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DOC 1

Advances in basin modelling: classic tool and new uses

GEO India 2022 Pre-Conference
Continuing Educational Course

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Advances in basin modelling: classic tool and new uses

The course is dedicated to any geoscientist who has an interest in Basin Modelling in general, and Petroleum System Modelling in particular. Those involved in integrated G&G studies are most welcome, as well as petroleum system analysts curious about recent technological advances.

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Who am I?

PhD on Siwaliks and Terai in Nepal (Himalaya foreland)

Measurement and modeling of erosion processes, thermicity, sedimentology of the foreland basin

Petroleum System Analyst at *Beicip-Franlab* since 2008

Expert in petroleum system modeling, involved in more than 40 studies worldwide. Advanced TemisFlow user.

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An IFP group company

TemisFlow™

Specific geochemical modelling

Paris Basin & Bakken Shale (2009), Western Siberia (2014), Kuwait (2015), Mexico (2016), Algeria (2017-2020), Bahrain (2021)

Specific biogenic gas modelling

Vietnam (2011), East Mediterranean (2012-2022), Indonesia (2015), Myanmar (2020), Worldwide Synthesis (2022)

Specific Energy Transition

H2 modelling in Colombia (2021-2022), Geothermal modelling (2021)

Experience in India

Bengal Basin (2009), Kerala-Konkan (2009), regional review (2017)…

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AGENDA

1. Introduction on the basics of the basin modelling

2. Some advanced uses of basin models
(documentation not included in this ppt)

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The basics of the basin modelling

Basin Modelling

- Petroleum Exploration
- Why using basin modelling techniques?
- A few words about Forward Stratigraphic Modelling
- Overview of Basin Modelling Principles
- Basin Modelling Interpretation (not in this ppt)
- A few study cases

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Petroleum Exploration

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There are various exploration studies objectives…

Classical Basin Exploration = Looking for new economical HC resources!

- **Is it an unexplored area?**
- **Are there already (declining) HC resources?**

Various objectives & **various contexts**…

Alternative valorisation of sedimentary basins?

- Geothermal energy
- CCUS (Carbon Capture Utilisation and Storage)
- Li, He, Natural H2, etc.

Specific technical challenges

- Avoiding (or looking for!) shallow gas pocket / hydrates
- Predicting overpressure
- Well planning in general, especially for wildcat wells
- Avoiding H2S & CO2
- Etc.

Various objectives = **Various workflows!**

Exploration → Appraisal → Development → Production → Downstream

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Sedimentary basins arround the world…

Small dots: *oil and gas fields*
Colors: *selection of basins recently studied by Beicip-Franlab in a worldwide review.*

There is still room for the exploration!
Not even mentioning that known basin can be reexplored…

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Exploration workflows and technological advances…

- More and more available data and improved data management,
- Better understanding of the inner earth in general and petroleum system in particular,
- Better imaging of the underground,
- Improved and less expensive drilling technologies,
- Improved production, refining, storage and transport technologies,
- New needs…

Seismic characterization

Numerical modelling

Drilling deep water wells, HP/HT…

Drilling horizontal well with hydraulic fracturing in unconventional plays

Technology: the game changer that revitalize the exploration.
Development of new workflows opening new basins and new plays!

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Frontier / Emerging / Mature Basins

Frontier basin = sporadic / extensive exploration
= very limited data / nothing known

→Analogy with known basin
→Models for "filling the gap"
→New concepts

Mature basin = producing hydrocarbon
= a lot of data / hard-to-find remaining targets

→New technologies
→New data processing
→New concepts

In the beginning all the basins were frontier ☺

e.g. Kalahari, Etosha, Congo, Tchad, Taoudeni basins in Africa

Petroleum exploration is active in both cases. But methodologies are adapted…

e.g. The Arabian Platform in the Gulf

"We usually find oil in **new places with old ideas**. Sometimes, we find oil in an **old place with a new idea**, but we seldom find much oil in an old place with an old idea.
Several times in the past, we have thought we were running out of oil, whereas actually, **we were only running out of ideas**".
(Dickey, 1958, in Sternbach, 2020)

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Frontier / Emerging / Mature Basins

Creaming curves are classical figures for identifying the exploration status of the basin

Idealized cumulative petroleum discovery or "creaming curve"

Rudolph and Goulding, 2016

In mature basins, play & prospect exploration is more risked. Discoveries are less numerous, smaller and less often economic…

Yield = ∑ commercial volumes / ∑ number wildcat wells

Creaming curve in East Mediterranean

Of course things are often more complex.
There are **old plays rejuvenated** by new technologies and also **"frontier plays"** in mature basins…

Lottaroli and Meciani, 2022

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A few words about the “Near Field Exploration” (NFE)

Today's industrial climate is much harsher than the boom times of the past. Upstream companies are looking for ways to maximize production, while streamlining processes and minimizing risk.

Near Field Exploration means exploration of new targets in already producing areas with existing data and available facilities (i.e., at lower cost).

The concept of “Near Field Exploration” in mature basins is all the rage…

Shell documentation (2016)

- Revaluation of contingent resources in the known fields/plays.
- **Looking for subtle traps / satellites… often through enhanced seismic imaging**
- Looking for new plays… sometimes with disruptive concepts!

“True” NFE in its “classical” acceptation

New technologies are key tools for the NFE.

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A few words about the “Near Field Exploration” (NFE)

Let’s imagine a large gas field producing from a carbonate pinnacle (e.g. Central Luconia Platform in Malaysia)…
What could mean NFE exploration in this case?

NFE studies can be done at field scale…
As well as at basin scale (global revaluation of near field potential at basin scale)!
It’s a bit semantics (in my opinion)…

1. **Smaller/other traps in the known play**
2. **Subtle traps associated to the known play**

} **NFE “classical” definition**

3. Other plays related to the same petroleum system
4. Unconventional play
5. Other deep plays related to another petroleum system

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Offshore Brazil: A new deep play at the border of a mature basin

- Both new technologies and better analysis of known petroleum systems lead to the discovery of the giant pre-salt play (Santos & Campos basins).

Meso-cenozoic turbidites… where is the main source rock?

In the concealed rift basin unexplored 15 years ago!

Deep plays may be new targets… and may be associated to already known shallower plays.

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Shale & tight plays in the US: A new kind of HC resources

There is something new in the US!

US shale gas production forecast

https://www.eia.gov/todayinenergy/detail.php?id=38372

A new kind of hydrocarbon plays in low permeability rocks, unveiled by new production technologies = A new paradigm!

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Reminder of the vocabulary…

Usage in OIL INDUSTRY	DEFINITION
Play (Petroleum Play)	A model of how a petroleum system (charge, reservoir, seal, trap) may combine to produce petroleum accumulations at a specific stratigraphic level (e.g., the Upper Jurassic deep marine play).
Play Fairway	Mapping of the geological/areal extension of the play (by analogy to golf courses).
Lead (Exploration Lead)	A geological or geophysical feature identified as a potential trap (but not yet sufficiently mapped as a prospect).
Prospect (Exploration Prospect)	A structural anomaly (or stratigraphic trap) fully mapped with sufficient 2D/3D seismic, but not yet drilled. *The seismic interpretation must be available for dealing with prospects, either an overall seismic interpretation or better a detailed interpretation.*
Lead Area (Prospective Areas)	Group of poorly defined leads, zone where leads could be identified (on the play fairway)
Exploratory Well Location	The precise coordinates and trajectory of an exploratory well ready to be drilled in a prospect. A location may have several drilling objectives (for example, in case of several plays).
Exploration Portfolio	A portfolio of identified and hierarchized Leads and Prospects

The concept of "play" is a tool for optimizing exploration strategies: the classification of know & potential HC accumulations put forward some characteristics which are useful for finding similar HC accumulations.
Whoever looks for the right clues finds better → **"Play Based Exploration"** (trendy vocabulary)

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Exploration steps

INDIRECT methods

DIRECT methods

Satellite images
Geological mapping
Gravimetry Magnetism
Aerial photography
Surface geology
Thermal Modelling

Regional 2D seismic
Detailed 2D seismic
Geochemistry
3D seismic
Petroleum System Modelling

Stratigraphic wells
Exploration wells
Well test, production tests
4D seismic
Reservoir Modelling

More knowledge → Reduction of Uncertainties

Reducing uncertainties → Targeting the best objects → Save time and money!

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Reducing the uncertainties before drilling? Two solutions…

Better mapping of the underground
for better **detecting** the targets

Data acquisition and analysis
G&G workflow (Geology & geophysics)

Purpose of this course

Better understanding of geological processes
for better **predicting** the location of the targets

Conceptual and numerical models
Basin Models

Of course, both techniques can (must) be developed in parallel in exploration workflows.

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Why using basin modelling techniques?

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At the beginning…

Oil seeps…

The Pitch Lake at Trinidad

https://www.geologyin.com/

And in India 150 years ago…

Bhagobaty, 2020

The anticline theory…

Petroleum accumulates in good reservoir with structural closures…

These concepts are no longer sufficient for a long time.

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The source of petroleum, geochemistry and thermicity

- The relationship ***Burial > Thermal Stress > Catagenesis*** was not obvious at the beginning…

Temperature in °C along a passive margin.

Burrial > Thermal Stress > Catagenesis

Tissot, 1987

Since the late 1960's: Looking for areas with organic-rich rocks sufficiently buried for being at high temperature.

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The concept of petroleum systems

- Organic matter and sufficiently high maturity levels – **mature Source Rock** – are not sufficient for finding hydrocarbons in a basin… We also need a **reservoir rock** with an efficient **seal** and a **trap** for accumulating the hydrocarbon.

- The integration of all these elements give a "**petroleum system**"… The concept itself appeared in the 1970s (Dow, 1974), formalized in the 1980s (Demaison, 1984; Magoon and Dow, 1994).

Dow, 1974

We will come back on this concept in next parts of the course…

Exploring basin looking for areas where a **petroleum system** can potentially develop?

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Development of exploration workflows, theories and maps

- Following petroleum system concepts, it is possible to use a map based approach for identifying potential HC accumulations…

Structural map of the top Aquitanian reservoir in Levant Basin.
(the structural maps of the source rocks is also usable)

Key data

- Structural map
- Thermal gradient
- Extent of source rock, seal, reservoir units

This map-based basin analysis technique is still used.
It gives first qualitative results when the data is very scarce…

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Let’s come back to the petroleum exploration…

Obvious oil-water contact visible on beautiful seismic data…

Research Gate

Well mapped structures…

Numerous well data…

In simple cases, there is no need of sophisticated modeling technologies to find petroleum….

NEVERTHELESS…

- ✓ There is not always a dataset giving all the answers, especially in “frontier” basins
- ✓ Most of the large and simple targets were already discovered in “mature” basins

Finding oil and gas is getting more and more challenging.

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“Frontier” basin example

- There is no “fancy” dataset to be used, just a few maps (sometimes conceptual), or a few “vintage” seismic sections, a few wells (sometimes nothing at all), a few analogs and regional concepts…

- Still, we must assess the petroleum potential of the study area / basin!

Lead identification, prospective HC volumes, preparation of block delineation in Offshore Lebanon???

Regional structural maps (2D seismic), no well.

Prospective HC volumes in Tendrara-Misour basin (Morocco)???

Just a few wells and one conceptual map.

You really need to do something more, since “observed data is insufficient.
→ **Fill the gap with a physical model able to predict the hydrocarbon distribution with limited geological data!**

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“Mature” basin example

Greater Burgan (Kuwait)

88 Bbbl oil initially in place

26.5 Bbbl already produced since 1946

20 Bbble remaining recoverable reserve (proved + probable)

About 0.6 Bbbl produced / year (decreasing)

Water invasion…

→It’s time to find new reserves!

But there is no more large obvious targets.

Where to drill?

“Near field exploration”. Unveiling new petroleum “plays” is required.
→ Among new technologies to be applied, **a physical model able to predict the hydrocarbon distribution is helpful!**

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“Mature” basin example

Finding new plays and new prospects?

For example, porous carbonates on the flanks of known structures – **subtle stratigraphic traps** – Identified by seismic characterization.

QUESTION

- Which one of this traps can be charged?
- What kind of hydrocarbon could be found?
- What are the drilling conditions (pressure)?

SOLUTION

- Drilling a new well!
- **But it is cleaver to save time and money guessing where is the best target first, i.e., a target filled with oil.**

The definition of new play concepts requires a good knowledge of **“petroleum systems”**.

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Needs of the oil industry

Where are hydrocarbon resources, how much is expected?

- How to **optimize HC exploration** when there is only **a limited amount of data?**
- A single well costs at least **5-7 M$**... up to several hundreds M$! **Targeting the well location before drilling is a priority**.
- Seismic acquisition cost **tens of millions $**. Geophysical studies are of key importance, but **they cannot give all the keys for an efficient exploration** (low seismic quality at basin scale or in some challenging contexts, ambiguous interpretation in many cases, incapacity to identify subtle elements, etc.).

Is there any risk ?

- The exploration is so costly that financial risks are high, even for big companies. **How to optimize exploration costs and risks?**
- Drilling may be dangerous, particularly in case of overpressure. **Predicting the danger allows reducing the risk.**

How can we optimize field developments?

- How to understand physical, chemical, and geological processes to **optimize hydrocarbon exploration and production?**

We will see that basin modelling is a cost-efficient solution to go further with data!

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Needs of the industry (exploration phase)

- Filling the gap in the geological models (continuous properties)
  - Pressure
  - Temperature
  - Maturity level
  - Lithofacies
  - Petrophysical properties (porosity, permeability, capillary pressure, etc.)
  - Etc.
- Predicting the presence of hydrocarbons and their composition
- Computing hydrocarbon volumes Initially In Place (HCIIP or PIIP, GIIP + OOIP)
- Assessing geological uncertainties and risks for decision-making and steering exploration strategies

Basin modelling can fulfil all or parts of these needs,
in combination with other techniques, depending on the context.

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What is Basin Modelling?

- **Basin Modeling helps understanding the processes of basin formation and evolution, and in particular the occurrence and behavior of petroleum systems.**

- **It simulates the geological, physical and geochemical phenomena driving a basin evolution:**
  - Sedimentation,
  - Structural evolution,
  - Burial and compaction history, diagenesis, petrophysical evolution,
  - Thermal history,
  - Generation of hydrocarbons from the source rock,
  - HC expulsion, secondary migration, HC accumulation and preservation…

- **Basin Modeling is a "forward modeling": it simulates the formation and evolution of a basin through geological time, from the deposition of the first sediments to the present.**

Forward modeling through geological time

Explaining present day state

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What is Basin Modelling?

Forward modelling through geological time

→ Modelling of geological / physical / bio & geochemical processes explaining the present state of the basin. **This modelized present state must be cross checked** (we usually say “calibrated”) with observed / measured data (temperature, pressure, lithology, etc.).

3D forward modelling of the sediment deposition

2D forward modelling of the thermal maturity

Shakerley et al. (2022), Larus Energy

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What is Basin Modelling?

- Usually, basin modelling is performed… at basin scale!

Basin modelling gives an exhaustive overview of all the potentialities of a basin to the explorationists.

Source Rock maturity E. Med.

800 km

Salt thickness & pressure Santos Basin

600 km

The super-large scale vision (>100km) is often mandatory for understanding and modelling the sedimentary basin evolution: **sediment flux / thermal flow / water flow / petroleum systems occur at the <u>basin scale</u>.**

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Different kinds of Basin Modelling

Basin Modelling

Stratigraphic Modeling

Understanding sedimentary architecture at basin scale

Structural Restoration

Understanding structural evolution at basin scale

Petroleum System Modeling

Forward simulation of all processes driving HC generation and migration at basin scale

Includes any other modeling of geological /physical processes occurring at basin scale through geological times.

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Different kinds of Basin Modelling

- Different kinds of basin modelling studies can be associated…

Forward Stratigraphic Modelling

DionisosFlow

- Forward Stratigraphic Modelling
- 4D sedimentary architecture reconstruction

Structural Restoration

KronosFlow

- Fault kinematic
- Structural restoration

We rely on IFPen Group Technology

Petroleum System Modelling

TemisFlow

- Quantitative Basin Modelling, in particular Petroleum System Modelling (PSM)
- Prospect Assessment & Ranking
- Pore-Pressure Prediction

This course is mainly dedicated to Petroleum System Modelling, especially with TemisFlow.

PSM helps determinate the presence and the quality of the Petroleum System components, as well as the timing of processes leading to the formation of HC accumulations, with associated uncertainties and risk.

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Definition of the “petroleum system” concept

The essential **elements** and **processes** as well as all genetically related hydrocarbons that occur in petroleum shows, seeps, and accumulations whose provenance is a **single pod of active source** rock.

(Magoon and Dow, 1994)

This strict definition may be sometimes a bit adapted…

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Modelling of petroleum systems

Need to evaluate the complex interactions between different elements and processes through quantitative modeling → TEMIS FLOW

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The petroleum system through geological time

To understand an oil system,
it is necessary to analyze the **entire geological history** of the basin (not only present-day state).

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Basin modeling as key tool for Petroleum System Chart building

NORTH KUWAIT (Najmah-Cretaceous Thermogenic System)

Mezosoic			Cenozoic						
Jurassic	Cretaceous		Paleogene			Neogene		Quaternary	
Upper	Lower	Upper	Paleogene	Eocene	Oligocene	Miocene	Pliocene	Pleistoc.	Holo.
145	100	65	56	33.9	23	5.32	2.58	0.0117	0

HC generation & expulsion
(and second phase of trap formation)

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Basin modeling as key tool for Petroleum System Chart building

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Petroleum System Modelling main objectives

Only limited data is required

- **Thermal modelling**

- **Source Rock geochemical modelling**

- **Description of petroleum systems** (chronology of maturation, migration, preservation, etc.). Can be done at basin scale in poorly explored basins.

- **Play assessment (geological characteristics of a family of HC accumulations, global In Place volumes, etc.).** Can be done in large study area with a limited amount of data.

- **Lead/prospect assessment (geological characteristics of a single HC accumulation to be drilled, precise In Place volumes, etc.).** Requires high resolution data.

- **Take up specific technical challenges at basin or field scale** (pore pressure prediction, diagenesis, biodegradation, etc.)

More and better data is needed

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Petroleum System Modelling added value

- **Reducing risk** in exploration by a **better integration** of geological + physical + geochemical data;
- Not only measuring and observing a state at present day but rather **understanding the processes**;
- **Quantitative testing** of **qualitative geological scenarios** proposed by the geologist, checking the consistency between the hypotheses and the observed data;
- **"Filling the box"** of geological model when data is missing.

A "model-based" approach with "trial-error" workflow.

In the case of Petroleum System Models…

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“Basin” versus “Reservoir” modelling

Basins scales:

- Assess what *had* happened over My… **structurally dynamic grid**
- Target: often the entire sedimentary column
- Time scale: millions to hundred of millions years
- Calibration/prediction of the present-day geological state
- Area: 10 000 Km² and more
- Fluid migration: 1 mm or less / year

10 km

Fields and reservoirs scales:

- Assess what *will* happen in a few years… **structurally static grid**
- Target: a reservoir layer
- Time scale: a few years to a few 10s of years
- HC production history matching
- Area: 1 000 Km² and less
- Fluid migration: a few 100s m / year

10 m

Basin Modelling ≠ Reservoir Modelling
The model resolution and the physics involved is not exactly the same.

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“Basin” versus “Reservoir” modelling

Strati-Sedimentology

Geophysics

Petrophysics
Geochemistry

Production data

BASIN MODEL

Input:
Present day structural map
Concept for structural restauration
GDE maps (lithofacies)
Laws for assessing petrophysical properties

Burial history
max-stress=f(burial history)
T=f(Λ,HF, depth)
Φ=f(max-stress,P,T,t)
K=f(Φ,S)
Pc=f(HCsat,Φ)
P, HCsat
HCIIP=f(Vrock,Φ,sat,dHC)
Etc.

*These parameters are **extremely variable** through geological time and cannot be defined as input of the model*

RESERVOIR MODEL

Input:
Present day structural map (cte)
Maps of petrophysical facies
Depth=cte
T=cte
Φ=cte
K=cte
Etc…

*These parameters are considered as **constant through time** at reservoir modelling scale.*

P*, HCsat*, Kr/Pc*, etc. for production planification
(dynamic model only)
HCIIP=f(Vrock,Φ,sat,dHC)

Input / output data are not exactly the same…

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Concept of boundary condition

There are 3 kinds of boundary conditions:

- **User-defined initial state** of the model before the simulation (initial temperature, pressure, porosity, etc.)
- **Provoked perturbation** of the system (e.g., an injection well, a rifting event…)
- **Normal interaction of the model with the rest of the world** ("classical" boundary conditions): the surface temperature, the heat flow from the inner earth, the water flow, the sediment flux (in Dionisos).

In basin models, the initial state correspond to the deposit of the first sediment, **thus the initial state is not explicitly defined by the user (except the source rock potential).**
This is a big difference compared to reservoir models…

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Different modelling scales

Characteristic Surface (Thickness)

Lithospheric plates: 1000s - 100s km (200 – 50 km)

Sedimentary basins: 100s – 10s km (20 – 2.5 km)

Oil & gas fields: 10s – 1 km (2 – 0.25 km)

Reservoirs: 10s – 1 km (0.5 – 0.01 km)

Flow units: 10s – 1 km (0.1 – 0.001 km)

Porous media (milli to nanometer)

Basin Modelling

Reservoir Engineering

Petrophysical data (core/log)

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Physics & measurements vs Models: challenge of the scale change

BASIN MODELLING scale

Core / Log scale

Data conversion / to a smaller scale

Thin section scale

Pore scale

Beware of data scale and model scale differences!

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Rationalization of the exploration: Play Based Exploration (PBE)

- The PBE refers to the multi-scale integration workflow of all the relevant geologic elements (& data) in order to fully describe the exploration opportunity from basin scale to prospect scale.

https://www.kindpng.com/

CRS = Common Risk Segment map (mapping of the risk on petroleum system elements & processes)
cCRS = combined CRS map
CSEM = Controlled Source ElectroMagnetic (geophysical method)
EMV = Expected Monetary Value (economical study)
MEFS = Minimum Economic Field Size
FSD = Field Size Distribution plot
YTF = Yet to Find (resources)
GDE = Gross Depositional Environment (litho)
PoS = Probability of success
PoS(g, e) = PoS geological, economical
DHI = Direct Hydrocarbon (HC) Indicator

It is important not to confuse workflow and tools…

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Geology & Geophysics study (G&G), Petroleum System Modelling?

- Petroleum System Modelling (PSM) may be used in G&G studies… or not.

WORKFLOW STEPS	TOOL
Usual milestones	***PSM usage?***
Wildcat and discovery ☺	
Hierarchized prospect portfolio	
Economical analysis, prospect risking	Risk on the charge?
Lead and Prospect, In Place ressources	Possible in favorable cases
Play mapping and risking, YTF	Possible, recommanded
Post drill and field data analysis	
Petroleum system processes	**YES**
Petroleum system elements	
Basin evolution through time (restauration)	Possible, thermal/pressure model
Basin characterization (structure, stratigraphy, lithology, geochemistry)	
Geodynamic setting	

Depending on the objectives / context, **the workflow won't start / end at the same steps…**

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Example of integrated G&G studies with Basin Modeling

- Integrated multidisciplinary exploration workflow… a practical illustration of the PBE concept.

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Example of integrated G&G studies with Basin Modeling

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Example of integrated G&G studies with Basin Modeling

- In this workflow the Basin Models are integrating the results of the G&G study at the end.

In preliminary exploration phases and in basin scale exploration studies,
the “in place” HC resource assessment and the prospect analysis can be fully provided by high resolution basin models…

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A few words about Forward Stratigraphic Modelling

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Forward Stratigraphic Modeling (FSM)

DionisosFlow™

RESULT:
3D geocube of environmental parameters & lithologies

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The added value of FSM

DionisosFlow™

Reservoir / Seal risking

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Combining Seismic Inversion & FSM

Cape Freels prospect

- Potential turbiditic reservoir
- A specific structurally conformable AVO has been picked on seismic

Seismic Inversion & Forward Stratigraphic Modeling

- Seismic characterization with **Interwell** confirmed the presence of a porous, sandy, oil-bearing reservoir and pinpointed its location
- Process-based modeling with **DionisosFlow** cross-validated the reservoir presence
- and delivered characterization of its genetic properties (2 sequences not visible on seismic, separated by a thin seal)

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Combining Seismic Inversion & FSM

Cape Freels prospect

- Potential turbiditic reservoir
- A specific structurally conformable AVO has been picked on seismic

Back and forth calibration with **Interwell**

Original Stratigraphic modeling Simulation

Stratigraphic modelling result optimization using SRC results

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Modelling of turbiditic lobes with DionisosFlow

Channel-Levee Complex

Water fluxes diversion around salt domes

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Source rock prediction and distribution

DionisosFlow™

Organic Matter Primary Productivity

Reference Primary Productivity

Distance to shore relation

Upwelling contribution

nutrients

Organic Matter Degradation/Preservation

(in sediments)

Oxygen profil

(anoxicity)

Confined areas

(local anoxicity)

Sedimentation rate

DionisosFlow™

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Source rock prediction and distribution

Input data can be:

- Rock eval TOC measures
- carbolog® spatialized analyses (calibrated to TOC measures)

DionisosFlow™

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Sedimentary mapping

1- 3D Stratigraphic Model Grid

2- Output properties

3- Depositional Environment Maps

4- Lithology Distribution Maps

Derisk lithological aspects
Provide litho cube to TemisFlow
(and Reservoir Modelling)

DionisosFlow™

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Wheeler diagram, play definition for PSM layering

Wheeler diagram
Play definition for PSM layering

Use of DionisosFlow and TemisFlow to **recognize plays and play elements**

KEY DELIVERABLES FROM FSM

Reservoir distribution (Carb. / Clastics)

- Reservoir presence
- NTG / Facies type (reservoir quality tied to primary porosity)
- High vertical resolution (4th order, m- scale)

Seal distribution

- Seal presence, effectiveness and extension

Fault-seal analysis

- Shale gouge and hanging wall juxtaposition rules

Source

- Unique capability for predicting TOC and organic matter type away from wells
- De-risking organic-rich intervals location, richness and effective thickness

DionisosFlow model

Reservoir & seal characterization at play level

CRS Mapping

High risk | Medium Risk | Low Risk

Source rock richness map

DionisosFlow™

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Overview of Basin Modelling Principles

Dynamic geological model at basin scale

Thermal modelling

Geochemical modelling

Pore pressure modelling

Hydrocarbon migration modelling

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Data Integration in Petroleum System Models (PSM)

Structure and Stratigraphy

(here structural maps)

Geological Environment Boundary Conditions

Tectonic evolution
Paleobathymetry
Surface paleo temperature
Bottom paleo heat flow…

Facies Distribution

("Lithofacies")

TemisFlow™

Geochemistry

Source Rocks (HC, H2)
Fluid properties

NUMERICAL SIMULATIONS

Petrophysical Behavior

OUTPUTS

- Thermal and pressure modelling
- Petrophysical properties prediction
- Fluid generation and migration prediction
- Evolution through time of geological systems, especially **petroleum systems processes**

Calibration data
Well Temperature, pressure, porosity
Fluid composition, etc.

Integration of available data in a coherent geological model.
Modeling of geological / physical / chemical processes occurring through geological time.

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TemisFlow "classical" workflow…

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Geological model building

- TemisFlow™ needs a **mesh** (=grid) to represent the main geological objects and to simulate the phenomena affecting them through time in a given domain (with associated uncertainty)

- The vertical mesh **evolves through time** following the sediment layer deposition and deformation.

Checking the seismic data

Importing structural maps / horizons

Importing sedimentary information

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Present day model (static)

Facies & SR distribution

*GRID RESOLUTION = 4 * 4 km*

Structural Maps from Seismic Interpretation

*GRID RESOLUTION = 0.1 * 0.1 km*

Layering / Subdivisions

TemisFlow™ 3D Block

*GRID RESOLUTION = 1 * 1km*

Geological Model at Present Day

⇩

But in the past ???

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Petrophysical properties: compaction laws

Many other parameters are taken into account!

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Defining past geometries: Backstripping

- The **Backstripping** is a simple decompaction method to reconstruct past geometry from present day state.
- The method assumes a preservation of solid volumes through time, during the compaction of sediments.
- The pore volume evolves through times, in particular due to the effect of the increasing sedimentary load (burial). Most of the time the porosity was higher in the past… So the bulk rock volume was higher in the past.

The backstripping is essential for modeling structural evolutions and petrophysical properties through geological times.

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Defining past geometries: Erosions

Other parameters to be restored:
- **Paleobathymetry**
- **Fault tectonics**

Obvious impact on the thermal history of the basin…

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Thermal modelling: Boundary conditions

Heat flow in a sedimentary basin

Surface boundary condition
(temperature evolution through geological time)

Basal boundary condition
(temperature or heat flow evolution through time)

TEMPERATURE
MATURITY (e.g. VR0)

Temperature and maturity are different concepts

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Fully coupled lithosphere/sediment thermal modelling

Relatively uniform temperature field before rifting
1330°C isotherm is merged with the base of the model

Blanketing effect caused by rapid sedimentation

Rifting

Thermal Relaxation

Blanketing

Heating due to the rifting
Thinning of the crust is stronger seaward

Slow cooling after rifting.
At the same depth below surface, temperature is lower seaward than below continental crust

The coupled lithospheric model is of key importance for reliable prediction of temperatures and maturity levels.

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Checking the model calibration: exemple of Thermics

Not that bad… **OK for next steps?**

WARNING:
Preliminary quality check of the data is mandatory!
The model can be "better" than the data…
☺

Can be improved…
Modification of the model for increaing the temperature in the past (maturity)

If the model reproduces calibration data at well location,
it is supposed to be predictive at basin scale.

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Geochemical modeling

- In TemisFlow source rocks are defined by:
  - Geochemical properties and maps (distribution of the kerogen, TOC0, effective thickness)
  - Initial SR properties are required (state of the kerogen before the catagenesis)
  - Maps are interpolated from well data with the constrain of geological trends

*The computation of the **initial source rock potential** requires a specific workflow…*

TOC present day
HI present day
Tmax
Mass and composition of generated HCs

Observed/measured SR characteristics are OUTPUTS of the model.

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Hydrocarbon expulsion

1. Langmuir Adsorption (gas)
2. Organic Porosity
3. Darcy Porosity

EXPULSION

after Ungerer et al. (1984)

Dembicki, 2014

The HC expulsion depends on the geochemistry, the maturity, AND the petrophysics (Darcy's Law)

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Water flow and pore pressure

- The water flow goes from the higher pressure to the lower pressure.
- The overpressure mechanism is highly variable, but it is always related to an insufficient permeability of the rocks.

Overpressure (Mpa)

Fracturing threshold

The water flow is described by the Darcy's Law.

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HC migration modeling

HC saturation

HC migration timing

The better solution for describing the HC migration in sedimentary basins is the Darcy's Law.

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Fluid flow: Darcy's Law

- Polyphasic Darcy's law for water and hydrocarbons flows in porous media
- Relates the flow rate Ui of phase i to the different driving forces (calculation of HCs and water movements within the porous media)

Henry Darcy (1803-1858)

Intrinsic permeability K=f(Φ, litho)

Relative permeability phase i kr_i=f(sat,Φ, litho)

$$\vec{U}_i = -\overline{\overline{K}}\,\frac{kr_i}{\mu_i}\left(\vec{\nabla}(P-\rho_w g z)+\vec{\nabla}(Pc)-(\rho_w-\rho_i)g\vec{\nabla}(z)\right)$$

(FLUID FLOW)

Viscosity phase I
μ=f(T,fluid)

Pore Pressure

Capillarity

Buoyancy

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Full Physics Simulator… Just for Fun!

Everything is connected.
Need of TemisFlow!

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HC accumulation modeling

TemisFlow **Full Darcy** modeling output

Modeled HC accumulations in TemisFlow

Potential leads/prospects to be studied

TemisFlow advanced « **Ray Tracing** » output (Camel)

In fact "vapor" and "liquid"

Direct estimate of in place volumes *and of other petroleum parameters (for play and prospect assessment).*
To be cross checked with other data (geophysics, petrophysics…)

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Finally… What can be learned from 1D models?

- Thermal history and maturity timing can be estimated.
- Present-day maturity is accounted for.
- Compositional kinetics and simple expulsion concept (mid 90's) to assess the nature of petroleum charge (GOR, API).

Well Calibration

Burial history

Thermal transfer often in 1D.
Arrhenius kinetics: a reasonable approximation

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Finally… What can be learned from 2D models?

- Relevant capabilities for pressure regime and hydraulic settings reconstruction.
- Better understanding of tight shales permeability.
- Emphasis on the need to use a detailed lithostratigraphic framework to evaluate migration pathways:
  - Darcy' law valid at basin scale,
  - Accumulation correctly localized,
  - Overpressure regime correctly reproduced.

Lateral migration is dominant during fluid migration.
Multiphase Darcy's law is a reasonable approximation for migration of oil and gas.

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Finally… What can be learned from 3D models?

- Realistic reconstruction of migration pathways (Real world is 3D).
- Volumetric estimation possible. Size of accumulations and balance of their content (GOR, API …). Prospects can be ranked in a quantitative way.
- Precise pore pressure estimation.
- 3D salt effect on temperature.

The most sophisticated modeling, but time consuming (building and processing of the model).

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A few Study Cases

Offshore Lebanon – **Frontier Basin Exploration (2011-2012)**

Offshore Canada – **Play Fairway Analysis (2010-2020)**

West Siberia – **Near Field Exploration**

Example of compressional basins

Kuwait – **Pore Pressure Prediction**

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Study Area – Offshore Lebanon

- Temis study performed in **2011-2012** for the Ministry of Water and Energy of Lebanon.
- **Question:** Is there a petroleum potential in the unexplored offshore Lebanon?
- **Objective:** Play assessment & elements for the blocks delineation.

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Offshore Lebanon – A frontier basin

- No well data / very uncertain stratigraphy
- Only 2S seismic lines

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Offshore Lebanon – What was known in 2011?

- Several oil and mainly gas fields have been discovered in the Southern Levant & Nile Delta, which confirm the high potential of the whole basin.

The most promising discoveries recently done south of the Lebanese border (L Miocene) :

Tamar, Leviathan, Aphrodite

→ **Associated to a "new" petroleum system:**

- Reservoirs in **Lower Miocene sands** (turbidites)
- **Methane dominant** (biogenic or highly mature?)

→ **Challenges for the exploration of offshore Lebanon:**

- **No well** in offshore Lebanon
- **Very few public data** from Israeli fields

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Offshore Lebanon – Comparison Tamar Zone / Lebanon

- **“Deep Basin”** vs. **“Mesozoic Platform”**
- The basin is **deeper** in Lebanon.
- Structure is **flatter** in Lebanon, where deeply rooted faults are uncommon in the central part of the basin.
- However, a much **higher density** of NW-SE Miocene faults exists in Lebanon.
- Reservoirs in **Miocene / Lower Miocene sands (BL2)** would exist in both places.
- The same **source rocks** could be active in both basins.

SOUTH LIBAN

TAMAR ZONE

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Offshore Lebanon – Basin Modeling Workflow

1/ Available data
Structural maps from Beicip's 2011 regional seismic analysis (from 2D lines)
Bibliography – No well data

2/ Geological Model
Structure
Lithology
Petrophysic
Geochemistry
Biogenic potential
…

Uncertainty
→ alternative geological scenarios

(definition of the biogenic potential)

3/ Maturity Modeling in 3D (TemisFlow 3D)

4/ Migration Modeling in 2D (TemisFlow 2D)

What is the charge?
Is there a good timing in the system?

5/ PLAY ASSESMENT (TemisFlow 3D)

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Offshore Lebanon – Thermogenic Source Rocks – VRo (present)

- The main SR is entering the dry gas window in the Deep Basin (West) at present day
- Lower maturity level on the Mesozoic Platform (East) → oil / condensate generation at present day

Vitrinite Reflectance maps for the 6 thermogenic Source Rocks

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Offshore Lebanon – definition of the Biogenic Potential

In the Lebanese Case Study:

- 7 layers of the 3D block have been defined as **potential biogenic SRs** (Lower Oligocene → Pliocene)
- The biogenic potential varies laterally but the TOC is assumed constant (1%)

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Offshore Lebanon – Biogenic Potential – CH_4 expelled mass

The expulsion modeling is reprocessed with the biogenic SRs. Finally in this model the amount of expelled biogenic methane depends on:

- The biogenic potential **(previous map)**
- The temperature and the time **(kinetic scheme)**
- The biogenic source rock lithology and petrophysical properties (satex, satmax, compaction curve, Pc, etc.)
- The burial and the compaction **(porosity decrease with the depth)**
- And of course, the layer thickness

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Offshore Lebanon – HC Saturation – HC Accumulations

Many HC accumulations would have a L. Miocene age.

TemisFlow™

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Offshore Lebanon – HC Composition – HC Phases

- Gas dominant in the very deep basin (with possible condensates)
- Oil fraction in liquid phase possible on the Mesozoic Platform

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Offshore Lebanon – HC Saturation – HC Accumulations

ALTENATIVE SCENARIO « Biogenic System only »

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Offshore Lebanon – Play Assessment

- The best play would be **BL2 sands** (L. Miocene), like in **Tamar-Leviathan**. In some alternative scenarios the play **BL1** (M. Miocene) becomes more interesting.
- At basin scale **Oligo-Neogene play systems** are much more prospective than the other play systems (Pliocene and Mesozoic).

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Offshore Lebanon – Example of the reservoir BL2 (Base Miocene)

TemisFlow™

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Offshore Lebanon – Frontier Basin Case Study Conclusions

→There is a petroleum potential in Offshore Lebanon.

The most active petroleum systems would be the **Oligo-Miocene biogenic SR → Miocene reservoirs** (rather deep offshore, West). Deeper thermogenic systems can be expected too.

- Many structures in **Neogene reservoirs** of the deep basin could be filled with **biogenic methane**, even without a thermogenic source rock contribution.

- **At least 2-3 times more gas than oil + condensate** at basin scale (mass ratio, reference scenario), 60% of the gas having a biogenic origin. Gas is particularly abundant in Neogene reservoirs. However, even in the deep basin, **some condensates should be found if Eocene and Campanian SRs are active**, in particular because of the dense Miocene fault network.

  → Consequently, Tamar gas composition would be hardly explained by an extremely mature thermogenic source rock.

- **The petroleum system timing is excellent for the biogenic gas.**
  - → The TOC is likely low (type II-III kerogen?) but the Oligo-Miocene source rocks are thick with likely many intercalations of thin carrier beds (turbiditic systems).
  - → The biogenic gas generation & preservation potential is high thanks to high sedimentation rates and relatively low thermal gradients.
  - → The main reservoirs are stratigraphically intercalated within the source rock thick interval, several shale layers act as seals
  - → Early trap structuration during the Miocene synchronous with methane expulsion

Prospective presented to the ministry

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Epilogue…

Temis basin modelling results (2012) have been validated by subsequent press releases (2013) that confirmed the existence in the Leviathan structure of a deep thermogenic system below Miocene biogenic gas plays.

Moreover, the model anticipated the possibility to charge Cretaceous Carbonate with biogenic gas through pinch-outs. (equivalent play in Zohr, the largest HC discovery in the world in 2015)

Several other basin modeling studies have been carried since 2012…

Perez-Drago et al., 2019

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A few Study Cases

Offshore Lebanon & Cyprus – **Frontier Basin Exploration**

Offshore Canada – **Play Fairway Analysis (2011+)**

West Siberia – **Near Field Exploration**

Example of compressional basins

Kuwait – **Pore Pressure Prediction**

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Nova Scotia – G&G study for Play Fairway Analysis (PFA)

Figure 2: Hopane traces (m/z 191) of 2 cutting samples

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Nova Scotia – Basin Modelling

TemisFlow™

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Nova Scotia – CRS and CCRS maps

Exemple of the Albian sands

Reservoir (from DionisosFlow, petrophysics and geophysics)

Seal (from DionisosFlow & petrophysics)

Charge (from TemisFlow)

U. Jurassic to L. Cretaceous SRs

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Nova Scotia – Final Zone Ranking, study Post-Mortem (2019)

- HC volumes computed with TemisFlow (TCA module)

The PFA has suggested that there is **significant potential untapped offshore Nova Scotia** (**~ 120 TCF of gas and 8 bnbbls of oil in place and unrisked**) that warrants the attention of industry.

The study has been peer-reviewed by major operators (Conoco Phillips, BP, Shell, Total, ENI).

Finally, Shell and BP have invested… in Zone 2… so far without success. However, the PFA predictions have been confirmed by drilling: absence of reservoir (Dionisos), excellent temperature / maturity / pressure prediction (TemisFlow).

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Continuing exploration in Labrador: Deep Offshore Megaproject

- 8 in-depth resources assessments over 6 years over the north Atlantic margin

Paleogeographic reconstruction at Early Campanian time

Merged Top Jurassic maturity map seen from the Orphan Knoll looking southwards

Atlas of Source Rocks in Mesozoic basins of the NA margin, Offshore Newfoundland-Labrador and Offshore Ireland

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Continuing exploration in Labrador: Deep Offshore Megaproject

- Evaluation of in-place resources (play & prospect)
- Exploration risk
- Block ranking
- Detailed prospect volumes and risk
- Planning for future exploration data acquisition

Orphan Basin 2016
Resource Assessment
https://goo.gl/CfK8e2

Flemish Pass 2015
Resource Assessment
https://goo.gl/OYG0tr

Data set

Prospective volumes

Block ranking

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A few Study Cases

Offshore Lebanon & Cyprus – **Frontier Basin Exploration**

Offshore Nova Scotia – **Play Fairway Analysis**

West Siberia – **Near Field Exploration (2012-2016)**

Example of compressional basins

Kuwait – **Pore Pressure Prediction**

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West Siberia – **Near Field Exploration**

Technical objectives

- Unveiling new prospective resources in mature areas, using forward stratigraphic modeling (FSM) & petroleum system modeling (PSM) techniques
- **Near Field Exploration / Unconventionals**

Study portfolio

1. Middle Ob – Lukoil
   - G&G, FSM, **PSM**, Play Assessment, Yet-To-Find
2. Yugansk – Lukoil
   - G&G, FSM, **PSM**, Play Assessment, Yet-To-Find
3. Messoyakha - Gaspromneft /TNKBP
   - Geochemistry, FSM, **PSM**, Lead Assessment, Yet-To-Find
4. Yurkharovo - Novatek
   - G&G, Seismic Inversion, **PSM**, Play Assessment
5. Khanty Mansiisk
   - Regional Oil Shale Evaluation (Bazhenov), **PSM**, Unc. Resources Assessment

Ulmishek, 2003

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West Siberia – **Near Field Exploration**

High-resolution mapping of subtle stratigraphic traps (Prograding Siliciclastic Complexes)

Conceptual Model

FACIES MAPPING – LOWER NEOCOMIAN

Channels in alluvial plain

Shelf sands

Turbditic sands (Achimov)

Interwell

DionisosFlow™

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West Siberia – **Near Field Exploration**

Review of known field

Geochemical analysis

Source Rock mapping

Forward Stratigraphic Modelling

DionisosFlow™

120 000 km² + local refinement over 5 000 km²

Integrated Basin modeling study with multiple technical challenges

Numerous innovations

Definition of new concepts for exploring the basin

Petroleum System Modelling

Prospect assessment and ranking

Play assessment & YTF

TemisFlow™

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West Siberia – **Near Field Exploration**

Lead delineation, valuation and ranking with TemisFlow

BF's lead definition in each play

BF's lead ranking (with geological risk)

Лицензионный участок	Ловушка №	X (м) UTM	Y (м) UTM	Геологические ресурсы нефти, тыс. т.	Геологические ресурсы газа, тыс.т.	Суммарные геологические ресурсы УВ, тыс. т. без учета рисков	Суммарные геологические ресурсы УВ, тыс. т. С учетом рисков	Ранжирование	Средняя плотность нефтей, АРИ	Содержание конденсата, %
1. закрытонеокий НГК										
ЯМАЛ	SARM-14	416800	7431700	18136	68884	87020	2080		*****	21%
ЯМАЛ	SARM-114	401800	7404700	2596	11003	14279	341		*****	21%
2. неокомальцевский НГК										
ЯМАЛ	NEAL-5	407800	7405800	6989	7995	14984	807		45	50%
ЯМАЛ	NEAL-50	408700	7412800	8625	5828	14453	694		41	60%
3. верхнеюрский НГК										
ЯМАЛ	UPLIR-2	499600	7422800	45828	2449	48277	3725	5	31	95%
ЯМАЛ	UPLIR-4	407700	7417800	10181	2570	12750	130		38	82%
ЯМАЛ	UPLIR-11	502800	7442800	12574	736	14710	503		31	95%
ЯМАЛ	UPLIR-20	404700	7501800	5681	3349	8945	451		43	63%
ЯМАЛ	UPLIR-26	499600	7427800	23677	1737	24914	5174		31	95%
ЯМАЛ	UPLIR-77	405700	7439800	16262	3688	19810	416		39	82%
4. нижнемеловой НГК										
ЯМАЛ	NEH-5	408700	7398700	7682	8170	9253	466		37	83%
ЯМАЛ	NEH-39	406700	7432800	13672	444	14116	1581		30	97%
ЯМАЛ	NEH-42	407700	7429800	76941	2950	79899	8054	2	30	96%
5. меловой НГК										
ЯМАЛ	MOKH-2	407800	7402800	18959	1366	22225	1917		32	89%
ЯМАЛ	MOKH-15	406800	7426800	7963	2654	10616	2497	10	31	75%
ЯМАЛ	MOKH-44	396700	7417800	2548	184	2732	230		31	95%
ЯМАЛ	MOKH-46	406700	7412800	14454	3632	18086	4172	3	32	80%
ЯМАЛ	MOKH-112	440700	7409800	13891	3439	17330	3494		33	80%
6. сеноманский НГК										
ЯМАЛ	SARM-77	424700	7409800	15238	4896	20124	4142	4	36	76%
ЯМАЛ	SARM-108	440800	7397800	12761	4459	16620	2932	9	34	73%
7. апт-альбский НГК										
ЯМАЛ	PKSUP-4	407700	7401700	42981	6331	50312	15214	1	37	87%
ЯМАЛ	PKSUP-16	407800	7430800	0	6273	6274	1129			0%
ЯМАЛ	PKSUP-34	409800	7411800	33870	2421	35491	3846	8	13	95%
ЯМАЛ	PKSUP-132	410700	7412800	15618	1079	16630	3605	6	13	94%

Client's lead contour vs. BF's lead localization

Client's lead contours (lines)
BF's lead localizations (points)

Client's well planing vs. BF's lead localization

Client's wells planning (circles)
BF's lead localizations (points)

Less risked targets

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A few Study Cases

Offshore Lebanon & Cyprus – **Frontier Basin Exploration**

Offshore Nova Scotia – **Play Fairway Analysis**

West Siberia – **Near Field Exploration**

Example of compressional basins (2018-2022)

Kuwait – **Pore Pressure Prediction**

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Beicip Franlab experience in Basin Modeling of compressive areas

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Basin Modelling of Accretionary Prism: example of Brunei

(Cullen, 2010)

South China Sea
(back-arc basin with an inactive spreading center)
Baram-Balabac Basin
(foredeep)

2D Basin Modelling KronosFlow
Accretionary Prism with small mud diapirs.
Biogenic gas generation and migration modelling.

KronosFlow

Basin Modeling in Subduction Zone: Barbados

2D Basin Modelling KronosFlow
Complex structural restoration of the accretionary prism (subduction).
Thermal and pressure modelling.
HC migration modelling.

Stratigraphy

Overpressure

bhpbilliton BHP

KronosFlow

Source Rock
Transformation Ratio

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Basin Modeling in Subduction Zone: Carribean Colombia

Sinu Fold Belt

Accressionary Prism and Fore Arc Basins (interaction with Magdalena River Delta)

2D Basin Modelling KronosFlow (several sections)

Complex structural restauration, including oceanic crust subduction.

Thermal modeling and pressure modelling.

Source rock modelling.

ecopetrol
ENERGÍA PARA EL FUTURO

KronosFlow

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Basin Modeling in Back-Arc/Fore-Arc: Peru (Tumbes Basin)

Temperature
& heat flow at base sediment

Vitrinite reflectance
& burial at base sediment

Lemgruber-Traby et al., 2021

A few Study Cases

Offshore Lebanon & Cyprus – **Frontier Basin Exploration**

Offshore Nova Scotia – **Play Fairway Analysis**

West Siberia – **Near Field Exploration**

Example of compressional basins

Kuwait – **Pore Pressure Prediction (2015-2017**

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Kuwait – Pore Pressure Prediction (context)

GEOLOGICAL CONTEXT & OBJECTIVES

Stratigraphic Chart – Petroleum System Elements

from Carman (1996)

Dubille et al., 2017

- Although Kuwait is a very mature province, no convincing model explaining overpressure variations at basin scale existed.
- Major oil pools in Cretaceous sands.
- Makhul sourcing potential is limited compared to Najmah SR and cannot feed on its own all the giant Cretaceous fields.
- Jurassic reservoirs are always overpressured.
- The Gotnia-Hith is undoubtedly a pressure barrier between Jurassic and Cretaceous units. This raises two questions:
  - Is it possible to explain and predict the overpressure in Jurassic units?
  - Is there a possible fluid flow from Jurassic to Cretaceous units?

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Kuwait – Pore Pressure Prediction (role of salt windows)

- Discontinuities have been mapped in Gotnia & Hith evaporites thanks to HR geophysical analysis
- Local “salt windows” exist both in Burgan and Sabriya-Raudhatain areas, locally elsewhere, and possibly offshore
- The most significant ones are the “pop-ups” observed along the Kuwait Arch

Discontinuities through Gotnia-Hith evaporites observed on seismic lines

Fault Types	Seismic Examples
	Strike-Slip faults affect the whole Gotnia Fm
	Localized ***collapse features*** affecting brittle layers of the Gotnia Fm
	Salt dissolution generating cavities and their collapse linked (or not with deep-seated faults ?)
	“Pop-up” (very narrow and elongated north-south structures associated to reverse faults, localized along Kuwait Arch). Salt creeping above the pop-ups (very often only remains the Hith fm.)

Example of a “pop-up” observed on seismic lines (Sabriya Ridge in Northern Kuwait)

Pop-up
Structural thinning of the Gotnia-Hith seal (« salt window »): only the Hith Fm. remains.

Collapse features
High fracture density / faults

Dubille et al., 2017

“Salt window” viewed on logs (Ahmadi Ridge, Burgan Area)

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Kuwait Case: PRELIMINARY BASIN MODELING RESULTS

Preliminary Basin Modelling Tests

The confinement of Jurassic layers beneath the Gotnia salt is certainly the primary cause of overpressure at basin scale. However, how can we precisely explain overpressure levels Overpressure completely dispels in Zubair Sandstones.

1/ Highly impermeable Gotnia-Hith Fm.

Overpressure would be far above fracture gradient → Not realistic, Jurassic fluids must escape the system. There are certainly active "salt windows".

2/ Gotnia-Hith Fm. with "open faults"

Lower overpressure would be observed

→ Salt windows are certainly localized, with a relatively low permeability.

3/ Faults with intermediate permeability

More consistent according to pore pressure measurements → However the pressure field is too homogeneous in the Marrat Fm.

4/ Faults with intermediate permeability + permeability variations in Marrat Fm.

Good match with measurements. Salt windows mainly localized along Kuwait Arch. Marrat Fm. is rather impervious (discontinuity of porous bodies).

Basin Modelling results

Patches with higher overpressure in Northern Kuwait and Offshore Kuwait would be related to "pressure plumes" = Jurassic fluids injected in low permeable Lower Cretaceous units above "salt windows".

Dubille et al., 2017

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DELIVERING EXPERT PPP SYTEM BY COUPLING BM, SRC & GEOMECHANICS

- **3D expert model:** Integration of 1D geomechanics, 3D seismic reservoir characterization, and 3D pore pressure

6

** INTEGRATED WORKFLOW FOR PREDICTING DRILLING HAZARDS DUE TO HIGH PORE PRESSURES IN THE NORTH KUWAIT FIELDS (AL-SAEED ET AL, EAGE 2017)

Dubille et al., 2017

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DELIVERING EXPERT PPP SYTEM BY COUPLING BM, SRC & GEOMECHANICS

3D Pore-Pressure cube from geophysics (SRC)

Pore Pressure cube (psi)

EMW cube (ppg)

Improved pressure cube from basin model

Geomechanical Finite Element Analysis (locally at well)

Maximum Overpressure in the model

Overpressure Reference Model

Minimum Overpressure in the model

3D expert model for well planning

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CLOSING REMARKS & DISCUSSION

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