ENERGY Geo Hackathon

Society of Petroleum Engineers

#DatafyingEnergy

From October 21, 2024

Geothermal Reservoir: Geology Basis

Italian Section

Croatian Section

Netherlands Section

London Section

Romanian Section

SPE France Section

SPE Vienna Basin Section

Central Ukraine Section

Geothermal Technical Section

Data Science and Engineering Analytics Technical Section

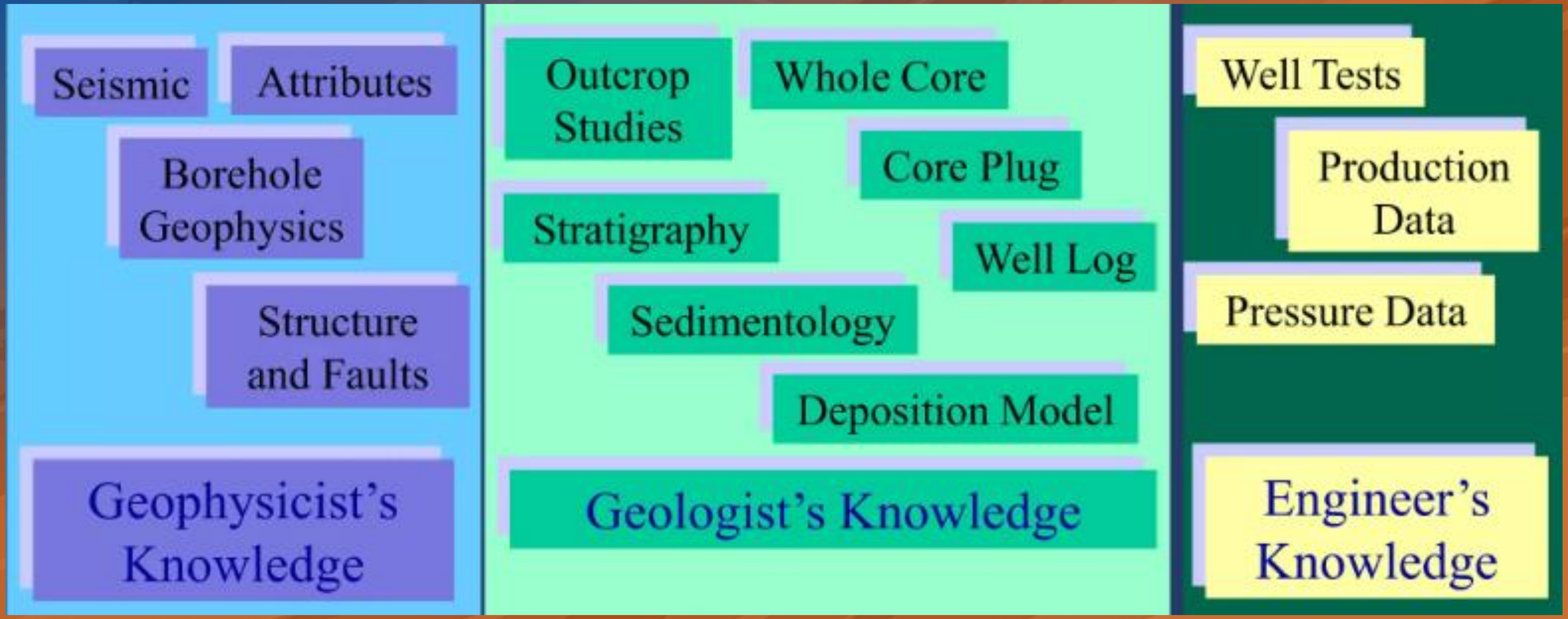
www.spehackathon-eu-com

Agenda

- The scope of geological models
- Data type
- Geological modelling workflow
- Geothermal systems definition and classification
- Conclusions

The scope of geological models

- 3D geological models are the best tool for integrating subsurface complex data, to monitor geological structures and analyze their potential uses, or their geodynamic & physical behavior (e.g. seismic activity):
  - Integration of data: a general framework capable of supporting decision makers & to define priorities between different geopotentials
  - Reservoir modeling requires a thorough understanding of the geology, rock and fluid properties
- The calculation via modeling software allows to quickly check different data for any inconsistencies and to constrain or modify quickly, obtaining more consistent results



Data type

Geological model is derived by extending the information from cores and logs to reservoir scale, using geological concepts, geophysics, depositional environment studies etc.

Input data

General
- Well coordinates, UWI, Total Depth, KB/GL
- Outcrop information
- Data from literature

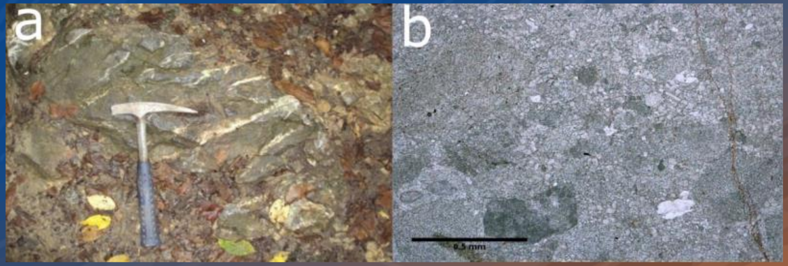
Seismic
- Velocities
- Horizons and faults interpretation
- Seismic Attributes

Lithostratigraphic
- Stratigraphy
- Age
- Lithology
- Deposition environment
- Unconformities/ faults
- Dipping/ azimuth

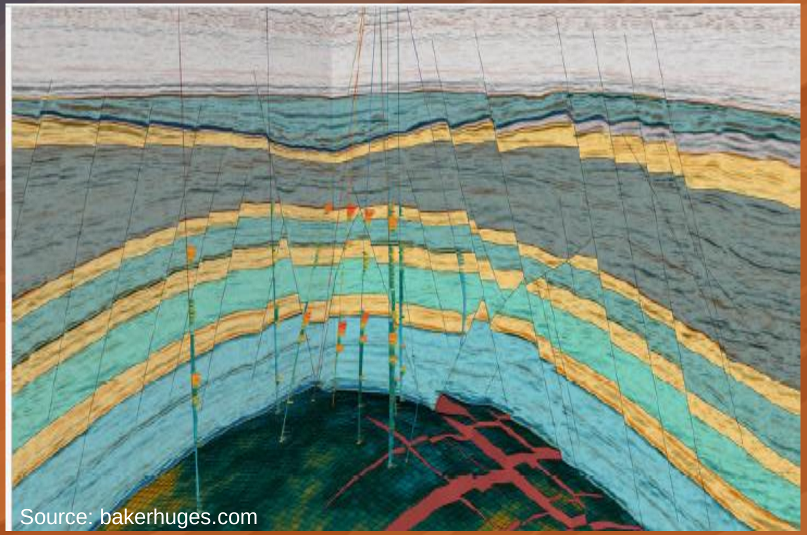
Petrophysics
- Volume of shale; N/G
- Porosity
- Permeability
- Fracture density
- Mineralization
- Temperature
- Fluid density

Production
- Flow rates
- Pressures
- Production tests

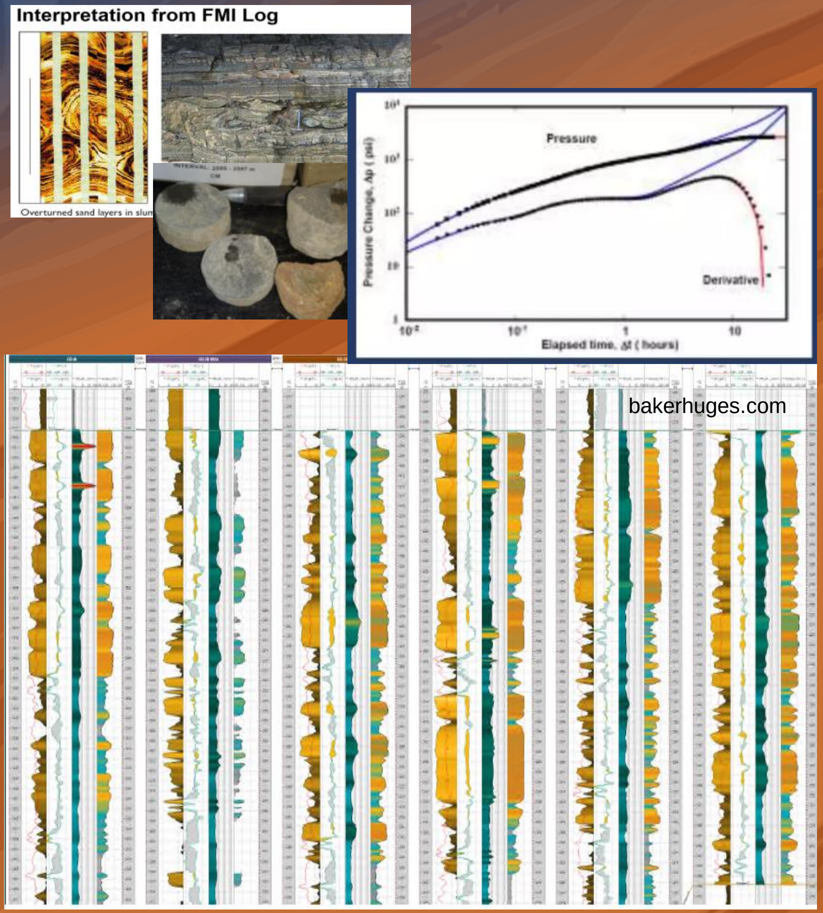
Regional information: Literature & Outcrops



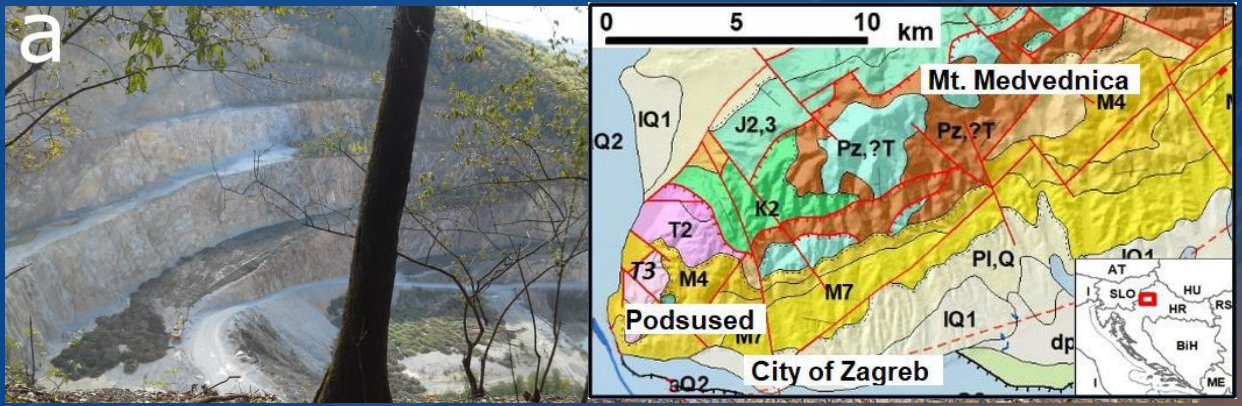
Seismic



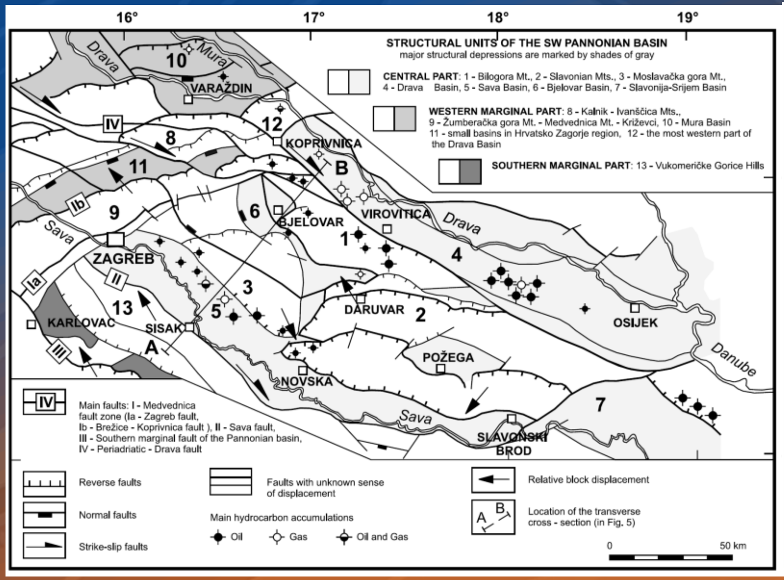
Well data

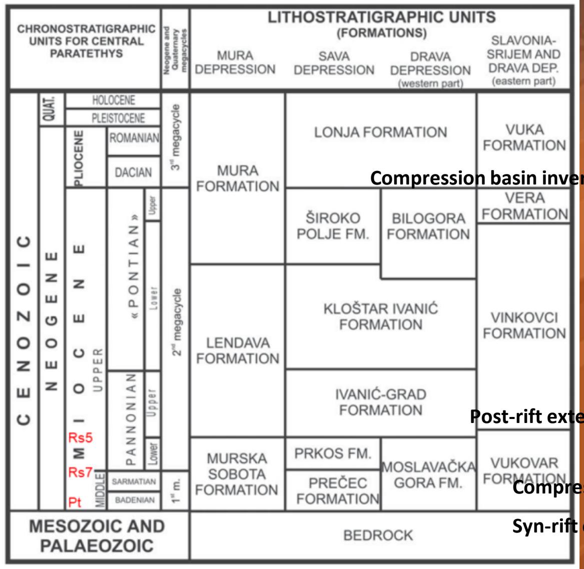


Regional Understanding

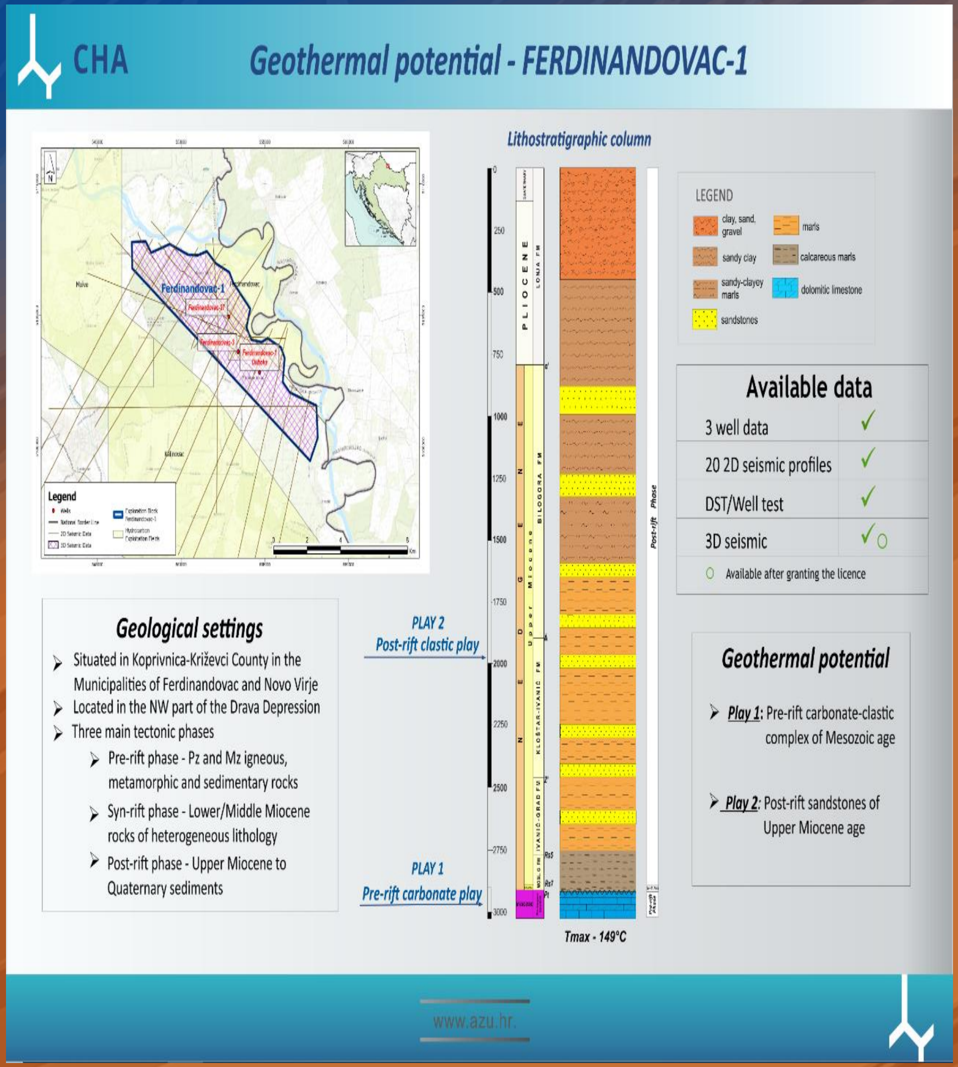


Malvic *et al.*, 2020: Outcrop with light grey dolomite in Medvednica Mt. (Ivanec Quarry);



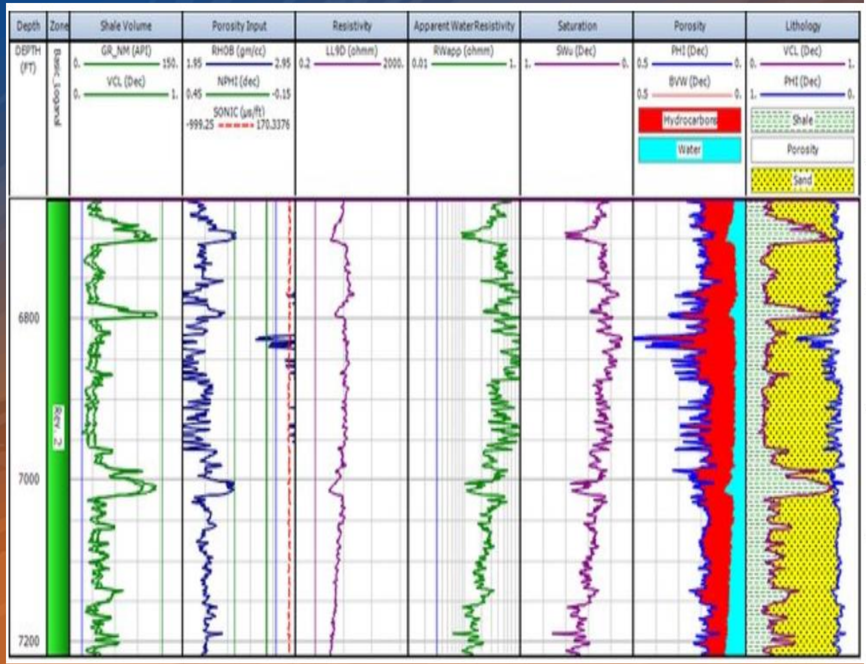


Chronostratigraphic units with lithostratigraphic units in the rank of formations valid for the Croatian part of the Pannonian Basin System (VELIĆ et al., 2002).

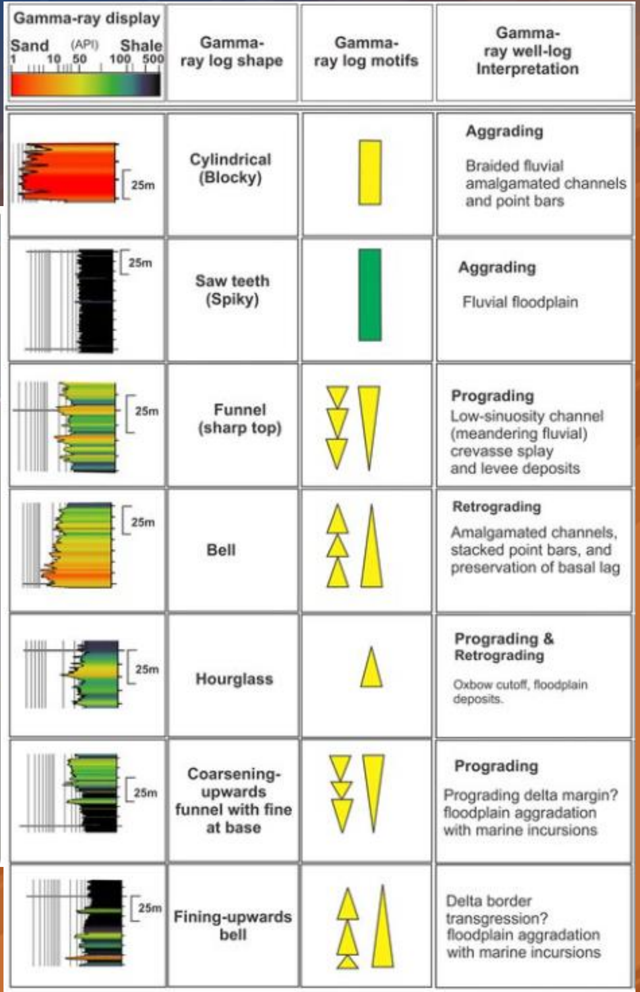


Well logs

- Well logs: detailed plot of formation parameters versus depth
- Types of logs
  - Well logs recorded directly in the borehole (GR/SP/Resistivity/ Neutronic /Acoustic)
  - Well logs interpreted by the petrophysicist (Vclay /Porosity/Permeability/Water Saturation)
- Well log applications:
  - Provide real time evaluation of formation while drilling
  - Well log correlation
  - Fault identification
  - Electrofacies identification
  - Reservoir properties evaluation (rock composition
  - Water/Hydrocabron presence (type/salinity/pressure/saturation)
  - Contact identification

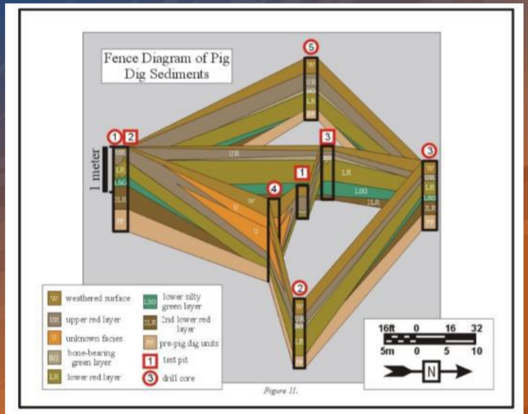


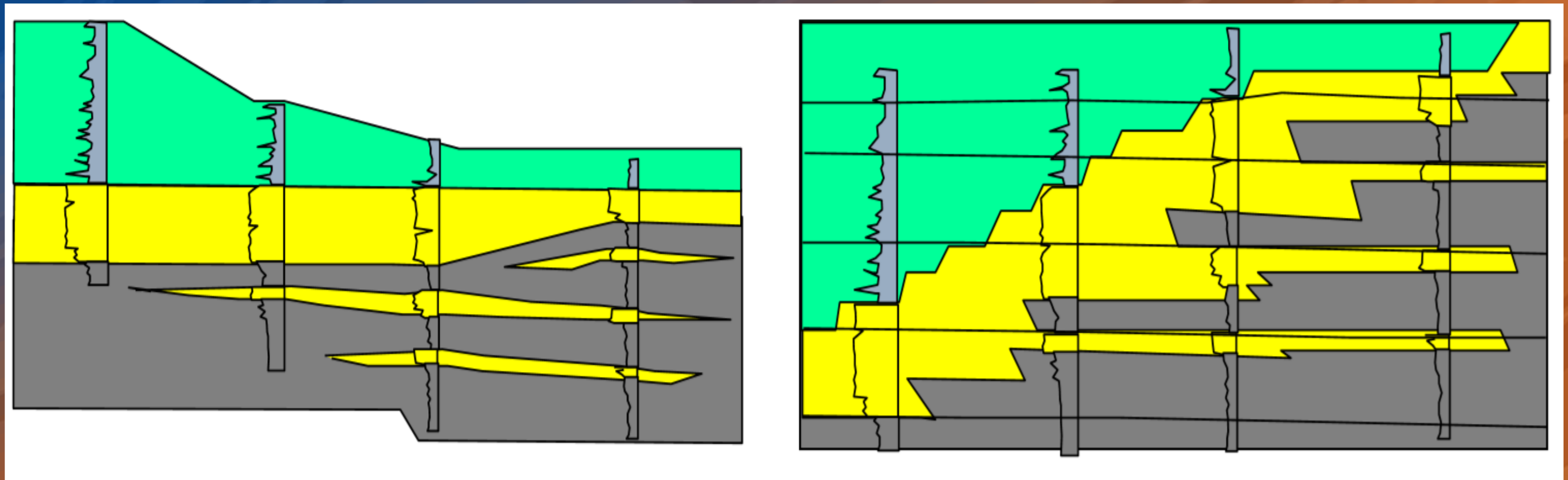
Example of well interpretation in Niger Delta Region

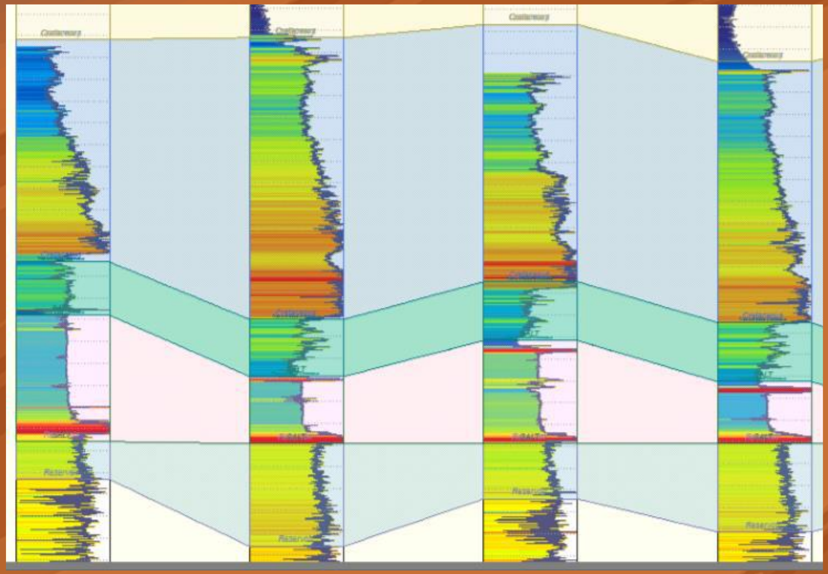


Well correlation

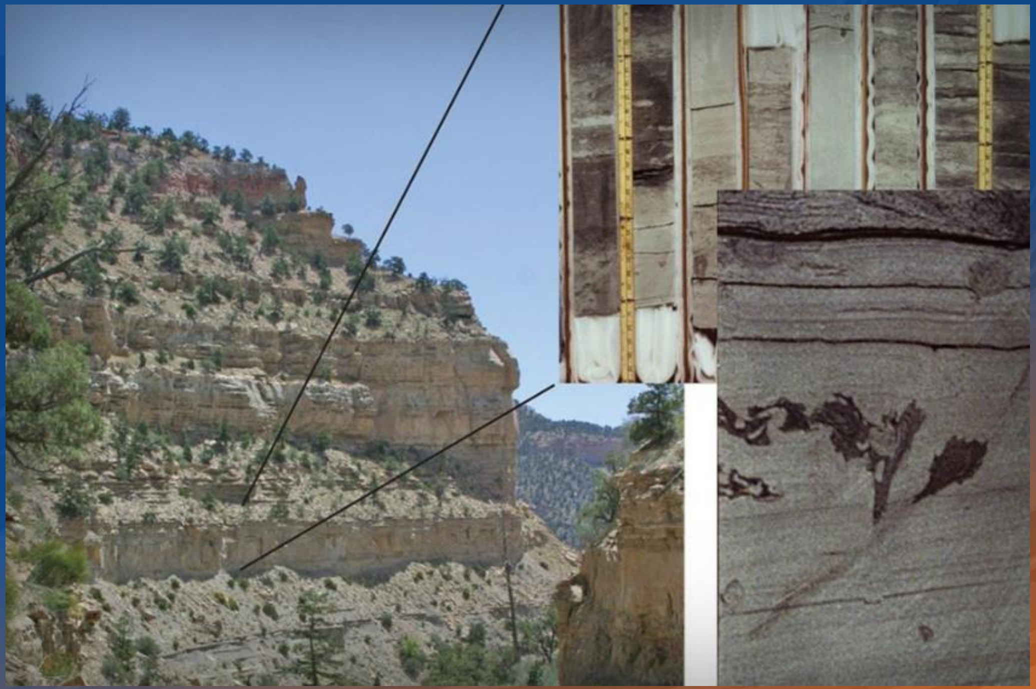
- Well log correlation is a key part in reservoir characterization, a necessary step in conducting a geological model and volume evaluation
- the process of establishing relationships and similarities between different wells in area of interest, considering different well log responses
- There are distinct approaches in correlation developed as a function of the individual routine job and/or the purpose of correlation: the most common in the industry are lithostratigraphic and chronostratigraphic

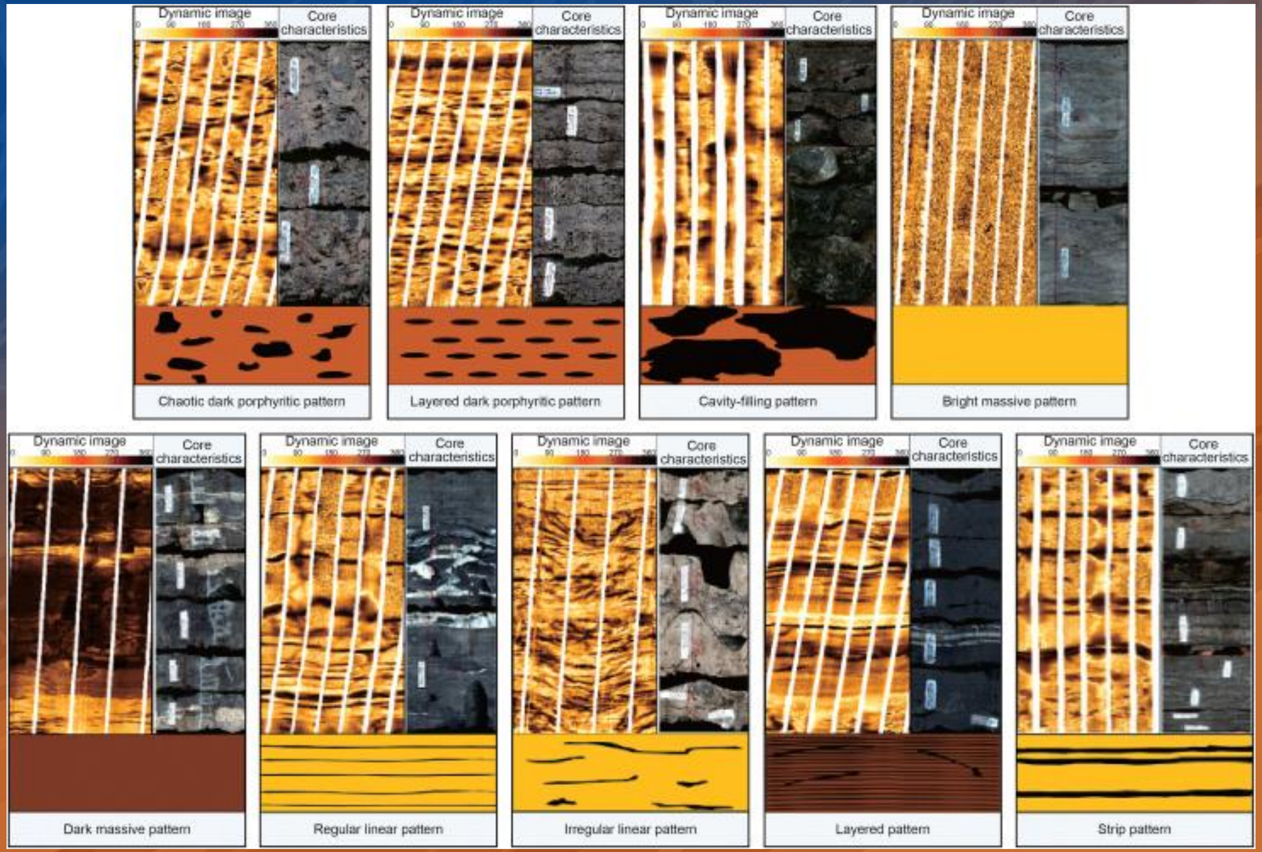






Core data and borehole image logs

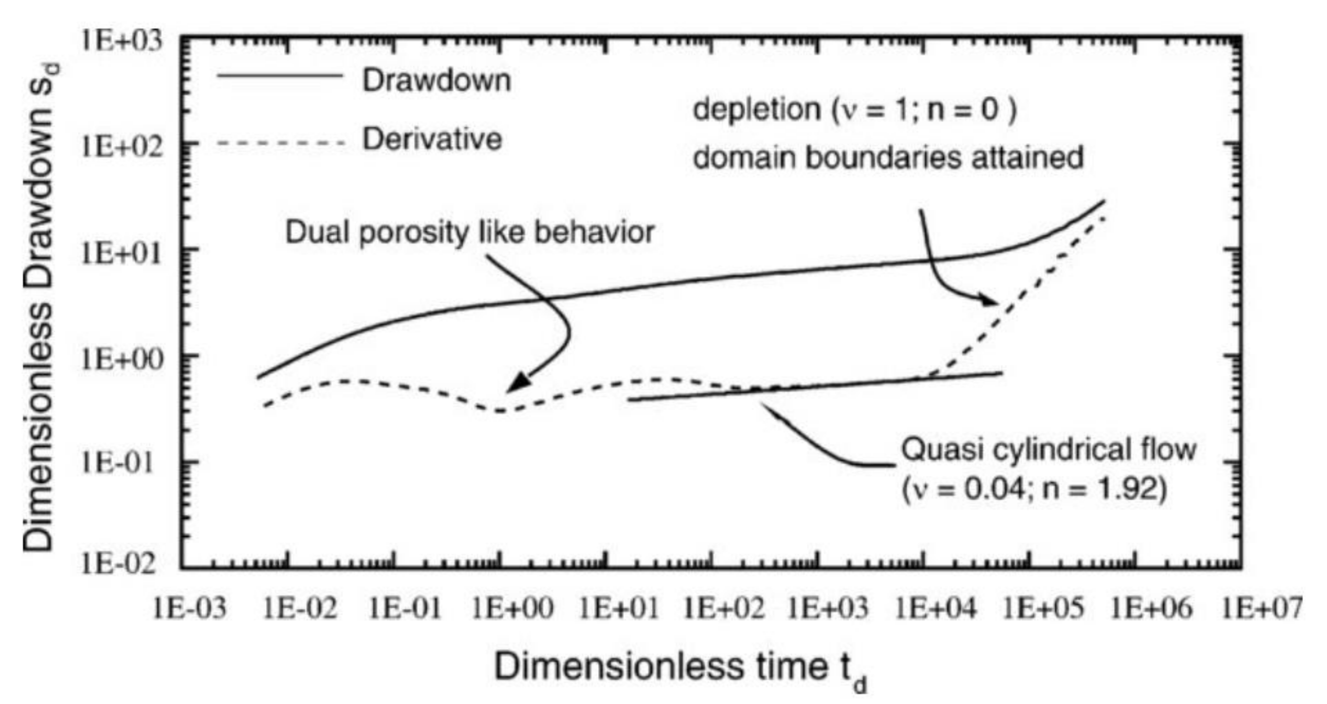




Feng *et al.*, 2020: Charts showing the image log facies/microfacies patterns in wells from Sichuan Region

Well tests and production data

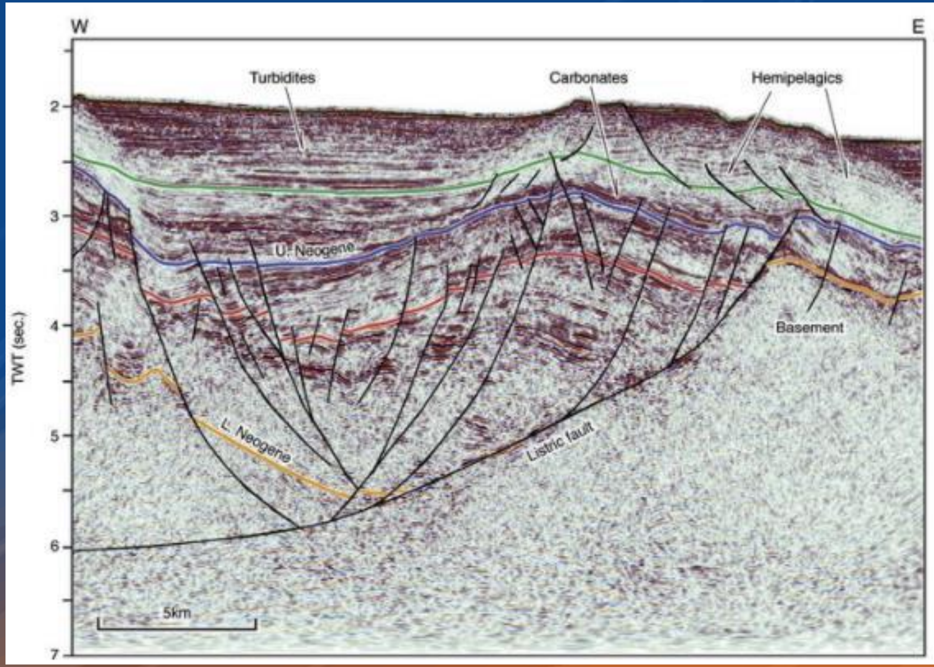
- Insights about the type of reservoir (lithology, layers, boundaries in flow, etc)
- How many phases are in the reservoir / which is the dominant phase
- Pressures and temperatures
- Bubble / dew point pressure
- Fluid contacts and production data



Hydrodynamic response and transient-well-test signature on the pumping well [Jourde et al., 2002]

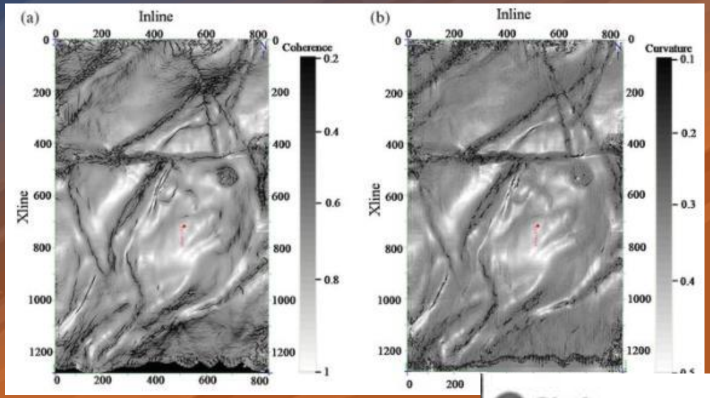
Seismic information

- Structural analysis
  - Study of reflector geometry, identification of faults, surface interpretations

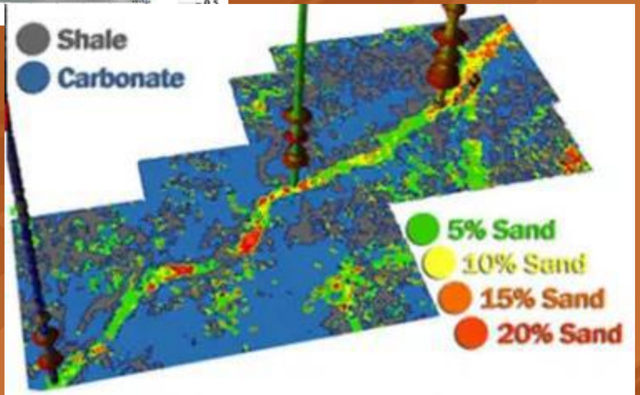


Seismic transect across the Nam Con Son Basin

- Seismic attribute analysis
  - Study of seismic attributes which provides information related to structure, stratigraphy and reservoir properties (porosity) or fluid content



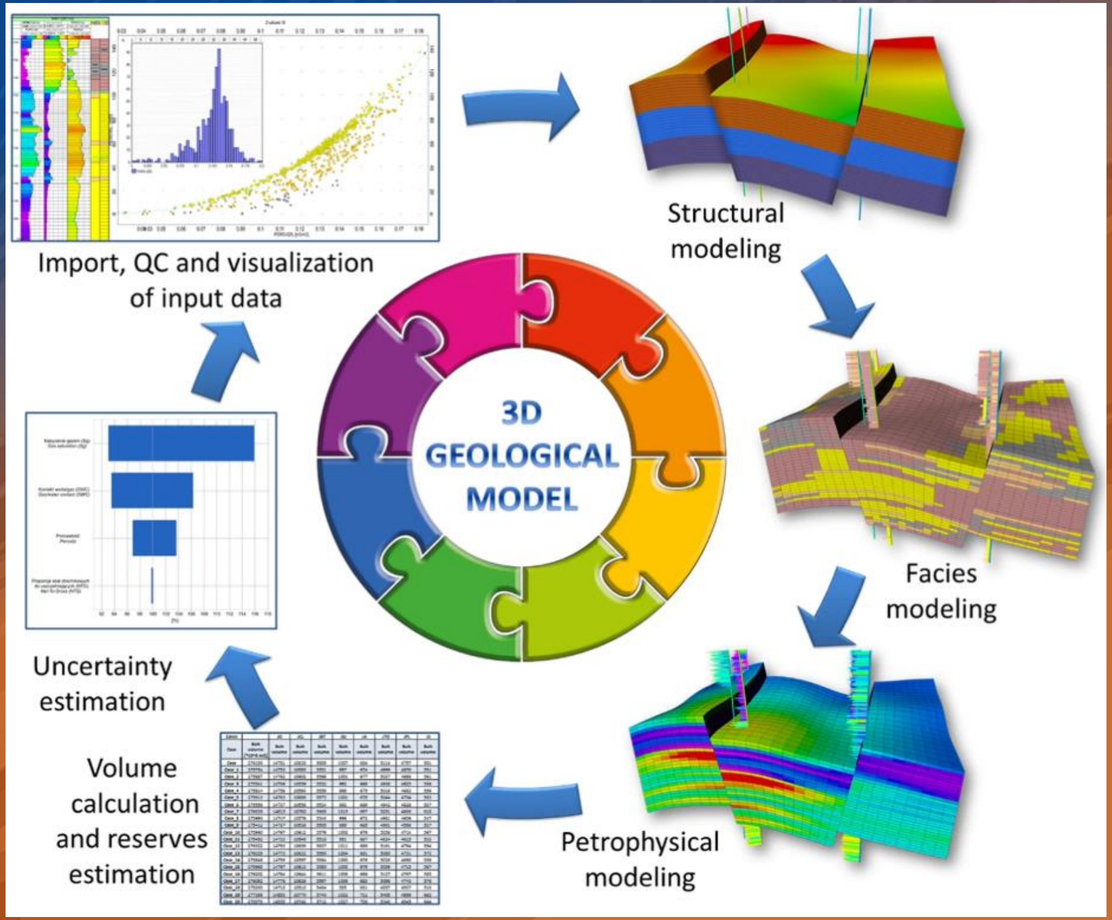
Fracture predictions of the coherence and minimum curvature attributes



Lithology prediction from different attributes

Geological modelling workflow

- Iterative process, which integrates seismic interpretation, depth conversion, well correlation and parameters analysis
- Performed in software (e.g Petrel SLB)
- The output is composed by structural model (the base of the model) and stratigraphic model, which considers facies variation and propagation of petrophysical parameters (volume of shale, porosity, permeability, Sw)
- The result depends on the data availability and the scope of geological model:
    - Resource calculation
    - Well placement and geosteering during drilling
    - Reservoir simulation
    - Field Development Plan

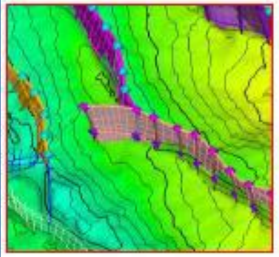


Static modelling workflow in petroleum and geothermic geology, Halaj *et al.*, 2021

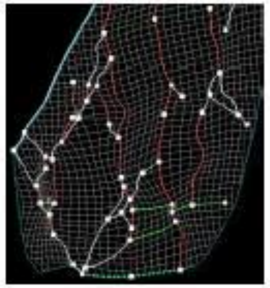
Structural model

- Can be performed both in structural framework and pillar gridding

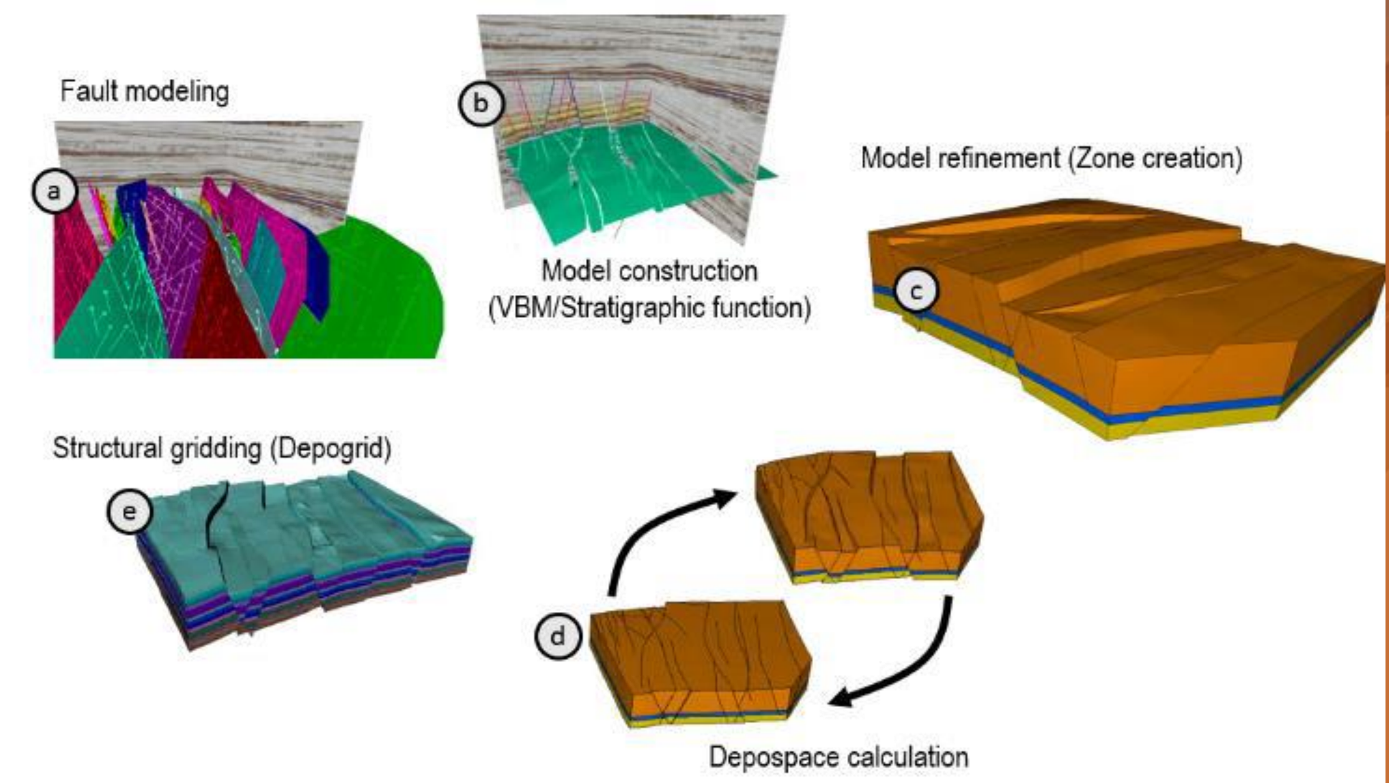
  - Input data:
    - Faults
    - Horizons
    - Thickness maps
    - Well tops



Fault Modeling



Pillar Gridding

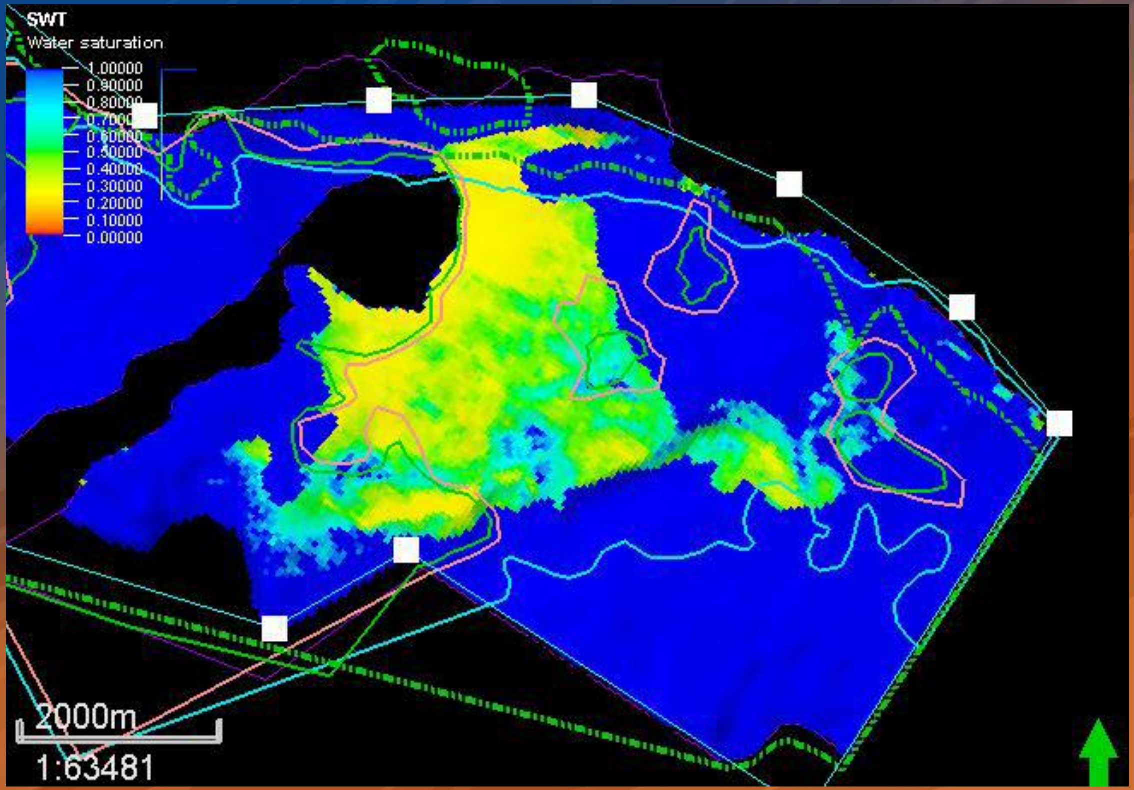


- Pillar gridding
- Structural framework

Facies and Petrophysical modelling

- The steps in data analysis and modelling of input data for facies and petrophysical modelling are carried out by:
  - Scale up well logs
  - Data analysis
  - Facies and properties distribution

- Input data:
  - Seismic attributes
  - Facies log
  - Well logs interpreted
  - Depositional environment maps



Geothermal systems classification

- **Geothermal energy**
  - Resource classification
    - Enthalpy*
      - High enthalpy resources (>190°C)
      - Low enthalpy resources (<190°C)
    - Heat Transfer
      - Convection
      - Conduction
      - Radiation
  - Uses
    - Electricity generation
    - Direct (Thermal use)
    - Geothermal Heat pump
  - Exploitation technologies
    - Deep Geothermal systems **
    - Shallow geothermal systems **

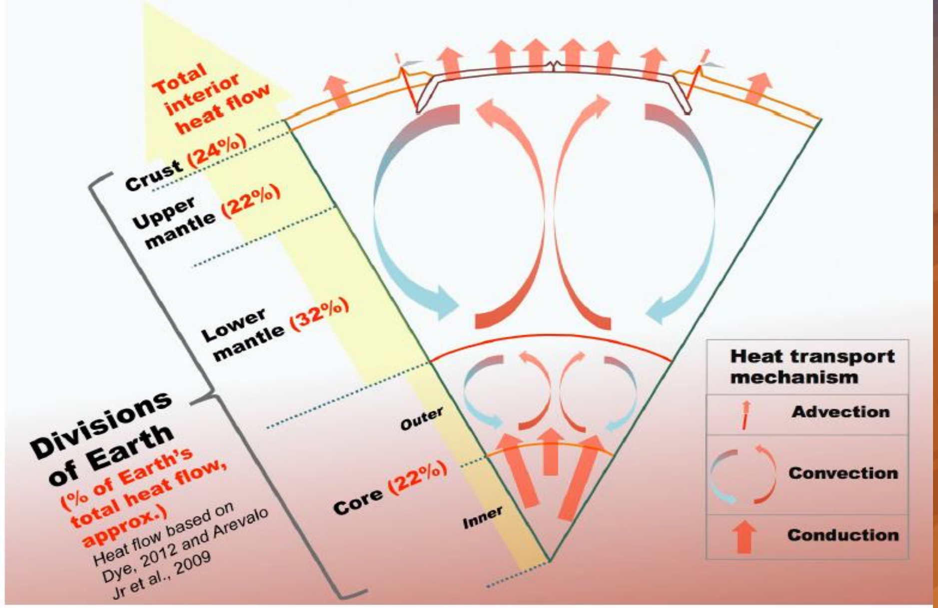
Modified after Crowdthermal D1.2, 2020

*different classification: a single limit of temperature was not established
** depths regulated by the requirements for drilling, commonly 500m

Resource classification

- While temperature, pressure, volume, enthalpy and entropy are thermodynamic properties of a given system, **heat** refers to “energy in transit”: is the energy that flows due to temperature difference
- **Enthalpy** is the measure of heat (energy) content of a system
- Geothermal resources are classified in relation to enthalpy of the heat carrier, into low, medium and high-grade enthalpy
- Different classification exist: a single limit of temperature was not established
  - It can be assumed roughly T<150°C for low enthalpy systems

	Muffler & Cataldi (1978)	Hochstein (1990)	Benderitter & Cormy, (1990)	Haenel et al., (1988)
Low Enthalpy	<90°C	<125°C	<100°C	<150°C
Medium Enthalpy	90–150	125–225	100–200	
High Enthalpy	>150	>225	>200	>150

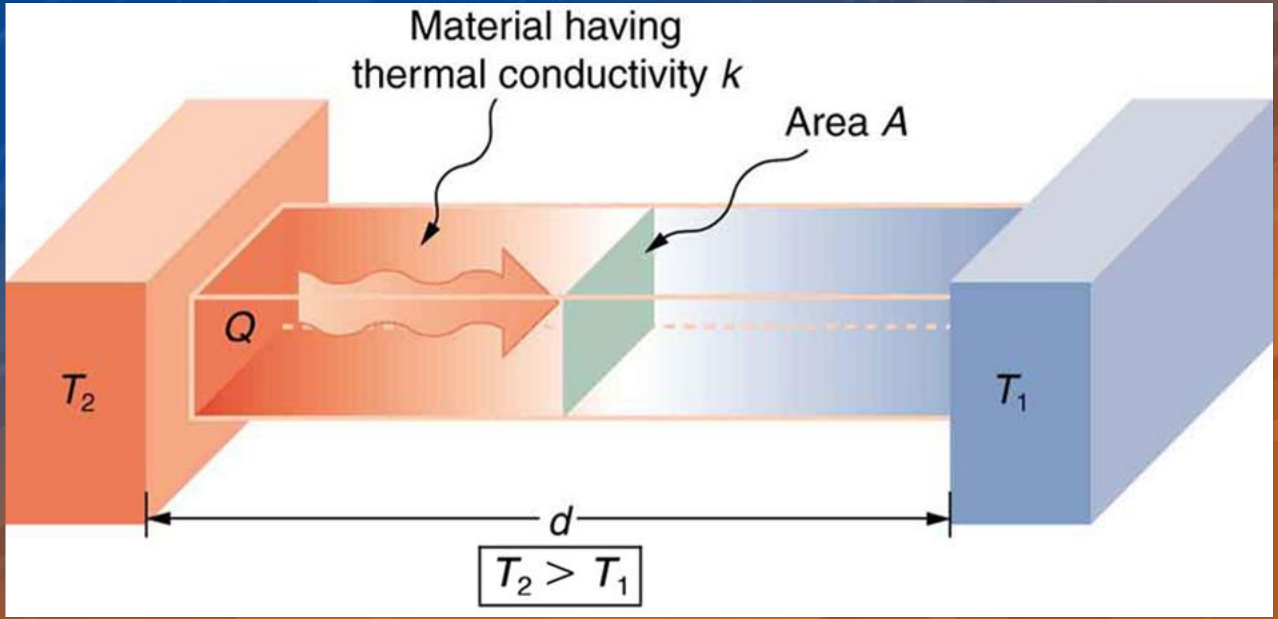


- Heat can be transferred by three processes:
  - Conduction: heat flows from hot temperature to a cold temperature (no fluid movement)
  - Convection: involves large scale movement of water -> heat moves with hot water
  - Radiation: heat transfer does not require a medium to pass through: sun to Earth radiation controls temperature at earth`s surface

Heat flow calculation

- The mean terrestrial heat flow of continents and oceans is between 65 -101 mWm-2, with a global mean of 87 mWm-2 (values from 24,774 measurements covering about 62% of the Earth's surface, Pollack *et al.*,1993)
- Heat flow (***q***) is determined according to the Fourier law

$$\mathbf{Q} = -\lambda \nabla T \cong -\lambda\ (\Delta T/\Delta z)$$



Q: Heat flow [W/m^2]

λ (k) :thermal conductivity of rocks [$W{\cdot}m^{-1}{\cdot}K^{-1}$]

$\Delta T/\Delta z$: geothermal gradient [°C/m]

Thermal conductivity

- Value describing how well heat is conducted through a material (symbol: k or λ)
- Thermal conductivity of rocks: in the range of 0.40–7.00 W m^{-1} K^{-1},
- In general, the thermal conductivity of rocks is measured in laboratory on rock samples
  - The method has several difficulties, like challenges to preserve the fluid content of porous rocks and representativeness of sample
- Thermal conductivity can also be estimated, based on lithological or petrological components
- For clastic sediments well-logs can be used to determine the TC of a sedimentary sequence (various authors)
- Fuchs *et al., 2018* propose the calculation of k for plutonic rock considering the k of constituting minerals & their percentage
- K is influenced by pressure and temperature

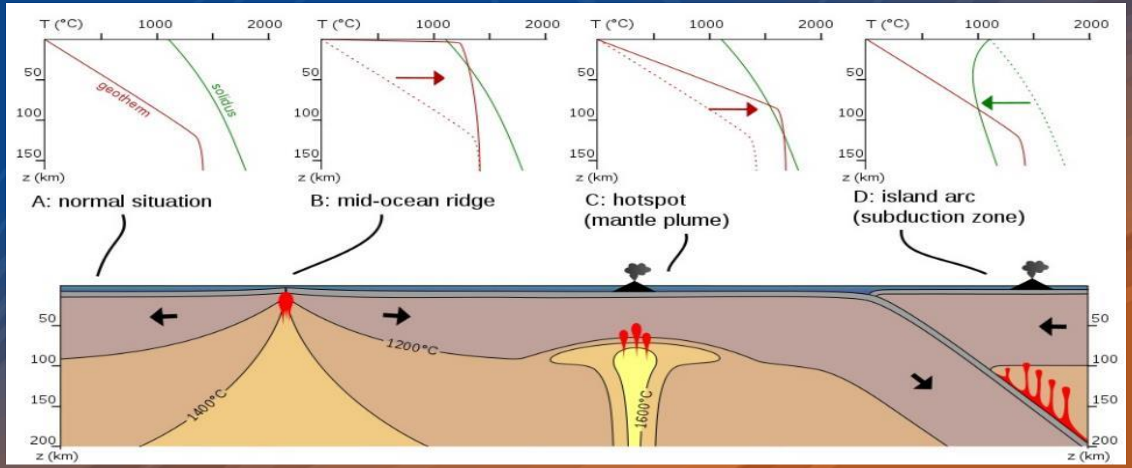
Rock type	Thermal conductivity coefficient λ (W m^{-1} $°C^{-1}$)		
	acc. Chmura [2]	acc. Blackwell and Steel [7]	acc. Clark [8]
Shale	1.26 - 2.63	1.05 - 1.45	1.1 - 2.1
Limestone	0.81 - 2.22	-	2.5 - 3.0
Sandstone	1.51 - 4.52	2.50 - 4.20	2.5
Mudstone	1.51 - 3.36	-	-
Claystone	0.93 - 2.88	0.80 - 1.25	-
Coal	0.09 - 0.70	-	-

Rock type	TC [W/(m.K)]
gneiss, biotite gneiss	3.12
greenschiest	3.3
calcareous & quartz fillite	3.3
chlorite schiest & amphibolite	3.6
clayschiest	3.1
dolomite	4.7
volcanite tuff	1.8

Thermal conductivity of the basement rocks (data after Kappelmeyer & Haenel, 1974)

Geothermal gradient

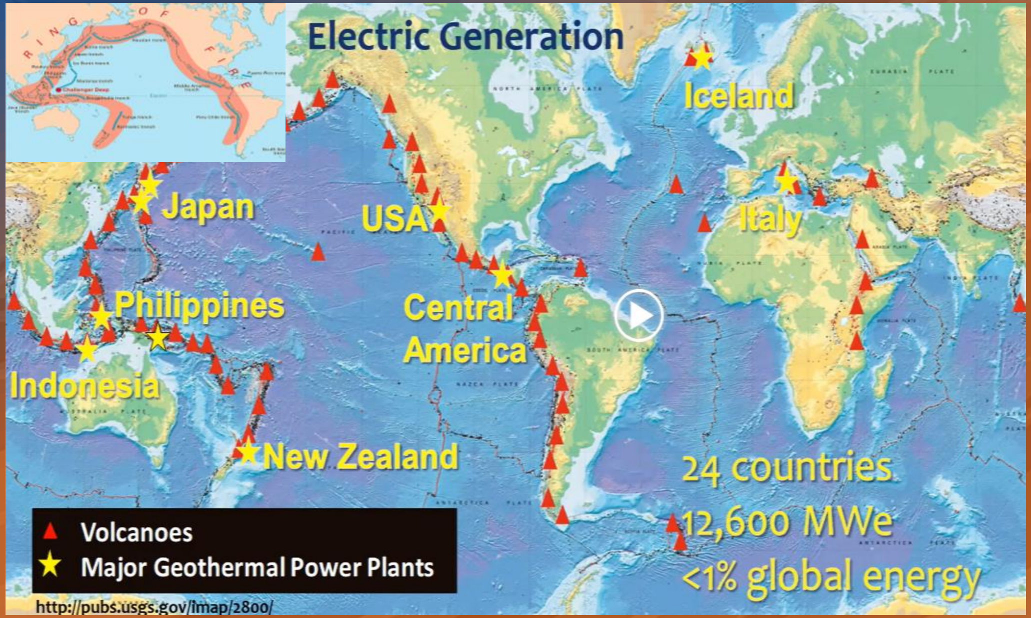
- The variation of temperature with depth is referred as geothermal gradient
- Away from tectonic plate boundaries, it is about 25-30°C/km of depth
- Geothermal systems can therefore be found in regions with a normal or slightly above normal geothermal gradient
- Geothermal gradient tends to be average in Europe; exceptions can be found in Italy, Iceland, Hungary, Croatia and other localized areas
- Geothermal anomalies occur also due to different geological processes like subsidence, isostatic rebound, paleoclimatic cooling, or rifting

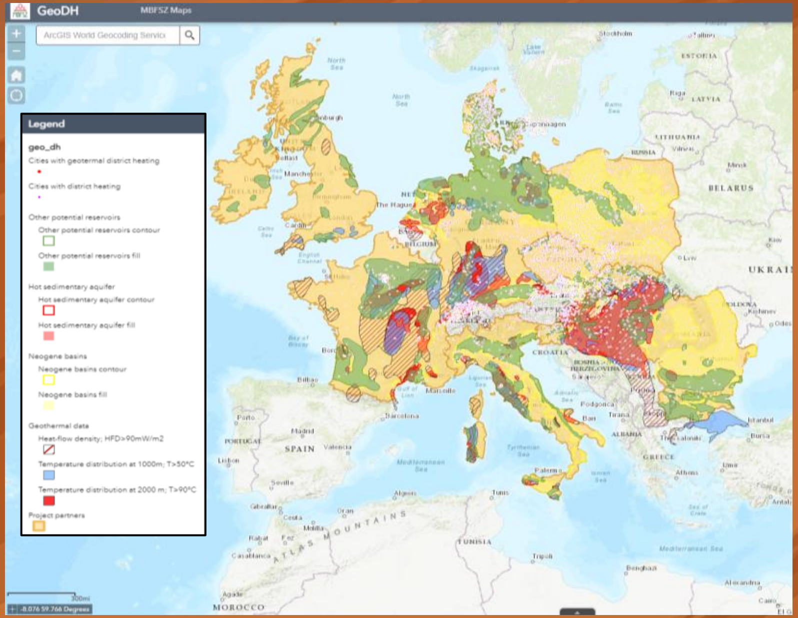


https://www.geologyin.com/2014/12/geothermal-gradient.html

- Source of data: production tests or drilling information (the last one need to be integrated with caution)
- Calculated as:

(T@TD-T@surface)/TD

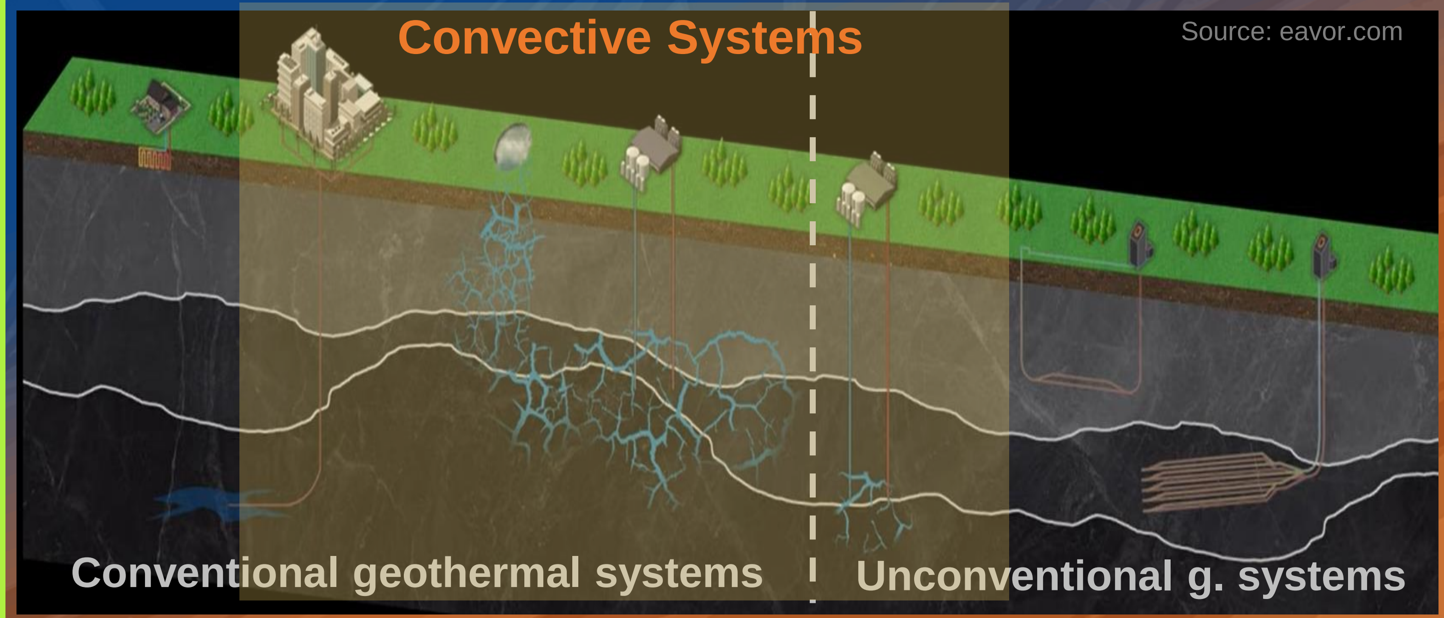




Exploitation technologies

Various technologies and uses:

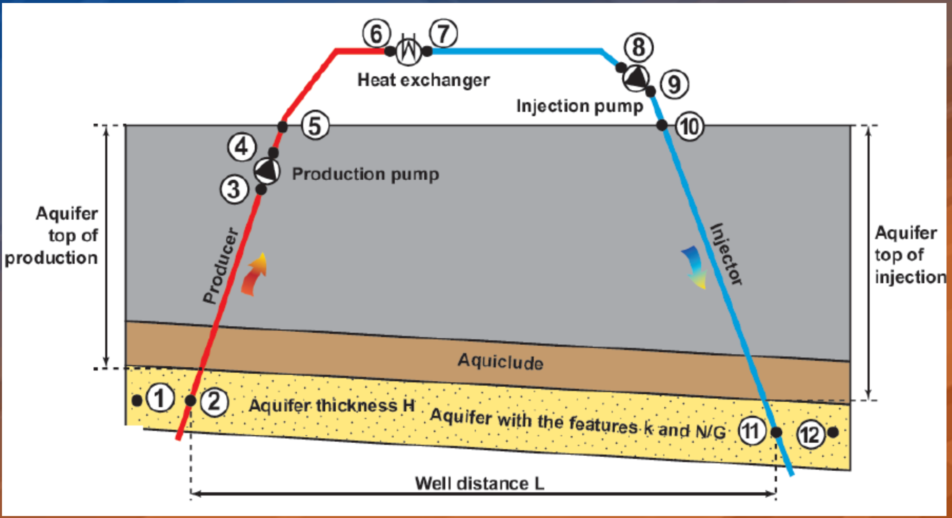
- Geothermal Heat Pumps
- Direct Use (heat):
  - Traditional geothermal - Hydrothermal systems
  - Hot water from springs
- Electricity Generation
  - Deep hydrothermal
  - Enhanced G. System (EGS)
  - Advanced G. System (AGS) & closed loop systems



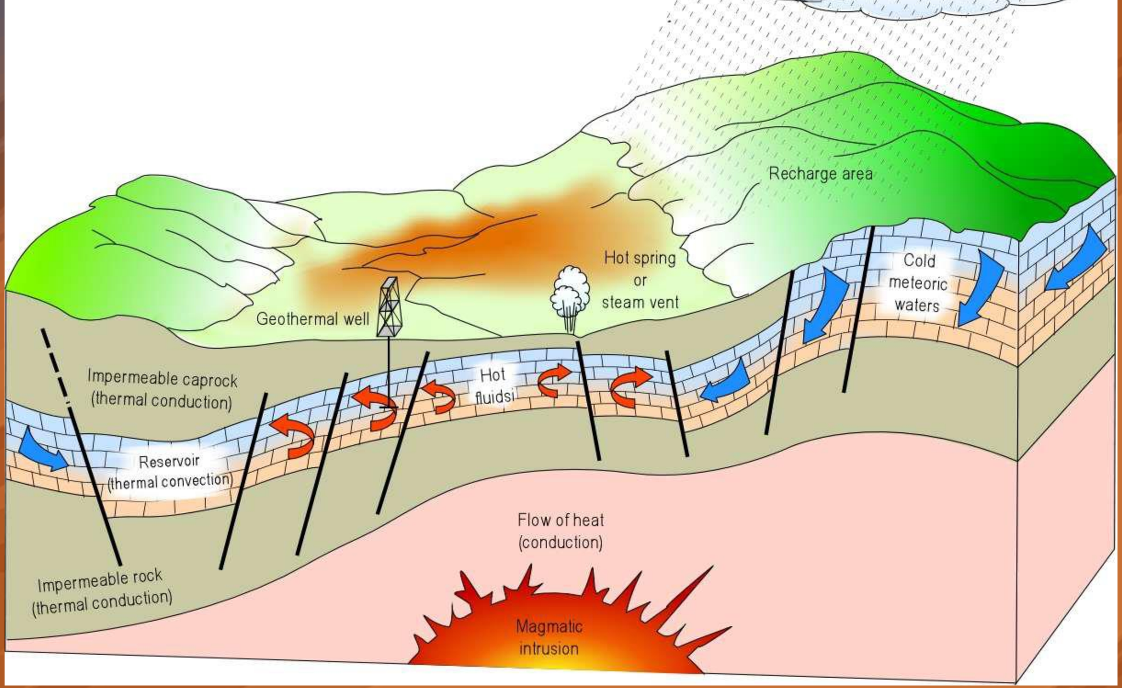
- Beside the information derived from wells & seismic, several workflows & skills from O&G can be applied (depending on the chosen technology)
- Similar approaches to O&G: detecting and delineating leads/ prospects, developing existing assets, looking at technological aspects and economical viability
- Requirements: resource estimation and assessment of uncertainty categories; all reserves categories have risk associated with the recovery
- Existing need to compile to reporting standards and guidelines

Hydrothermal systems

- Exploitation of deep geothermal is done by a doublet system: injection & producing well
- The characteristics of a geothermal system are controlled by its specific geology
- Essential requirements for a classical geothermal system:
  - A reservoir to accumulate heat
  - A large source of heat
  - A barrier to hold the accumulated heat



Schematic representation of an ideal geothermal system.
Dickson&Fanelli, 2004



Resource calculation: volumetric method

- Estimation of heat considers geological & petrophysical parameters of the reservoir and thermal properties of the rocks and liquid
- The thermal output is usually calculated via software

$$Q = A \cdot h \cdot \left\{ \underbrace{\left[C_r \cdot \rho_r \cdot (1-\phi) \cdot (T_i - T_f) \right]}_{\text{heat in rock}} + \underbrace{\left[\rho_{si} \cdot \phi \cdot (1 - S_w) \cdot (h_{si} - h_{wf}) \right]}_{\text{heat in steam}} + \underbrace{\left[\rho_{wi} \cdot \phi \cdot S_w \cdot (h_{wi} - h_{wf}) \right]}_{\text{heat in water}} \right\}$$

Q = stored heat
A = areal extent of the reservoir
h = average reservoir thickness
C_r = specific heat of the rock at reservoir conditions
T_i = initial average reservoir temperature

T_f = rejection temperature
ρ_r = rock density
ρ_{si}, ρ_{wi} = steam and water density at reservoir temperature
h_{si}, h_{wi} = steam and water enthalpies at reservoir temperature
h_{wf} = water enthalpy at cut off temperature

Example of volumetric calculation of "stored heat", Prof. Dr. Gioia Falcone, 2012 (after AGCC, 2010)

Doublet Calculator 1.4.3 Result Table

probabilistic plots | fingerprinting | export base case details

file: D:\program files\doubletcalc143\compare_dc2d.xml

Geotechnics (Input)

Property	min	median	max
aquifer permeability (mD)	199.0	200.0	201.0
aquifer net to gross (-)	0.99	1.0	1.01
aquifer gross thickness (m)	99.0	100.0	101.0
aquifer top at producer (m TVD)	1800.0	2000.0	2200.0
aquifer top at injector (m TVD)	1800.0	2000.0	2200.0
aquifer water salinity (ppm)	69999.0	70000.0	70001.0

Property	value
number of simulation runs (-)	1000.0
aquifer kh/kv ratio (-)	1.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.03
[mid aquifer temperature producer (°C)]	0.0
inital aquifer pressure at producer (bar)]	0.0
[initial aquifer pressure at injector (bar)]	0.0
exit temperature heat exchanger (°C)	35.0
distance wells at aquifer level (m)	1500.0
pump system efficiency (-)	0.61
production pump depth (m)	500.0
pump pressure difference (bar)	30.0
outer diameter producer (inch)	7.0
skin producer (-)	0.0
skin due to penetration angle p (-)	-0.94
pipe segment sections p (m AH)	500.0,1054.0,1930.0,2678.0
pipe segment depth p (m TVD)	500.0,1054.0,1833.0,2505.0
pipe inner diameter p (inch)	5.0,12.38,8.62,6.62
pipe roughness p (milli-inch)	1.2,1.2,1.2,1.2
outer diameter injector (inch)	7.0
skin injector (-)	0.0
skin due to penetration angle i (-)	-0.94
pipe segment sections i (m AH)	50.0,1054.0,1930.0,2645.0
pipe segment depth i (m TVD)	50.0,1054.0,1833.0,2468.0
pipe inner diameter i (inch)	5.0,12.38,8.62,6.62
pipe roughness i (milli-inch)	1.2,1.2,1.2,1.2

Geotechnics (Output)

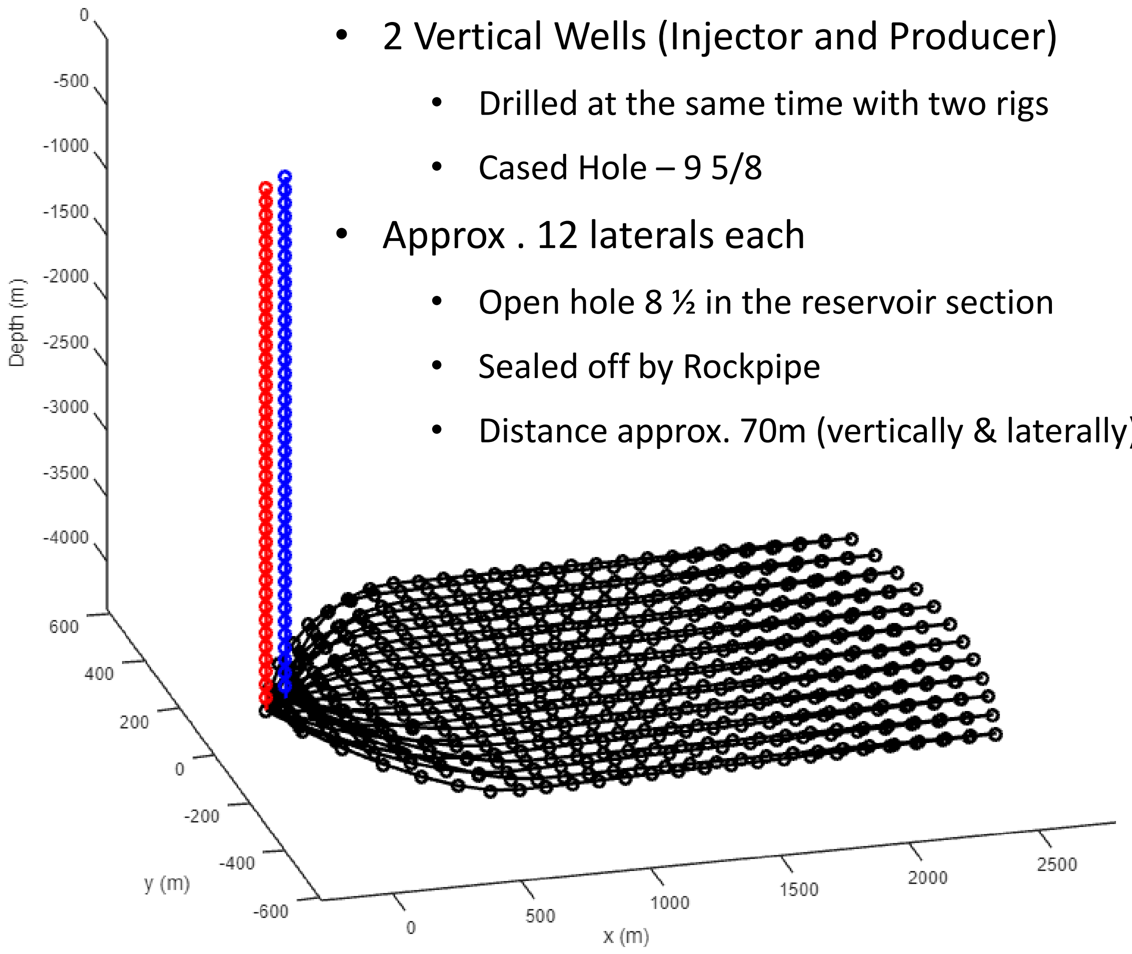
Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	19.85	19.99	20.16
mass flow (kg/s)	30.71	31.36	32.07
pump volume flow (m³/h)	107.2	109.6	112.3
required pump power (kW)	146.4	149.7	153.4
geothermal power (MW)	3.72	4.17	4.63
COP (kW/kW)	25.4	27.8	30.2
aquifer pressure at producer (bar)	240.8	252.42	264.24
aquifer pressure at injector (bar)	237.27	248.65	260.0
pressure difference at producer (bar)	11.51	11.72	11.95
pressure difference at injector (bar)	17.97	18.36	18.75
aquifer temperature at producer * (°C)	68.19	71.5	74.82
temperature at heat exchanger (°C)	66.43	69.39	72.44

base case (median value inputs)	value
aquifer kH net (Dm)	20.0
mass flow (kg/s)	31.35
pump volume flow (m³/h)	109.6
required pump power (kW)	149.7
geothermal power (MW)	4.16
COP (kW/kW)	27.8
aquifer pressure at producer (bar)	252.4
aquifer pressure at injector (bar)	248.58
pressure difference at producer (bar)	11.71
pressure difference at injector (bar)	18.35
aquifer temperature at producer * (°C)	71.5
temperature at heat exchanger (°C)	69.39
pressure at heat exchanger (bar)	14.35

* @ mid aquifer depth

Example of DoubletCalc (TNO) input parameters and results

Closed loop systems



- 2 Vertical Wells (Injector and Producer)
  - Drilled at the same time with two rigs
  - Cased Hole – 9 5/8
- Approx . 12 laterals each
  - Open hole 8 ½ in the reservoir section
  - Sealed off by Rockpipe
  - Distance approx. 70m (vertically & laterally)

$$Q = m*c\_p \; * \Delta T$$

- Q = Thermal Energy [kwth]
- m = massflow rate in [kg/s]
- cp = specific heat capacity of the fluid in [kJ/(kg*K)]
- ΔT = Temperature difference between inlet and outlet in [K]

Conclusions

- Geological models offer the ability to integrate all available data, the possibility of updating of the model upon acquisition of new information and the extraction of information dedicated to specific needs (simulation of the reservoirs, resource calculation, geosteering of wells)
- Even there are several aspects that differ in detail, Oil & Gas and Geothermal industries share similarities
- Subsurface information must be integrated and harmonized and the methodologies consistent: in this way the obtained results represent a strong basis for planning/development of the oil& gas or geothermal fields
- To build a model that matches the data, is mandatory to take the time and understand the available data and always quality check them
- Interdisciplinary communication is a key factor in providing models as accurate as possible

Thank you!

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