2023 SPE EUROPE ENERGY GEOHACKATHON

1. Intro to Geothermal Energy and the Role of Seismic in this field

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#DatafyingEnergy

2nd Oct2023

Elisabeth Moellendorff – Baker Hughes

Elisabeth Moellendorff
Geothermal Sales
Reservoir Technical Services

RTS
Geothermal Sales Lead
Europe 2023+

Supporting European Geothermal market with Geomechanical studies, Reservoir analysis, fracture modelling and other subsurface support.

Service Delivery Coordinator
Wireline
Norway, 2021 - 2023

Planning Norwegian wireline ops, focus on cement logging, interventions and perforations.

Data Acquisition Coordinator
(Wireline)
UK, 2019-2021

In-house support at Total Energies

Geoscience
Formation Testing &
Sampling Support
UK, 2017 - 2019

Planning, modelling & supporting all wireline & LWD formation testing and sampling in the North Sea. Focus on HPHT testing, ultralow mobility pressure testing.

Wireline Field Engineer
UK, Norway, 2012-2017

OH/CH Wireline Engineer (FE to Senior to General)

M.Sc. Project at Baker Hughes
on Deep Geothermal
Germany 2011-2012

Feasibility study of innovative casing designs to improve the economics of deep geothermal wells. 2 patents as co-author.

Education

* M.Sc. Mech. Eng. 2012 TU Bergakademie Freiberg
* B.Sc. Geology 2012 TU Bergakademie Freiberg

Patents:

US patent 9303487:	*Heat Treatment for removal of Bauschinger Effect or to Accelerate Cement Curing*
US patent 10081845:	*Tubular strengthening and patterning method for enhanced heat transfer*

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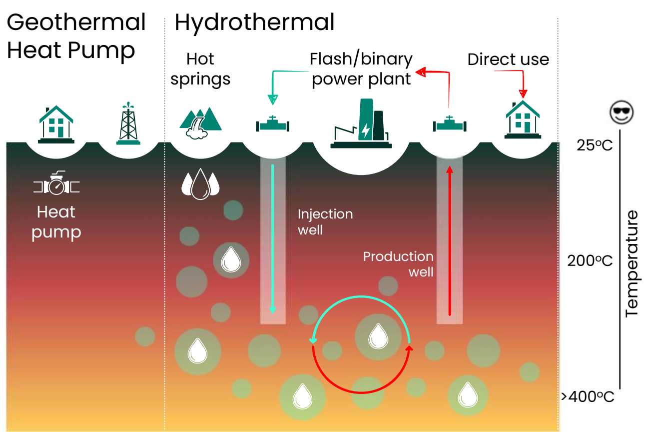
Agenda

5 min	Overview over Deep Geothermal systems
5-10 min	Existing capacity, applications and potential of Deep Geothermal in Europe
25 min	Seismic Basics: wave types, reflection vs refraction, acquisition Processing, CDP, migration, resolution 2D vs 3D VSP Limitations and other methods
10 min	Q & A

GEOTHERMAL DEVELOPMENT: EGS & AGS

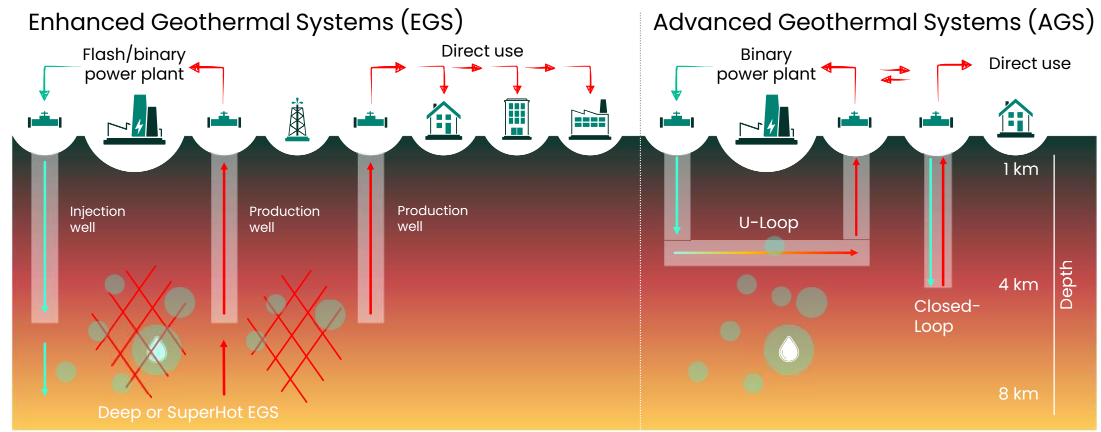
The Geothermal Ecosystem

Conventional



- ✓ Sufficient access to natural hot brine
- Successful hydrothermal industry. Geographically limited to areas with natural underground reservoirs

Unconventional

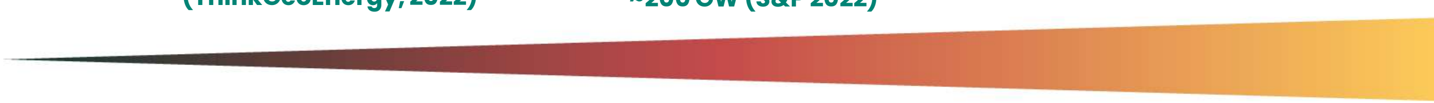


- ✓ Access to hot rock but insufficient permeability or fluid saturation. Engineered reservoirs, injecting fluid into the subsurface, or using closed-loop.
- Less geographic restrictions allowing for geothermal expansion and growth – ultimately geothermal anywhere

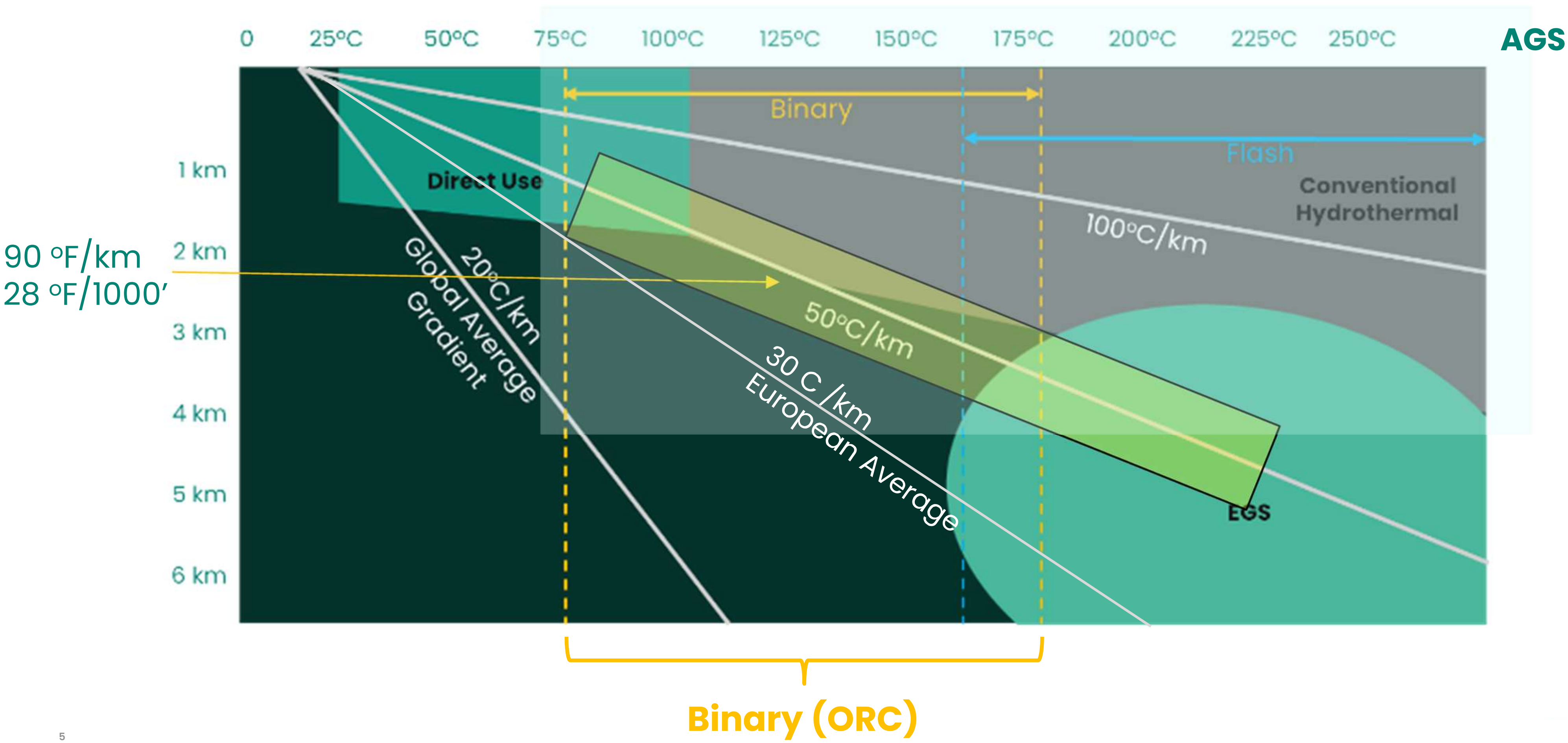
Installed Power of ~16 GW (ThinkGeoEnergy, 2022)

Conventional Power Potential of ~200 GW (S&P 2022)

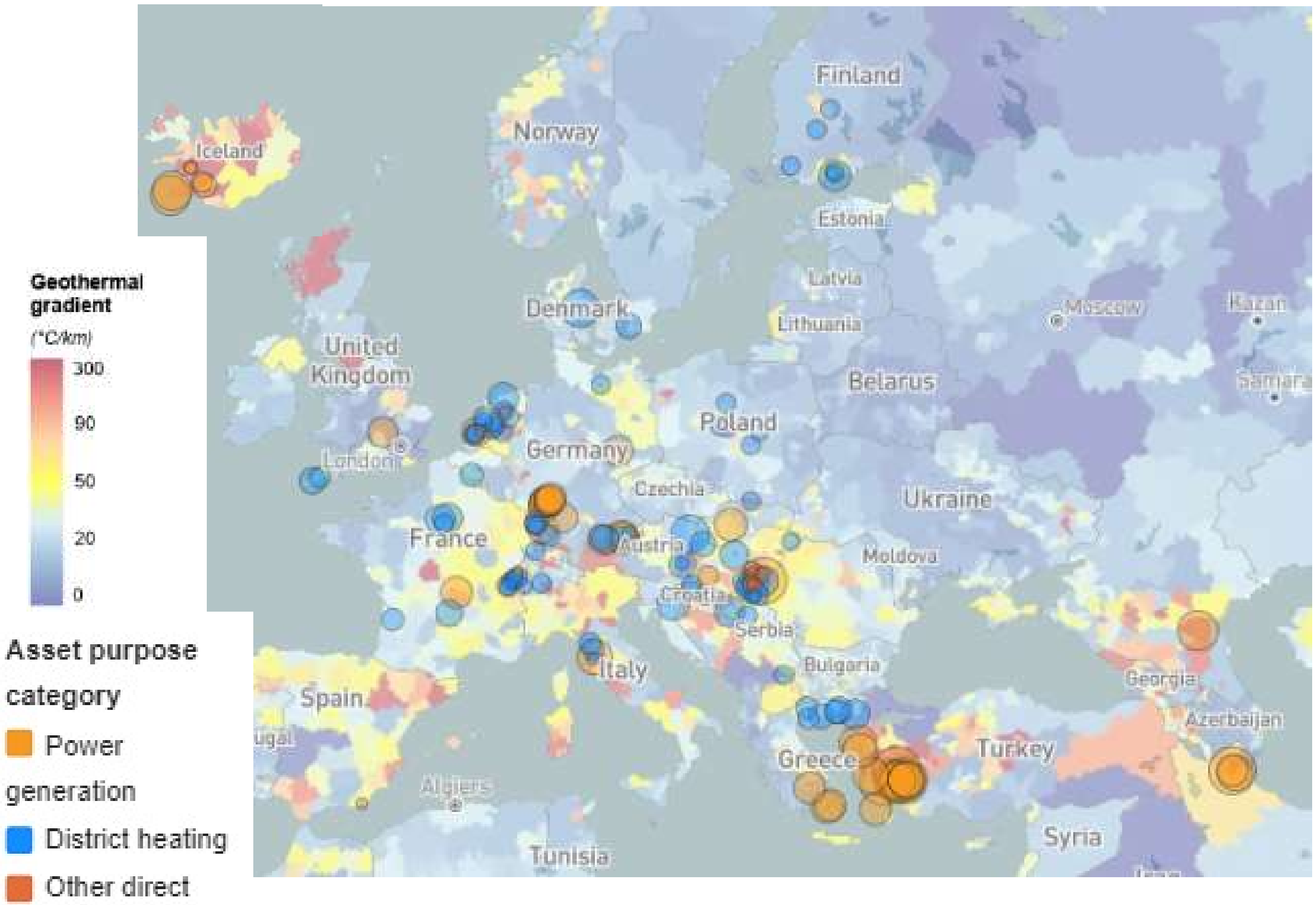
Unlimited Potential of Geothermal Anywhere



Depth-Temperature for Geothermal Resources



Deep Geothermal projects in Europe



District Heating in Europe

- Germany
- Population: 83 million
- Circa 11 million are connected to district heating network

- UK
- Population: 67 million
- Circa 2 million are connected to district heating network

- Netherlands:
- Population: 17.5 million
- Circa 0.7 million are connected to district heating network

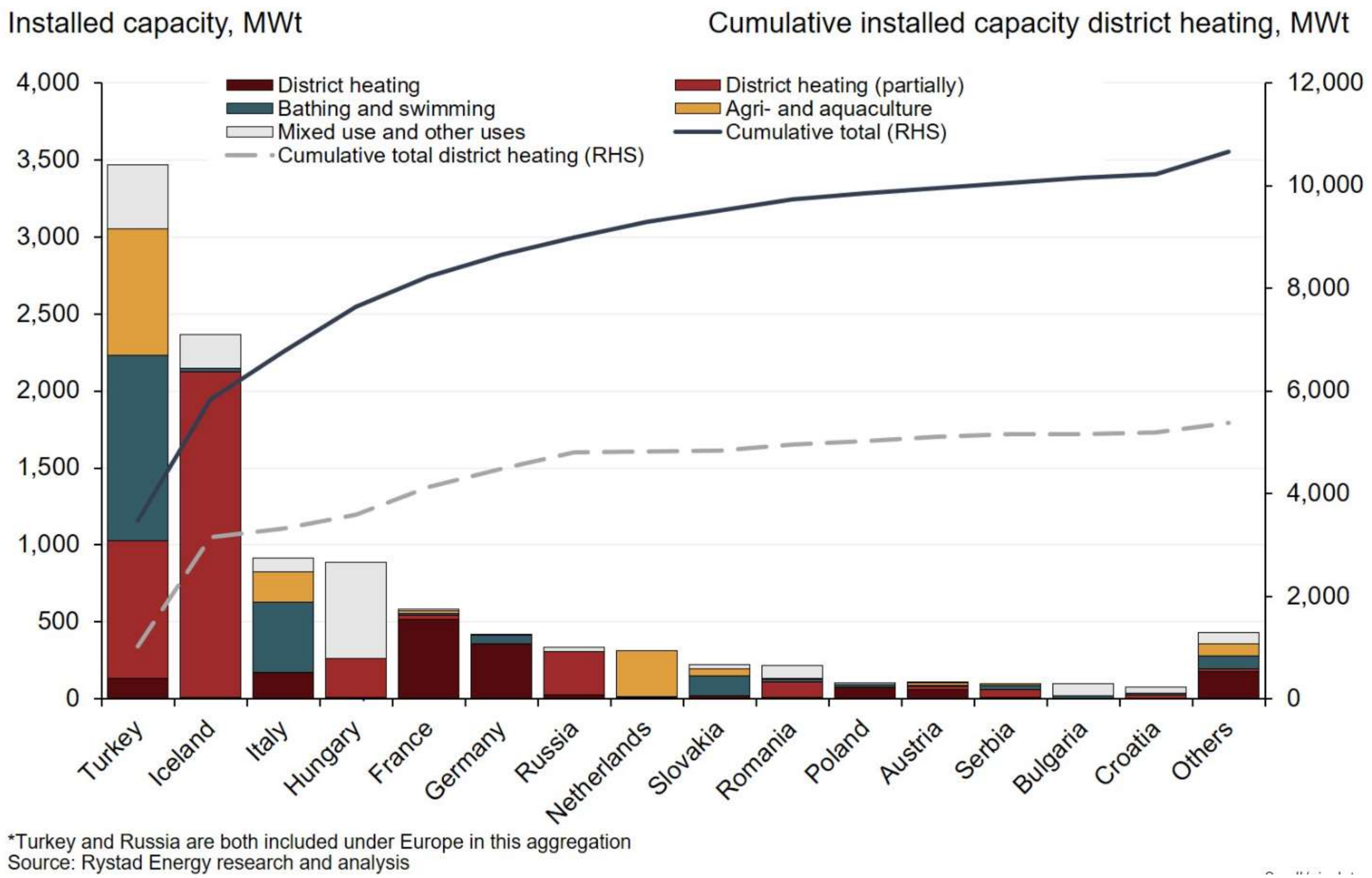
- Denmark:
- Population: 5.8 million
- Circa 3.6 million are connected to district heating network

- Poland:
- Population: 38 million
- Circa 16.5 million are connected to district heating network

- Hungary
- Population: 9.7 million
- Circa 1.6 million are connected to district heating network

Source Rystad

Geothermal direct use installed capacity in Europe



Source Rystad:
https://clients.rystadenergy.com/clients/report?rid
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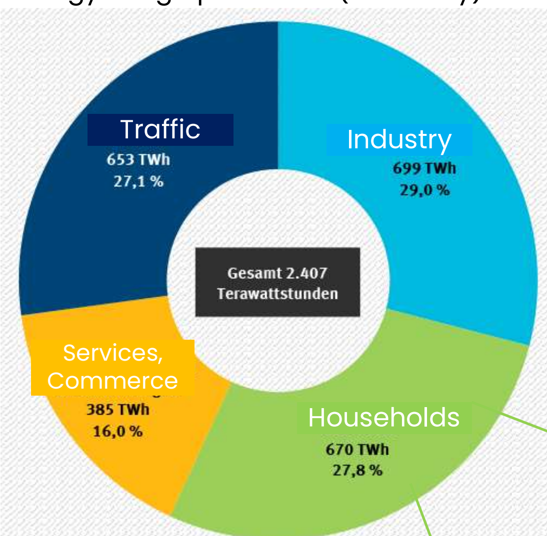
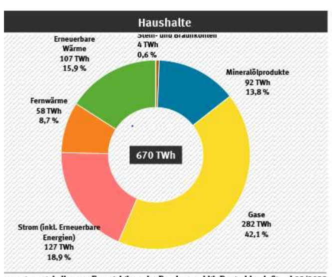
Potential of the Geothermal Heating Market (Germany)

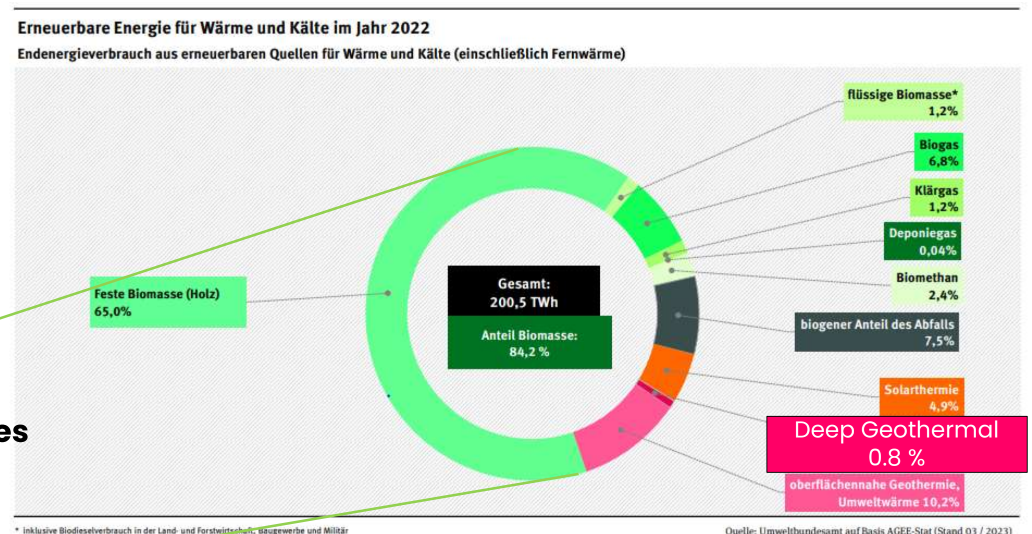
Energy usage per sector (Germany)

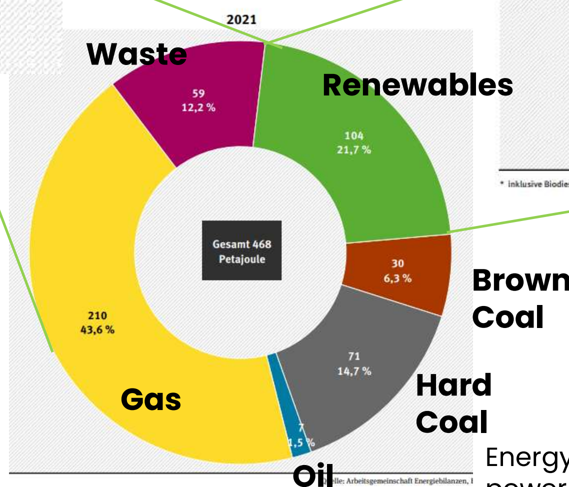


Ca. 9% district heating



Renewables Mix in Heating(Germany)

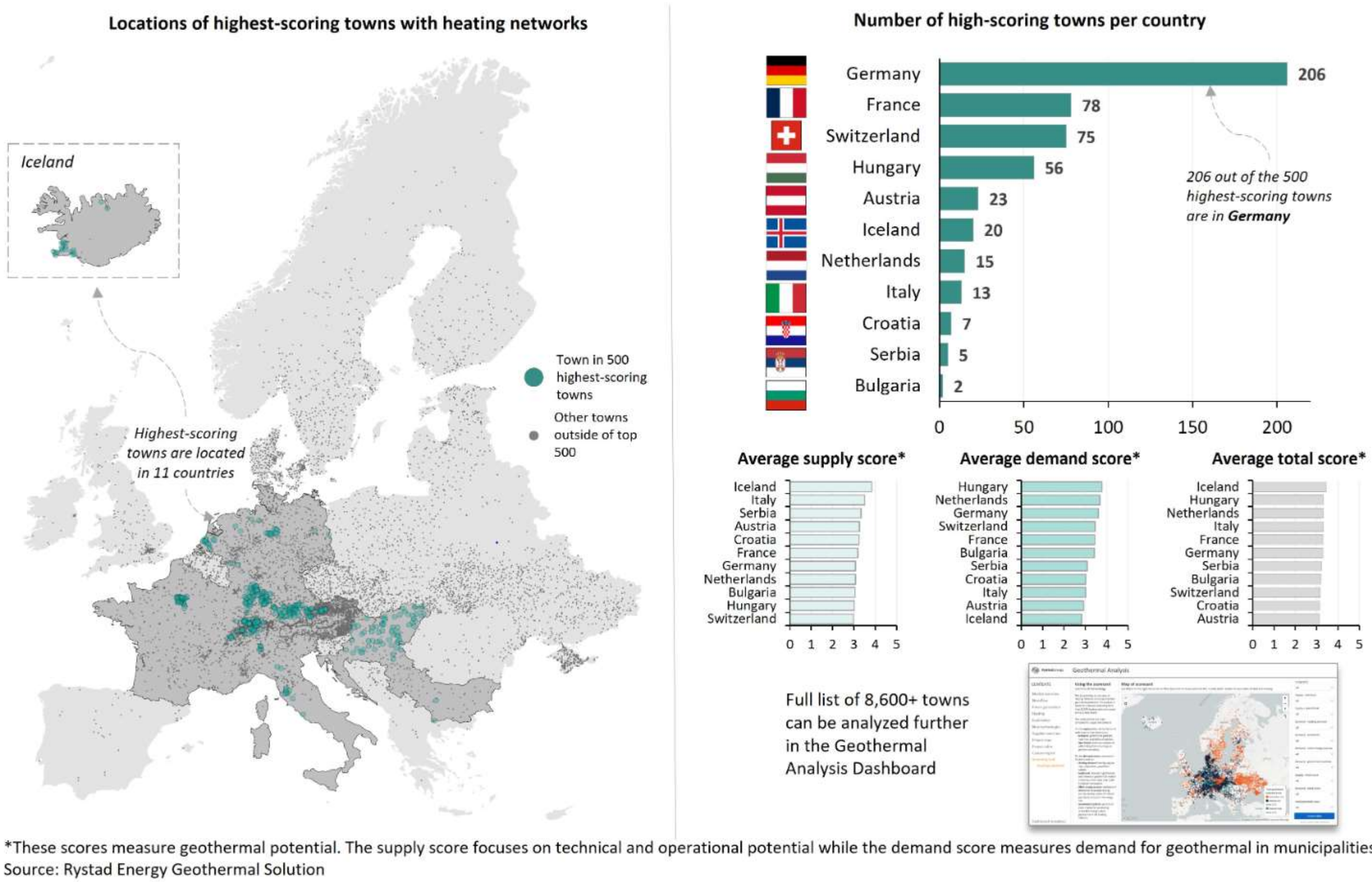




Energy sources in District Heating power plants (Germany)

Source: https://www.umweltbundesamt.de/daten/energie/primaerenergieverbrauch#primarenergieverbrauch-nach-energietragern

Rystad: Europes 500 highest-scoring heating networks by geothermal potential



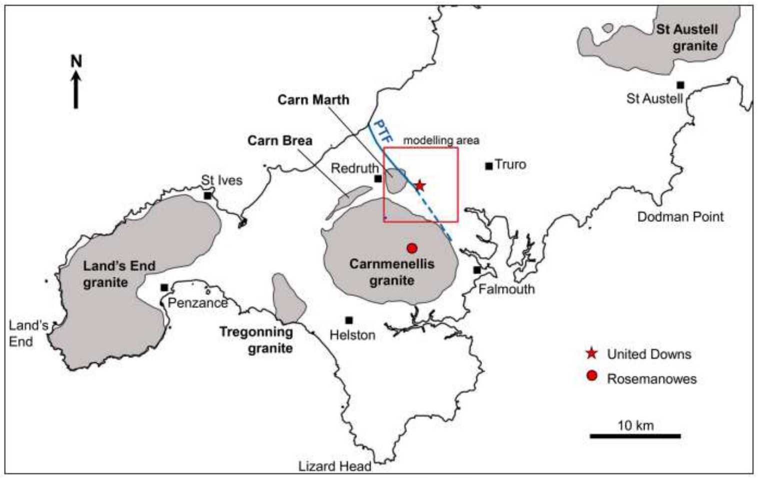
Source: Rystad: https://clients.rystadenergy.com/clients/report?rid=371725&

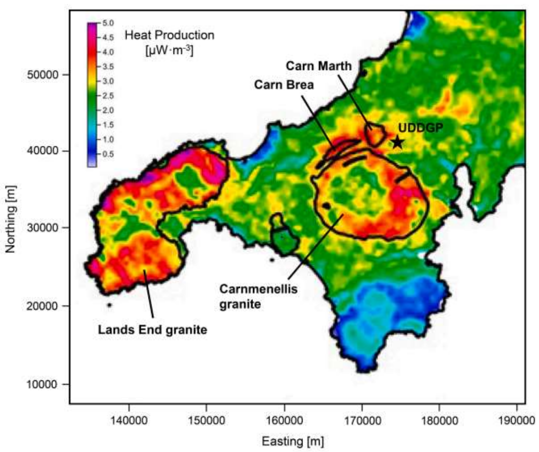
Examples of geothermal systems in Europe

* United Downs UDDGP, Cornwall
* Upper Rheingraben, France/ Germany
* TU Delft, Netherlands

UDDGP – United Downs Deep Geothermal Project

From Reinecker et al in Geothermics 97 (2021) 102226





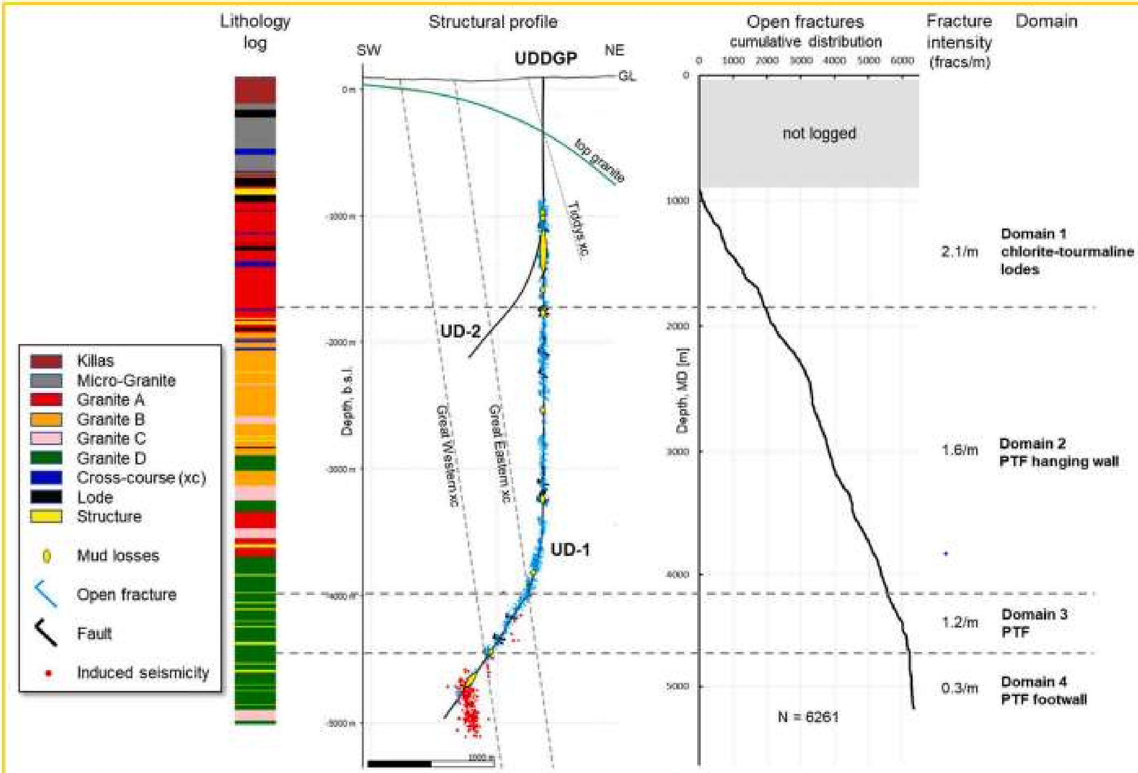


Fig. 6. Fracture data along UD-1 as interpreted from ultrasonic (UXPL) image logs. Note depth scale of the structural profile is true vertical depth below sea level. Cumulative fracture distribution and lithology log originally in measured depth below ground level are shifted and stretched to fit the true vertical depth scale.

Upper Rheingraben (URG)

From Glaas et al Structural characterization of naturally fractured geothermal r

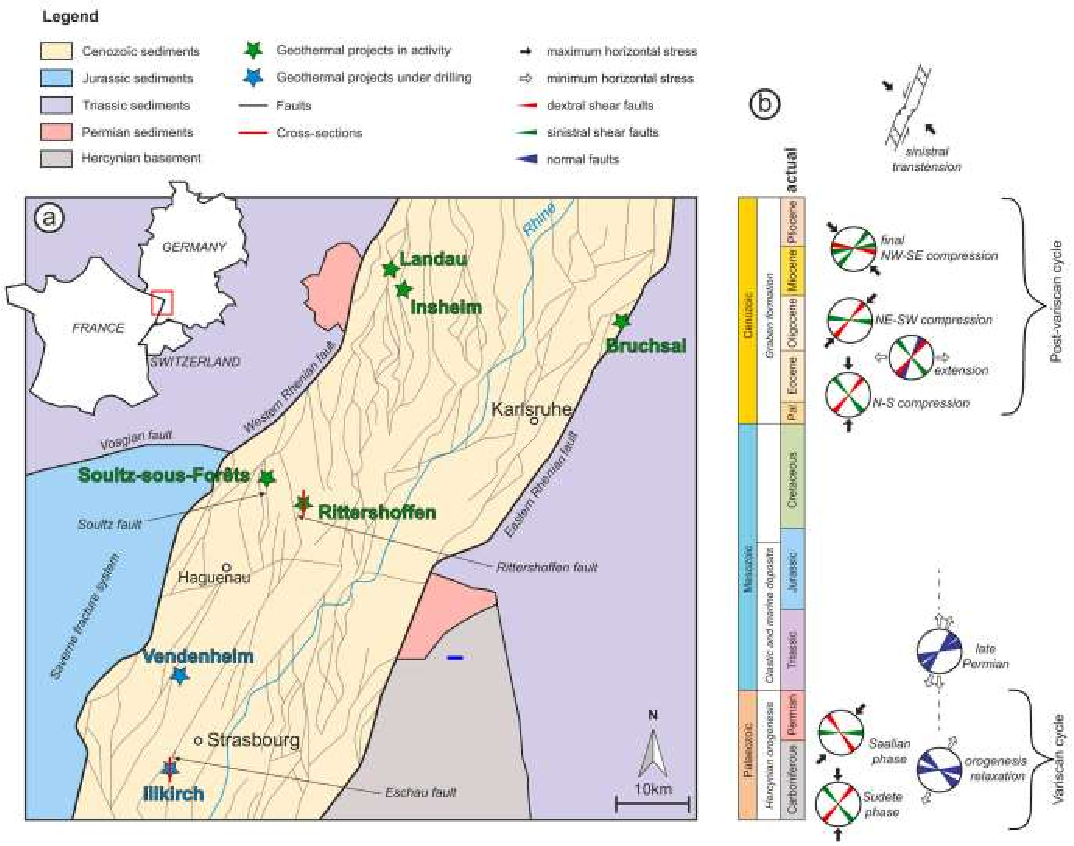


Fig. 1. a) Structural map of the centre of the Upper Rhine Graben showing the faults at the surface from the geoportal GeOrg (2017) in which the faults are derived from 2D vintage seismic data acquired in the Tertiary sediments for oil industry. The locations of the geothermal power plants under exploitation and under drilling are also shown. Two cross sections in reference to Figs. 4 and 5 are represented on the map. b) The orientations of faults and stresses in the URG during the several tectonic phases are presented along the geological timescale from the Palaeozoic to the Cenozoic ages.

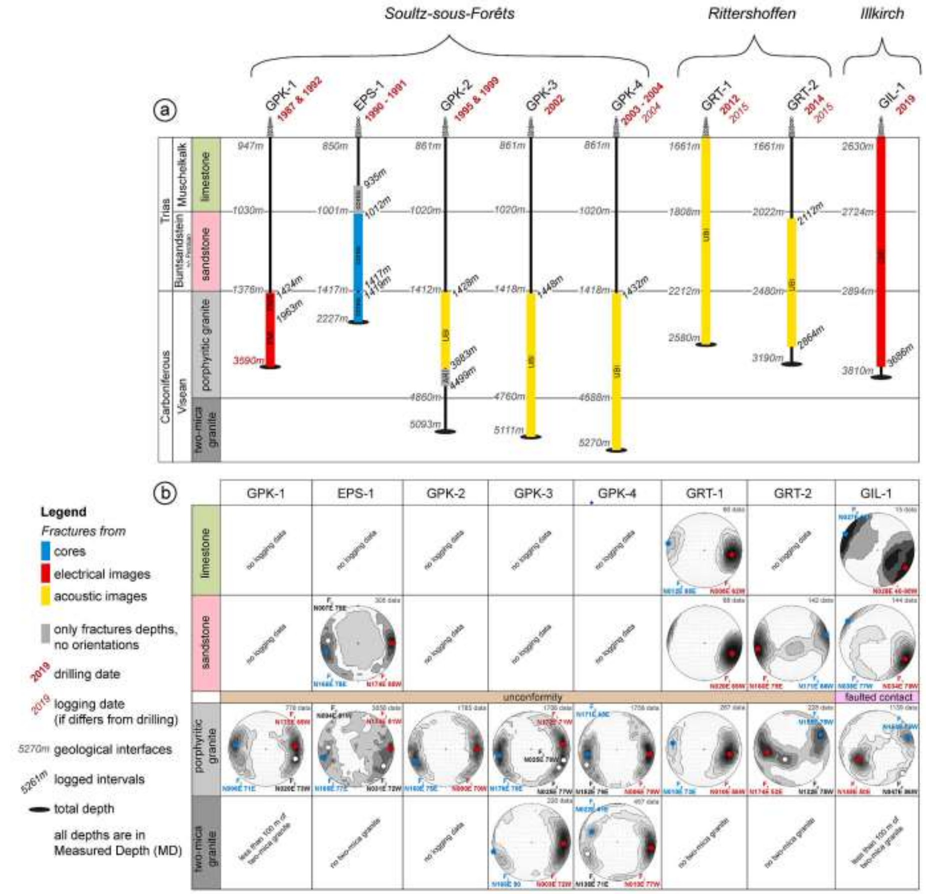
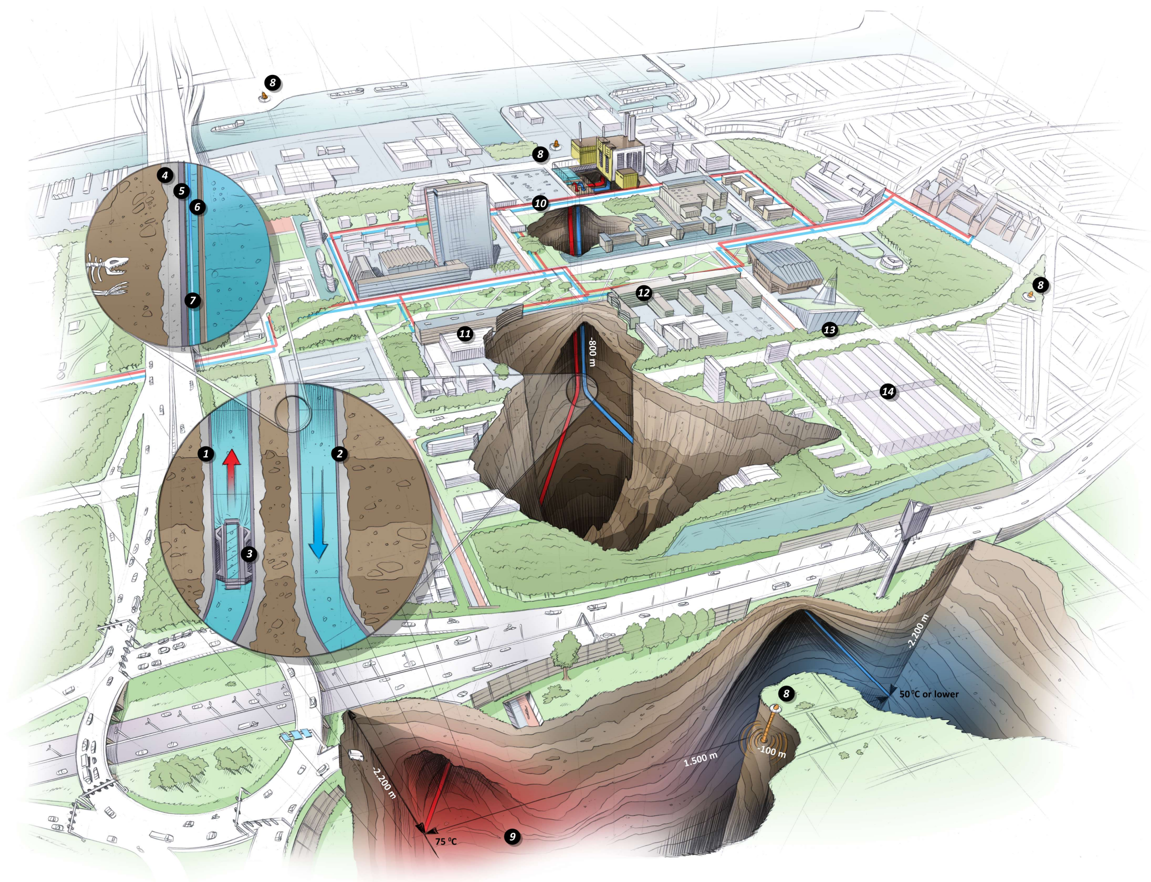


Fig. 2. a) Type of data available in each geothermal well, specifying the depth of the logged interval, the depth of the main geological interfaces, the drilling date and the logging date. b) Stereoplots (Schmidt lower hemisphere) per lithology in each geothermal well. The main fracture set is in red, the secondary set is in blue and the less represented one is in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

TU Delft, Netherlands

Source: https://www.tudelft.nl/en/delft-outlook/articles/campus-switching-to-geothermal-energy



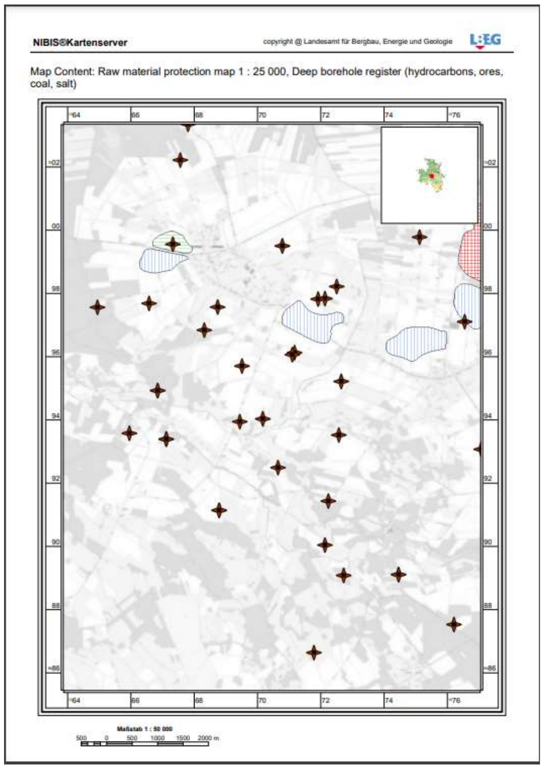
TU Delft Geothermal Doublet

- Depth ca. 2300m
- Reservoir: Sandstone
- Planned temp:
- Ca. 75CdegC, return of ca. 50 degC.
- Thermal output→ ca. 8 MWth
- Distance of doublets at TD ca. 1500m

Risks and costs in deep geothermal exploration

Challenges

Oil and Gas



z.B.

- Commercial Viability
- Unknown Technical Challenges
- Rate of Penetration
- ...

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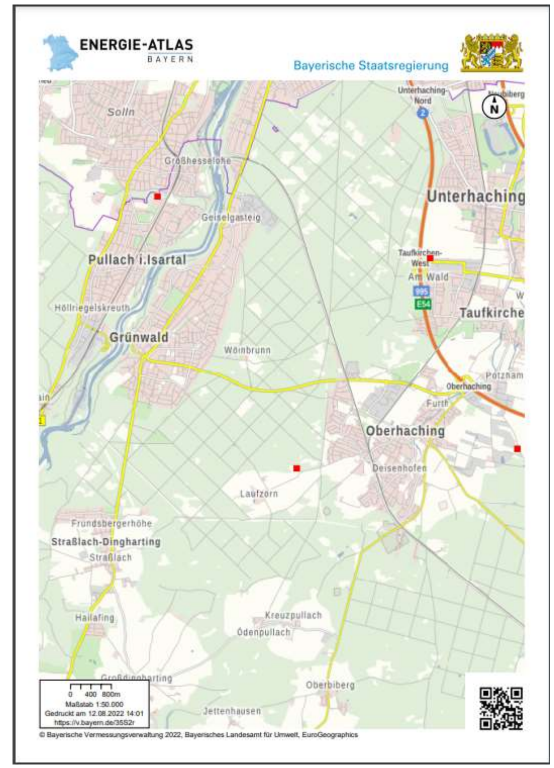
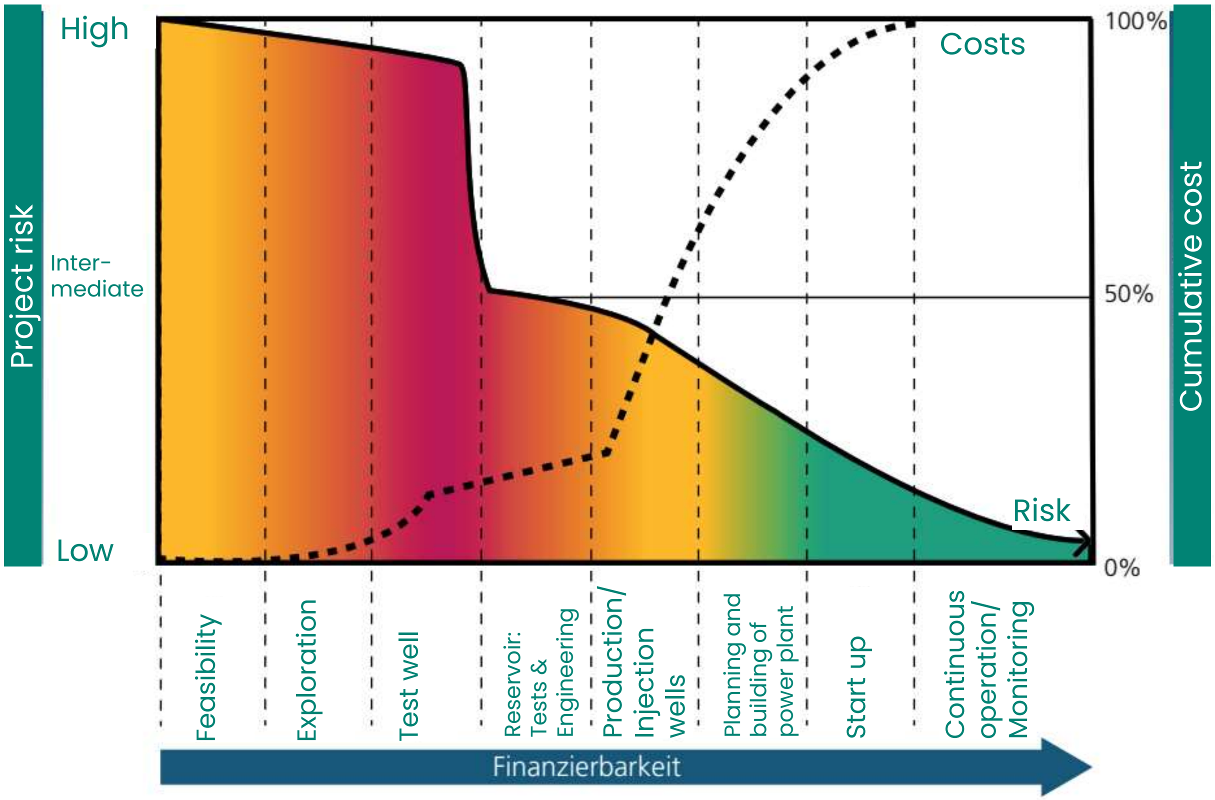
RISIKO

Geothermal



Cost vs. Risk in geothermal exploration



Source: ROADMAP TIEFE GEOTHERMIE FÜR DEUTSCHLAND – Fraunhofer Institut

What do we need for a successful geothermal project

- **HEAT**
- Effective porosity
- Permeability (matrix or fracture based)
- ROI < 20-25 yrs

Why do geothermal projects fail?

#1 Unforeseen drilling issues

- Challenging rock formation
- Wellbore stability issues
- Unplanned sidetracks and equipment lost in hole

#2 Reduced flow and heat production lowers ROI

- Suboptimal well placement
- Poor reservoir cooling management
- Corrosion, scaling and plugging
- Inappropriate completion design

#3 Induced Seismicity risks and public acceptance

- Lack of geomechanical knowledge
- No passive seismic monitoring
- Unsuitable injection and production rates
- Reservoir containment issues

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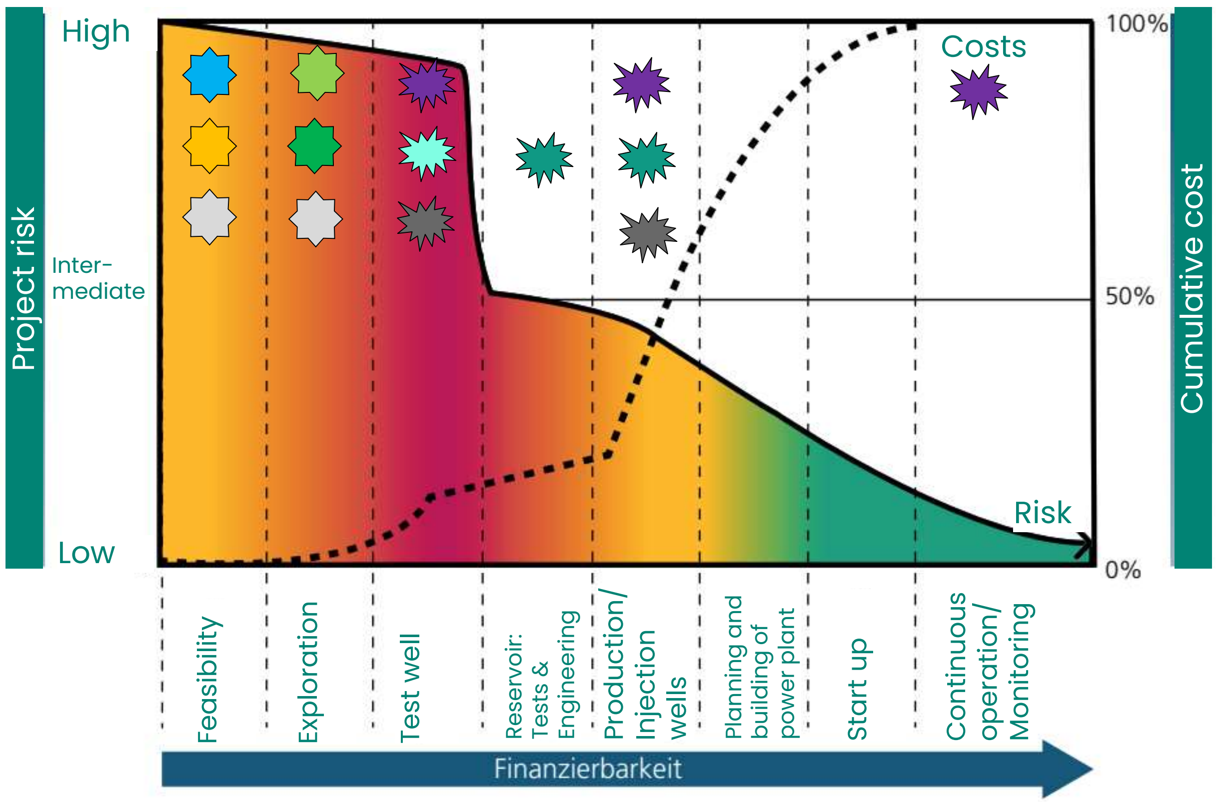
Data derisks geothermal exploration



Source: ROADMAP TIEFE GEOTHERMIE FÜR DEUTSCHLAND – Fraunhofer Institut

Data available

- Offset well data
  - General stratigraphic column, depths, temp gradients, porosity, permeability, etc.
- Old Seismic (reprocessed)
- 2D Seismic
- 3D Seismic
- Other geophysical surveys (magnetic, electrical or other)
- Logging data (e.g. Temperature, GR, Density, acoustic, caliper, porosity, imaging, permeability, NMR …)
- Cores
- Drilling data (cuttings, DDR, surveys, temps, ROP, mud density, losses, …)
- Well test

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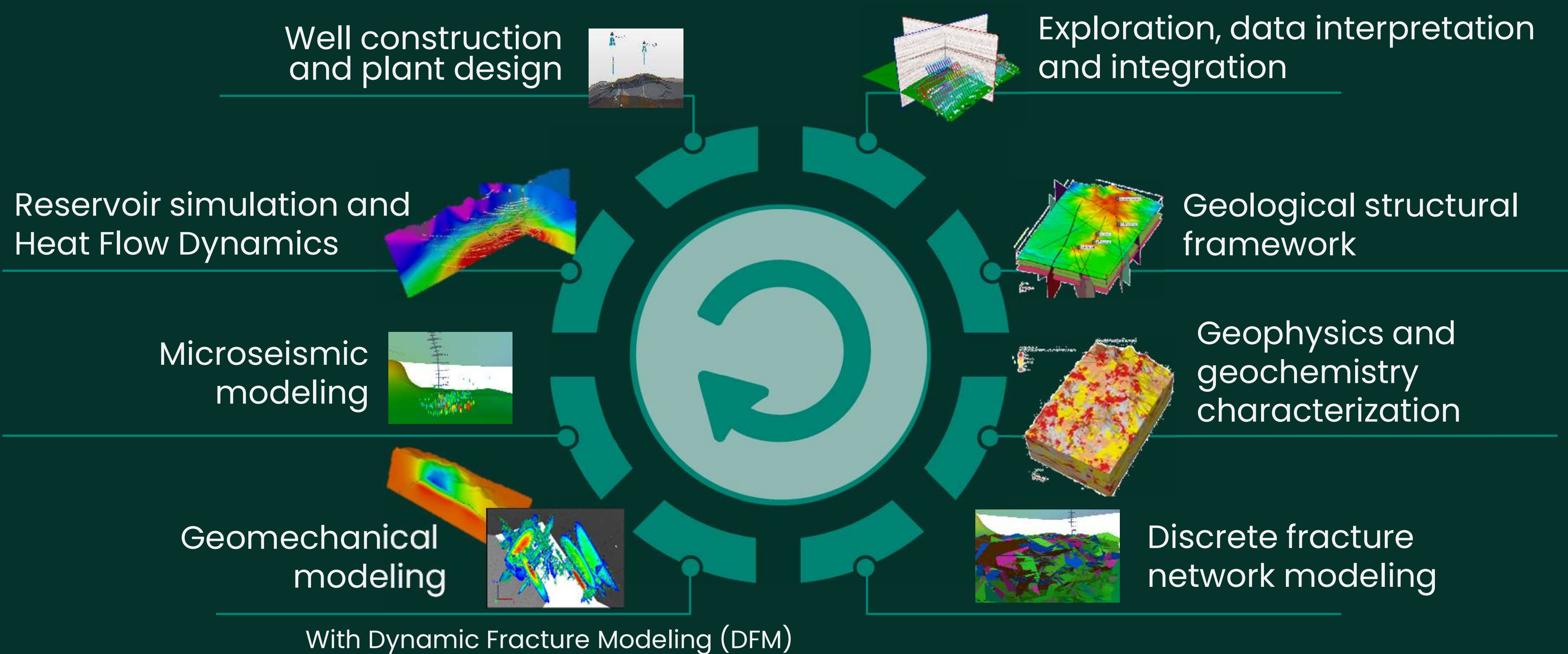
WORKFLOWS AND MODELING

Subsurface Geothermal Engineering (using JewelSuite)



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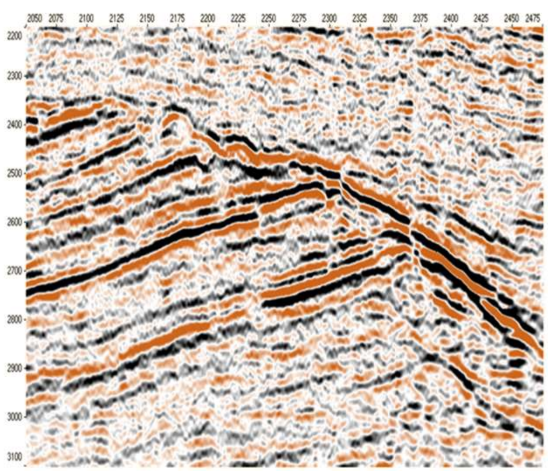
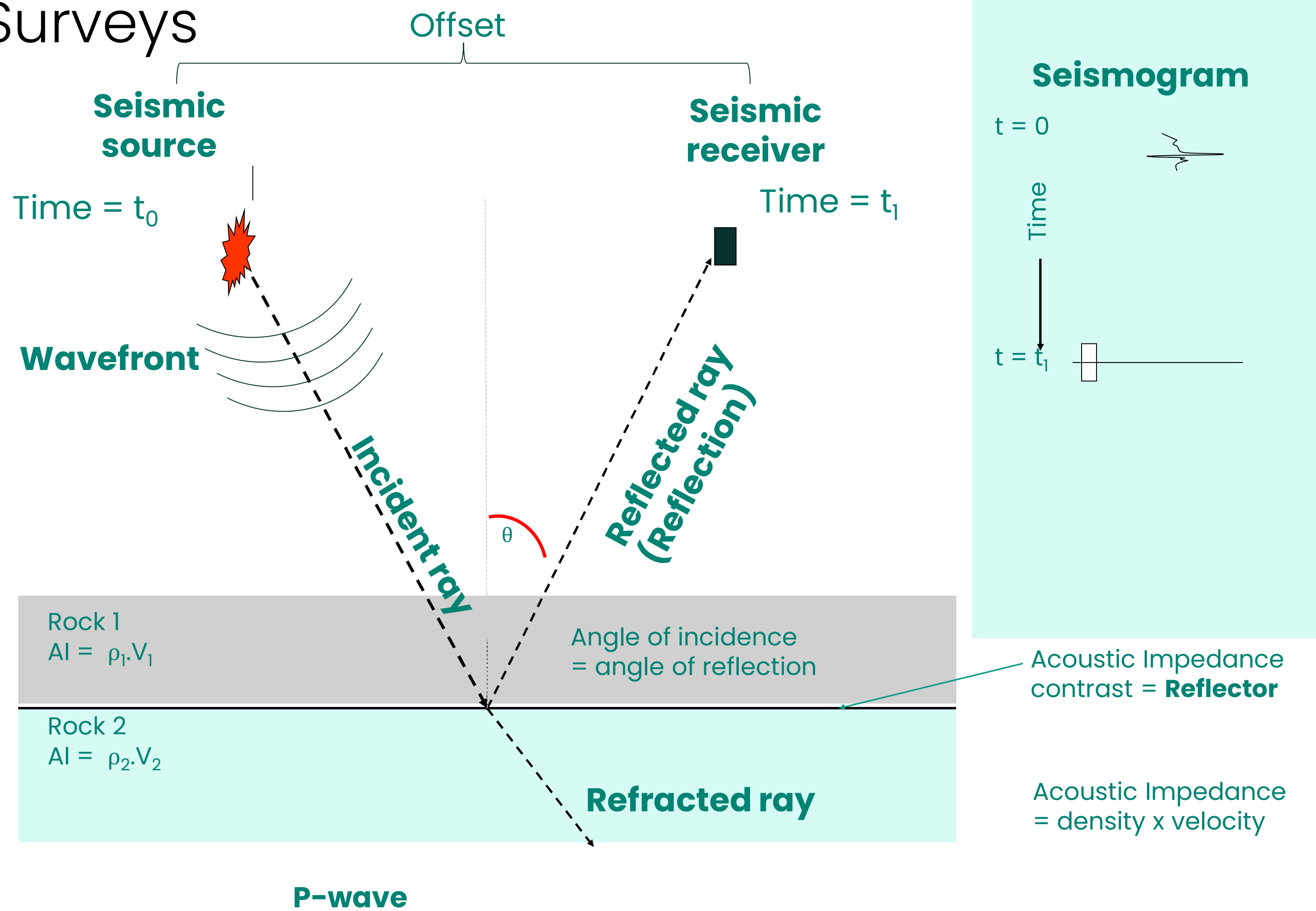
Seismic

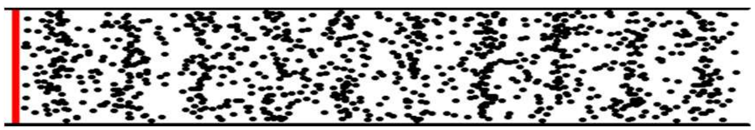
Seismic Reflection Surveys

- A source is triggered to send acoustic energy into the ground
- The resulting "echoes" from rock layers are detected by arrays of geophones or hydrophones. These sensors output electrical signals proportional to the intensity of the echoes.
- These signals are recorded and processed.
- The resulting "data", when properly processed, can reflect the structure of strata in the earth.





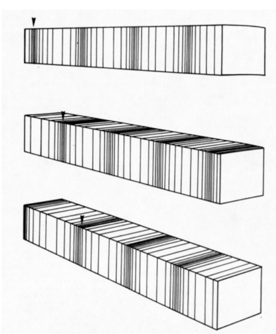
P wave vs S Wave

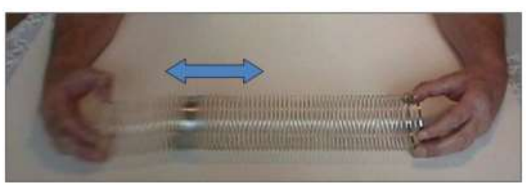


Pressure wave (P)

- Particle motion aligned with direction of travel
- Faster velocity
- Reflection depends mainly on density and velocity contrasts
- Will travel through rock matrix and fluids

Affected by pore fill of rock



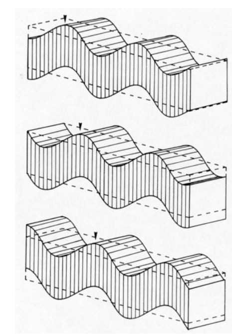


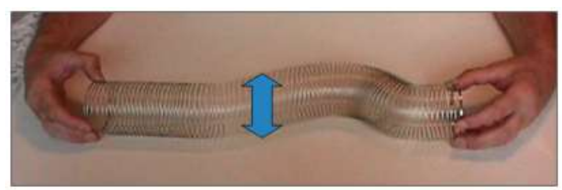
Shear wave (S)

- Particle motion at right angles to direction of travel
- Slower velocity (higher resolution?)
- Reflection depends on shear strength contrasts
- Will not travel through fluids
- Not affected by pore fill of rock
- Obtain Vp/Vs, Anisotropic effects

Good for:

- Reservoirs with no P impedance contrast
- Lithology and Fluid discrimination (with P)
- Seeing through shallow gas / gas chimneys
- Fracture detection and orientation





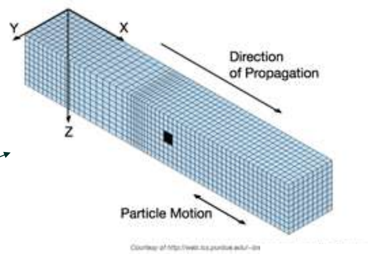
Types of seismic waves

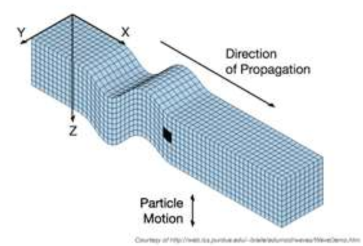
Body Waves

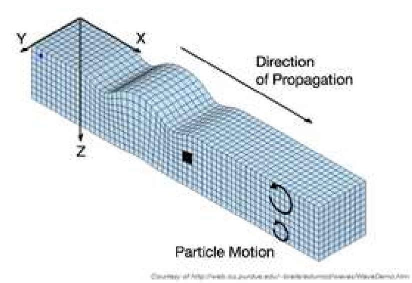
- P- waves
- S- waves

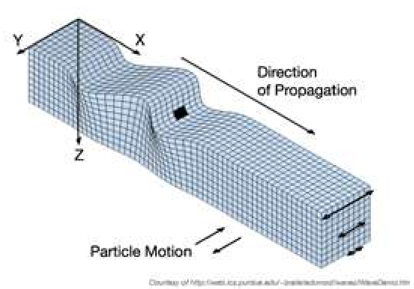
Surface Waves

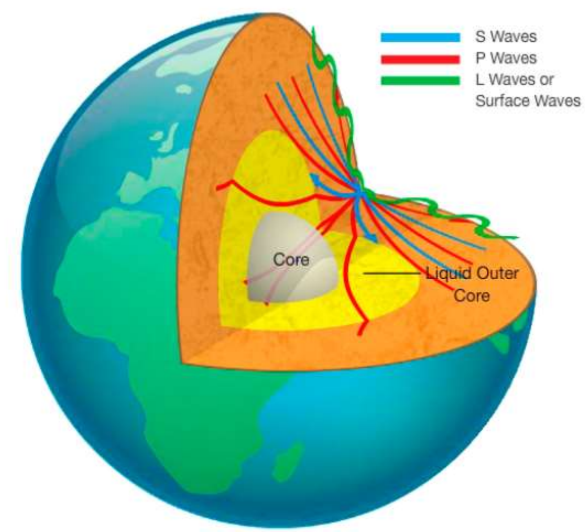
- Rayleigh waves
- Love waves



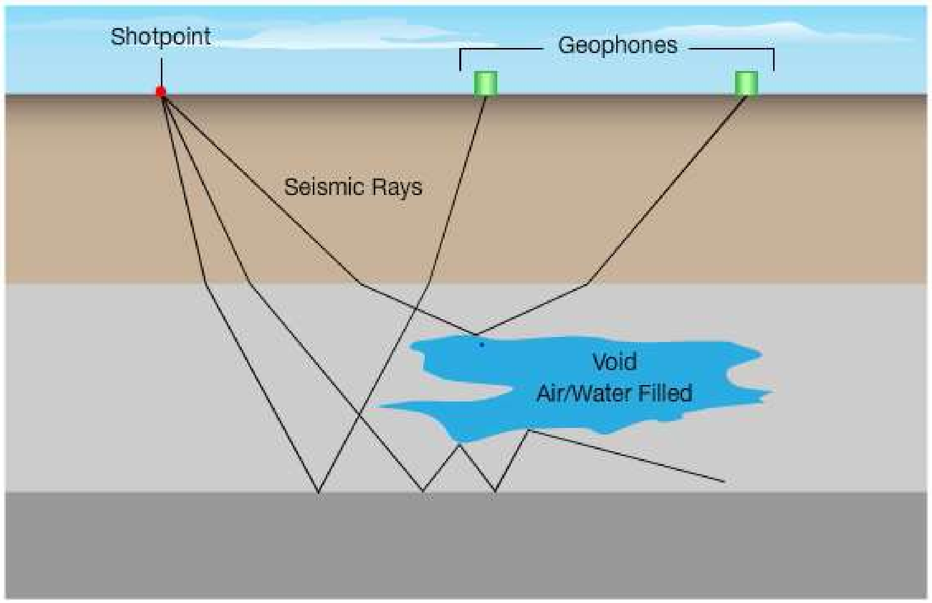


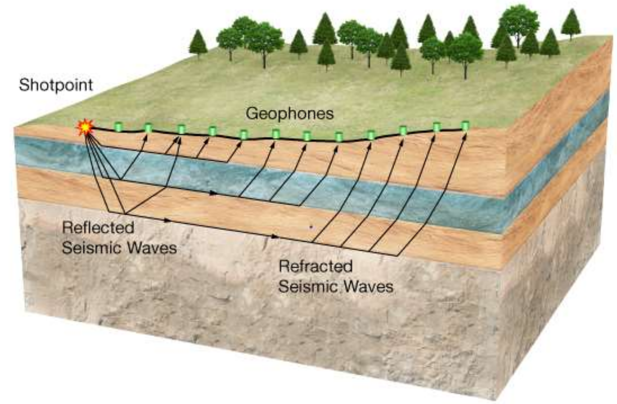


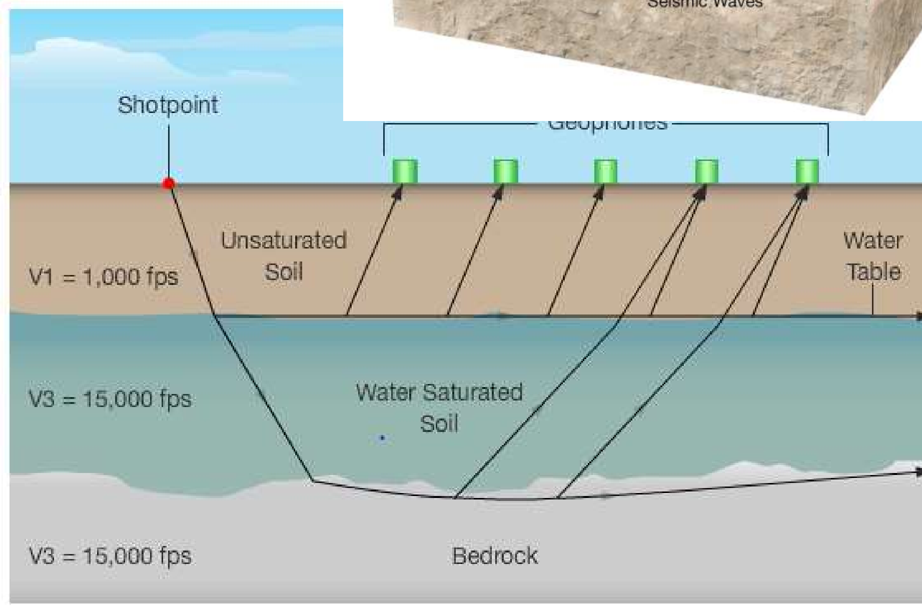




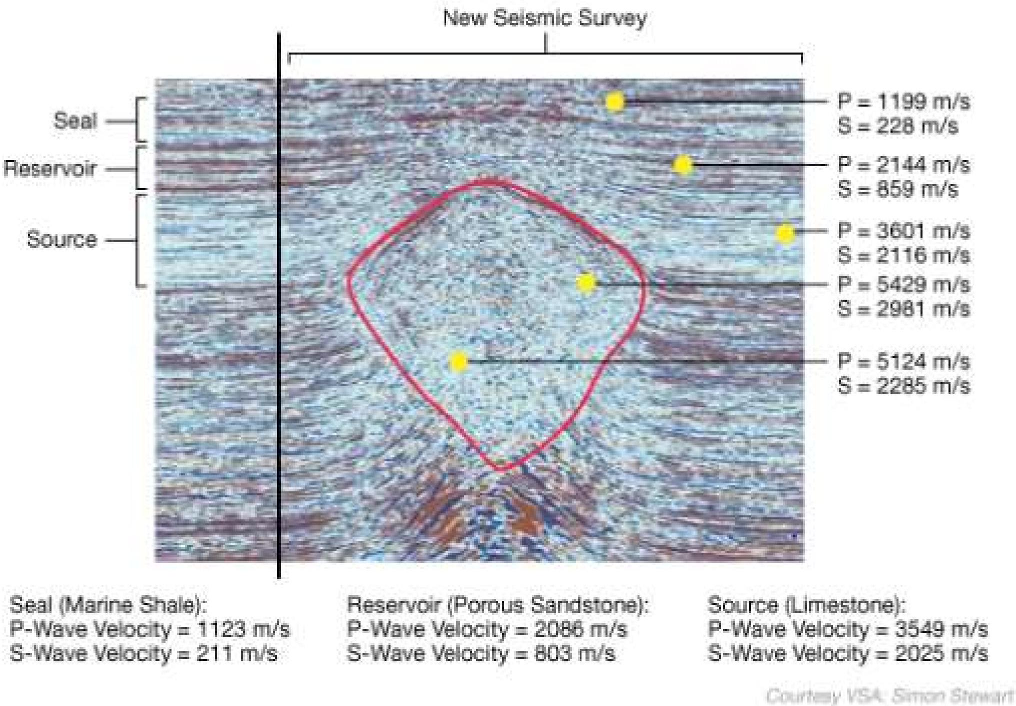
Reflection vs Refraction







Example



Parameters That Influence Seismic Velocity
(Modified from Bourbie et. al., 1987)

Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm^3)
Scree, vegetal soil	300-700	100-300	1.7-2.4
Dry sands	400-1200	100-500	1.5-1.7
Wet sands	1500-2000	400-600	1.9-2.1
Saturated shales and clays	1100-2500	200-800	2.0-2.4
Marls	2000-3000	750-1500	2.1-2.6
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4
Limestones	3500-6000	2000-3300	2.4-2.7
Chalk	2300-3600	1100-1300	1.8-3.1
Salt	4500-5500	2500-3100	2.1-2.3
Dolomite	3500-6500	1900-3600	2.5-2.9

Acquisition

- Things that make a “bang” - **Sources**
  - Airgun
  - Dynamite
  - Vibroseis
  - Thumper
- Things that listen for the echo - **Receivers**
  - Hydrophones - record pressure changes
    - use in water or swamp
  - Geophones - record partical velocity
    - Use on land or gimballed in cable)

Seismic Processing

Why?

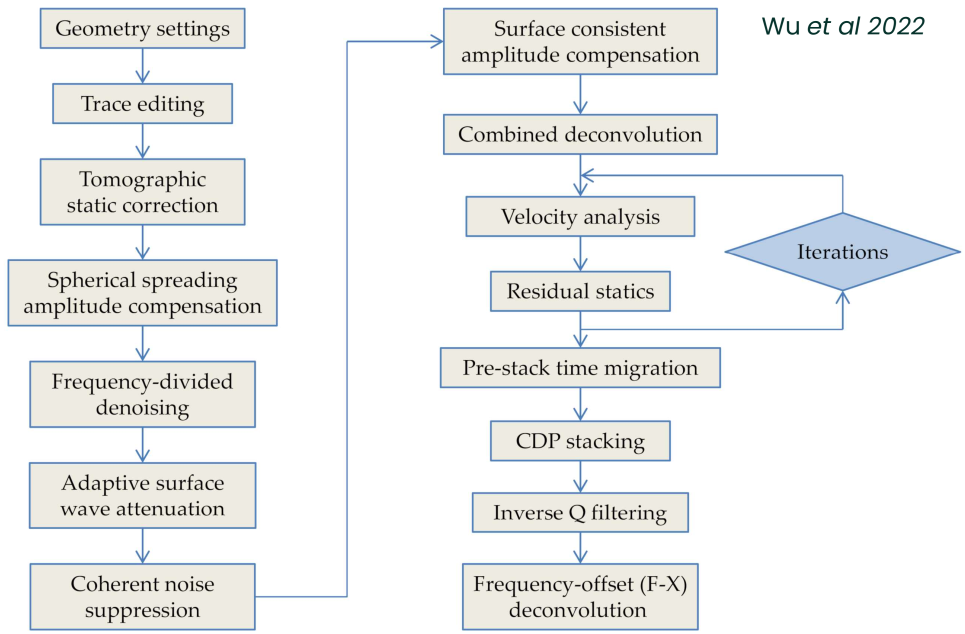
- Reduce data volume & standardize presentation
- Enhance "Signal" and suppress "Noise"
- Improve image resolution and fidelity

Critical Requirements

- High fold data - each Common Depth Point (CDP) sampled many times
- Ability to stack multi-sampled CDPs using correct velocities
- Attenuate noise, e.g. multiple attenuation
- Move CDP data to correct location using seismic migration

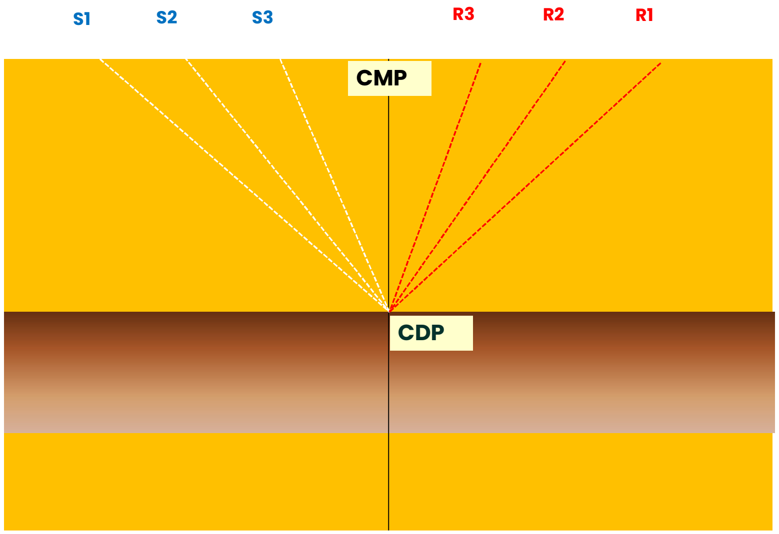
Re-Processing

- Initial processing may have been fast tracked and sub optimal
- New requirement for improved data
- New technology or processing algorithms
- Poor initial processing
- New objectives

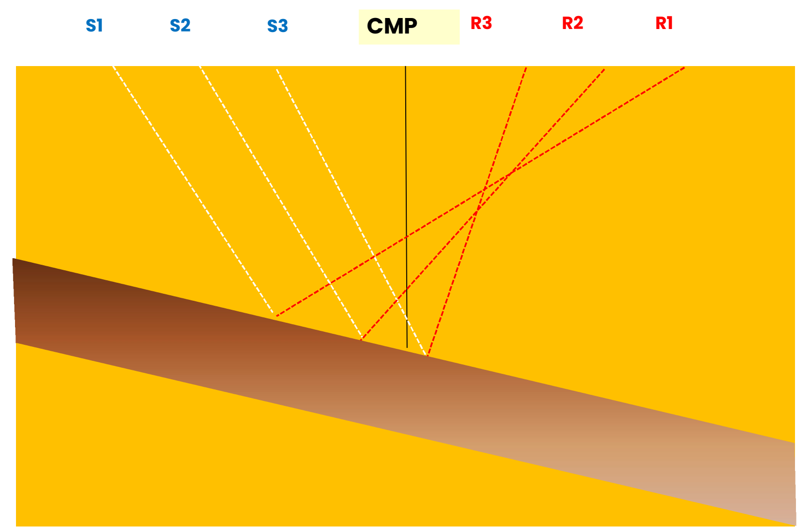


Wu *et al 2022*

Common Mid Point / Common Depth Point



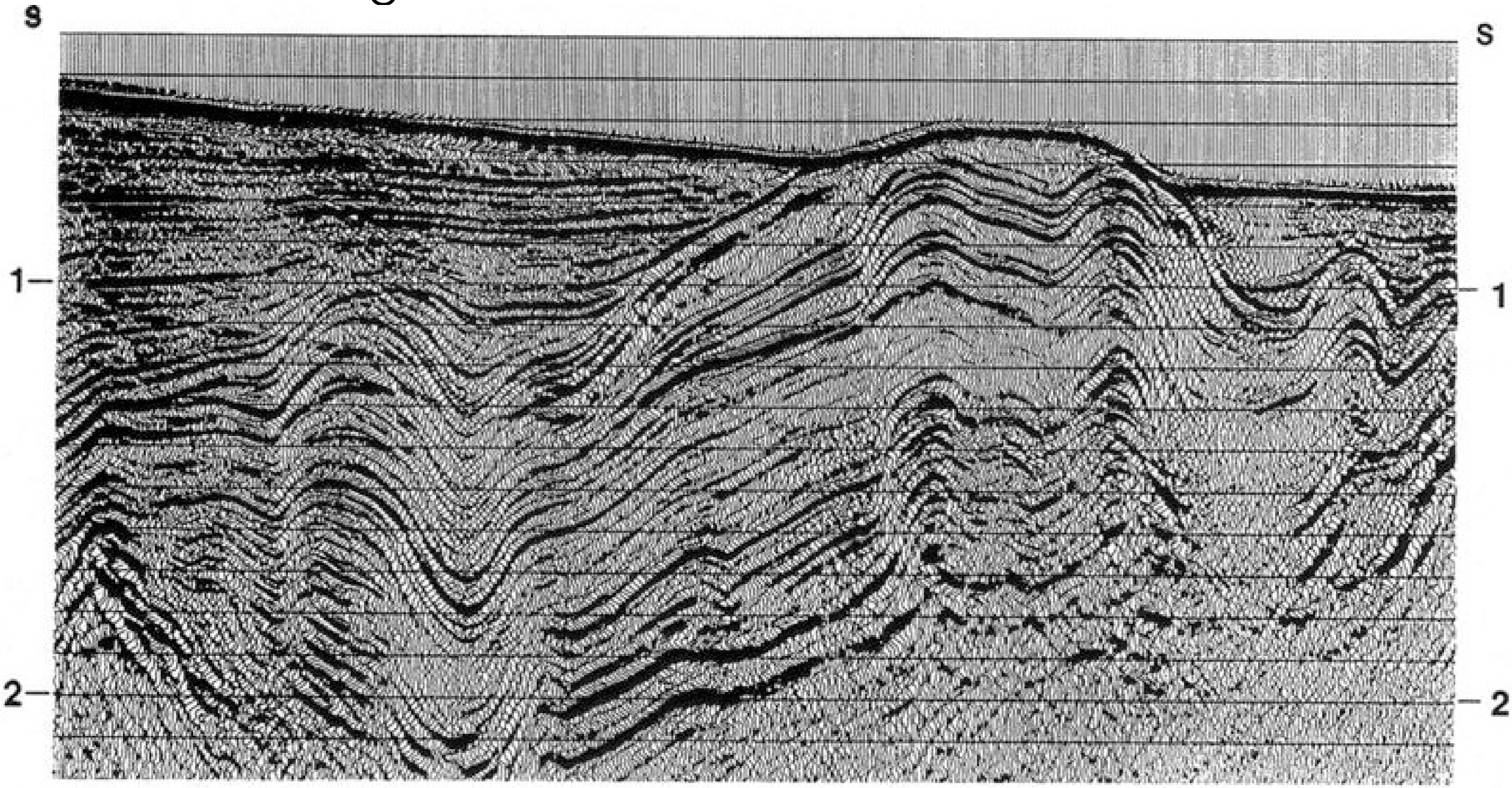
- The Common Mid Point is the point at the surface, halfway between source and receiver, that is shared by several source-receiver pairs
- The Common Depth Point is the point on a flat-lying reflector shared by source-receiver pairs



•In the case of dipping beds there is **no** CDP
•Therefore dip-moveout is required to remove inappropriate mixing of data (smearing)
•Do not use CDP and CMP interchangeably!

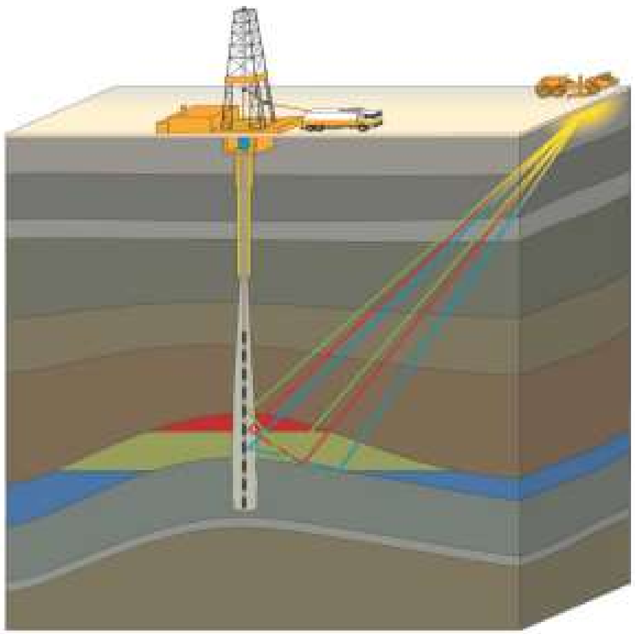
Seismic Data Migration

Larner & Hale, 1992

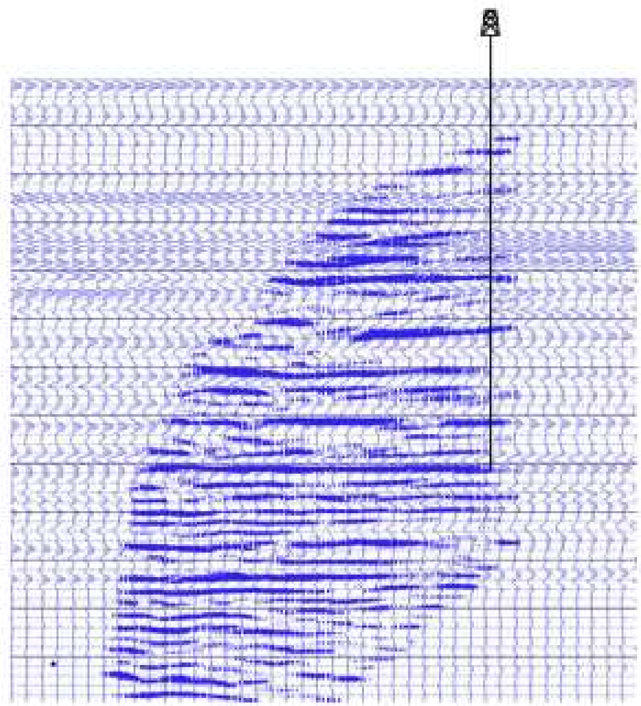


(b)

VSP – Vertical Seismic Profiling



Large offset from well and receivers



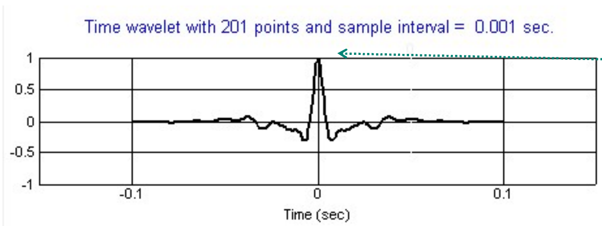
High resolution lateral image away from well

Seismic Resolution

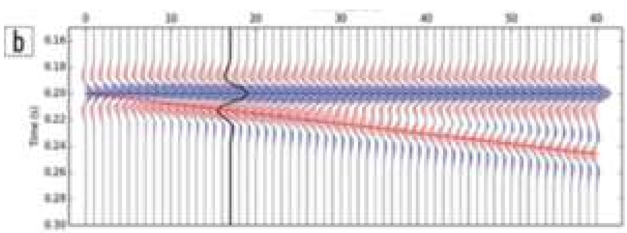
What can we actually "see" using seismic data?

$$\text{Wavelength} = \frac{Interval\ Velocity}{Central\ Frequency}$$

$$\text{Vertical Resolution } = \frac{1}{4} * Wavelength$$



Frequency from extracted wavelet



$$\text{Tuning Thickness} = \frac{1}{2} * Thickness(TWT) * Interval\ Velocity$$

Velocity 4,580 m/s

30 Hz Wavelet

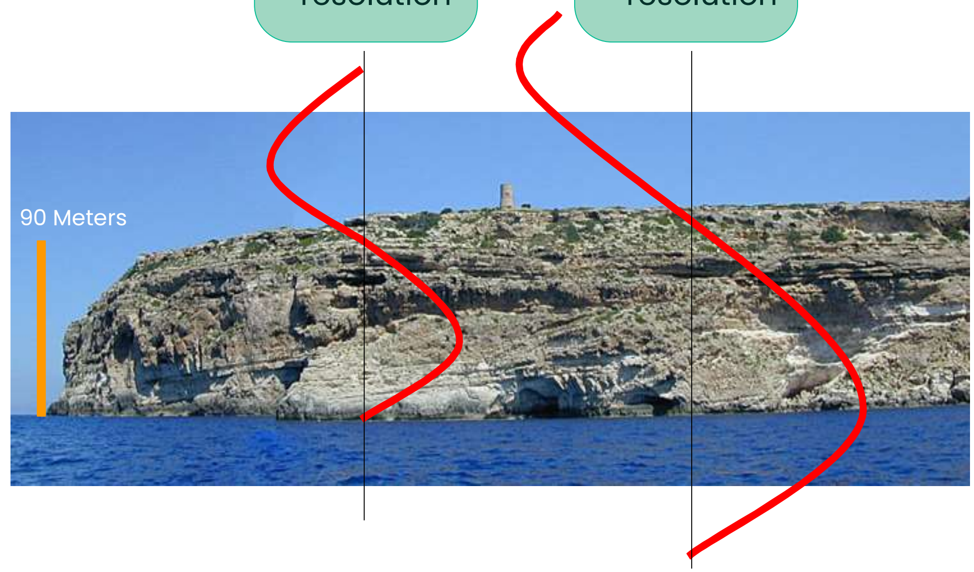
152 m wavelength

38 m resolution

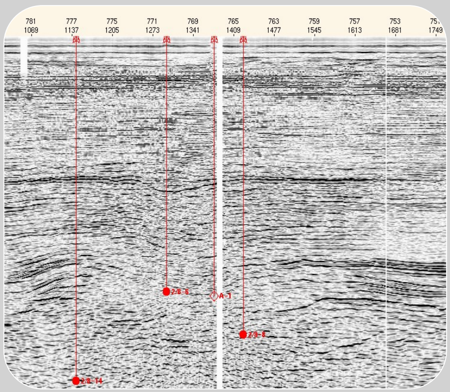
15 Hz Wavelet

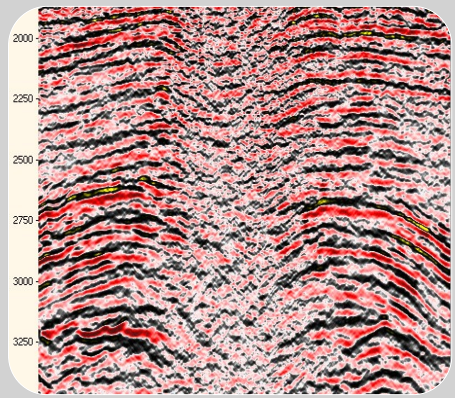
305 m wavelength

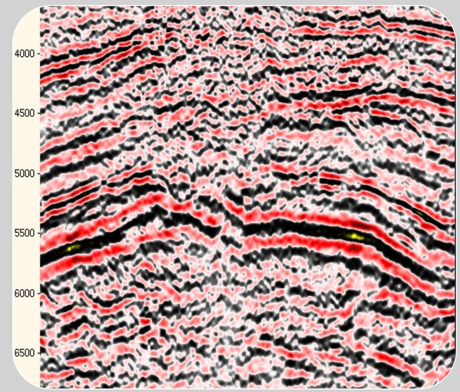
76 m resolution



How Seismic Data is used







2D

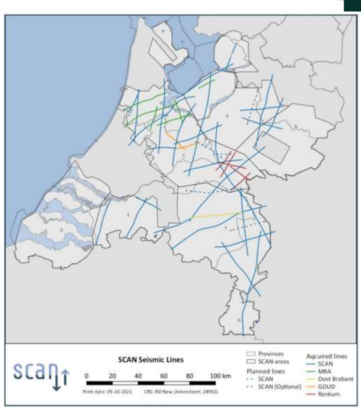
Exploration: Basin to Prospect scale descriptions of geology for first well

3D

Development: Appraising discoveries and defining subsurface to optimise well requirements (also reprocessing, multiple surveys?)

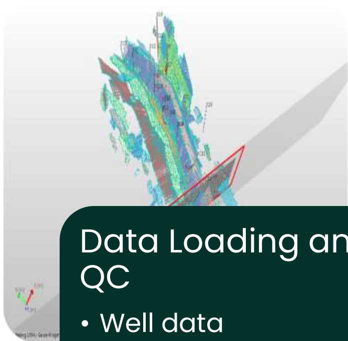
4D / 4C

Production: Time-Lapse monitoring of hydrocarbon movement & depletion in the reservoir



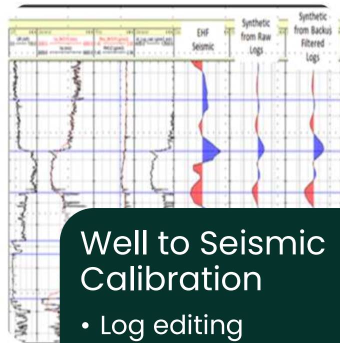
Interpretation

Seismic Interpretation Workflows



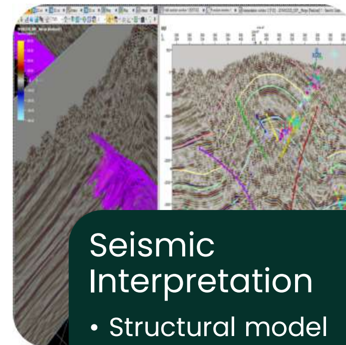
Data Loading and QC

- Well data
- Seismic interpretations



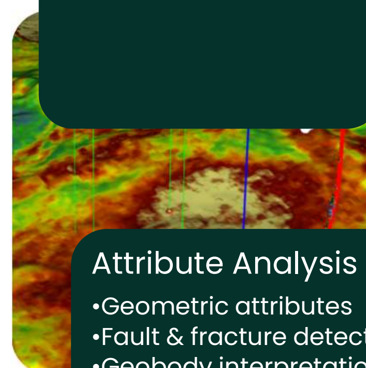
Well to Seismic Calibration

- Log editing
- Synthetics
- VSP integration
- Rock Physics Modelling



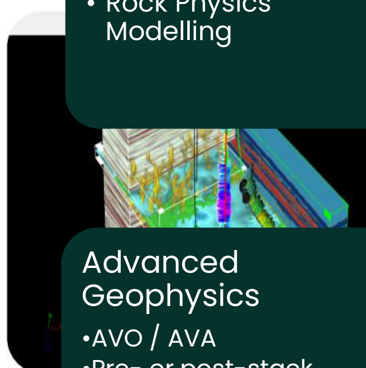
Seismic Interpretation

- Structural model
- Stratigraphic framework



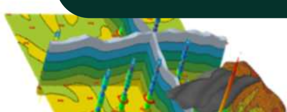
Attribute Analysis

•Geometric attributes
•Fault & fracture detection
•Geobody interpretation



Advanced Geophysics

•AVO / AVA
•Pre- or post-stack
•Reservoir quality
•Elastic properties

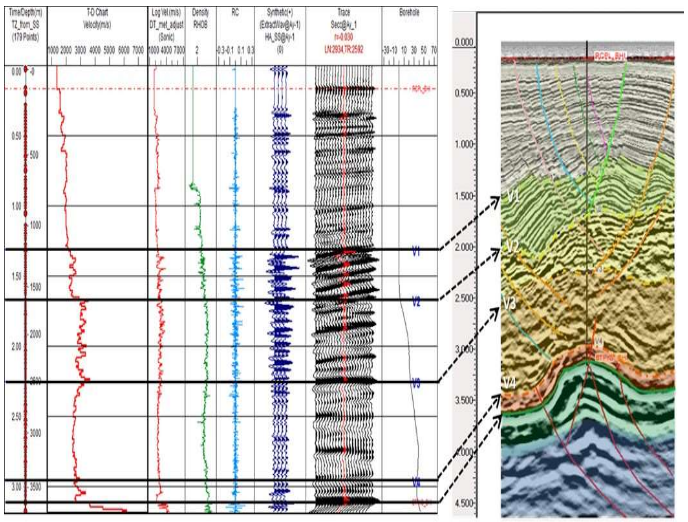


Integration

•Prospectivity / asset evaluation
•Geological modelling and dynamic reservoir simulation
•3D / 4D Geomechanical modelling

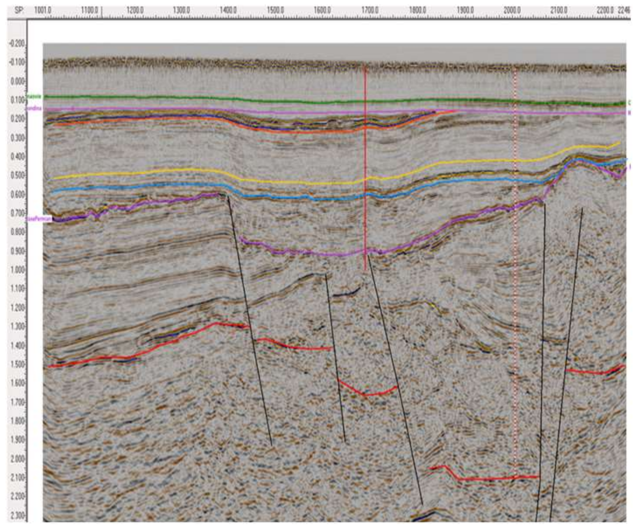
Seismic Interpretation

Defining the physical dimensions of the reservoir. Locating optimal drilling sites. Guiding well construction.



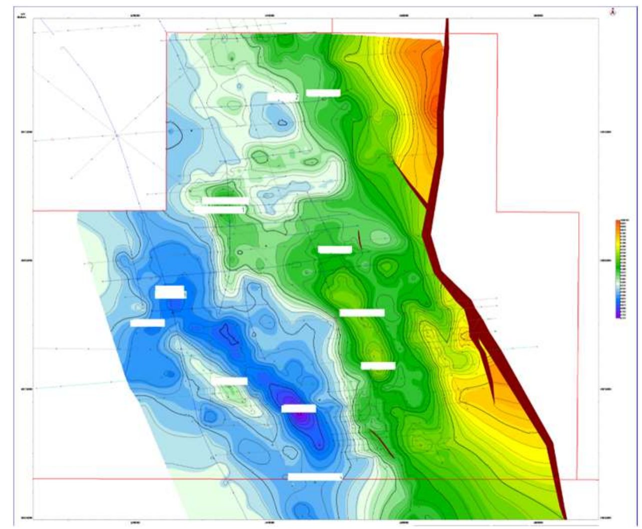
Seismic – Well Calibration (Well Ties)

- Uses acoustic and density log data to generate acoustic impedance (AI) log
- AI log is integrated to generate a reflection coefficient (RC)
- RC is convolved with a suitable wavelet (theoretical or extracted from seismic data) to create a synthetic trace
- Synthetic trace is matched to real seismic.



Horizon and Fault Intepretation

- Key markers from the wells are posted on the seismic section to allow horizon interpretation
- Precise requirements of the interpretation may be specific to the reservoir type (aquifer or basement)
- Other structural and stratigraphic features are interpreted as required



Mapping

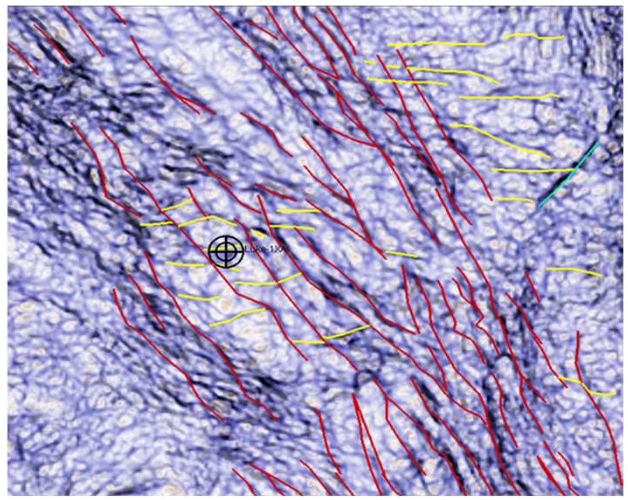
- Usually maps are generated for key reservoir horizons, using the seismic interpretation and fault polygons as input
- This highlights areas of high and low structural relief, structural traps indicated by closed contours etc.
- Maps are then typically converted from the two-way time domain to depth.

Next Step - Seismic Attributes

Assessing reservoir extent, geometry, faulting and fracturing

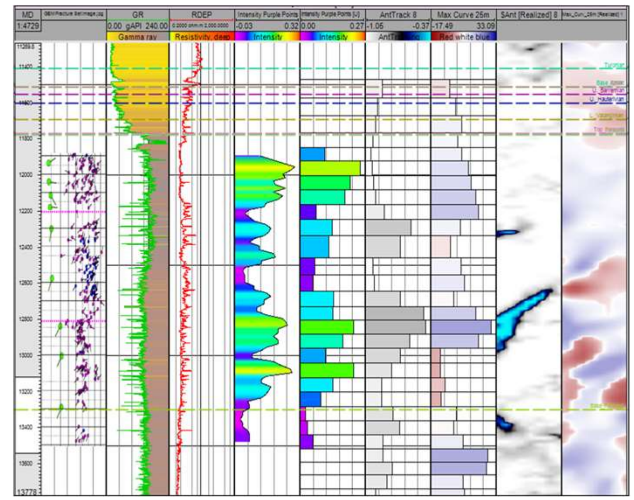
Faults and fractures

- Faults may act as conduits for, or barrier to, fluid flow in a reservoir
- Fractures can play an extremely significant part in geothermal reservoirs
- Naturally occurring fractures may enhance permeability and therefore the rate at which fluid moves through the reservoir



Attribute generation

- Attributes can be generated from seismic data that highlight the distribution of faults, and may indicate the presence of fractures
- These include similarity / coherency, curvature, thinned fault likelihood and many others
- Typically these are generated on 3D seismic volumes



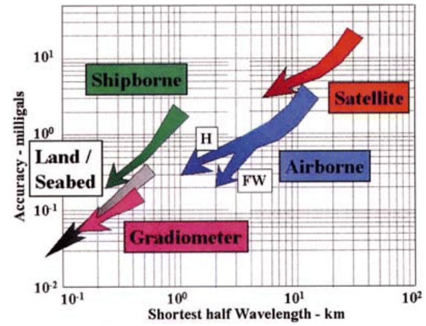
Calibration to well data

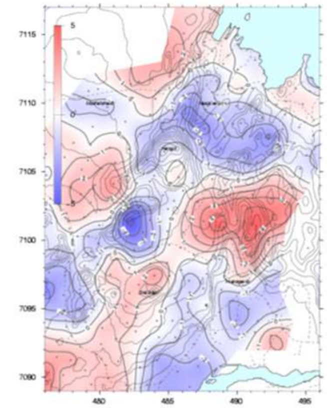
- We can compare the seismic attribute response to well data such as image logs, acoustic anisotropy and cores
- Once verified, seismic attributes can be used to guide the distribution of fractures in a Discrete Fracture Network model.

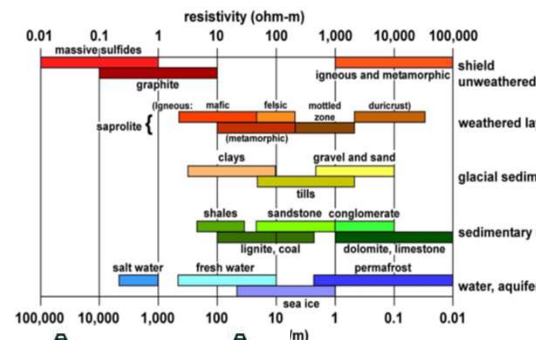
Limitations of Seismic and other measurements

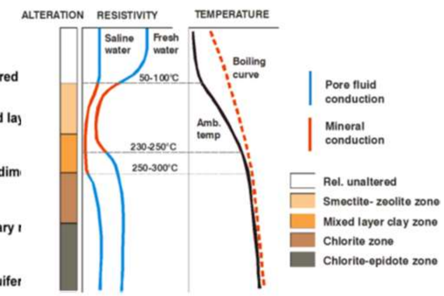
Geophysical Methods for Geothermal resource evaluation

1. Seismic Methods
2. Gravimetric Methods
3. Magnetic Methods
4. Electrical Methods





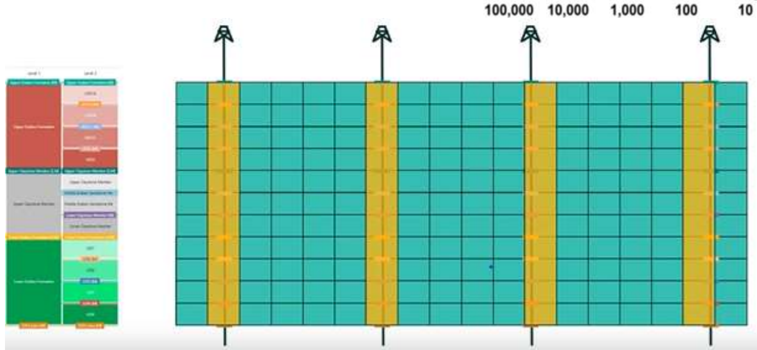




Very Important:

Offset and exploration well data:

Log, cores, VSP, well tests, cuttings etc.



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Q&A

SPE International — Italian Section
SPE International — Netherlands Section
SPE International — London Section
SPE International — Romanian Section
SPE International — Croatian Section
SPE International — Central Ukraine Section
SPE International — Geothermal Technical Section
SPE International — Data Science and Engineering Analytics Technical Section

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