Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment – SUCCEED

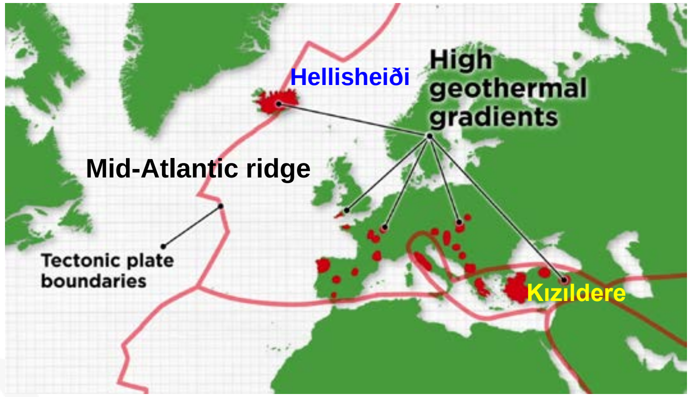
"ACT – Accelerating CCS Technologies" Project No: 294766

01 September 2019 – 28 February 2023

Middle East Technical University

The Project

An industrial CO_2 storage project utilising the existing wells and infrastructure at producing geothermal fields in Kızıldere (Turkey) and the CarbFix technology site Hellisheiði (Iceland).



The objectives of the project include:

i) to research and demonstrate the feasibility of utilising produced CO_2 for re-injection into a carbonate reservoir to maintain reservoir pressure and improve geothermal performance, while also storing the CO_2,

ii) to develop further, test and demonstrate innovative monitoring technologies applicable in all CO_2 storage field sites:

   a. the new higher signal-to-noise ratio Distributed fibre-optic Acoustic Sensing systems iDAS and Carina®
   b. the new permanent and highly repeatable and environmentally friendly seismic monitoring EM-vibrators

to provide semi-continuous seismic monitoring capability at HPHT environments,

iii) to investigate rock-fluid interactions under simulated HPHT conditions in the laboratory and determine geochemical, geomechanical and geophysical response of the reservoir rocks to supercritical CO_2,

iv) to model and investigate performance of injected CO_2 in the reservoir

v) to develop reliable technoeconomic and life cycle environmental impact assessment methodologies for CO_2 storage in geothermal projects

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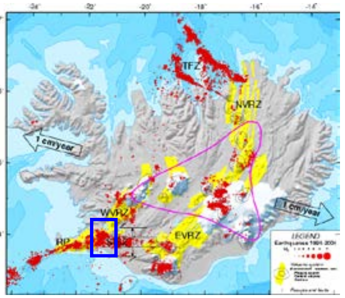
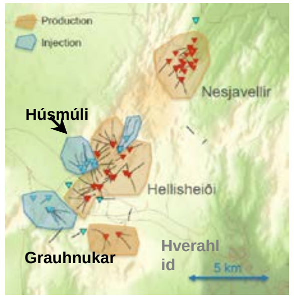
Two Geothermal Field Sites

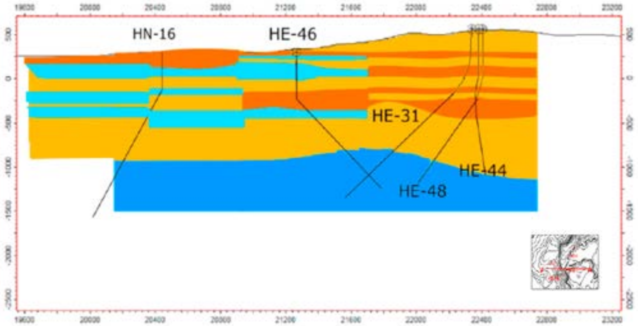
Hellisheiði site operated by Reykjavik Energy:

- 303 MWe installed capacity.
- 700 – 2,500 m reservoir depth, 270 – 320 °C temperature in the fractured basalt reservoir.
- Producing ~4,500 tonnes/hr geothermal fluid and reinjecting 3,800 tonnes/hour.
- CarbFix site re-injecting 12,000 tonnes per annumCO_2 dissolved in spent geothermal fluid since 2014.

Hengil volcanic system

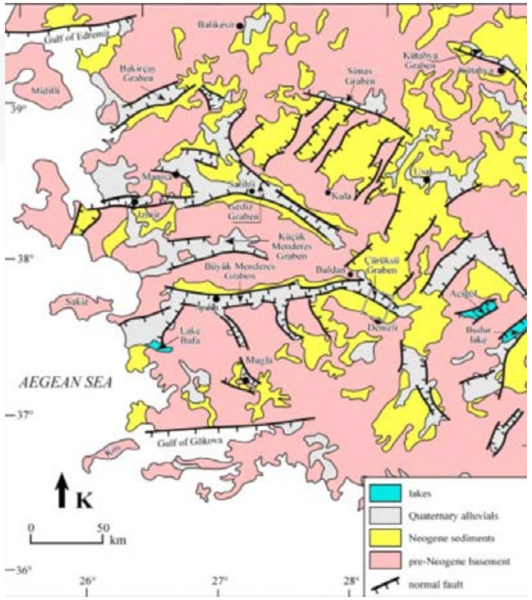




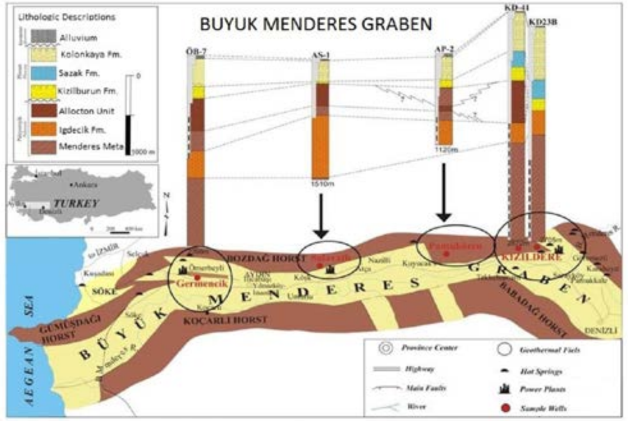


Kızıldere site operated by Zorlu Energy:

- 260 MWe installed capacity.
- 2,000 – 3,500 m reservoir depth, 220 – 245 °C temperature in the carbonate reservoir.
- Producing ~7,000 tonnes/hr geothermal fluid from 41 wells and reinjecting 5,300 tonnes/hour back into the reservoir from 27 wells.
- Aimed at reducing CO_2 emissions while at the same time enhancing geothermal performance and storing CO_2.



Buyuk Menderes Graben



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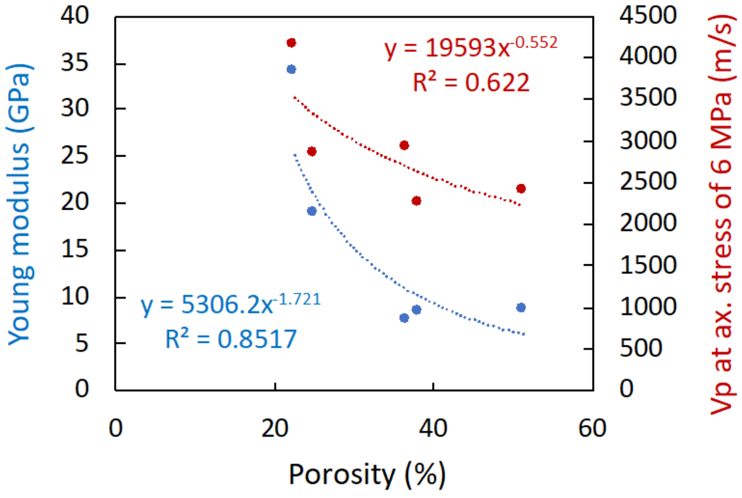
Reservoir Characterisation Studies

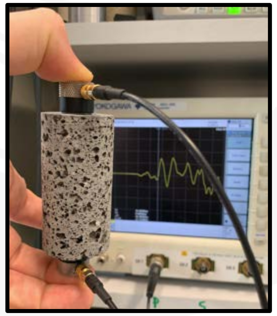
- Large bocks of reservoir rocks from Kızıldere and Hellisheiði delivered and cored at TU Delft laboratories.
- Mechanical and elastic properties, and seismic response characterisation of the reservoir rocks carried out at TU Delft laboratories (Janssen et al. 2021; Janssen et al. 2022a-c).
- Combined stress, temperature, pore pressure, and pore fluid effect on seismic properties established
- Basaltic formations display Porosity-dependent Young's modulus and Vp.



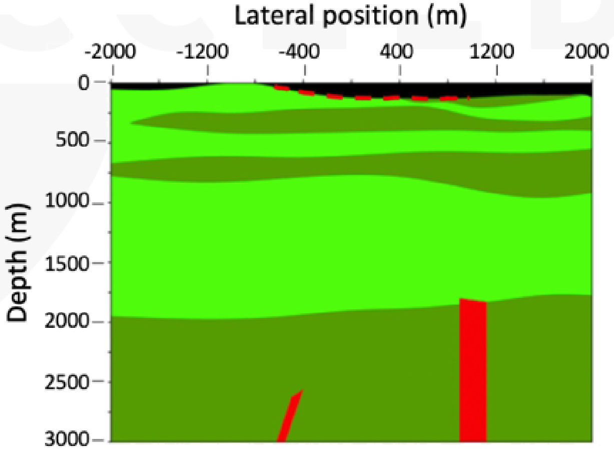
Basalt
ϕ=25.1±3.1%

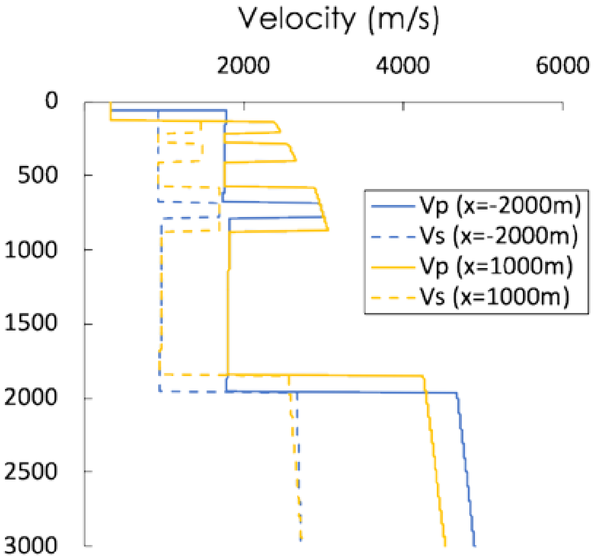
Basalt
ϕ=39.7±1.8%

Hyaloclastite
ϕ=44.7±2.3%



Basalt





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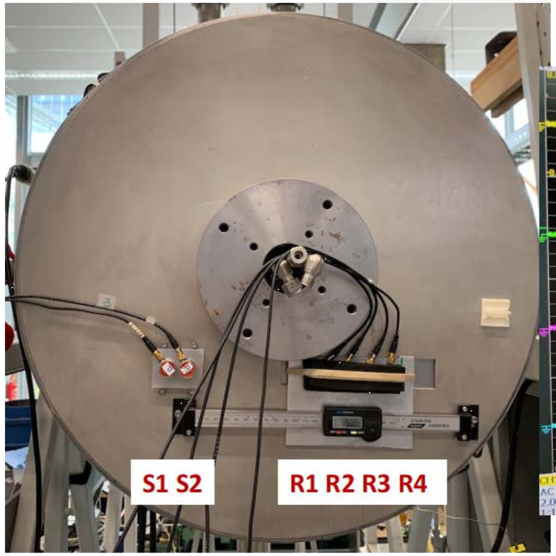
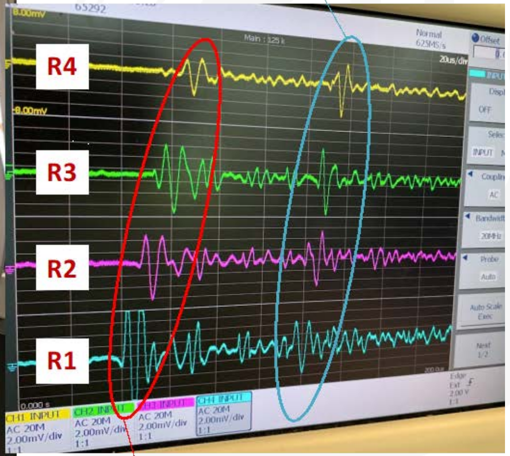
Large Scale Borehole Simulator Experiments

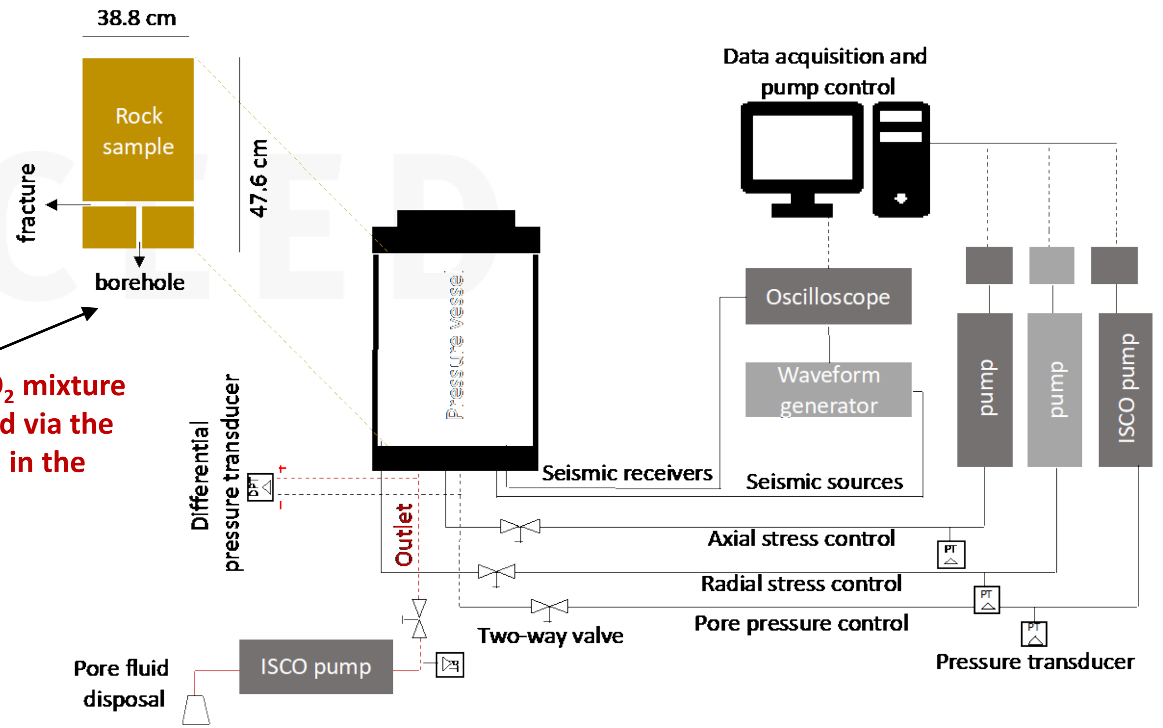
Seismic response and alteration of reservoir rocks with CO_2/brine-saturated flow

- The large-scale borehole simulator is running and the first dry tests on a large (476mm length, 388mm diameter) basalt sample from Hellisheiði have been performed successfully.
- The baseline measurements in dry conditions at an axial and radial stress of 186 and 144 bars, respectively, were carried out
- Able to identify the reflector of interest (reflection related to the artificial fracture). The intermediate step for upscaling from cm scale to 10 m scale achieved





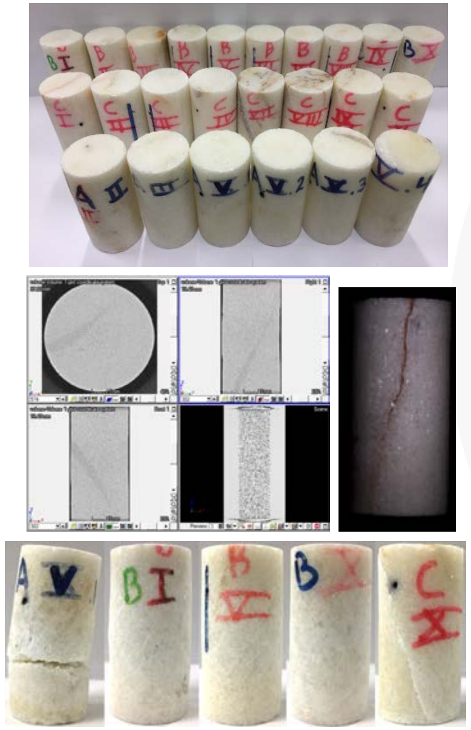
Brine/CO_2 mixture is injected via the borehole in the fracture



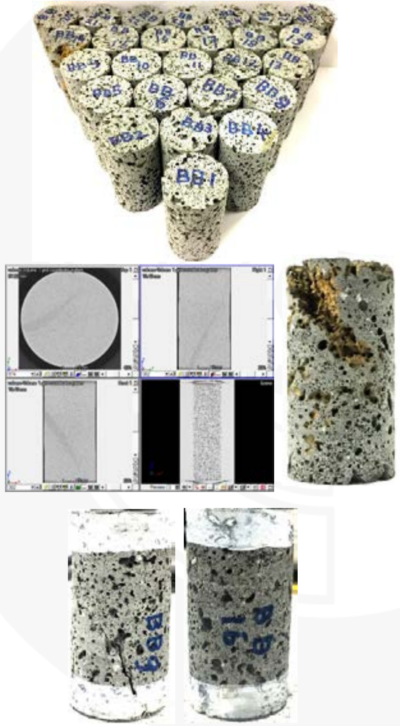
Long-term HPHT Treatment of Reservoir Rocks

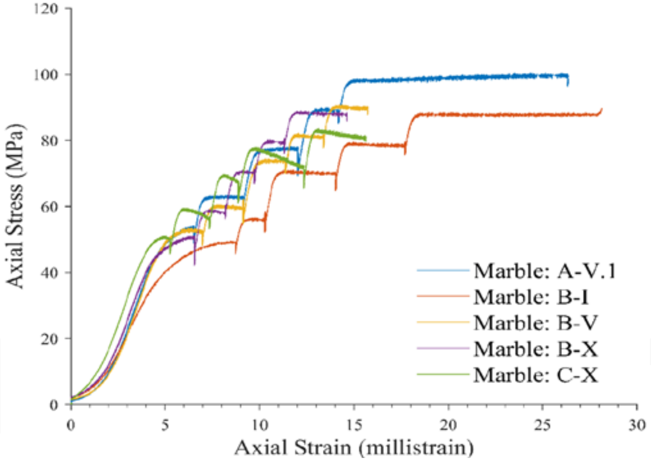
Baseline porosity, permeability, mechanical and elastic properties characterisation

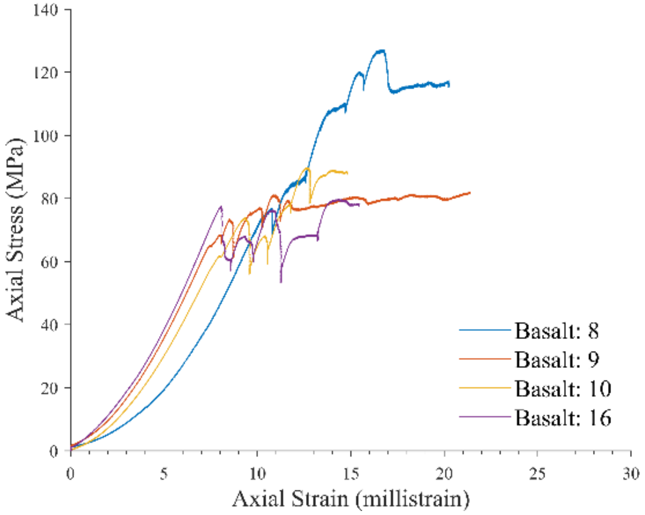
Kızıldere marbles

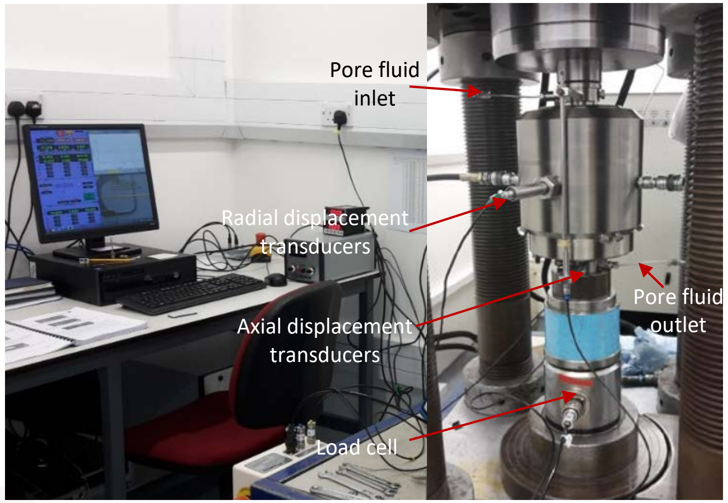


Hellisheiði basalts









Sample	Mean Porosity (%)	Mean Hassler cell Permeability (m^2)
Basalt	39.7±1.8	9.64×10^{-13}
Marble.	2.64±0.52	2.76×10^{-18}

Sample	Young's modulus (GPa)	Poisson's ratio	Ultimate strength (MPa)	Permeability under stress (m^2)
Marble A-V-1	15.40	0.20	101.46	5.00×10^{-20}
Marble B-I	10.83	0.18	89.78	2.00×10^{-20}
Marble B-V	14.79	0.27	90.82	2.00×10^{-20}
Marble B-X	15.20	0.31	88.94	3.00×10^{-20}
Marble C-X	15.64	0.24	93.66	2.00×10^{-20}
Basalt 8	12.20	0.13	127.30	2.01×10^{-14}
Basalt 9	10.03	0.26	82.17	5.00×10^{-16}
Basalt 10	5.42	0.32	89.91	3.54×10^{-13}
Basalt 16	12.82	0.23	79.91	1.06×10^{-14}

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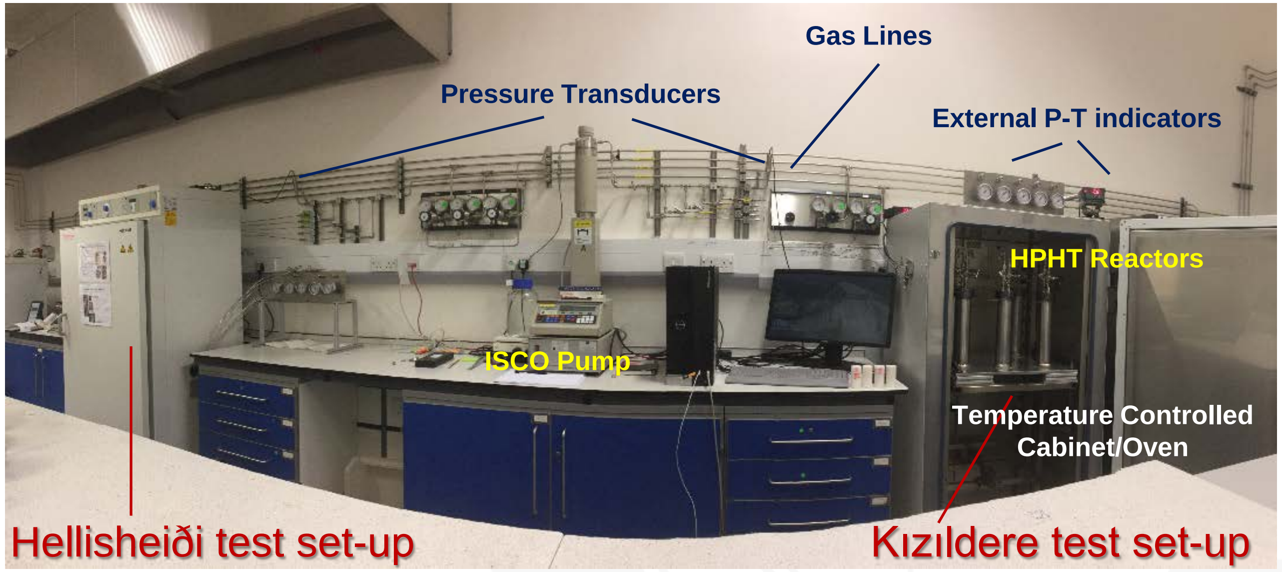
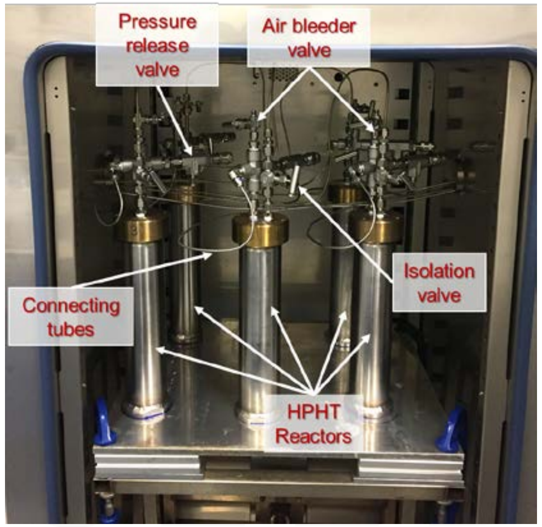
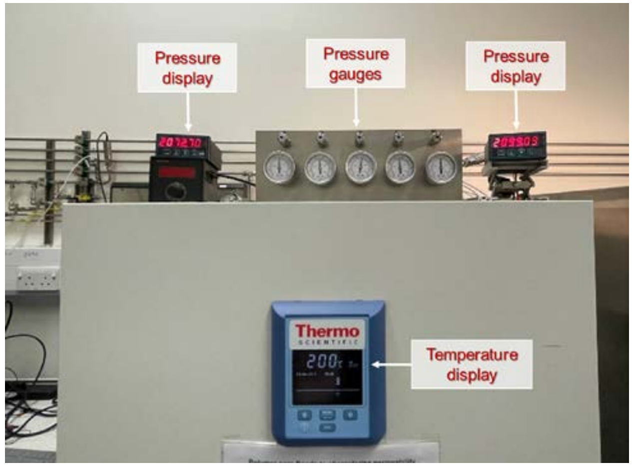
Long-term HPHT Treatment of Reservoir Rocks

Multiple reactor cells layout





Temperature controlled oven



External P-T indicators

Volume of brine and CO_2 in each cell for 0.5% CO_2 saturation (Hellisheiði)

Sample	V_{brine} (ml)	V_{CO_2} (ml)
Cell 1	311.95	623.91
Cell 2	311.23	622.47
Cell 3	313.08	626.17
Cell 4	311.53	623.05
Cell 5	337.55	675.11

	w (mg/l)
NaCl	117
$CaSO_4$	79

Volume of brine and CO_2 in each cell for 4% CO_2 saturation (Kızıldere)

	w (mg/l)
Na_2SO_4	2000
KCl	500
$CaCO_3$	5.7

Sample	V_{brine} (ml)	V_{CO_2} (ml)
Cell 1	308.20	6235.63
Cell 2	307.75	6226.66
Cell 3	308.22	6236.06
Cell 4	308.32	6238.23
Cell 5	310.73	6286.98

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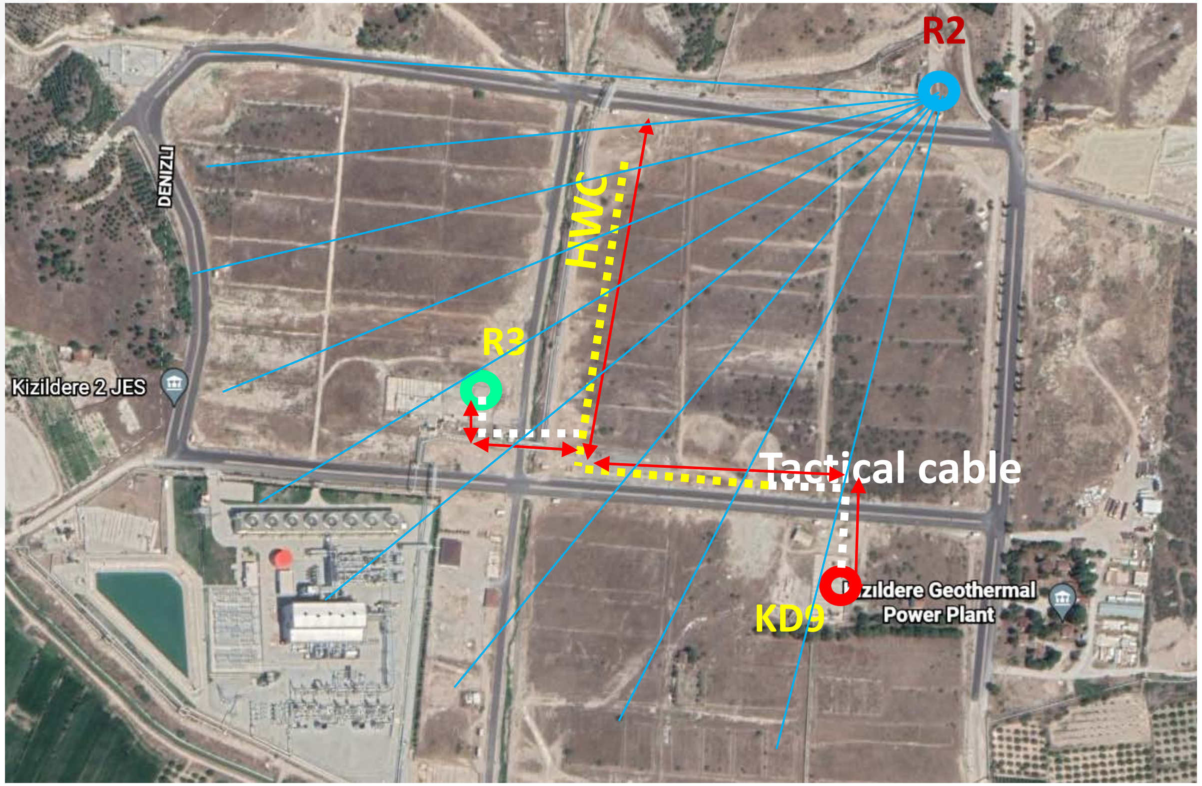
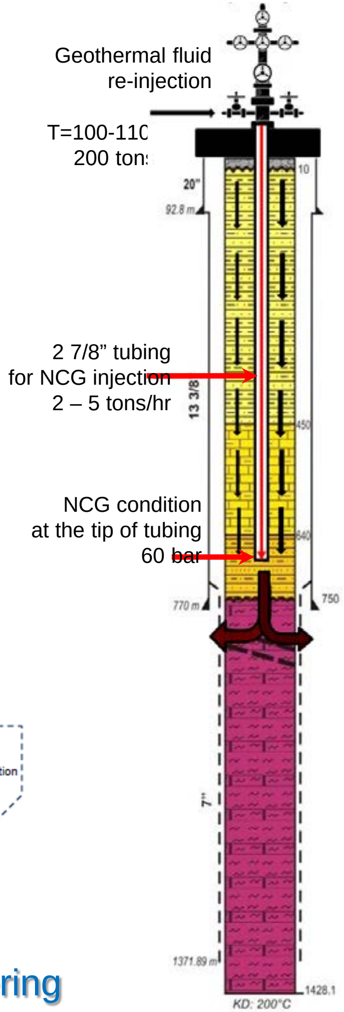
Injection and Monitoring Wells at Kızıldere

- R2 was selected as the injection well and wells R3 and KD9 were selected as the monitoring wells.
- Surface HWC path was revised through the analysis of geothermal fluid flow paths and land conditions.
- Downhole fibres are designed for both temperature and seismic profiling in wells R3 and KD9 (rated at 260°C).

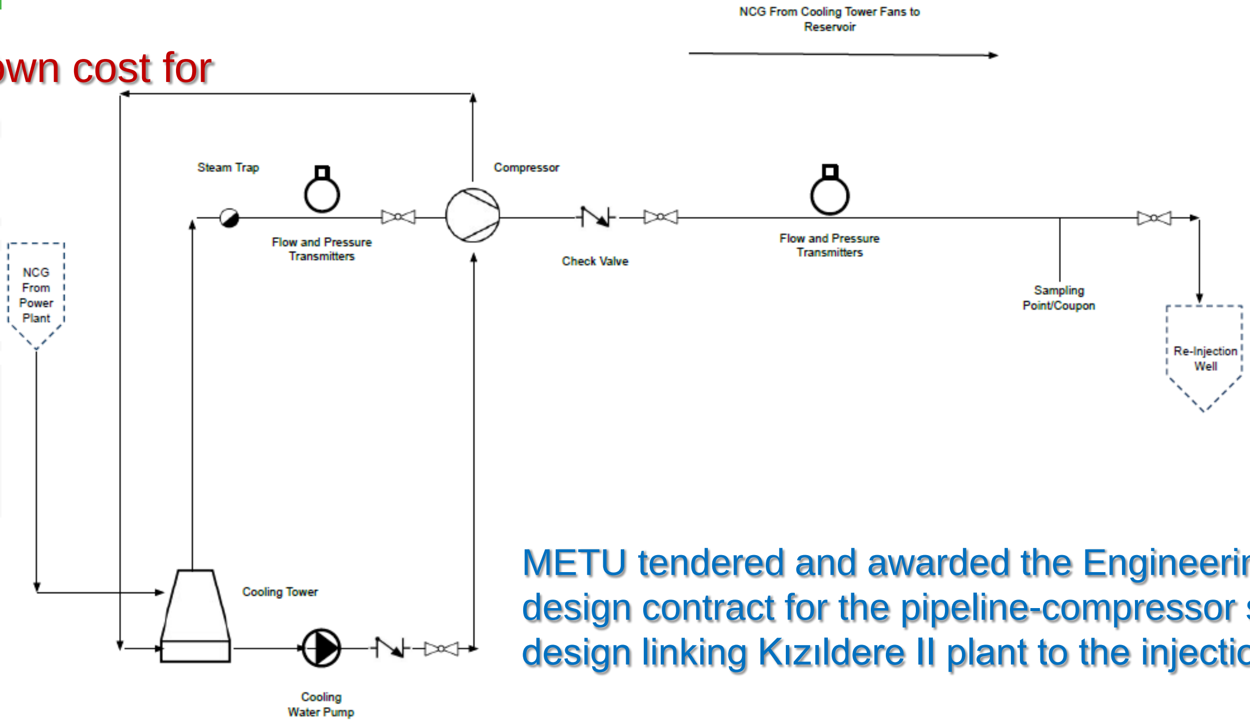


CO_2 Injection Infrastructure at Kızıldere

- Wellhead pressure at R2: 23 - 27 bar
- Water injection rate at R2: 200 tonnes/hr
- Planned CO_2 injection rate: 2 - 5 tonnes/hr
- Tubing length required: 500-540m
- Compressor pressure required: ~60 bar



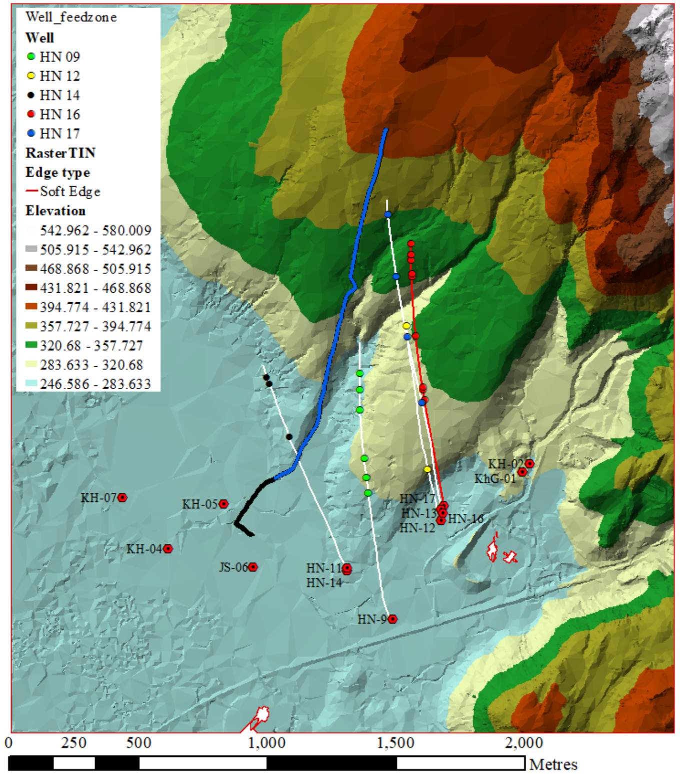
Zorlu ordered two compressors at its own cost for construction by Lupamat in Turkey
LYPS 200 / 1-14 Bar NCG
LYPS 132 / 14-60 Bar NCG-DHK



METU tendered and awarded the Engineering design contract for the pipeline-compressor system design linking Kızıldere II plant to the injection well

Planning and Design of Fibre Optic Cable Installations at Hellisheiði

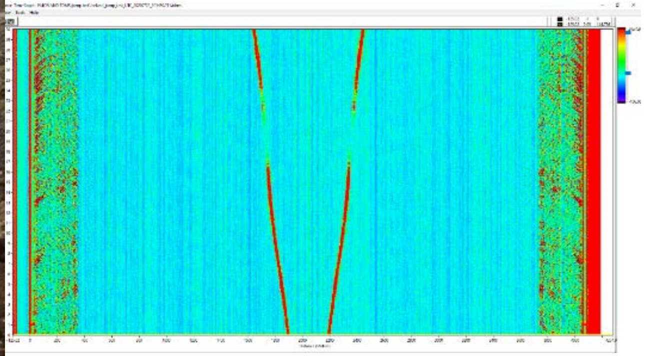
The field at Hellisheiði was surveyed in November 2019. Cables delivered, the 1,500m Helically Wound (HWC) and 350m Tactical Cable were installed at during 20-24 July 2020. A 6-weeks long passive seismic survey followed.



Tactical cable (FO)

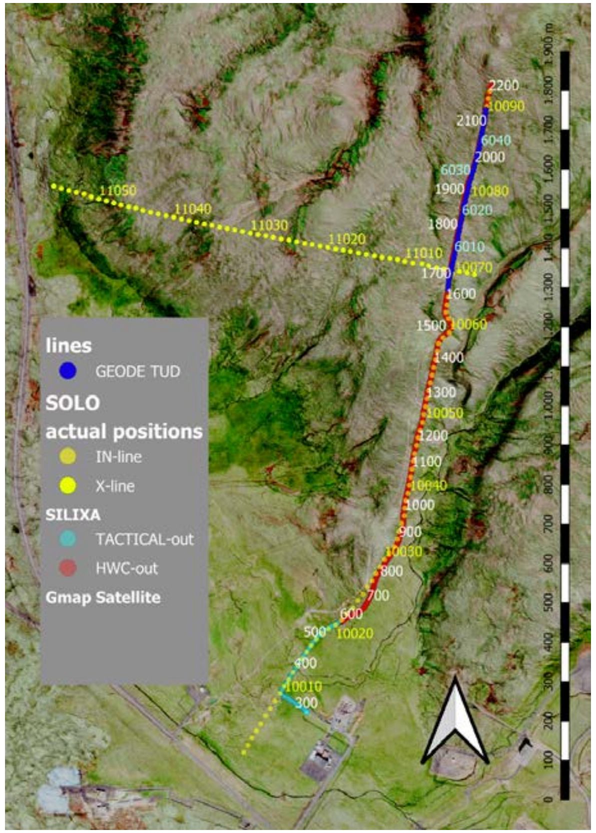
Helically Wound Fibre Optic Cable

The FO cable route



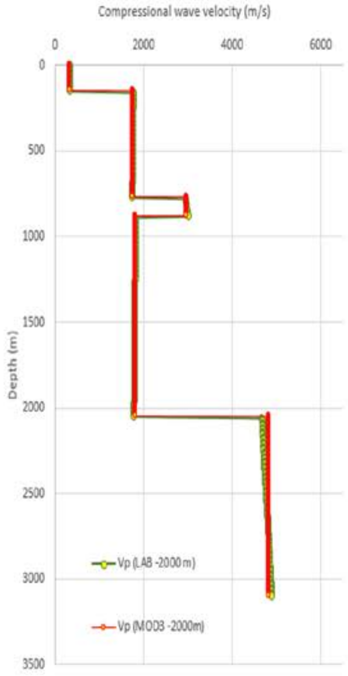
Field Seismic Monitoring at Hellisheiði

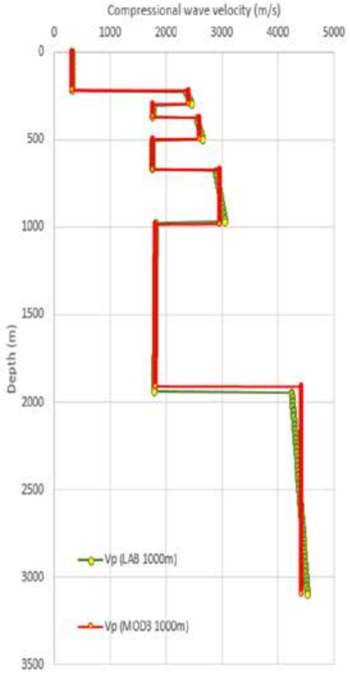
- The Mechantronics EM-vibrator was successfully utilised during the first field survey at Hellisheiði during 19-30 July 2021.
- 148 3C-SmartSolo stations loaned from the Geothermica DEEPEN project and 48 bi-axial TUDelft geophones deployed for both passive and active seismic.
  - Comparison of (correlated) signals from different sensors
  - Noise estimation and subtraction in DAS (before correlation)
  - Correlation using Vibro ground-force
  - Analysis of shallow data/model
  - Analysis of deeper data
- The final survey will be carried out during June 2022.
- 1st survey at Kizildere is planned for October 2022.

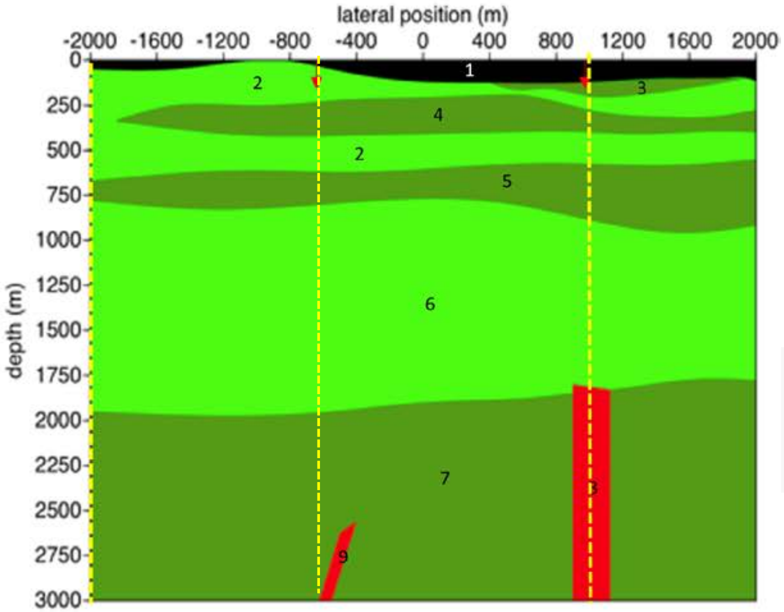


Hellisheiði Data Processing and Interpretation

Numerical simulations







1D – Vp profiles at x=-2,000 m and x=1,000 m

	Lithological Units	MOD3 VP (m/s)	MOD3 Vs (m/s)	MOD3 rho (g/cm³)
2	Hyaloclastite	1768	932	1600
3	Porous Basalt	2415	1458	1600
4	Porous Basalt	2600	1470	1600
5	Semi-porous Basalt	2975	1685	2000
6	Hyaloclastite	1820	972	1700
7	Low-porous Basalt	4830	2720	2450
8	Intrusion	4430	2670	2800
9	Intrusion	4430	2670	2800

MOD3 – Vp, Vs, ρ
updated using TUDelft LAB results

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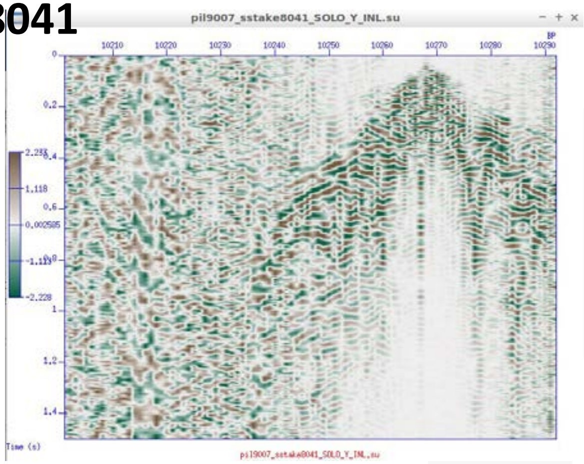
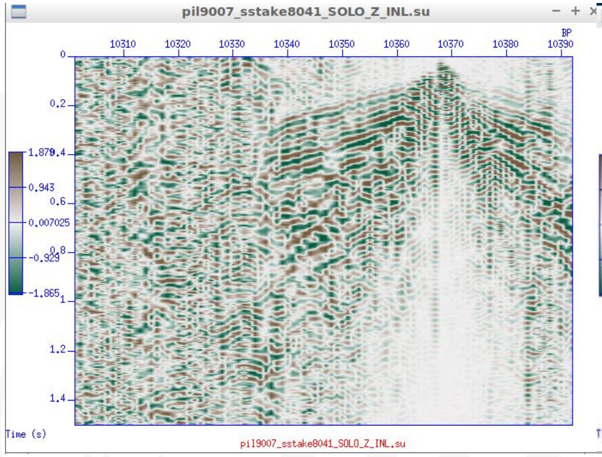
Hellisheiði Data Processing and Interpretation

Comparison of different signals in the baseline survey

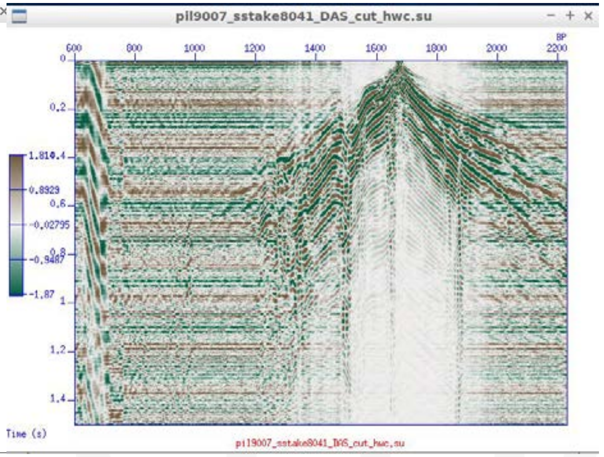
EP8041



SOLO Y

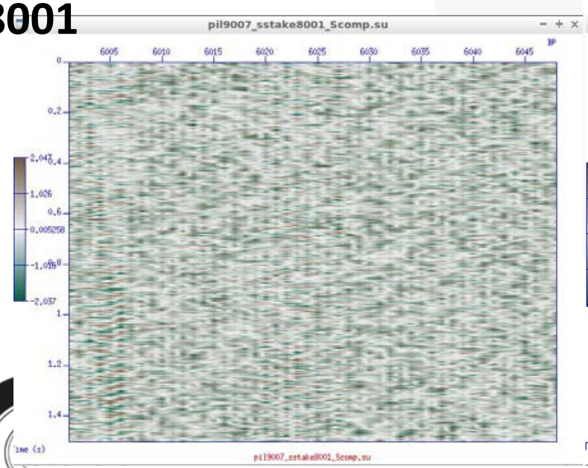


SOLO Z

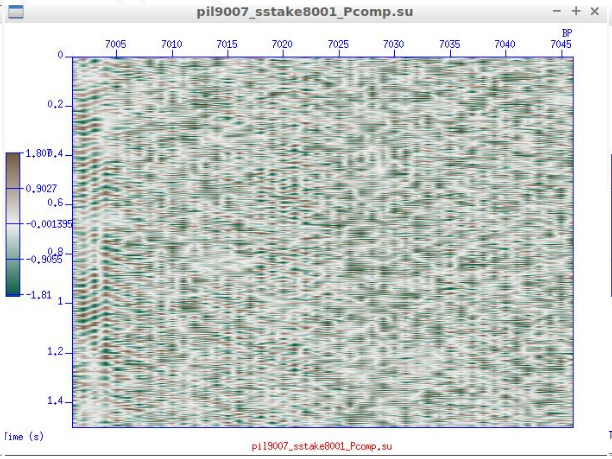


DAS HWC

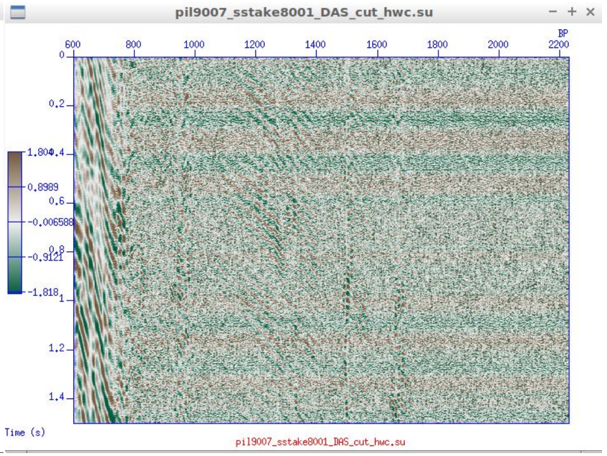
EP8001



TUD X

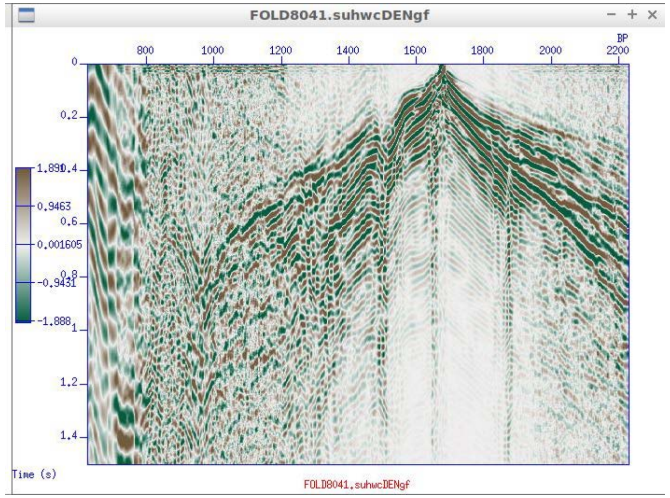


TUD Z



DAS HWC

Estimation and removal of optical noise from HWC

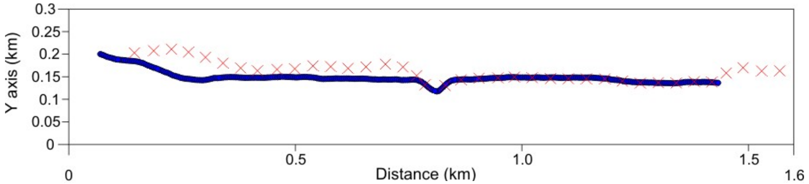


EP8041

Hellisheiði Data Processing and Interpretation

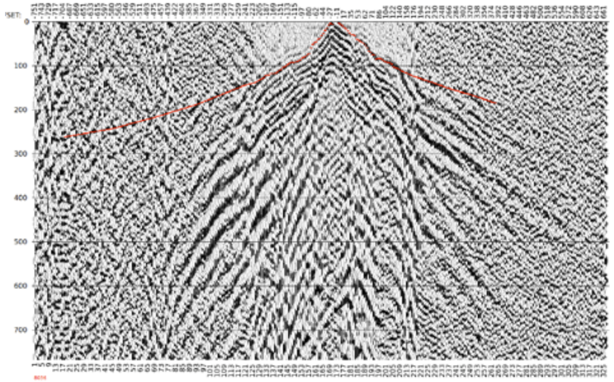
Tomographic inversion

Cross-section of acquisition

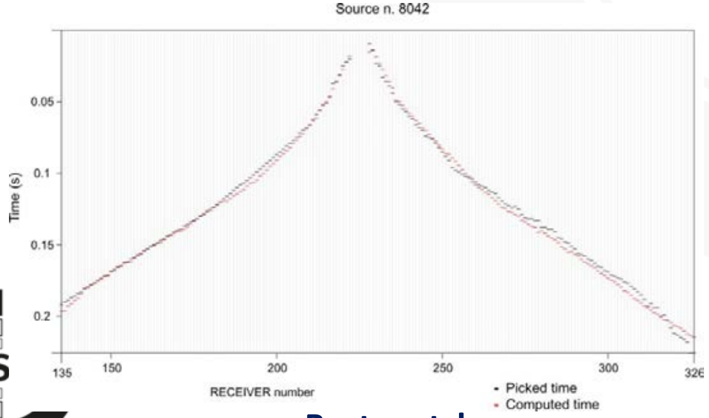


First break picking

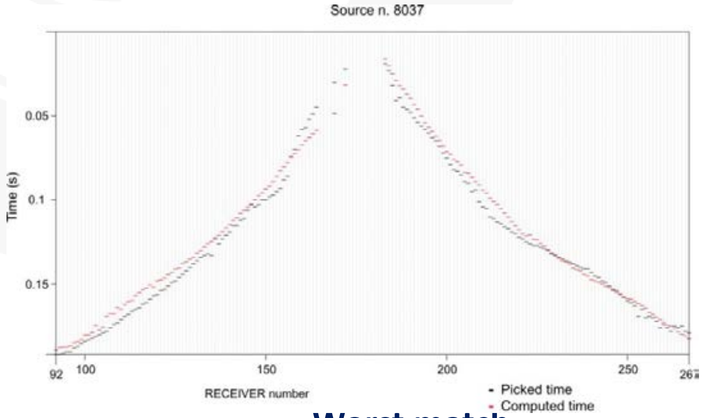
In common shot gather



Comparison between picked (black) and computed (red) travel times

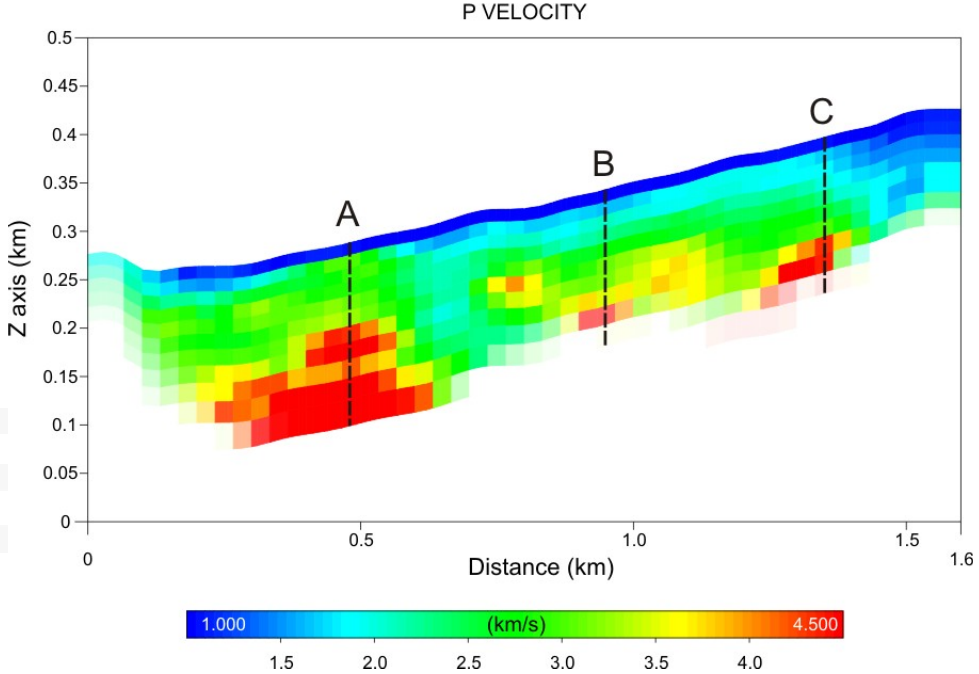


Best match



Worst match

P-wave velocity field

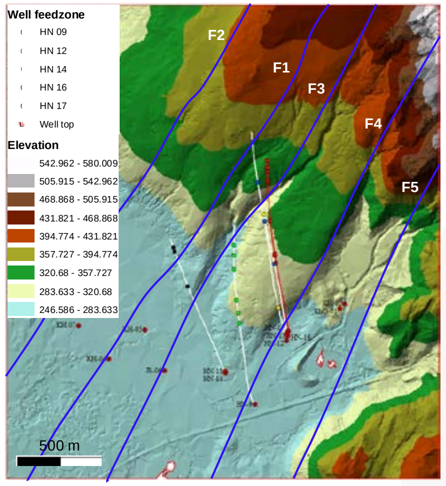


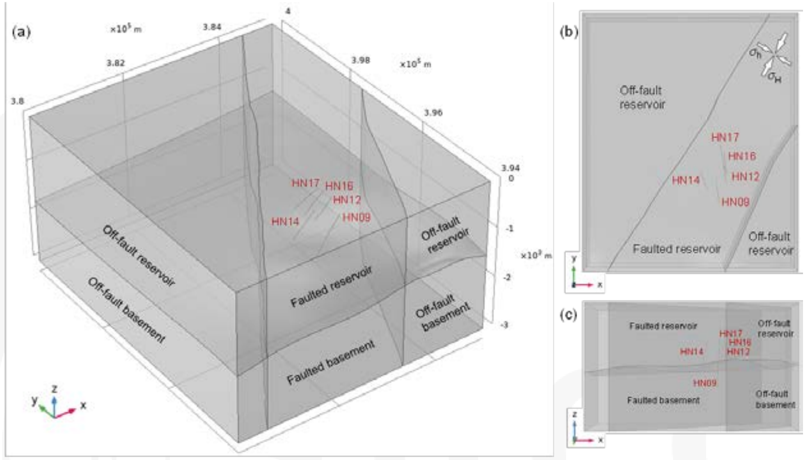
Vertical section - shallow heterogeneity

- Velocity calibration/confirmation by real and synthetic model
- Now time results
- Signal improvement by array simulation
- Time migration
- Next depth results using data derived velocities
- Intergration with passive seismic

Hellisheiði Injection Induced Seismic Monitoring and Interpretation

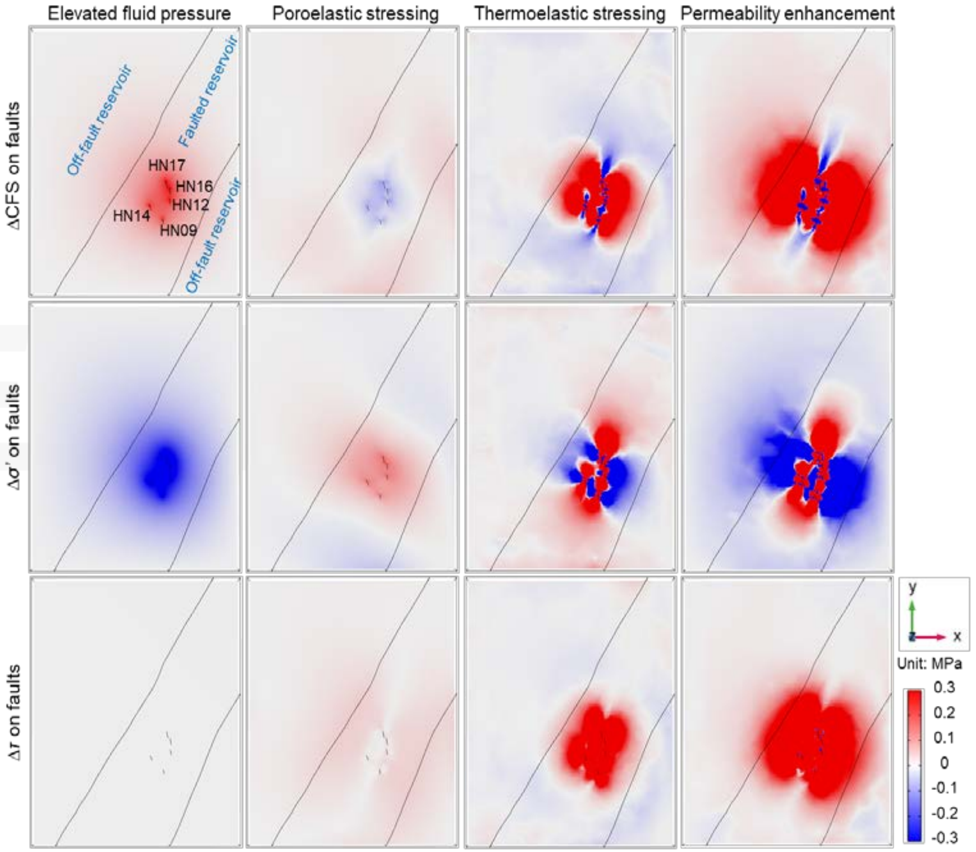
Coupled THM modelling to evaluate causal mechanisms for induced seismicity

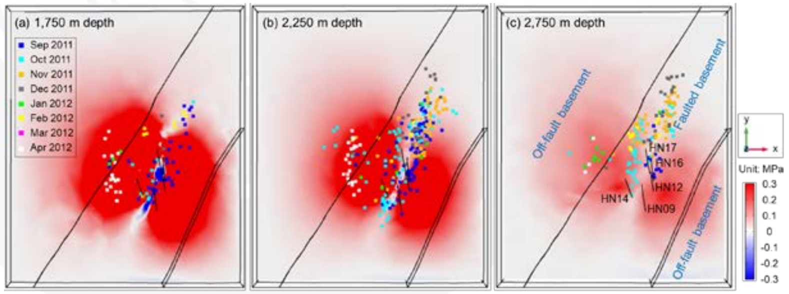




Geometry of the 3D fully-coupled THM model

Four causal mechanisms evaluated





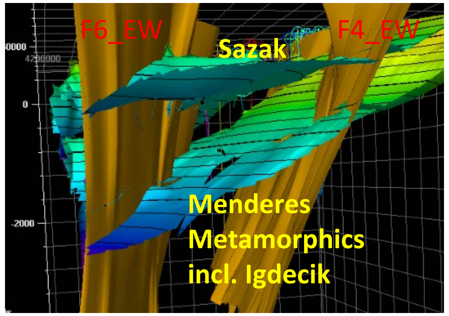
Comparison against recorded seismicity

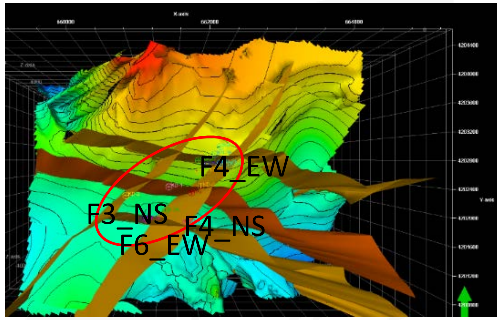
- The temperature dependence of field injectivity is governed by transient cooling-induced permeability enhancement,
- The temperature-dependence of induced seismicity is attributed to both direct thermoelastic effect (related to temperature change) and transient cooling-induced permeability enhancement (related to increased mass flow).

Reservoir Modelling of Injection Scenarios and Reservoir Performance at Kızıldere

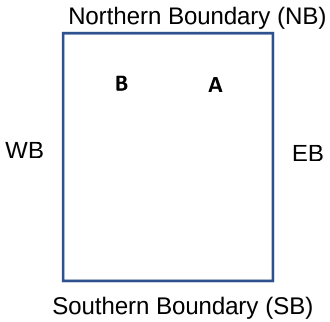
Reservoir simulation of historical geothermal fluids production

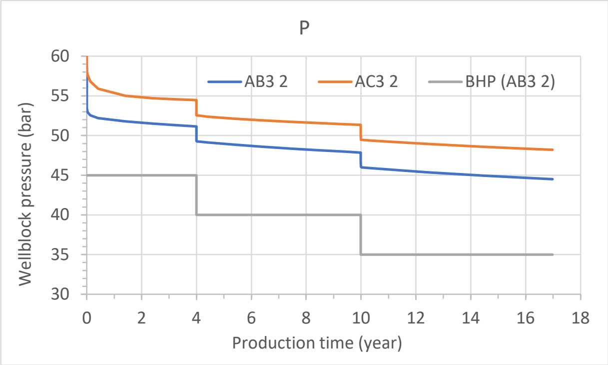
Around 135 million tons of fluid produced between 1984 and 2004, at an average rate of ~550 ton/h during 1984–1987; 920 ton/h during 1988-2000, >1,000 ton/h after that

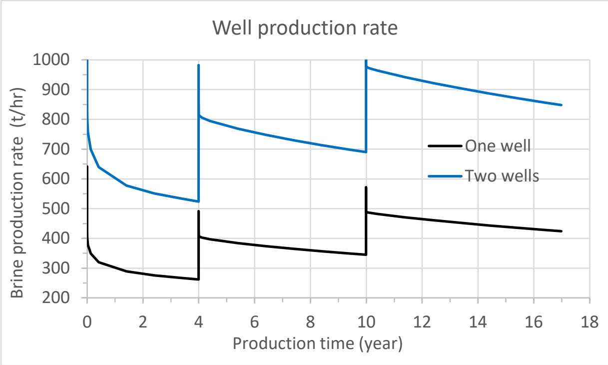




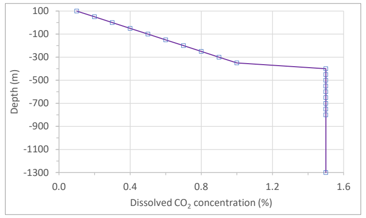
Dynamic model, mesh generated with faults and the wells



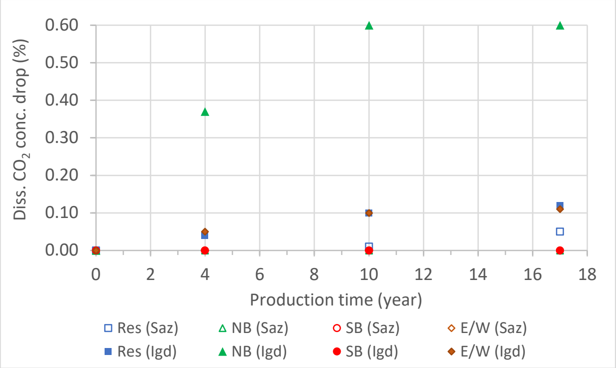




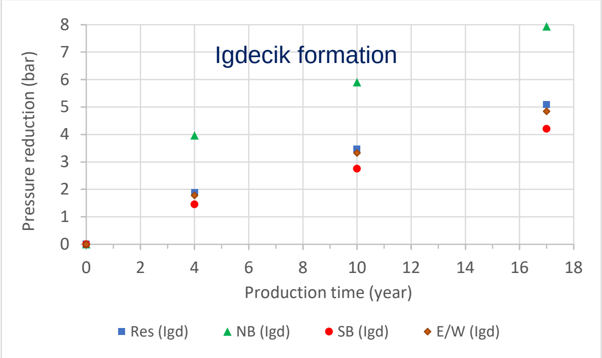
- Two production wells, A (2,3) and B (2,8) completed in Igdecik formation (-400 to -500m) are modelled.
- The BHP is reduced from its initial value (58.6 bar) in steps to 45 bar (1984-1987), then 40 bar (1988-1993) and finally 35 bar (1994-2000).
- The simulated aggregate fluid flow rate from the two wells averages around 550 t/h during the period 1984-1987. It then increases to ~750 t/hr and ~900 t/hr in the periods 1988-1993 and 1994-2000

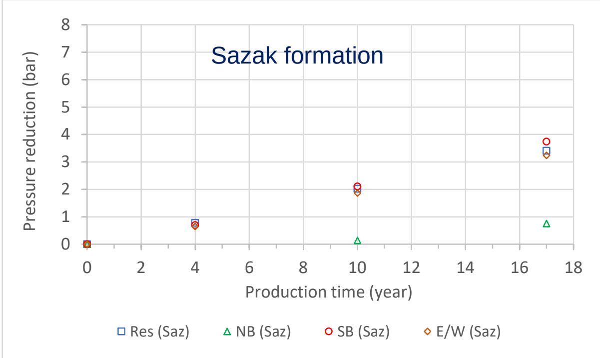


- Field CO_2 concentration distribution with depth
- Dissolved CO_2 partial pressure of 5 MPa at Igdecik



Simulated reduction in CO_2 concentration in the formations





Regional pressure reduction over the same period

Other Work in Progress

- Life cycle environmental impact assessment work on Kızıldere progressing with the LCI completed by Zorlu Energy
- Life cycle inventory (LCI) forms to include the role of CO_2 storage at Hellisheiði completed for an updated model development and implementation
- Work on techno-economic assessment and optimisation of a field-wide/regional CO_2 injection strategy for the Büyük Menderes Graben is running in parallel with Kızıldere reservoir model implementation
- Plans are being drafted for an industrial dissemination workshop to be held in collaboration with the Turkish Geothermal Energy Association in the Autumn 2022
- Around twenty journal papers, conference proceedings and/or poster presentations on SUCCEED have already been made with 5 further abstract submitted towards conference proceedings in the next 10 months.

SUCCEED

Accelerating CCS Technologies

Department for Business, Energy & Industrial Strategy

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TÜBİTAK

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