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Seismic velocity characterisation and survey design to assess CO₂ injection performance at Kızıldere geothermal field

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Abstract: The noncondensable gases in most geothermal resources include CO₂ and smaller amounts of other gases. Currently, the worldwide geothermal power is a small sector within the energy industry, and CO₂ emissions related to the utilisation of geothermal resources are consequently small. In some countries, however, such as Turkey and Iceland, geothermal energy production contributes significantly to their energy budget, and their CO₂ emissions are relatively significant. SUCCEED is a targeted innovation and research project, which aims to investigate the reinjection of CO₂ produced at geothermal power production sites and develop, test, and demonstrate at field scale innovative measurement, monitoring and verification (MMV) technologies that can be used in most CO₂ geological storage projects. The project is carried out at two operating geothermal energy production sites, the Kızıldere geothermal field in Turkey and the CarbFix project site at the Hellisheiði geothermal field in Iceland. Together with a brief description of the project, this paper presents the details of the two field sites and the progress made in seismic velocity characterisation and modelling relevant to the Kızıldere geothermal field in Turkey.

Key words: Geothermal energy, CO₂ emissions, CO₂ utilisation and storage, Kızıldere

1. Introduction

Emission of noncondensable gases is one common feature of most geothermal energy plants. The noncondensable gases in geothermal resources are mainly comprised of CO₂ and smaller amounts of ammonia, nitrogen, methane, hydrogen sulphide, and hydrogen (Holm et al., 2012). The noncondensable gases typically make up less than 5% of the geothermal fluid by weight, and the concentration of CO₂ in the noncondensable gases can be as high as 97.8% by mole (Bloomfield and Moore, 1999). Despite the difference in the lithology of their reservoir rocks, geothermal power plants in Turkey and Iceland emit considerable amount of noncondensable gases. Nearly all geothermal reservoirs are formed from carbonate rocks in Turkey and basaltic rocks in Iceland. One common feature of geothermal reservoirs in Turkey is the presence of considerable dissolved carbon dioxide in the geothermal fluids, which is produced as noncondensable gas at the outlet pressure and temperature conditions of the turbines or heat

exchangers and is usually exhausted to the atmosphere. The concentration of dissolved CO₂ can reach up to 4% by weight depending on site characteristics, which also is a valuable feature of the geothermal resource, as it behaves as a natural pump during the ascend of geothermal fluid in the well. Noncondensable gases are separated from the geothermal fluid at the cooling tower of power plants and released to the atmosphere, and geothermal fluid depleted in CO₂ is generally reinjected into the reservoir. Emission of CO₂ into atmosphere and reduction in CO₂ content of the geothermal fluid in the reservoir can be reversed by reinjection of produced CO₂ along with the spent geothermal fluid.

Considerable experience in CO₂ injection into carbonates has been gained in Turkey by the Turkish petroleum industry at the Batı Raman CO₂ - EOR operations (Şahin et al., 2007). An important concern closely related to CO₂ storage in carbonates is that the injected CO₂ may dissolve into formation brines, causing

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acidification and possible dissolution of carbonate minerals within the reservoir. To date, the only European pilot study to investigate monitoring of permanent storage of CO_2 in a fractured carbonate system has been the Hontomin research pilot in Spain (Humphries et al., 2016). Reinjection of produced CO_2 back into the geothermal fields has been proposed by several researchers (Pruess, 2006; Salimi and Wolf, 2012). However, the harsh and high temperature downhole environments in geothermal reservoirs pose an added challenge for field implementation of CO_2 injection and downhole monitoring of its fate in the reservoir.

SUCCEED (Synergetic Utilisation of CO_2 storage Coupled with geothermal EnErgy Deployment) aims to research and demonstrate the feasibility of utilising produced and subsequently vented CO_2 for reinjection to the reservoir to improve geothermal performance while also storing the CO_2. In order to achieve its objectives, the project takes advantage of the already existing deep well infrastructure at the two partner geothermal field sites, Kızıldere in Turkey and the CarbFix project site at Hellisheiði in Iceland, which also provide different geological settings and two different techniques of CO_2 injection in the reservoir. The project also aims at field testing and implementation of a new, higher signal-to-noise ratio DAS (Distributed Acoustic Sensing) technology, and a new and innovative vibratory-type electric seismic source to provide semicontinuous seismic monitoring capability for CCS and geothermal applications.

The main requirement for high-resolution images of the subsurface is a sufficiently dense placement of seismic sources and receivers at the surface and/or boreholes, which has always been a limiting factor. The new developments in recent years of fibre-optic sensing of acoustic and seismic wavefields addresses the challenge of sufficiently dense receiver sampling. Silixa's new intelligent Distributed Acoustic Sensors (iDAS) provide the latest achievements in the field of DAS technology available. Furthermore, the Carina Sensing System, which uses the new family of engineered Constellation fibres, provides 20dB (100 times) improvement in signal-to-noise performance (Naldrett et al., 2020) and, therefore, significantly improve the results of both passive and active seismic surveys. Fibre-optic cables can be installed in trenches at the surface, deployed into existing boreholes, or cemented behind casing in permanent installations to provide enhanced coupling. Once deployed the fibre provides a long-term and repeatable monitoring solution because the fibre can be left in place and data collected for up to tens of years (Stork et al., 2020).

Another challenge faced in seismic sensing is having active seismic sources with sufficiently broad spectrum, especially at lower frequencies, that emit a repeatable source signal. Mechanical vibroseis sources were invented

to tackle the repeatability, but having mechanical driving mechanism limits their utilisation as broader-band sources. This is especially the case for broadening the spectrum of the emitted signal to the lower frequencies. The lower frequencies are required to perform a correct full-waveform inversion that finds the global minimum instead of finding a local minimum due to the cycle-skipping problem. The seismic vibrator driven by electric linear synchronous motors (LSM) developed by Seismic Mechatronics BV easily generates this low frequency content with high force, without suffering from low repeatability issues due to its frictionless design (Noorlandt et al., 2015). A more detailed description of the seismic monitoring technologies used in SUCCEED project is presented in Durucan et al., (2021).

The preparatory work in the project focused on field investigations at the two pilot sites, selection of the CO_2 injection and monitoring wells at Kızıldere, surface and downhole fibre-optic cable installation planning for both project sites, and the design work towards the seismic surveys for the monitoring of CO_2 injection performance in the field. Reservoir and caprock samples collected at Kızıldere were characterised for their acoustic velocities under simulated subsurface stress conditions in the laboratory. A 3D geological model of the Kızıldere pilot site was developed and used as the basis for calculating synthetic seismic data for the first seismic survey design. This paper presents a brief description of the two field sites and the progress made in seismic velocity characterisation and modelling to optimise the active source positions at surface at the Kızıldere geothermal field.

2. Project pilot sites
The SUCCEED project is an industrial CCUS project, which focuses on CO_2 utilisation and storage. It benefits from the existing facilities of producing geothermal fields at Kızıldere in Turkey and Hellisheiði in Iceland. Common characteristics of both fields are as follows: high-enthalpy reservoirs (over 245 °C reservoir temperature), utilised for electricity production and heating applications, considerable amount of noncondensable gas production and fairly long production history with large databases. The main difference, on the other hand, is the lithology of reservoir rocks. Kızıldere field is producing from carbonates, while the main production zones of Hellisheiði are within the basaltic rocks.

### 2.1. Hellisheiði geothermal field
The Hellisheiði geothermal field lies within the Hengill volcanic system of the western volcanic zone of Iceland, about 30 km east of Reykjavík (Figure 1). The reservoir temperature is between 280–340 °C in the main production zones within the basaltic rocks. Operated by Reykjavík Energy (OR), the Hellisheiði power plant started operation
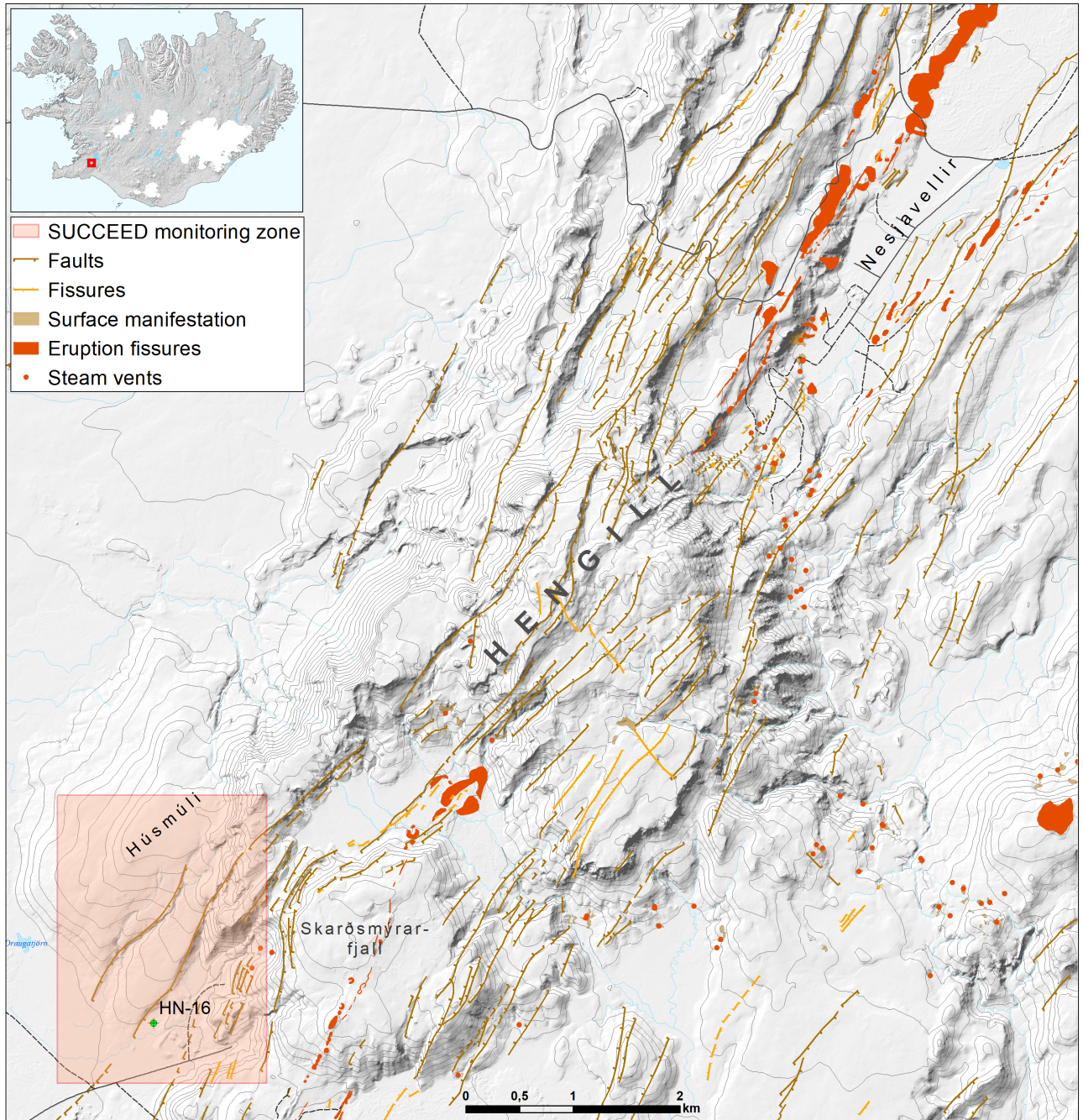
Figure 1. The Hengill volcanic system and the SUCCEED seismic monitoring zone around the HN-16 CO_2 injection well at the Hellisheiði site marked with a red rectangle (Durucan et al., 2021).

in 2006 and currently utilises the field production capacity of 303 MW_e and 200 MW_{th} energy. In total, 61 production and 17 reinjection wells have been drilled at depths from 1500 to 3300 m. The EU funded CarbFix project developed a technology to dissolve CO_2 in the reinjected brine, encouraging solubility trapping and carbonation of CO_2 in the subsurface. The storage formation consists of basaltic lavas of olivine tholeiitic composition. In 2014, the

CarbFix2 project was set up and industrial scale injection of CO_2 started, which was scaled up in 2016, and later in 2017. CO_2 charged water and the spent geothermal fluid are injected to a depth of 750 m at well HN-16 at the Hellisheiði geothermal field (Gunnarson et al., 2018). It is allowed to mix until it enters the main feed zones at 1900 m and 2200 m depth in the injection well (Figure 2). Modelling and field geochemical monitoring results for
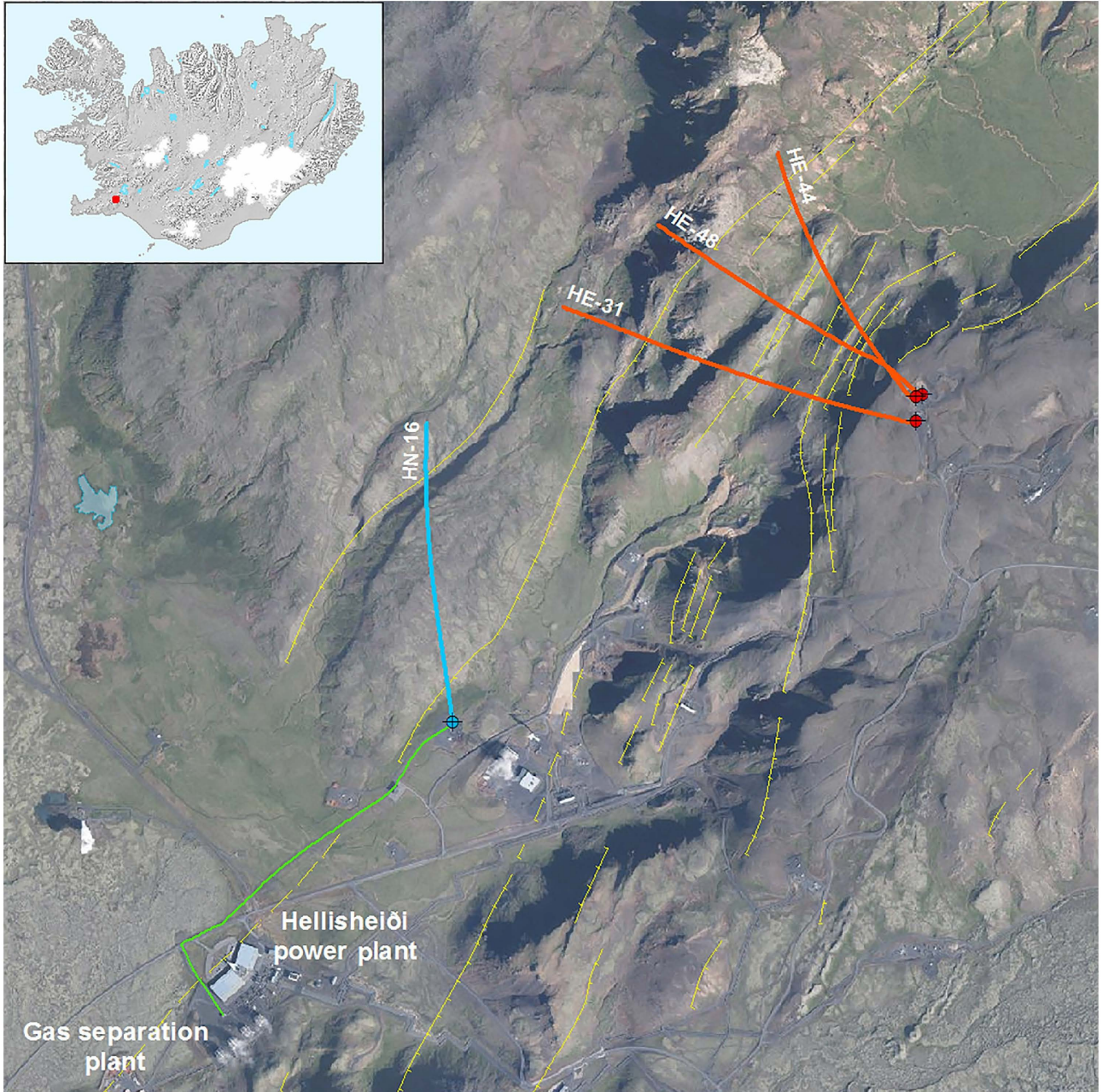
Figure 2. The CarbFix2 site at the Húsmúli injection site. HN-16 is the injection well HN-16, and HE-31, HE-48, and HE-44 are the monitoring wells (Gunnarson et al., 2018).

basaltic rocks suggested that complete mineralisation of injected CO_2 takes less than two years (Snæbjörnsdóttir et al., 2017). During the SUCCEED project, it is planned to inject 12,000 tonnes/annum CO_2 at the Hellisheiði geothermal field.

2.2. Kızıldere geothermal field
The Kızıldere geothermal field is located in the East of Büyük Menderes graben in Western Anatolia near Denizli (Figure 3). The geothermal field is made up of two main reservoirs: the upper reservoir within the Pliocene limestones of the Sazak Formation, and the 2nd reservoir, which comprises the Palaeozoic marble–quartzite–schist intercalations of the Iğdecik Formation and the deeper gneisses and quartzites (Menderes Metamorphics) that are intercalated with and underlie the schists (Figure 4). The geothermal fluid at Kızıldere carries a significant amount of dissolved CO_2 (over 3% by weight depending on depth). Operated by Zorlu Energy, the Kızıldere geothermal site
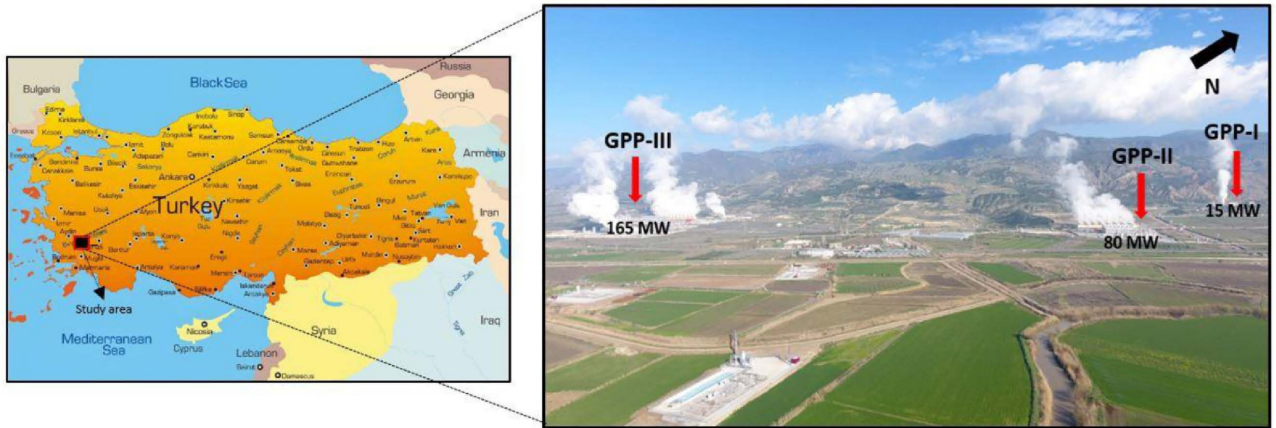
Figure 3. Location map and three power plants of Kızıldere geothermal field (Haklıdır et al., 2021).

has three power plants in operation with a total installed capacity of 260 MW$_e$ (Figure 3). Currently, there are 49 production and 28 reinjection wells drilled at depths from 500 to 3500 m into carbonate rocks at 220–245 °C reservoir temperature. Current production and reinjection rates are 8400 tonnes/hour and 6200 tonnes/h, respectively.

3. Progress towards the design of field seismic surveys at Kızıldere

At Kızıldere, R2, which is currently used as geothermal fluid re-injection well, was selected as the CO_2 injector and, after careful review of the tracer test results (red dotted lines in Figure 5), wells R3 and R5A were selected as the two monitoring wells as presented in Figure 5. A 500 m long Helically Wound Fibre-Optic Cable (HWC), which has increased P-wave sensitivity (the blue line in Figure 5), and a 600 m long Tactical Cable (TC) will be installed in a ~50 cm deep surface trench. These surface cables will be connected to the high-temperature engineered Fiber-Optic cables to be installed downhole the two observation wells (950 m in R3 and 1700 m in R5A) and close the loop.

3.1. Development of a static model for the Kızıldere field

A 3000×4000 m section of Zorlu Energy's license area in the Kızıldere field, which includes most of the wells drilled to date, was selected for the development of the static model. This model is currently being used to develop the SUCCEED dynamic model for reservoir simulations. Data from 77 wells within the area designated for the static model and the information provided by Zorlu Energy included:

1. Surface and bottomhole coordinates, and the altitude of well-collars.

2. Depths of formation tops for 6 formations (Alluvium, Tosunlar, Kolankaya, Sazak, Kızılburun and Menderes Metamorphics) cut by the wells in the field.

3. Drill logs with cut formations and lithologies, well completion and mud loss data.

4. Well trajectories, which helped introduce the wellbores into the static model.

5. Depth, volume, and mud loss rate recorded at each well during drilling.

Combining surface geological maps, drill hole data and seismic surveys, Zorlu Energy developed fault maps at three different surfaces in the reservoir and made these available to the project. Figure 6 illustrates examples of such fault maps along the top surfaces of Sazak, Menderes Metamorphics and deep marble zone, respectively. Faults that are continuous in all reservoir levels were used to develop the fault surfaces in the static model.

Developing the Kızıldere static model, the locations of all wells were introduced to Petrel first (Figure 7). Next, the geological surface maps of each formation were constructed using the formation tops' depth data. The next step was to interpret the fault lines as the flow of geothermal fluids depends heavily on the fracture and fault system in the reservoir (Figure 8). Using fault lines, the geological surfaces were rearranged and structural top contour maps of each formation were obtained. The gridding process was followed by the development of the 3-D model (Figure 9).

3.2. Seismic velocity characterisation

It was aimed to determine acoustic velocities and elastic constants of the geothermal reservoir rocks to guide the design of field seismic surveys at project pilot sites, as well as the long-term HPHT borehole simulator experiments in the laboratory. Rock samples, including limestone, siltstone, mudstone, marble, quartzite, quartzschist, micaschist and calcschist, were collected from outcrops in the region around the Kızıldere site. A large number of cores were drilled, perpendicular to any visible bedding, from these collected rock samples (Figure 10). After determining porosity, matrix density, and bulk density, each dry core was used for performing the seismic velocity characterisation experiment at field-representative subsurface stress conditions. The resulting seismic
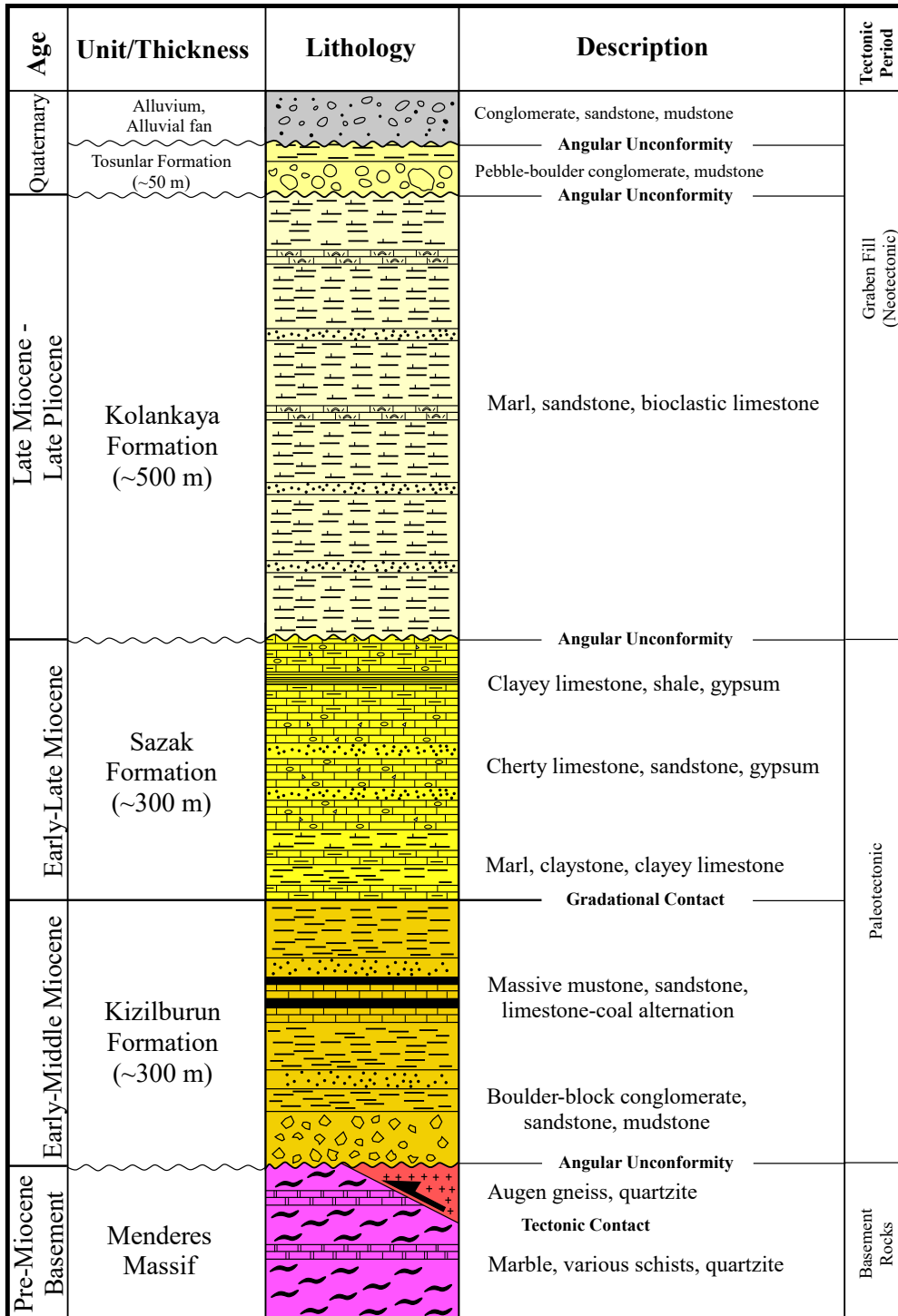
Figure 4. The generalised tectono-stratigraphic column of the Kızıldere geothermal field (Alçiçek, 2007).

velocities have already served as input for modelling seismic wave propagation in the design of field seismic surveys at Kızıldere site. Table presents an overview of the physical properties as well as the imposed stress conditions for each of the cores used.

Acoustic-assisted triaxial compressive strength experiments, where both axial stress (σ_1) and radial stress (σ_2) were applied on the specimens, were conducted for each of the core samples presented in Table. During the course of the eight experiments, σ_2 was held constant
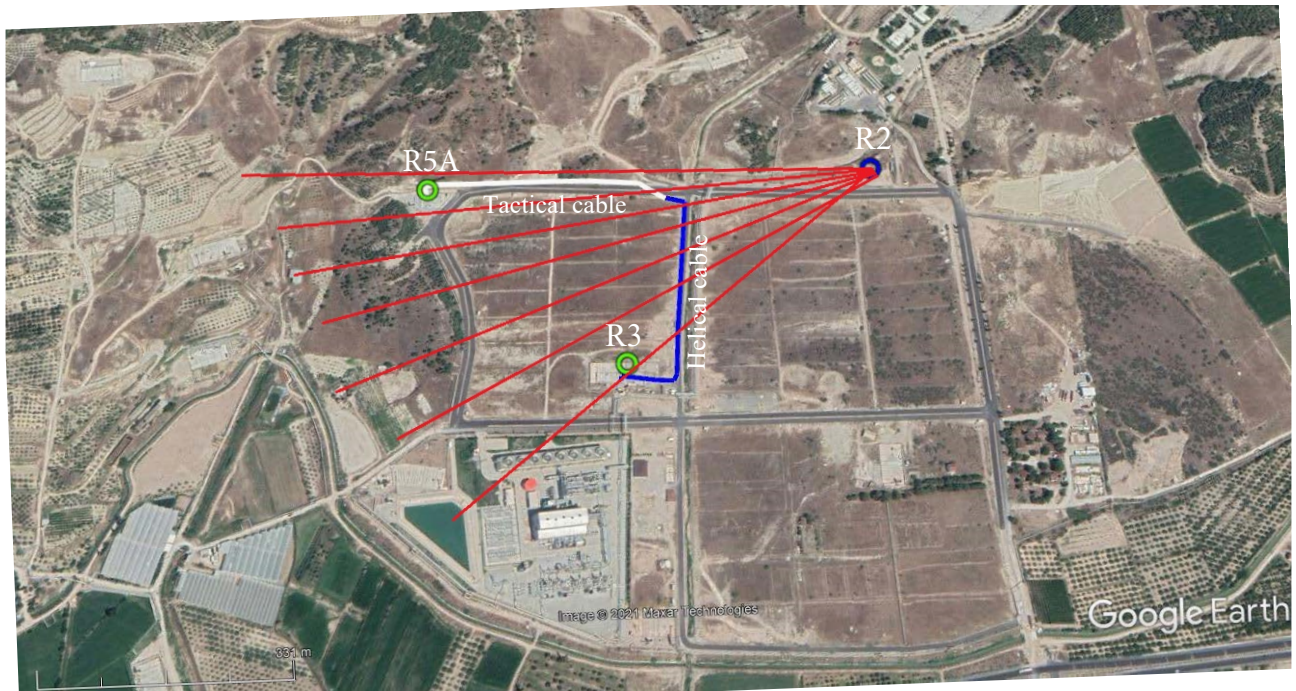
Figure 5. CO_2 injection and seismic monitoring wells and the fibre-optic cable installation layout at Kızıldere.

while σ_1 was varied, the latter reflecting various depths within the Kızıldere geothermal reservoir. Active-source acoustic transmission measurements, yielding the seismic velocities, were carried out as a function of varying σ_1. Representative magnitudes for σ_1 and σ_2 were taken from Çiftçi (2013). All eight experiments were performed at ambient temperature conditions (22 ± 1 °C). The seismic source and receiver were placed at the top and bottom of the core sample, respectively. A more detailed description of the materials and equipment, the experimental procedure, and the experimental set-up utilised are presented in Janssen et al. (2021). Most of the seismic velocity data presented in the top graphs of Figure 11 show gradual increase in velocities as a function of increasing σ_1, and thus, depth. This is most likely due to the closure of microcracks and open pore-space within the porous media studied, yielding an increased mineral-to-mineral contact area, and thus, velocity. The softest material investigated, i.e. siltstone, shows the lowest P- and S-wave velocities measured. After ach loading cycle, the core samples were unloaded following the same loading path, and more acoustic measurements were taken. The circular data points within top-left and top-right plots in Figure 11 represent velocity measurements during the unloading stage at the end of each experiment. It can be observed that, generally, they follow the loading trend, suggesting that no permanent deformation occurred within the rock's internal structure during the loading cycle (Table). For the

reservoir intervals that contain multiple rock types (mud- & siltstone, marble & calcschist, and calc- & quartzschist), a 50/50 distribution was assumed. Since the claystone could not be tested in this study, a literature value for its seismic velocity was assumed (Dalfsen et al., 2005). Note that the stratigraphic section shown in Figure 11 does not contain any micaschists.

3.3. Field seismic survey design and synthetic signal analysis

The teams analysed the velocity models and calculated synthetic seismic data for the seismic survey designs of both the Kızıldere and Hellisheiði sites before active-seismic data acquisition. This information is of paramount importance to verify the illumination zones at depth by seismic reflections and to optimise the wavefield interpretation.

The six horizons in the Kızıldere static model developed in Petrel format were imported in the OGS' Cat3D seismic tomography software, which was used to build the seismic model at depth for 3D ray tracing and simulation analysis. The imported horizons, from top to bottom, are as follows: Alluvium, Tosunlar, Kolankaya, Sazak, Kızılburun and Menderes Metamorphics. The geometries of the R2 (injection), R3 (DAS monitoring) and R5A (DAS monitoring) wells, as well as the faults, were also imported in the model (Figure 12).

The initial seismic velocity data for the modelled formations were taken from the laboratory experiments
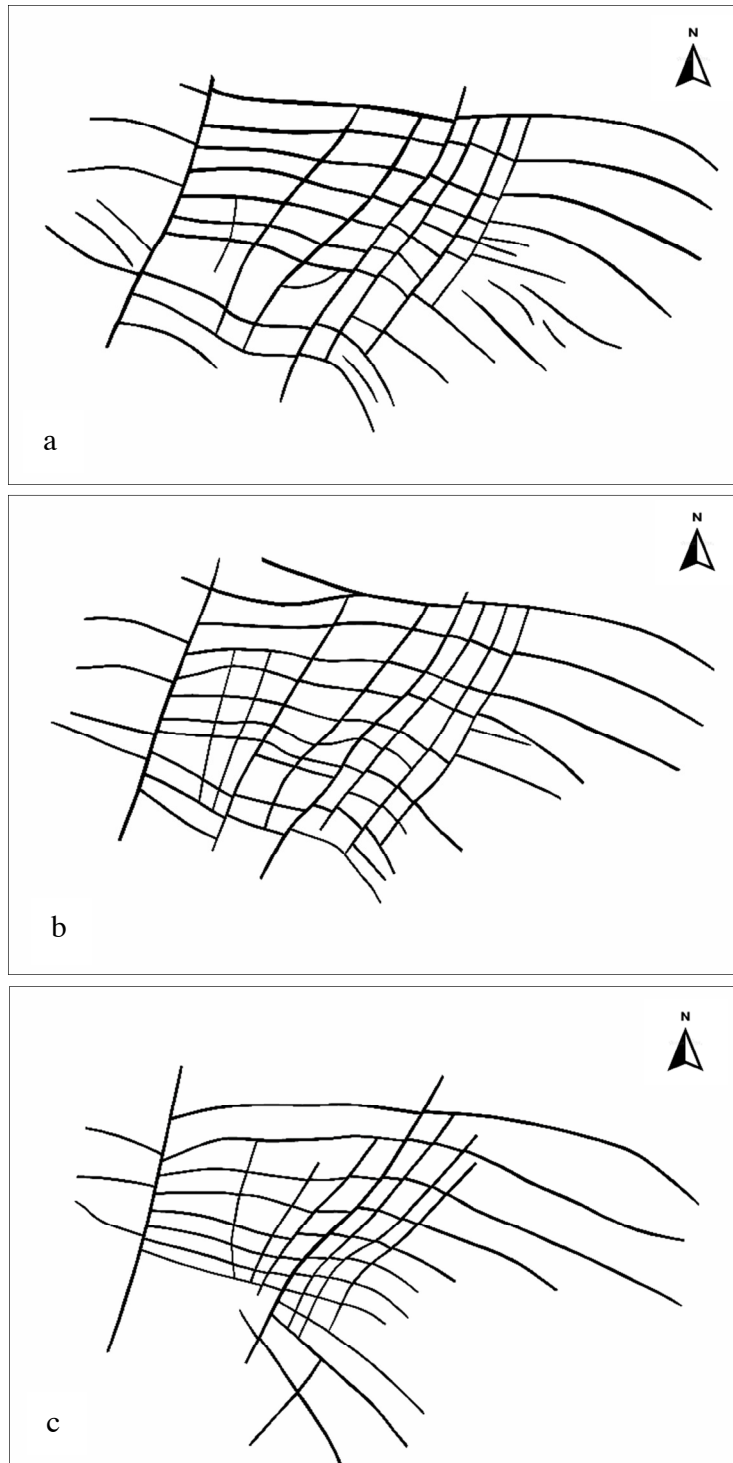
Figure 6. Kızıldere field fault polygons: a) top Sazak formation, b) top Menderes Metamorphics, c) top deep marble zone.

described above (Janssen et al., 2021). Subsequent calibration at depth will come from real DAS VSP seismic data after the field surveys. As an example, Figure 13 presents the vertical section from the Cat3D model taken

along the length of the HWC (blue line in Figure 5).

The field survey design study used the selected observation well locations and the surface fibre optic cable layout to optimise the source positions at surface.
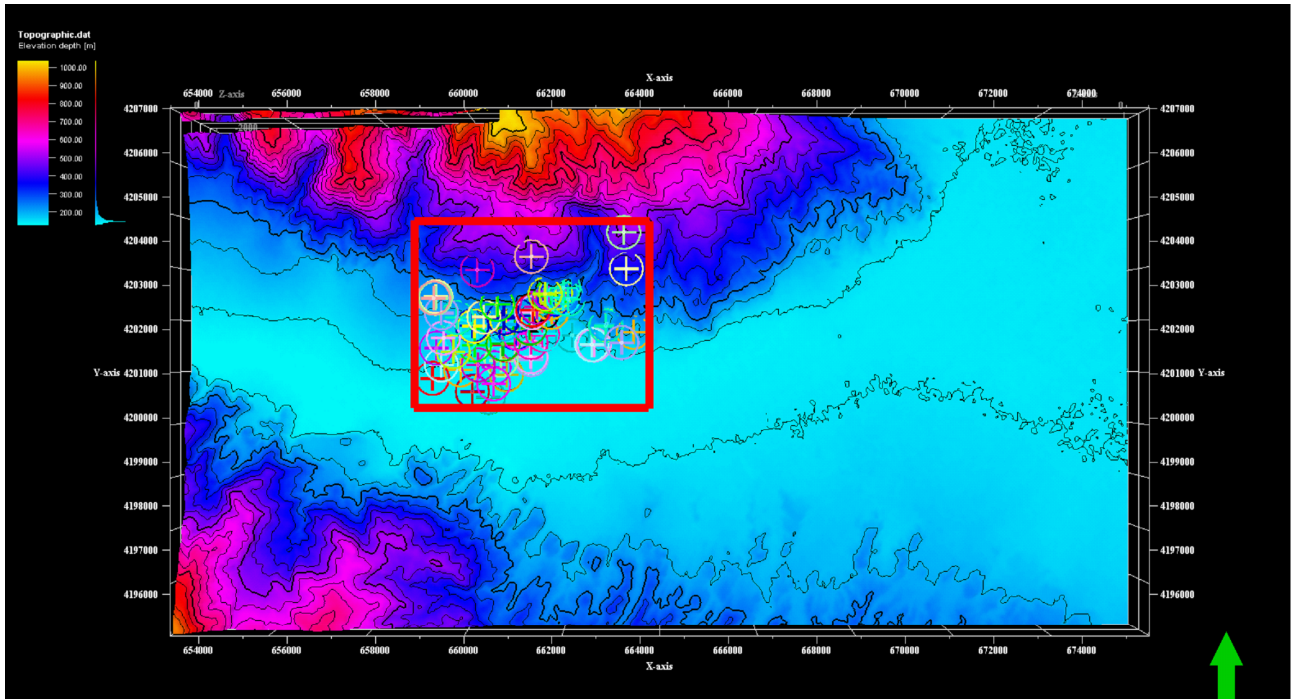
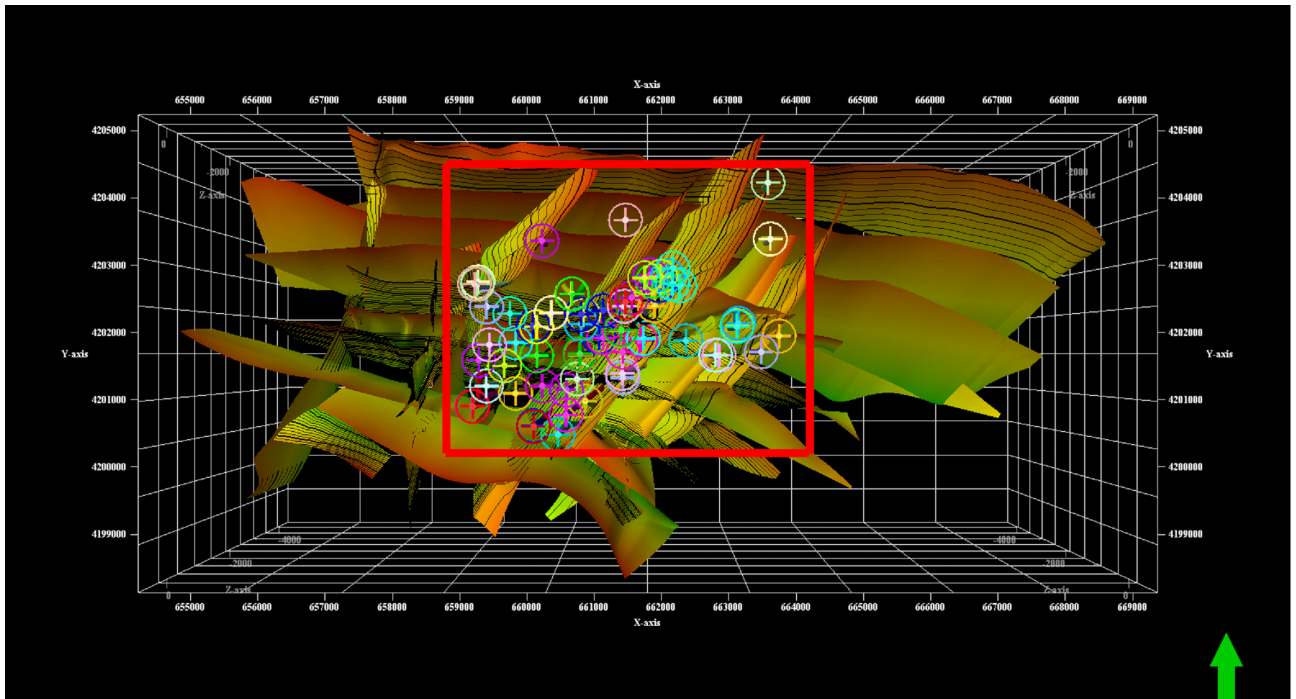**Figure 7.** Well heads and topography of the wider geothermal field.

Figure 8. Fault surfaces and well locations.

Thanks to the dense DAS receiver arrays available, each source position at the surface provides VSP in wells with appropriate sampling. The use of the source at several energisation points (shot points, SP) in the area will enrich the dataset by multi-offset and multi azimuth information, if required. Therefore, the main objective of seismic simulation was to observe seismic response in the zone of interest, to verify and design the Seismic Mechatronics source acquisition layout by analysis of illumination conditions at depth.
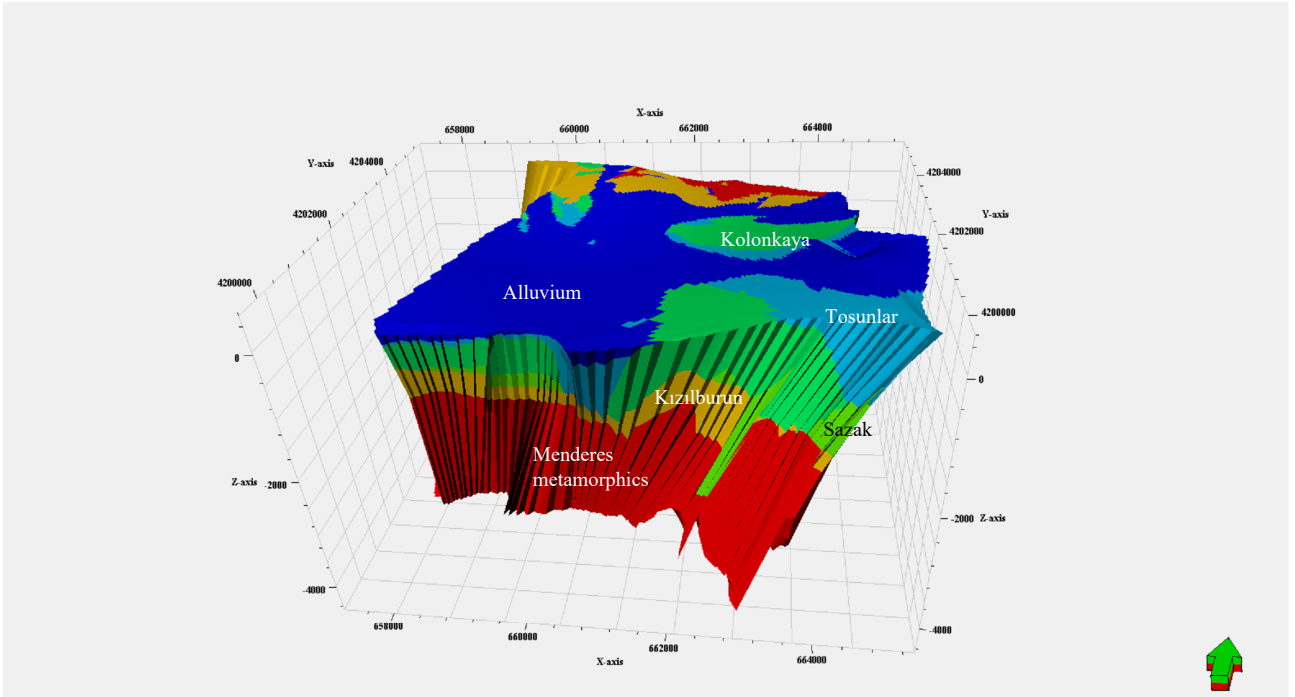
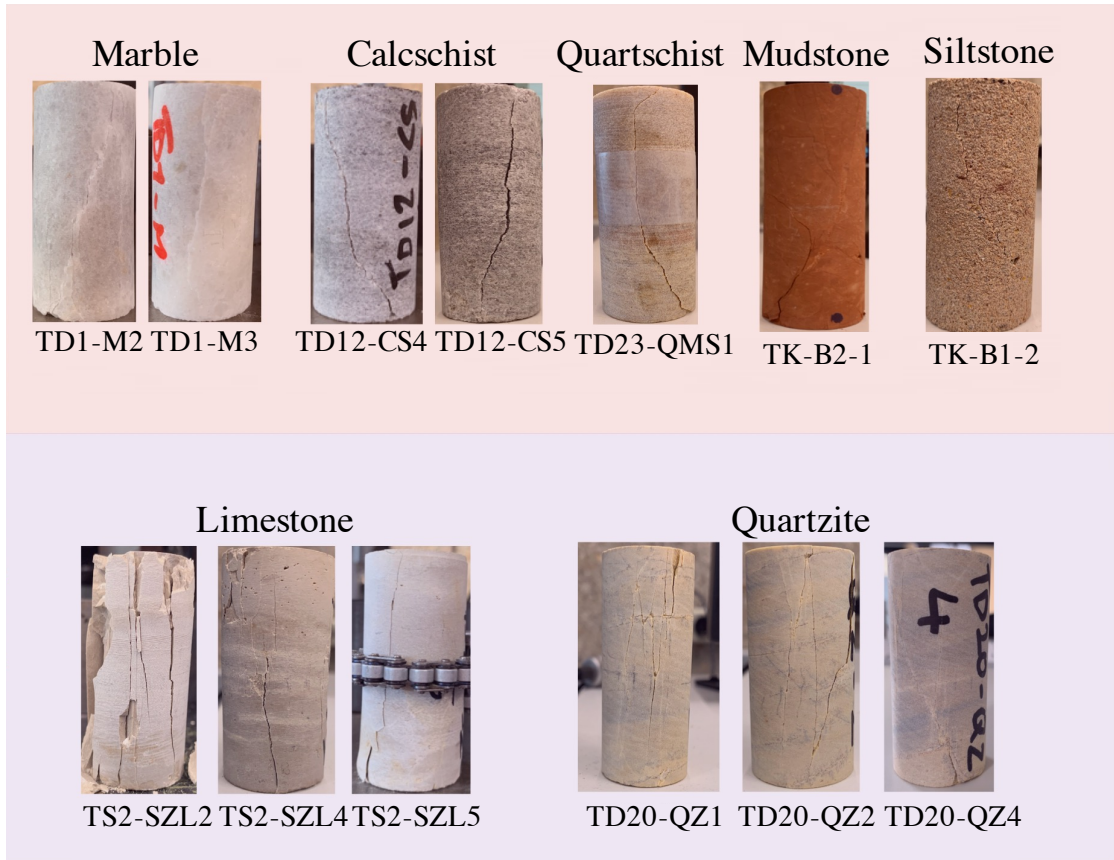**Figure 9**. Spatial distribution of all formations.

Figure 10. Core samples from Kızıldere field outcrop samples after triaxial testing for their acoustic velocities.

Table. Properties of the core samples used in the laboratory acoustic velocity measurements. Note that the axial stress (σ_1) was varied, reflecting the various depths in the reservoir, whereas the radial stress (σ_2) was kept constant.

| Rock Type	Length (mm)	Diameter (mm)	Porosity (%)	Matrix density (g/cm³)	Bulk density (g/cm³)	Axial stress - σ_1 (MPa)	Radial stress - σ_2 (MPa)
Calcschist	61.5 ± 0.1	29.8 ± 0.1	2.42 ± 0.03	2.75 ± 0.01	2.68 ± 0.02	17–40	17
Marble	62.5 ± 0.1	29.8 ± 0.1	2.15 ± 0.09	2.75 ± 0.01	2.69 ± 0.02	17–40	17
Limestone	60.8 ± 0.1	29.8 ± 0.1	10.48 ± 0.24	2.75 ± 0.01	2.47 ± 0.02	9–30	9
Quartzite	62.8 ± 0.1	29.8 ± 0.1	2.77 ± 0.16	2.89 ± 0.01	2.81 ± 0.02	33–70	33
Siltstone	62.7 ± 0.1	29.8 ± 0.1	22.55 ± 0.01	2.78 ± 0.01	2.15 ± 0.02	12–20	12
Quartzschist	62.5 ± 0.1	29.6 ± 0.1	1.71 ± 0.29	2.80 ± 0.01	2.76 ± 0.02	31–70	31
Mudstone	63.7 ± 0.1	29.7 ± 0.1	16.60 ± 0.15	2.82 ± 0.01	2.36 ± 0.02	12–17	12
Micaschist	41.0 ± 0.1	29.7 ± 0.1	8.52 ± 0.37	2.92 ± 0.01	2.67 ± 0.02	31–68	31
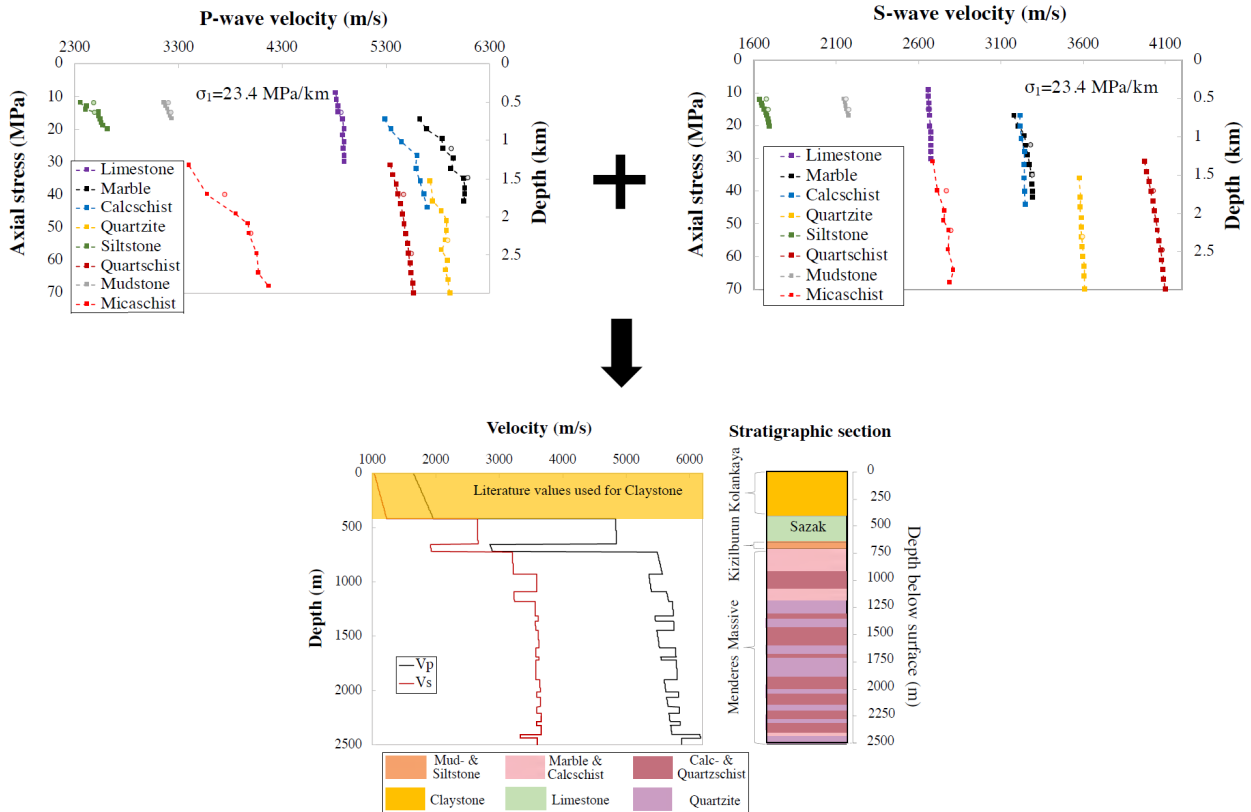
Figure 11. Top-left: P-wave velocity as a function of axial stress. Top-right: S-wave velocity as a function of increasing axial stress. Bottom: Seismic velocity profiles for the stratigraphic section shown on the right-hand side.

The preliminary evaluation of active seismic illumination and coverage aimed at providing information for the evaluation of acquisition layouts by surface source and DAS array in well R5A, simulating VSP data. The analysis focused on downhole measurements, which make it possible to characterise the seismic reflection response at depth, on the target horizon. Preliminary work considered 1000 m fiber optic cable in well R5A from the surface, and different surface source positions to investigate the illumination. As the first and very preliminary scenario to investigate geometry, two N-S and E-W crossing shot point lines, with SP every 100 m from –1.5 km and 1.5 km offset were simulated. Two circular shooting lines of radius 0.6 and 1.2 km with SPs every 10 degrees were also simulated. 3D ray tracing analysis was performed, and synthetic seismic propagation was calculated to simulate
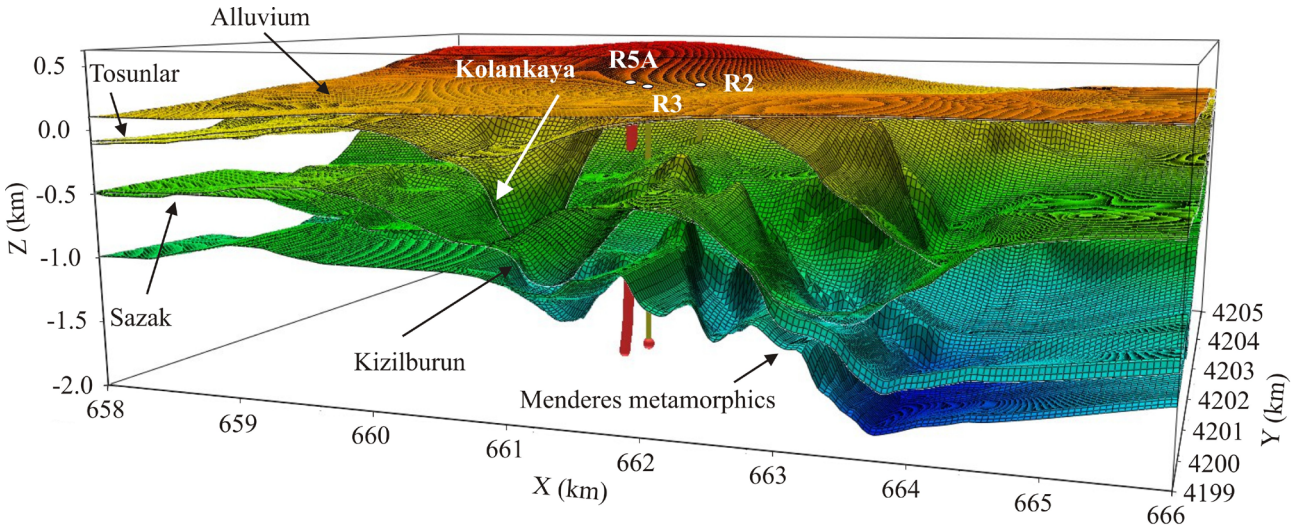
Figure 12. Kızıldere horizon model including wells and faults imported in OGS' Cat3D seismic tomography software. The target horizon used for subsequent illumination analysis is the Menderes Metamorphics.
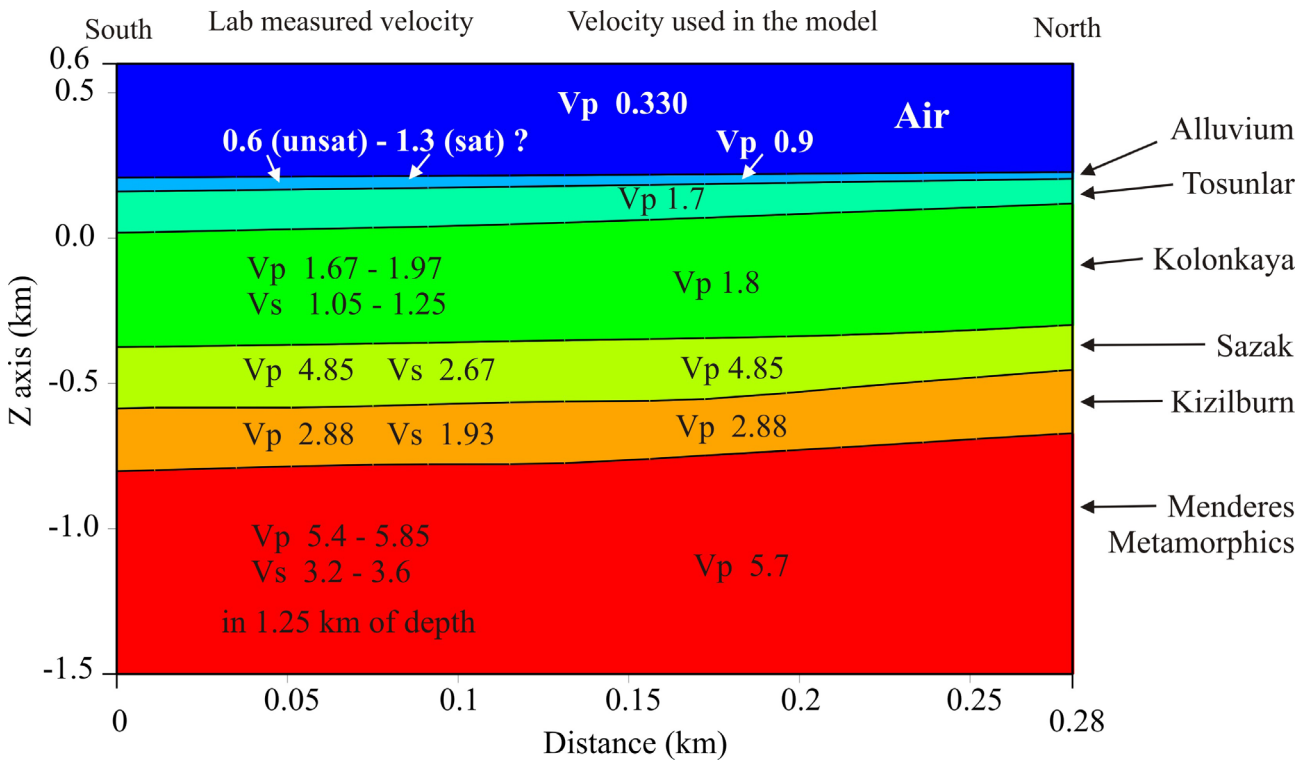
Figure 13. Kızıldere velocity model in the 2D section along the 2D HWC line.

VSP geometries. Figure 14 shows the ray tracing with the illumination on Menderes Metamorphics obtained by the North-South line. The layout scheme is shown in the small box at the top left of the figure. Two DAS VSP panels are calculated using the VSProwess software (VSProwess Ltd., 2017) with the DAS option every 5 m depth with the SPs at near and far offset, as shown at the bottom of the Figure. These results illustrate the differences in the signals recorded with the source at short (near) and large (far) offset because of the different sensitivity response of the DAS for the different arrivals. It is noted that the direct arrivals (say, down-going waves) are clearly observable in the near offset results, with reflection (say, up-going waves) from the layers.
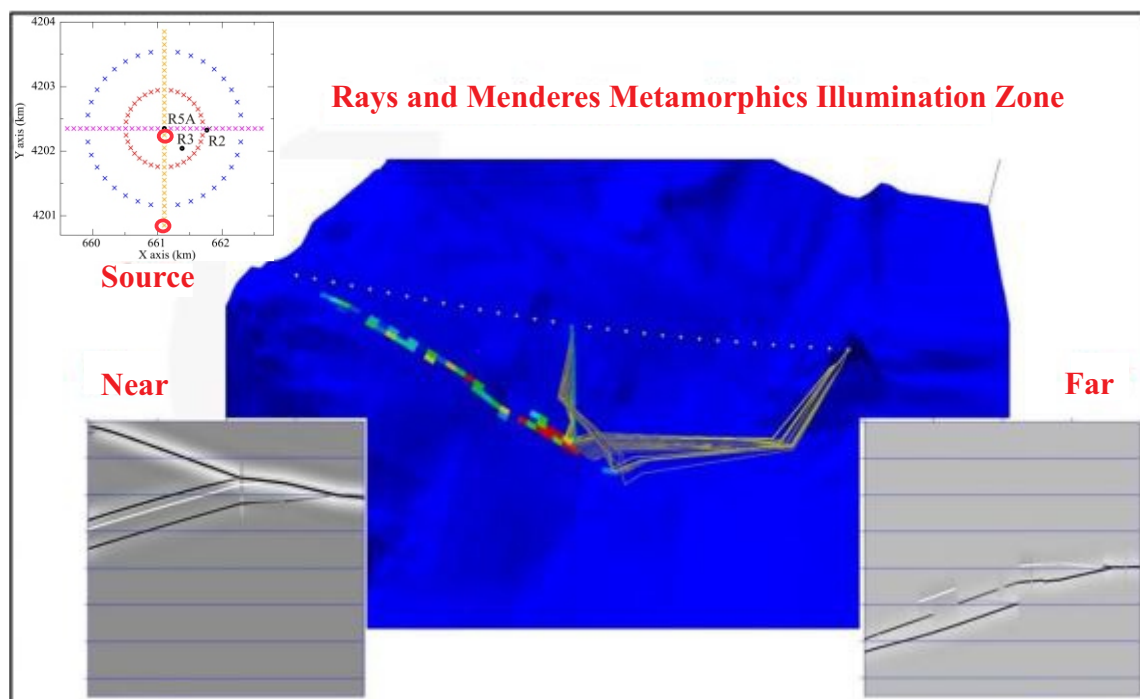
Figure 14. Reflections on Menderes Metamorphics by surface SPs along the North-South line. Due to the structural inclination, the illumination is up-dip. Synthetic signals of near and far offset VSPs relative to well R5A are calculated by code accounting for the DAS response.

In comparison, direct arrivals in the far-offset signal are not observable, as expected for the directional sensitivity response. Conversely, the reflections from the investigated horizon are clearly interpretable. In other words, these total wave fields may convey different (complementary) information, and a large offset can be used to illuminate the reservoir at depth.

On the other hand, Figure 14 shows one example only, and the interpretation of seismograms as a general rule must be cautious. In fact, significant variations in the direct and reflected signals obtained at different azimuths and medium-large offsets are observed. As a preliminary observation these changes are due to two main reasons: 1) the presence of faults, and 2) the strong contrast in the velocity at the caprock layer, between Sazak, Kızılburun and Menderes Metamorphics (*see* Figure 13), where a small change in the geometry can lead to total reflection (i.e. refraction) condition. Figure 15 summarises the results of illumination conditions at depth, mainly up-dip on Menderes Metamorphics in, where the reflection maps obtained with the crossing lines and circles are shown.

Field seismic survey designs for Kızıldere will be refined further after the confirmation of available source positions in the field by taking into account the logistic environmental-access conditions for the vibrator source. Other wavefields and responses from other target horizons can also be simulated in well R3 and below the surface DAS line. The design by continuous or sparse SP lines includes, last but not least, the planning of the resources in the framework of the project to obtain optimal illumination by multioffset DAS VSP. This analysis includes the active-seismic interferometry option to create virtual sources at depth.

4. Concluding remarks

In preparation for the field seismic surveys large number of rock samples were collected from outcrops around the Kızıldere geothermal field. These were cored and characterised for their acoustic velocities under simulated subsurface stress conditions in the laboratory. A 3D geological model of the Kızıldere pilot site was developed and, together with the laboratory determined acoustic velocities, the model was used in simulating synthetic seismic data for the first seismic survey design. The main objective of the seismic simulation work was to observe seismic response in the zone of interest, verify and design the Seismic Mechatronics source acquisition layout by analysis of illumination conditions at depth. The field survey design study used the selected observation well locations and the planned surface fibre optic cable layout at Kızıldere to optimise the source positions at surface. Field seismic survey designs for the pilot sites will be refined further once the source positions in the field are finalised, taking into account
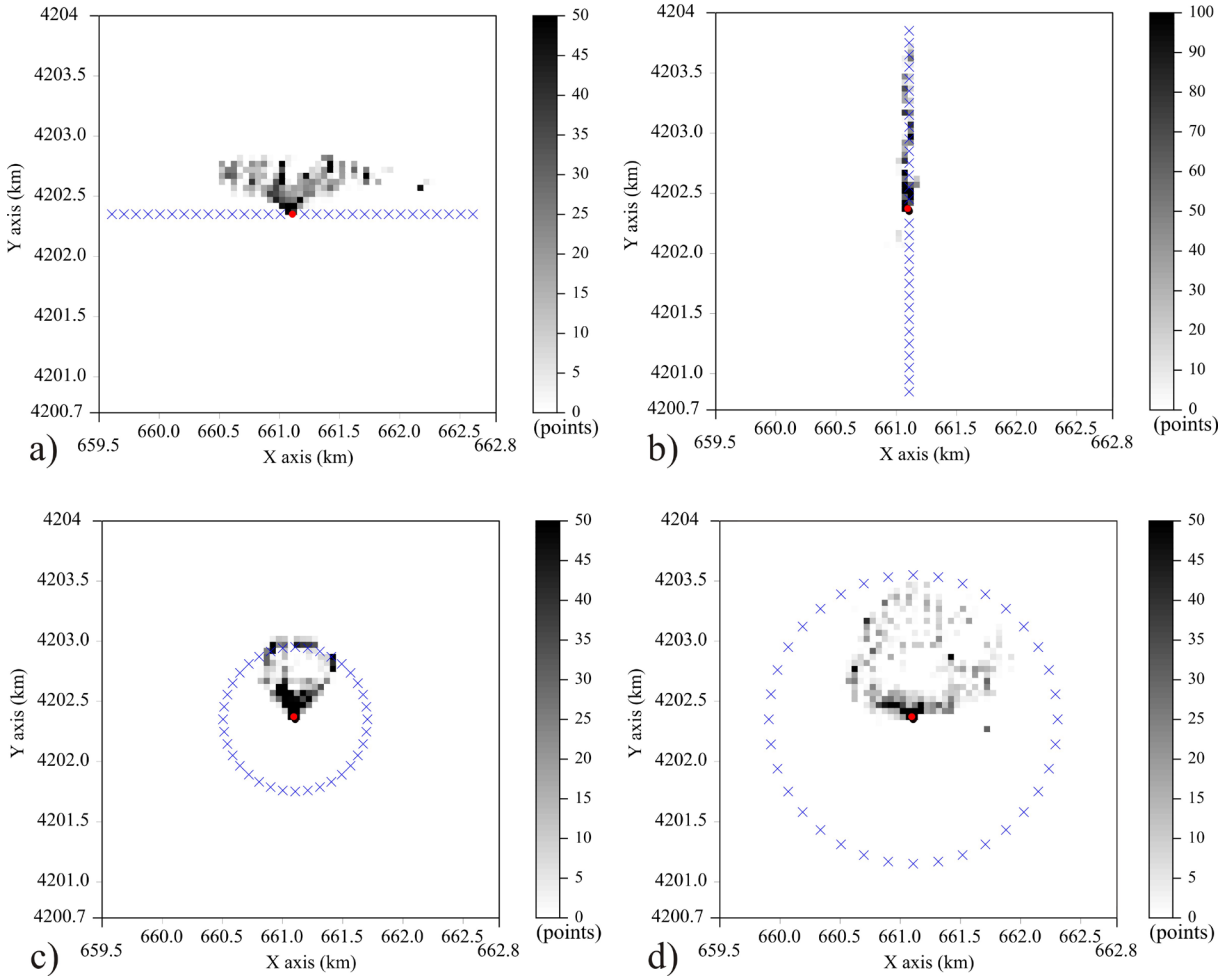
Figure 15. Summary of illumination conditions by a) E-W and b) N-S SP lines, and by the c) small (0.6 km) and d) large (1.2 km) circles of SPs at Kızıldere. The illumination trends are up-dip on Menderes Metamorphics.

the logistic environmental-access conditions for the vibrator source.

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