therefore the effect of temperature and time can vary widely depending on the type of organic matter in the source rock. However, laboratory analyses can be performed to measure the kinetics parameters and these can be used on geologic time scales. The industry has now been doing this for more than 30 years, so the methodology is well established and proven. If no direct source rock data is available, analogues can be used, but direct source-specific measurements of kinetics data will always provide improved accuracy. As gas is often not generated directly, but is obtained from a process of secondary cracking of previously generated oil, secondary cracking kinetics play a critical role for accurate petroleum property predictions.

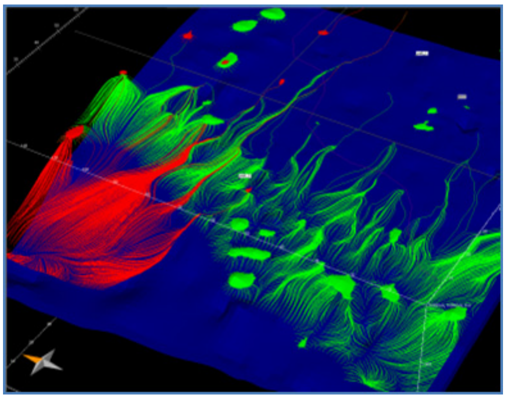
Expulsion of the generated petroleum from source rocks is a pressure controlled process and can be critical for exploration risk assessments. Initial oil generation does not mean that oil is immediately expelled from the source rocks and various methods and models are used to enable the expulsion process to be modeled more accurately. With the increasing importance of shale resource plays, expulsion has become an even more important factor, as the amount of oil or gas that is retained in a source rock will determine the value of the resource. As already mentioned, **conventional** petroleum occurences result from petroleum that has been expelled and can migrate within a petroleum system to form discrete accumulations, while **unconventionals** such as shale resource plays are based on producing the petroleum that is retained in the source rocks. The geological and petroleum systems framework and the processes are the same for both conventionals and unconventionals.

Petroleum Migration Modeling

Petroleum migration modeling has been a key development topic in basin-scale modeling for more than 20 years, starting with 2D and map-based modeling in the early 1990s and with the first full 3D simulators then being released in the late 1990s. Petroleum migration modeling is technically challenging due to the complexities within basin-scale geological models which evolve through geologic time: model geometries and physical properties can change drastically in time and space, and scaling and resolution issues need to be addressed in order to provide meaningful results. The principle controlling physical rock property is capillary entry pressure, which offers a resistive force to the movement of petroleum and in effect defines a seal. Secondary controlling properties include permeabilities which control petroleum migration rates.

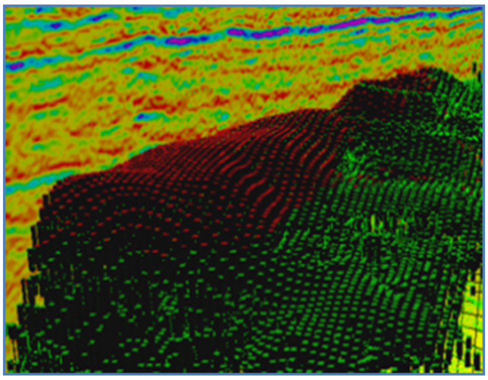
Different approaches are used for petroleum migration modeling and there are no perfect solutions: no single method will work for every task and model. The most widely used approaches are:

- **Flowpath modeling** in which petroleum (oil and gas) migration is controlled by buoyancy and occurs along mapped surfaces. Petroleum, as it has a lower density than water, migrates updip along surfaces which are are defined as having seal properties (see capillary entry pressures). The image shows migration of oil and gas along a regionally mapped surface.



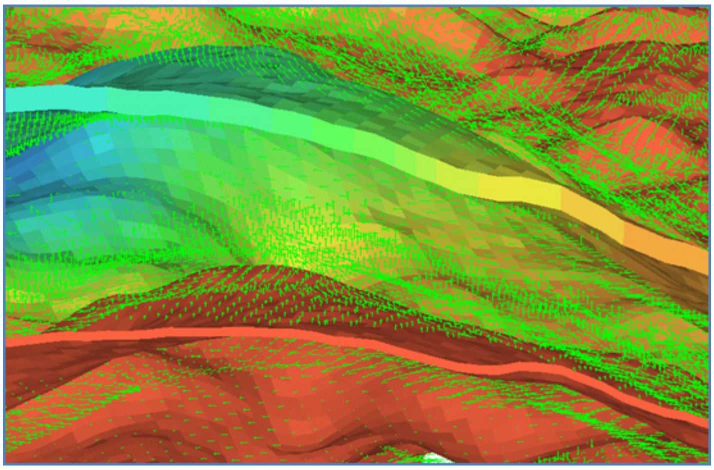
  The method is generally available as a low-cost option and enables fast processing of high-resolution data models. It is therefore mostly used for initial assessments and screening workflows and software tools. It works quite well in petroleum systems which have specific characteristics such as well-defined regional migration pathways, e.g. continuous high-permeability regional sands, but has some limitations when used in more complex geological conditions, for example if migration is controlled by complex lithofacies distributions. It also does not enable expulsion directions (upward vs. downward) to be modeled, or migration rates to be determined.

– **Invasion Percolation** (IP) modeling is physically similar to Flowpath modeling, as petroleum migration is buoyancy controlled, i.e. by capillary pressure distributions in the model. However, instead of being a set of maps, the model is cellular and can have very high resolutions. This means that physically meaningful capillary pressure distributions must be derived to populate the cells in the model with the correct physical properties. The image shows IP modeled oil and gas saturations in cells, the properties of which have been derived from seismic data using special workflows.

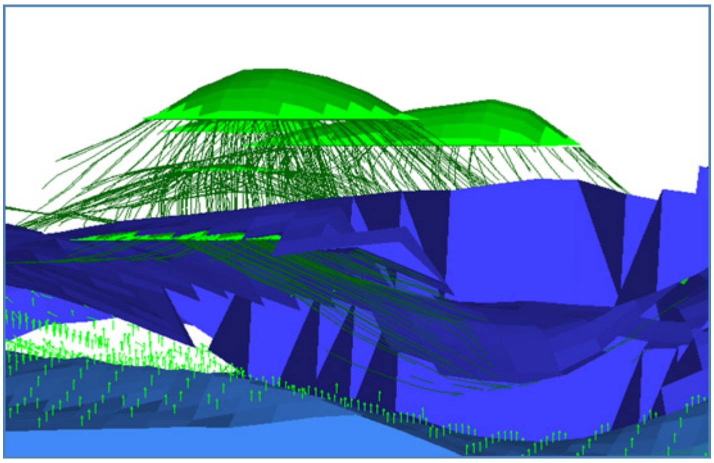


The method is particularly suited to data models which are, for example, based on seismic data which has been converted to high-resolution geological information using special inversion workflows. These can also be used in local areas, for example in a high-resolution field scale model which is included in a regional model using Local Grid Refinement (LGR). The underlying physics are very similar to the Flowpath method (buoyance control only), so the migration rates are not controlled by geological parameters and migration is instantaneous within a specified time step.

– **Darcy Flow** modeling is often described as 'full physics' modeling as migration is controlled by the 3D distribution of the properties of the 3D model and by the full pressure field. For example, Darcy flow is the only method that can be used to determine upward vs. downward expulsion and the effects of overpressuring on migration. It is also the only method that enables petroleum migration rates to be determined. Depending on the geological conditions such as rapid recent generation and migration, these can be important. They are essential for slow oil migration processes in shale resource plays. The image shows Darcy flow (vectors) of full 3D pressure controlled upward and downward expulsion from two source layers in the pre-salt in Brazil.



In theory, Darcy flow is an advanced and accurate technology, however in practice it has disadvantages such as longer processing times than other methods which often limit the resolution of the data models that can be processed in a given time.



– **Hybrid** methods are a combination of petroleum simulator types, in which different methods are used in different areas of the data models. Hybrid Darcy/Flowpath simulators are widely applied and Darcy is used in the lower-permeability parts of the model where pressure control and flow rates are important, while Flowpath is used in higher permeability stratigraphic units which represent potential reservoirs. The image shows detail from a 3D model with the vectors indicating petroleum expulsion from source rocks modeled with Darcy flow, and the dark green Flowpath flowlines indicating petroleum migration in higher-permeability units into petroleum accumulations. The dark blue colours show salt.

  The method combines the benefits of the Darcy method (pressure controlled expulsion and migration in low-permeability units), with the faster Flowpath method in higher-permeability stratigraphic units which is also geologically more meaningful as oil and gas migration is a very effective process in these units.

Special Modeling Technology

Petroleum Systems Modeling software needs many special technical capabilities to make it applicable in specific geologic environments and for specific tasks. Due to time contraints, these cannot be presented in detail during the lecture, but they include for example:

– **Local Grid Refinement (LGR)** techniques which enable specific areas, reservoirs or stratigraphic units within a basin-scale model to be simulated with much higher resolutions
– **Crustal modeling** tools which enable paleo-heatflow histories to be more accurately assessed so that they can be used as thermal boundary conditions
– **Links to structural modeling** to enable petroleum generation and migration modeling to be performed in complex geological environments such as thrustbelts
– Combinations of deterministic and statistical modeling which enable the effects of **uncertainties** in the geological model to be rigorously analyzed
– Fully integrated **geomechanics** modeling which is directly coupled with pore pressure simulations and enables stress/strain and fracture/failure risks to be assessed
– Special tools for **unconventionals** such as shale resource plays which include Langmuir and organic porosity modeling and enable, for example, more accurate predictions of shale oil vs. shale gas prone areas
– **Gas hydrate** modeling which not only models the location of the Gas Hydrate Stability Zone (GHSZ) through geologic time, but also the process and effects of hydrate formation
– Special **geochemical** modeling tools such as biodegradation, so-called Phase Kinetics for more accurate petroleum property predictions, SARA kinetics for Saturates, Aromatics,

Resins and Asphaltenes which enable better petroleum property predictions, and Thermochemical Sulfate Reduction (TSR) which enables H2S predictions to be made.

Summary of Principle Results

Temperature, pressure and petroleum property predictions are often described as the three key deliverables that petroleum systems modelers are expected to provide. In summary, information (through geologic time) which is obtained from petroleum systems models can be summarized as follows:

1. **Temperatures** (thermal histories) which is a function of the lithological properties and their distributions, as well as of boundary conditions such as basal heat flow and surface temperatures through geological time
2. **Maturity** (maturation histories), which is a function of the thermal history
3. **Pressure/overpressures** (pressure/overpressure histories) which is a function of burial rates, lithofacies distributions, lithological properties and their effect on fluid movements, as well as of the geomechanical conditions during geological time
4. **Hydrocarbon generation timing and location** which is a function of the type of organic matter and the maturation of the source rocks in the petroleum system
5. **Hydrocarbon type** (oil and gas or component mix) which is a function of the type of source material and the maturation level
6. **Hydrocarbon retention** (in unconventional systems) vs. **expulsion** (in conventional systems) which is a function of the hydrocarbon properties, the lithological properties of the source rock and adjacent rock units, as well as of the ambient conditions for pressures, etc.
7. **Hydrocarbon migration** which follows expulsion and is determined mainly by buoyancy as oil and gas is lighter than water, by the pore pressure distributions in the system, by the physical properties of the carriers and seal units in the petroleum system, as well as by the evolving structure of the petroleum system through geologic time, taking factors such as fault properties into account.
8. **Hydrocarbon accumulation and loss** which are determined by the geometry of the trap, by the quality of the seal and the quality of the reservoir through geologic time. The properties of the accumulated hydrocarbons will be determined by the entire charge history, as well by the pressures and temperatures (PVT) of the accumulation at present and throughout geologic time. Additional factors such as hydrocarbon compositions, biodegradation, etc can then be analysed within the framework of the petroleum systems model.

A key point is that a *dynamic* model which evolves through geologic time is essential in order to assess the importance of the relative timing of all parameters and processes, for example did the traps exist when hydrocarbons were migrating in the system. The petroleum systems model must also be *structurally correct through geologic time* – if the geometric framework is not correct, then the properties and processes that are simulated in this framework will also not be correct.

1D vs 2D vs 3D Petroleum Systems Modeling

A frequently asked question when petroleum systems modeling software or services are discussed is whether **1D, 2D or 3D modeling** should be performed and what the main benefits and deliverables of each approach are.

Petroleum systems modeling can be done in 1 dimension (**1D**) at a single point in a basin such as a well or a 'pseudo-well', in 2 dimensions (**2D**) along geologic cross-sections, or in 3-dimensions (**3D**) for a complete 3-dimensional data model which can cover an area ranging from a charge area for a single prospect to an entire basin or region, and which are mostly constructed from 2D seismic lines. The depth/thickness of the data models is selected to include all of the relevant elements of the petroleum system (source, carrier, reservoir), as well as additional zones such as the basement which can be required to define the boundary conditions more accurately and thereby obtain more accurate results.

The dimensions of the modeling tool, i.e. whether it is 1D, 2D or 3D, controls the type and quality of the results that can be obtained:

1D Modeling can be used for items 1-6 (see previous section), even though there are some limitations and pitfalls:

- *Temperatures* will be reasonably accurate as heat transfer from deeper levels of a basin to the surface is a mostly vertical process. This can, however, be severely perturbed by more complex geological situations and processes such as salt domes, igneous intrusions or water flow which will have lateral effects which cannot be taken into account in a 1D data model, or if a 2D or 3D data model is simulated with a multi-1D simulator!
- *Maturation* calculations will therefore have the same limitations as temperatures.
- *Pressure* calculations can be performed with 1D tools but only have limited value, as there is always a lateral component in property distributions and fluid movements in sediments
- *Hydrocarbon generation timing, location, and type,* as well as *expulsion* can also be calculated in 1 dimension, but the same limitations apply as to the thermal and maturation histories

Petroleum migration, accumulation and loss cannot be assessed with 1D modeling, as petroleum migration always has a lateral component which does not exist in a 1D model.

2D Modeling can be used for items 1-6 with significant improvements compared to 1D, even though there are still some limitations and pitfalls:

- *Temperatures* are more accurate than with 1D modeling as lateral effects *along* the cross-section will be taken into account, including fluid movements *along* the section. More complex geological situations and processes such as salt domes or igneous intrusions can also be taken into account if they located in the section. If these geological complications are not in the section (for example, if a salt dome or intrusion is next to a section), 2D modeling will not be able to take them into account. This also applies if fluid movements cross the section.
- *Maturation* calculations will therefore have the same improvements but also the same limitations as temperatures.

- *Pressure* calculations will be much more accurate than with 1D tools and can be very useful if the sections and their boundary conditions are located and defined properly
- *Hydrocarbon generation timing, location, and type,* as well as *expulsion* can be calculated much more accurately in 2 dimensions, but the same limitations apply as to the thermal and maturation histories

Petroleum migration, accumulation and loss can be assessed with 2D modeling, but only *along* the cross-section. If the 2D section is positioned appropriately, it can be a useful tool for some basic hydrocarbon risk assessments, for example for hydrocarbon column height vs. seal quality calculations. However, it must be emphasized that *hydrocarbon volumetrics* are not possible and 2D results cannot be quantitative as petroleum migration always has a lateral and *areal* component. A structure on a 2D section is charged from an area, a so-called charge area, and not just from active source units along the section.

A particularly important point for 2D modeling is their location within the *regional structural framework*. This must also take the structural evolution *through geologic time into account*. In order to deliver meaningful results for a 2D simulation, the cross sections must be in the correct position relative to the controlling structures. For example, if the effect of water flow is to be investigated, the section must be located in the direction of the water flow. Or if petroleum migration is to be analysed, then the section must be located along a migration path from the kitchen to the potential accumulation sites. This is not always possible as the 2D sections are mostly taken from seismic sections and their position is rarely related to the orientation of the geological features. 2D modeling therefore has significant additional benefits when compared to 1D, but users need to be aware of the limitations and pitfalls and must have knowledge of the regional 3D structural development through geologic time.

3D Modeling can be used for all of the items 1-8 with no limitations or pitfalls which are related to geometries and dimensional limitations:

- *Temperatures* will always have the optimum accuracy as all lateral effects will be taken into account in a *full 3D* temperature simulation. Complex geological situations and processes such as salt domes or igneous intrusions, as well as fluid movements are taken into account.
- *Maturation* calculations will therefore have the same improvements
- *Pressure* calculations will be much more accurate than with 1D or 2D tools as all lateral property variations can be included in the data model. And 3D Geomechanics modeling can be used to provide significantly more accurate results in complex geological environments.
- *Hydrocarbon generation timing, location, and type,* as well as *expulsion* can be calculated with the highest possible accuracy with no dimensional limitations.

Petroleum migration, accumulation and loss can clearly be most accurately assessed with 3D modeling. No functional or dimensional limitations apply and quantitative modeling is possible. There are no concerns with the orientation or position of 3D models, only with the resolution of the data model which may be limited by computing memory and performance. However, Local Grid Refinements (LGR) techniques can be used to provide the highest possible model resolution where is needed, and PetroMod processing performance as well as the hardware have improved dramatically during the last few years to enables modeling tasks to be performed in hours that previously took days.

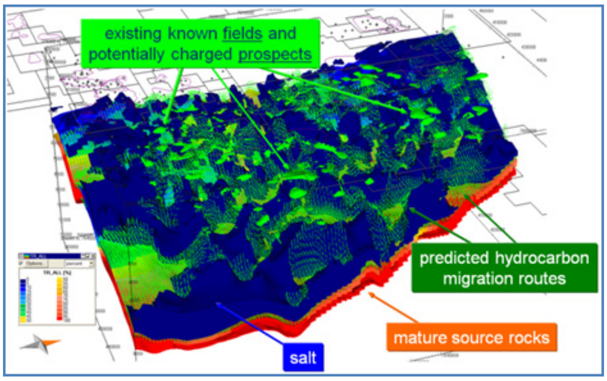
In summary, a 3D data model should always be compiled if permitted by the available time, budget and data for a project. The additional effort that is required to build the data model is always worth it in terms of the quality of the results. Constructing a 3D data model is the only way to obtain a comprehensive volume risk assessment, which is always the key question in exploration with respect to charge.

Case Studies

Several case studies will be used during the lecture. Due to time constraints, only the first two will be used in most cases. However, the additional case studies can be used to present specific technical points or to address specific academic interests.

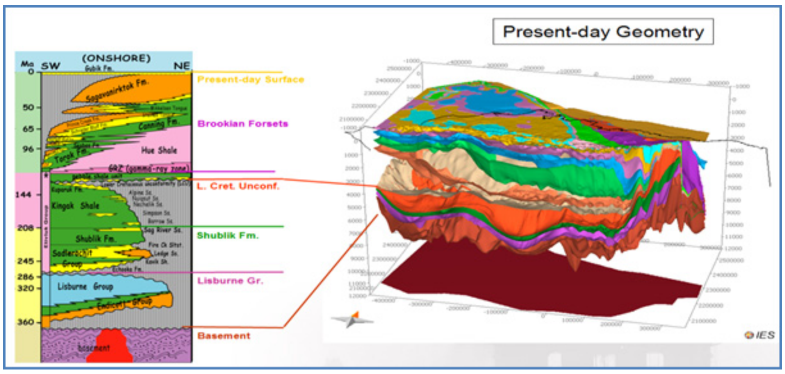
Brazil: Campos Basin Subsalt Exploration

This is a 3D modeling project from the Campos Basin in Brazil. It was used during the 7th licensing round to assess risk factors related to petroleum generation in the pre-salt and migration to post-salt targets. It is an excellent example of petroleum systems modeling workflows now routinely applied by Petrobras in all basins in Brazil.



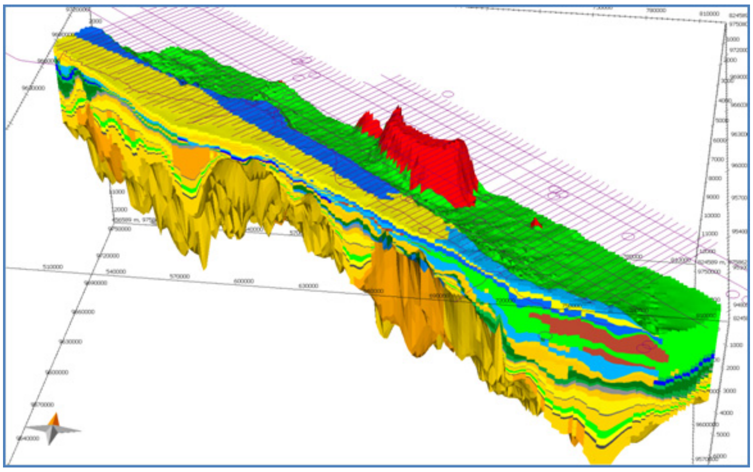
USA: Alaska North Slope Conventional and Unconventional Exploration

This is a 3D model which covers the entire North Slope of Alaska. It was started as a resource assessment project in cooperation with the USGS, but has evolved to become a reference project for both conventional and unconventional hydrocarbon resources. It is also an excellent example for workflows which are used to create and then utilize the results from petroleum systems modeling.



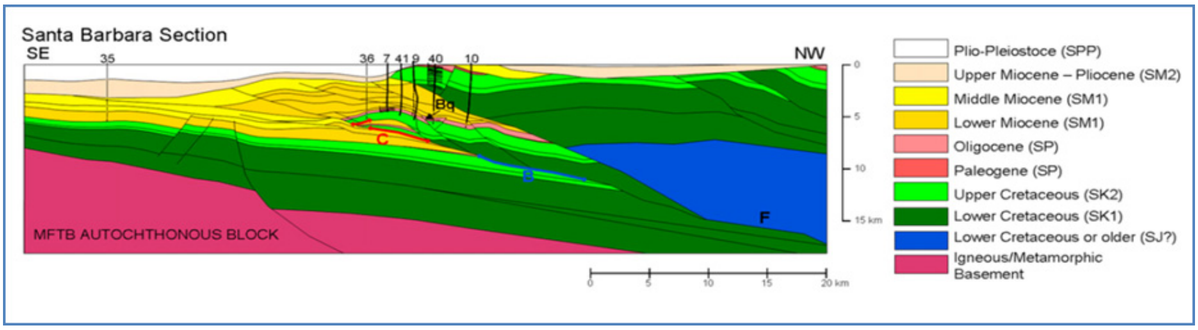
Brazil: Potiguar/Ceara Basin Deepwater Exploration

This is a 3D exploration model which is directly linked to multi-client seismic and CSEM data. It is used to show the value of integration workflows, of basin to prospect scaling, and of using multiple lines of evidence to assess prospect risks.



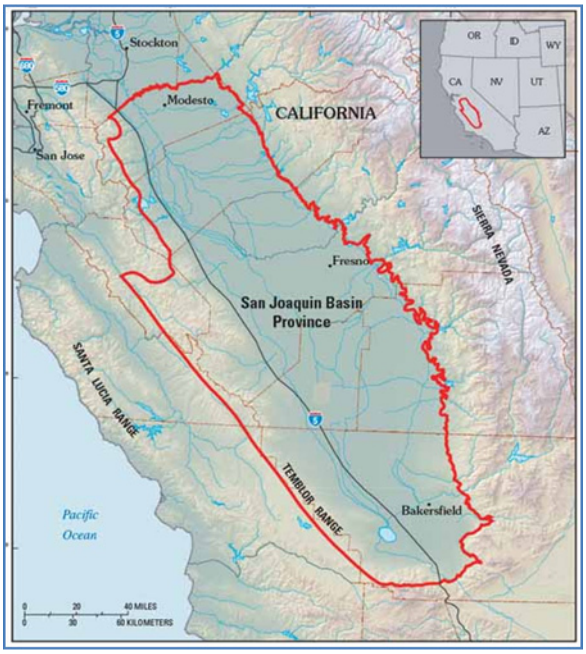
Venezuela: Santa Barbara Thrustbelt Exploration

This is a 2D study which is used to demonstrate the special workflows that are required in structurally complex areas and especially in compressive settings. Standard petroleum systems modeling reconstruction workflows cannot be used in these environments, and structural reconstructions must first be performed in order to better validate interpretations, and then to reconstruct paleo-geometries which are then used for petroleum systems modeling.



USA: San Joaquin Basin/California

This is a 3D study which is documented in a complete series of papers by the USGS as Professional Paper 1713 (http://pubs.usgs.gov/pp/pp1713/). It includes a unique and detailed sequence of separate papers which describe the geological framework and exploration history, the development of the petroleum systems model, and the resulting petroleum resource assessment of the basin.



Appendix

Further Education and Career Opportunities

In this part of the lecture, educational opportunities will be presented such as the Basin and Petroleum Systems Modeling Group at Stanford University https://pangea.stanford.edu/researchgroups/bpsm/. Career opportunities in the industry will also be presented.

References and Recommended Reading

Introductions for Students:

- Gluyas, J., and R. Swarbrick, 2003, Petroleum Geoscience *(excellent standard reference)*
- Bjorlykke, K., 2011, Petroleum Geoscience *(excellent introduction to the topic including basin modeling fundamentals)*
- Keary, P., M. Brooks and I. Hill, 2002, An Introduction to Geophysical Exploration *(excellent introduction to geophysics for geoscience students, includes good examples)*
- Killops, S.D and V.J. Killops, 2005, An Introduction to Organic Geochemistry *(good introduction for students, maybe dated, but good structure)*
- Selley, R.C., 1997, Elements of Petroleum Geology *(good introduction for students, easy to read, includes description of petroleum industry)*
- Fossen, H., 2010, Structural Geology *(good introduction to the topic for students, easy to understand, includes geomechanics)*
- Stuewe, K., 2007, Geodynamics of the Lithosphere: An Introduction *(good introduction to the topic for students)*

For Advanced Studies:

- Hantschel, T. and A. Kauerauf, 2010, Fundamentals of Basin and Petroleum Systems Modeling *(very complete reference of the theoretical aspects of the topic, the only reference which also covers the physics)*
- Jaeger, J., N.G. Cook and R. Zimmermann, 2007, Fundamentals of Rock Mechanics *(the best reference on the topic, for physicists and engineers)*
- Twiss, R.J. and E.M. Moores, 2006, Structural Geology *(excellent and advanced reference on the topic)*
- Krauskopf, K.B. and D.K. Bird, 1994, Introduction to Geochemistry *(advanced reference on the topic, in-depth chemistry knowledge required)*