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# The Potential of Deep Geothermal Energy in Tyrol—Based on a Pre-feasibility Study

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**Abstract:** The economic use of deep geothermal energy is fundamentally controlled by the factors of rock permeability, temperature gradient, and depth. The carbonates of the Northern Limestone Alps are considered possible hydrothermal deep aquifers in Tyrol. This is the so-called main dolomite and Wetterstein limestone. For an initial assessment of the geothermal potential, information from the deep Kramsach Th1 borehole was used. With a temperature gradient of approx. 1.8 °C/100 m, which could be derived from the Kramsach Th1 borehole, temperatures of 65 °C at depths of approx. 3000 m and 100 °C at a depth of 5000 m occur in the Inn Valley expect. In addition, it is noted that further in the northwest of the Limestone Alps, at the deep boreholes Vorderriß 1 and Hindelang 1, higher temperature gradients of 2.2 °C/100 m and 2.6 °C/100 m were observed, respectively. Successful thermal water development at these depths requires that hydraulically well-permeable rocks are present. To clarify this question, extensive investigations of the reservoir rocks through exploration drilling are still required. Deep geothermal energy can lead to associated seismicity. In order to quickly detect associated seismicity and to be able to react in a timely manner, seismic monitoring is required during drilling activities and during operation of the systems, whereby the accompanying seismic monitoring must be able to distinguish between natural and induced seismicity.

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**Das Potenzial von Tiefengeothermie in Tirol – basierend auf einer Vor-Machbarkeitsstudie**

**Zusammenfassung:** Die wirtschaftliche Nutzung von tiefengeothermischer Energie wird grundsätzlich von den Faktoren Durchlässigkeit der Gesteine, Temperaturgradient und Tiefe gesteuert. Als mögliche hydrothermale Tiefengrundwasserleiter werden in Tirol die Karbonate der Nördlichen Kalkalpen betrachtet. Hierbei handelt es sich um den sogenannten Hauptdolomit und Wettersteinkalk. Für eine erste Abschätzung des geothermischen Potentials wurden Informationen aus der tiefliegenden Bohrung Kramsach Th1 herangezogen. Bei einem Temperaturgradienten von ca. 1,8 °C/100 m, der aus der Bohrung Kramsach Th1 abgeleitet werden konnte, sind im Inntal in Tiefen von ca. 3000 m Temperaturen von 65 °C bzw. 100 °C in 5000 m Tiefe zu erwarten. Ergänzend wird dazu festgehalten, dass weiter im Nordwesten der Kalkalpen, an den Tiefbohrungen Vorderriß 1 und Hindelang 1, höhere Temperaturgradienten von 2,2 °C/100 m bzw. 2,6 °C/100 m beobachtet wurden. Eine erfolgreiche Thermalwassererschließung in diesen Tiefen setzt voraus, dass hydraulisch gut durchlässige Gesteine vorhanden sind. Zur Klärung dieser Frage bedarf es noch umfangreicher Untersuchungen der Reservoirgesteine durch Explorationsbohrungen. Tiefe Geothermie kann zu assoziierter Seismizität führen. Um assoziierte Seismizität rasch zu erkennen und in Folge rechtzeitig reagieren zu können, ist ein seismisches Monitoring während der Bohrtätigkeiten sowie im Betrieb der Anlagen erforderlich, wobei das begleitende seismische Monitoring natürliche und induzierte Seismizität unterscheiden können muss.

  

**Schlüsselwörter:** Seismik, Seismische Verarbeitung, Geologische Interpretation, Geothermie, Geologische Modellierung

## 1. Introduction

The aim of the study discussed here was to create an initial overview of existing data and explorations, to carry out an evaluation of these, and to carry out an interpretation regarding the potential of deep geothermal energy in Tyrol. In the field of deep geothermal energy, a distinction is made between hydrothermal and petrothermal systems as well as open and closed systems. Figure 1 gives an overview of the different systems.

In petrothermal open systems "Engineered Geothermal Systems" (EGS), heat exchange takes place on the basis of hydraulic stimulation (hydraulic fracturing). For this purpose, an injection well (>3000 m) is drilled into the hot rock and one or more production wells are sunk. The existing fissure systems are widened by injecting water. There is a seismic risk when the fissure systems are widened by injecting water. Similar to this is the hot dry rock process, which aims at high-temperature applications with temperatures of more than 150–200 °C and depths of more than 3000 m. The target horizon is usually the crystalline basement. The fissures are partly open, filled with highly mineralized water and connected to each other by a network of fissures, so that water circulation is basically possible. The crystalline basement behaves like an aquifer with very low permeability. After a borehole has been sunk, the naturally existing fissure system is widened or new fissures are created by injecting water. The natural permeability is increased and additional and better waterways are created; the river in the mountains is, so to speak, "stimulated". In order to consistently achieve the necessary flow rates and temperatures, the crack system must have a minimum size for the heat exchange surface. The stimulated area must be penetrated with the second hole. Through this "heat exchanger" and "instantaneous water heater," surface water is sent via injection and production wells to absorb the mountain heat. In this system, water is the heat carrier and the mountains are the heat source. In hydrothermal use (doublet), water is pumped from deep groundwater aquifers; The heat is removed via a heat exchanger. The cooled water could, in principle, be discharged when mineralization is low. In most cases, however, the cooled water has to be injected into the same aquifer at a certain distance from the extraction well for renewal or for disposal reasons. Such a system consists of a production well and an injection well (double). In principle, a combination of several production and injection wells is possible. Aquifers that have high permeability are suitable for this type of use. The crucial parameter, in addition to the temperature of the aquifer, is the yield, i.e. the delivery rate to be achieved with a temperature reduction that is still economically and technically acceptable. Deep geothermal probes are vertical, closed heat exchangers installed in boreholes more than 400 m deep. In a deep geothermal probe, a heat transfer medium circulates in a closed system, currently up to depths of approx. 3000 m. Heat is transferred to the fluid circulating in the probe through heat conduction from the rock via the piping and backfill material of the probe. In the annular space of a double pipe system (coaxial pipe), the cold fluid is guided downwards in a quantity-controlled manner. As it moves slowly, it heats up convectively and rises heated up in the insulated inner tube. From the probe outlet, the warm fluid reaches the above-ground utilization system, where the heat is exchanged and it is returned to the annular space using a probe circuit pump. The removal of heat causes the surrounding rock to cool down. A horizontal temperature gradient is created, which results in the flow of heat from the wider environment. Deep geothermal probes do not rely on well-drained aquifers and can therefore theoretically be installed almost anywhere. Since deep geothermal probes have a closed circuit, there is no interference with the material balance of the mountain.

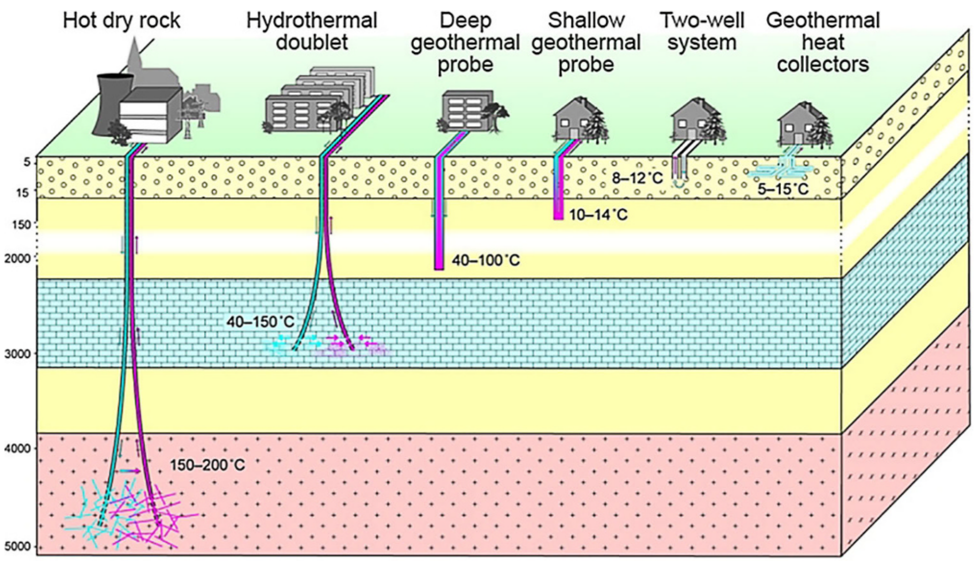


**Fig. 1:** Overview of geothermal systems (LFU Bavaria)

  

## 2. Petrophysics

As part of laboratory tests, at least the parameters of thermal conductivity in W/mK, the grain density in g/cm$^3$, the effective porosity, the compression wave velocity $v_p$ in m/s, and the uniaxial compressive strength in MPa must be measured. These laboratory test results help to understand the rocks better and are essential for subsequent geophysical data evaluations and modeling. Compared to samples from the Vienna Basin, the same geological formation, the measured values for the rocks from Tyrol were in the same range.

## 3. Seismic

In order to be able to geologically describe and subsequently model the calcareous alpine subsurface beneath the Inn valley, 13 existing seismic data were reprocessed. From these 13 seismic profiles, nine seismic profiles could be completely reprocessed based on raw seismic data. For the remaining four seismic profiles, only paper sections exist. Therefore, the existing stack results were scanned, digitized, and improved by a so-called post-stack processing.

### 3.1 Reprocessing

Essentially, the following processing steps were carried out during the seismic reprocessing: Reading and editing of raw seismic data; reconstruction of coordinates based on analog position plans; definition of geometry; amplitude correction (spherical divergence correction); static correction to the "processing datum" ("NMO datum"); single-channel and/or multichannel spike deconvolution; velocity analysis; dynamic correction (NMO) and "stretch mute"; residual static correction; amplitude correction (AGC); stacking and correction to the seismic reference level; bandpass filtering; coherence filter; weighted trace mixing; time migration.

Post-stack processing was performed on four seismic profiles, where the coherence of the seismic signal and the signal-to-noise ratio could be increased by applying FX deconvolution and a time-varying bandpass filter.

### 3.2 Drilling Information and Interpretation of Seismic Profiles

The well Kramsach Th1 is the only well to reach the calcareous rocks and was drilled in 1999 as a thermal water well to a final depth of 1645 m. It encountered artesian thermal water in carbonate rocks with a temperature of about 40 °C at a depth of about 1640 m. Two of the profiles described above are part of the Transalp seismic research project [1]. All existing seismic profiles were used for geological interpretation in the time domain. Only the Transalp profile was depth converted (Fig. 2).

Although the seismic profiles, with the exception of the Transalp seismic, were acquired and dimensioned for Quaternary and Oligocene (Inntal Molasse) sediments, regional geological elements (lithostratigraphic horizons and geological faults) could be interpreted in almost all seismic profiles. As an example, the interpretation of a 40 km section (Fig. 1) of the Transalp profile in the Inn Valley is presented.

### 3.3 Time-depth Conversion Transalpine Profile

The interpretation of the reflection seismic profiles was done in the time domain (vertically, the two-way travel time is plotted in milliseconds). A simplified three-dimensional velocity model was created for the Transalp profile to convert the seismic and interpretation results to the depth domain and model (Fig. 3). Because there are no sufficiently deep wells in the area of the Transalp profile, it was not possible to calibrate the time-depth relationship. The seismic velocities were derived from the boreholes Hindelang 1, Vorderriß 1, and Kramsach Th1 as well as petrophysical investigations on outcrop analogies.

## 4. Geologic Model

### 4.1 Geologic Units and Their Evolution

The rocks in the studied area (Fig. 4) have a complex deformation history starting after the Variscan orogeny in the late Paleozoic and extending into the late Miocene. All geological units belong to the Austroalpine Nappe System [2]. South of the Inn valley, a crystalline basement is found. Its uppermost unit, the Greywacke Zone, is overlain by Permian to Oligocene sediments, which are part of the Tyrolic-Noric nappe system [3] and are assigned to the Staufen-Höllengebirgs cover of the Northern Calcareous Alps (NCA) [4]. North of the Inn Valley lie the Tannheim and Karwendel nappes of the NCA [5].

The tectono-sedimentary evolution of the Northern Calcareous Alps passed through different stages (Fig. 5): Permian and Triassic rocks were deposited at the passive continental margin of the Tethys Ocean, reaching thicknesses of up to 6 km [e.g. [6]]. Carbonate platforms of the Middle and Upper Triassic (Wetterstein limestone/dolomite and Hauptdolomit) make up the thickest part of the sedimentary sequence. With the onset of the Jurassic, the breakup of Pangaea during the opening of the Penninic Ocean separated the Adriatic plate and thus the Eastern Alpine depositional area from its European hinterland [7]. The subsidence of the passive margin results in the sedimentation of deep-water limestones, marls and radiolarites [8]. In the Early Cretaceous, mountain building started within the Adriatic Plate [2, 9, 10]. The overthrusts reached the present-day external part of the orogen at the boundary from the Lower to the Upper Cretaceous. There, the Permo-Mesozoic sediments of the NCA were sheared from their basement and the latter was subducted [5, 11, 12]. Subduction marks the beginning of folding of the stacked nappes that accompanied the transport of the Austroalpine Orogenic Wedge across the subducting Penninic Ocean [5, 13]. In the Late Eocene, the European continental margin reached the subduction zone, and the European continent collided with the Adriatic continent [2]. The Alpine foreland basin is formed, which extends onto the Alpine wedge with the Intraalpine Molasse [14]. Due to the crustal thickening of the orogen and continued postcollisional northward thrusting of the rigid Dolomite block into the Alpine nappe stack, combined with a decrease in crustal thickness towards the Pannonian Basin, the eastward lateral escape of the orogen (lateral extrusion) occurs during the Oligocene-Miocene [15]. The Inntal shear zone east of Innsbruck formed during lateral extrusion pre-determined the present-day Inn Valley (Fig. 4, Studied area). This fault has about 40 km of left-lateral offset, and is anastomosing [16]. The fault branches dissect the previously deformed rocks.

### 4.2 Reservoir Properties of the Rock Sequence

Reservoirs are rock bodies that have suitable extension and rock properties to store liquids or gases. These are mainly the two carbonate platforms of the Middle and Upper Triassic (Wetterstein and Hauptdolomit platforms). The Alpine Muschelkalk often adjoins these at the base (Fig. 5, Tekt Sed). The superimposed platforms thus result in a reservoir with a cumulative thickness of 3000–4000 m. The remaining rocks, often rich in mudstones, marlstones or evaporites, and the mostly phyllitic basement, are not suitable as reservoirs. They rather play the role of sealing potential reservoir rocks.

## 5. Geothermal Potential

In order to be able to make statements on the geothermal potential despite the limited data available, a hydrogeological-geothermal model was created. This combines existing data on parameters, such as soil temperature, groundwater recharge, rock water level, hydraulic conductivity, thermal conductivity, and temperature conditions in the subsurface.

An important factor for the geothermal potential is the expected temperature of deep groundwater bodies. Indications for the rise of deep circulating thermal waters that would indicate a positive temperature anomaly in the region, as is the case e.g. in the Styrian Basin, could not be observed so far [18, 19]. Rather, it is evident from deep boreholes and tunnel projects that the geothermal gradient in the region is 1.8 to 2.4 °C/100 m, and thus significantly below the average gradient of 2.8 °C/100 m assumed for Austria. The heat flux with 50–60 mW/m$^2$ is also below the Austrian average [21]. Groundwater recharge is significantly higher in the area north of the Inn Valley, in the Northern Calcareous Alps, than in the Inn Valley and south of it in the Greywacke Zone and the Innsbruck Quartzphyllite units [20]. This increased groundwater recharge, combined with the increased hydraulic conductivity of the Northern Calcareous Alps [22], indicates a groundwater circulation system moving from north to south. The water table was determined on the basis of natural springs and serves as a hydraulic boundary condition for the model. Thermal conductivities range between 2 and 5.3 W/mK [23, 24] and were assigned based on the generalized lithological composition of the rock units. The 2D numerical model was created using FeflowTM software and is geometrically based on the results of the reinterpretation of the Transalp seismic profile performed as part of this project.

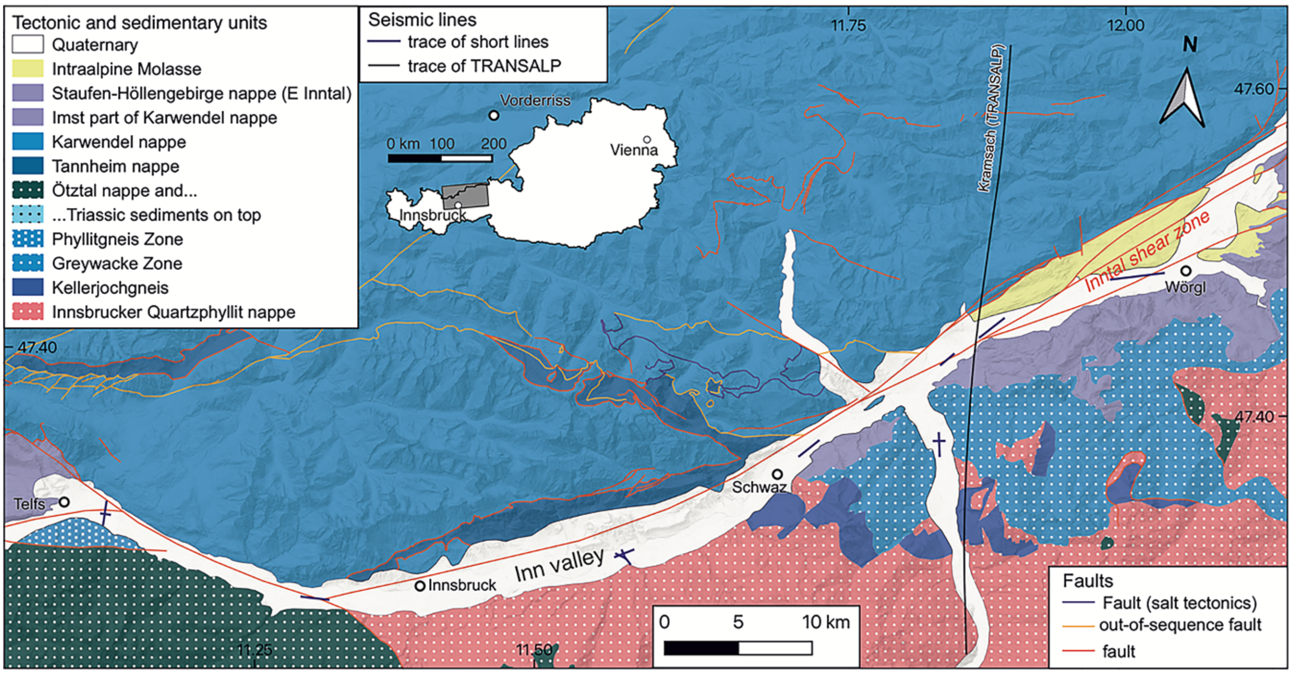


**Fig. 4:** Studied area; Tectonic map of the Inn valley in the studied area [adapted from 5]. Positions of seismic lines used in this study are indicated

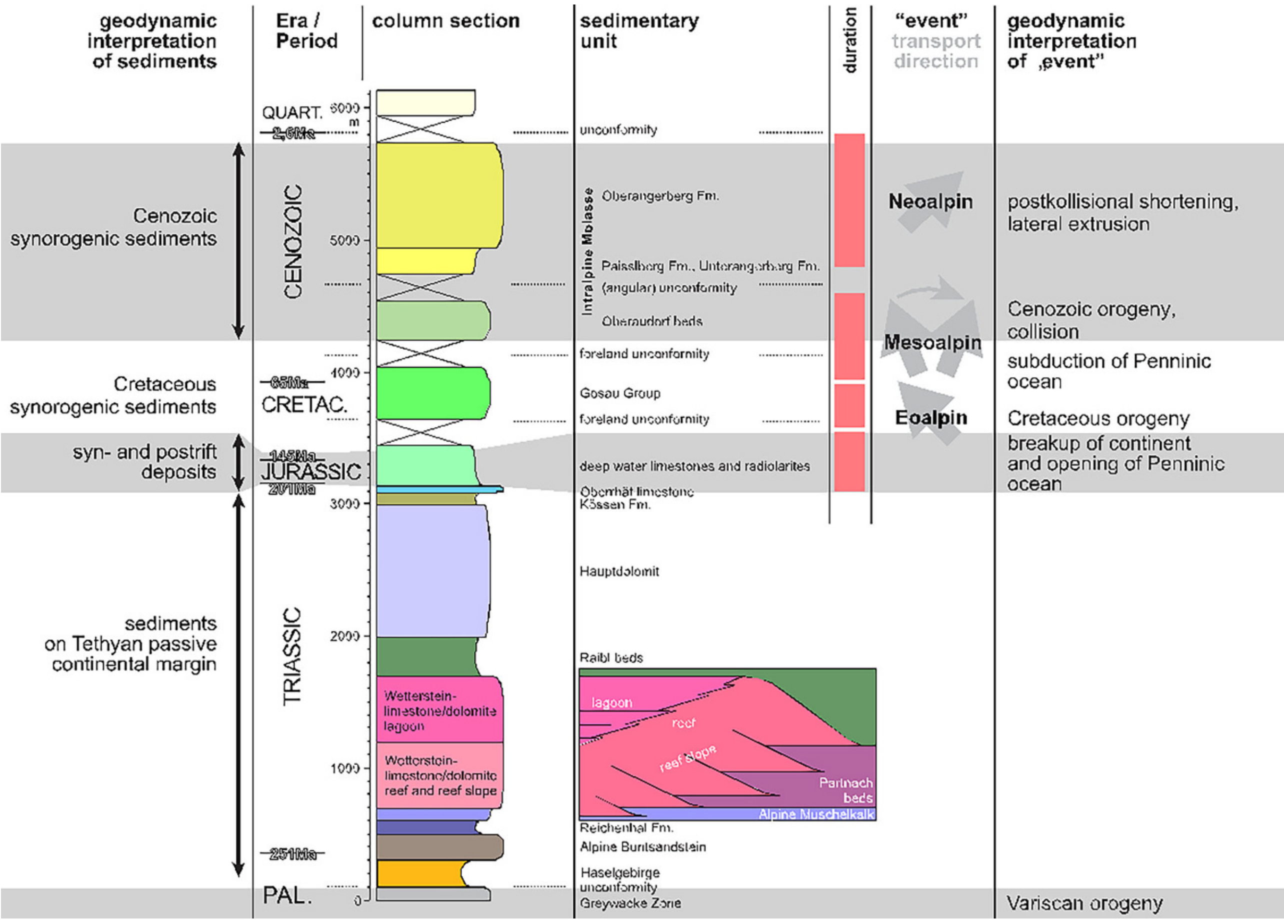


Fig. 5: Tekt Sed; Tectonosedimentary evolution of the Eastern Alps based on a columnar profile of the Northern Calcareous Alps and the geodynamic interpretation of sediments and events. The nomenclature of the units is based on the Austrian stratigraphic table [17]

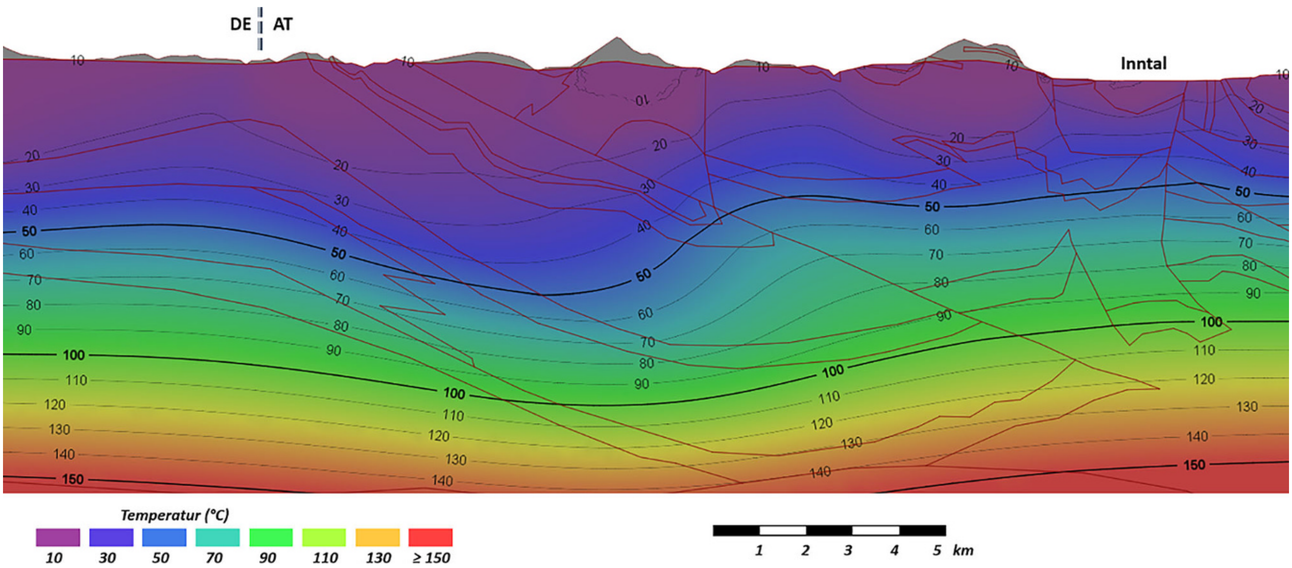


Fig. 6: Result from the numerical 2D model of the Transalp Cross-Section: temperature and isolines in the Inn Valley and north of it

With the help of numerical modelling, the results regarding temperature and age of the thermal water of the Kramsach TH1 well could be adequately reproduced. Likewise, a forecast for the temperature of the potential target horizons was determined. According to this forecast, the 100 °C isotherm is located in the area of the Inn Valley at a depth of about 5 km (see Fig. 6), the Alpine muschelkalk or a deep block of the Wetterstein limestone are potential target reservoirs there. The modelled temperatures can in general be regarded as rather conservative.

## 6. Seismicity and Stress State

The use of deep geothermal energy can lead to associated seismicity, induced and triggered. However, a careful site selection and adaptations in the planning process can reduce the risk. For this purpose, existing data such as the Austrian Earthquake Catalogue (AEC) of GeoSphere Austria were evaluated, and the location accuracy, magnitude detection, and perception thresholds were modelled. The resulting data give insight into which areas would be particularly susceptible to induced seismicity and which areas require further investigation. Tyrol has been repeatedly affected by earthquakes in the past (in 1572, 1670, 1689) and today around 14 quakes are felt in Tyrol every year. The AEC contains 8400 tectonic earthquakes located in the project area, at least 530 of these were felt by the population and 28 caused documented damage to buildings (above intensity V–VI). In accordance with ÖNORM EN 1998-1 [25] large sections of the area along the Inn valley are in the two highest seismic hazard zones 3 and 4. In the development of deep geothermal energy projects, it is important to ensure that seismic monitoring is capable of differentiating between natural and induced seismicity especially in areas with seismic activity and shallow earthquakes. The evaluation of the location accuracy uses the data from tectonic earthquakes after 2010 and additionally synthetic earthquakes simulated on a grid of 1 km with the software NonLinLoc [26]. The result is shown in Fig. 7. The location quality between Innsbruck and Hall is very high with with a depth error margin of less than 2 km, while the detection threshold is around a magnitude of 1.0. East of Hall the network needs to be densified to allow more reliable conclusions and to exclude the possibility of shallow seismicity. Shallow earthquakes are particularly relevant for deep geothermal energy, as they indicate seismically active faults that could be reactivated by changes to subsurface conditions, such as pressure and temperature. Between Innsbruck and Hall and further south some earthquakes were localised to very shallow depths of less than 5 km. The majority of the earthquakes have hypocentres at depths between 5 and 10 km and further east, between Hall and Schwaz, most earthquakes occur at depths over 10 km. Earthquake focal mechanisms describe the fault orientation and slip. They are relevant to deep geothermal energy as they reflect the local stress field and can provide information about fractures and water pathways. For the project area, 79 focal plane solutions are available [27, 28] Between the Stubaital and Innsbruck, the dominant mechanism is strike-slip, while, along the Inn valley, reverse faults are more prominent. Ideally, seismicity caused by geothermal energy is imperceptible at the surface. Therefore, the minimum detection threshold for monitoring during the production stage needs to be clearly under the perceptibility threshold to know if taking action is necessary. Figure 8 shows the location of all felt earthquakes since 2015 and the number of reports. According to this study, only one event below magnitude 1.0 was reported while 60% of recorded earthquakes over magnitude 2.0 were felt. As geothermically induced earthquakes occur shallower at injection depth, the perceptibility threshold will be lower. Depending on hypocentre depth, slight building damage is possible for earthquakes of magnitude 3.5 upwards.

## 7. Geomechanics

### 7.1 Stress Directions

The regional stress directions in western Austria are broadly north-south [29] associated with the Alpine orogeny (collision of the Adriatic microplate with the Eurasion plate). Based on focal mechanisms and structural indicators, the stress directions in the Inntal vary along the length of the valley and there is no indication that stress directions change significantly with depth [31].

### 7.2 Implications

#### 7.2.1 Drilling

The drilling of vertical and deviated wells requires an understanding of the in-situ stress orientations for optimal drilling directions to ensure wellbore stability. In the areas with thrust faulting conditions (eastern part of the Unterinntal), the most stable drilling direction will be deviated in parallel to the compressional direction (e.g. NNW-SSE). In contrast, in the areas with normal faulting conditions (western part of the Unterinntal), the most stable drilling direction will be deviated in parallel to the extensional direction (e.g. NW-SE). In the areas south of Innsbruck, where strike-slip conditions dominate, any well deviation direction will be most stable, whereas the vertical direction will be least stable. In summary, if the target rock masses are in the Northern Calcareous Alps, then drilling generally NW to NNW from the Unterinntal should align with the most favourable stability conditions for deviated wells.

#### 7.2.2 Fault Reactivation

Based on the presence of active seismicity in the area of the Inn Valley [31], critically stressed faults are likely to exist. The area around and the Inn Valley east of Innsbruck exhibits a comparable high seismicity. Hypocentral depths range between 2 and 15 km, with a maximum between 5 and 10 km [30]. This could be favourable for identifying fractured zones with high permeability and natural feed zones with the potential for large volumes of water.

  

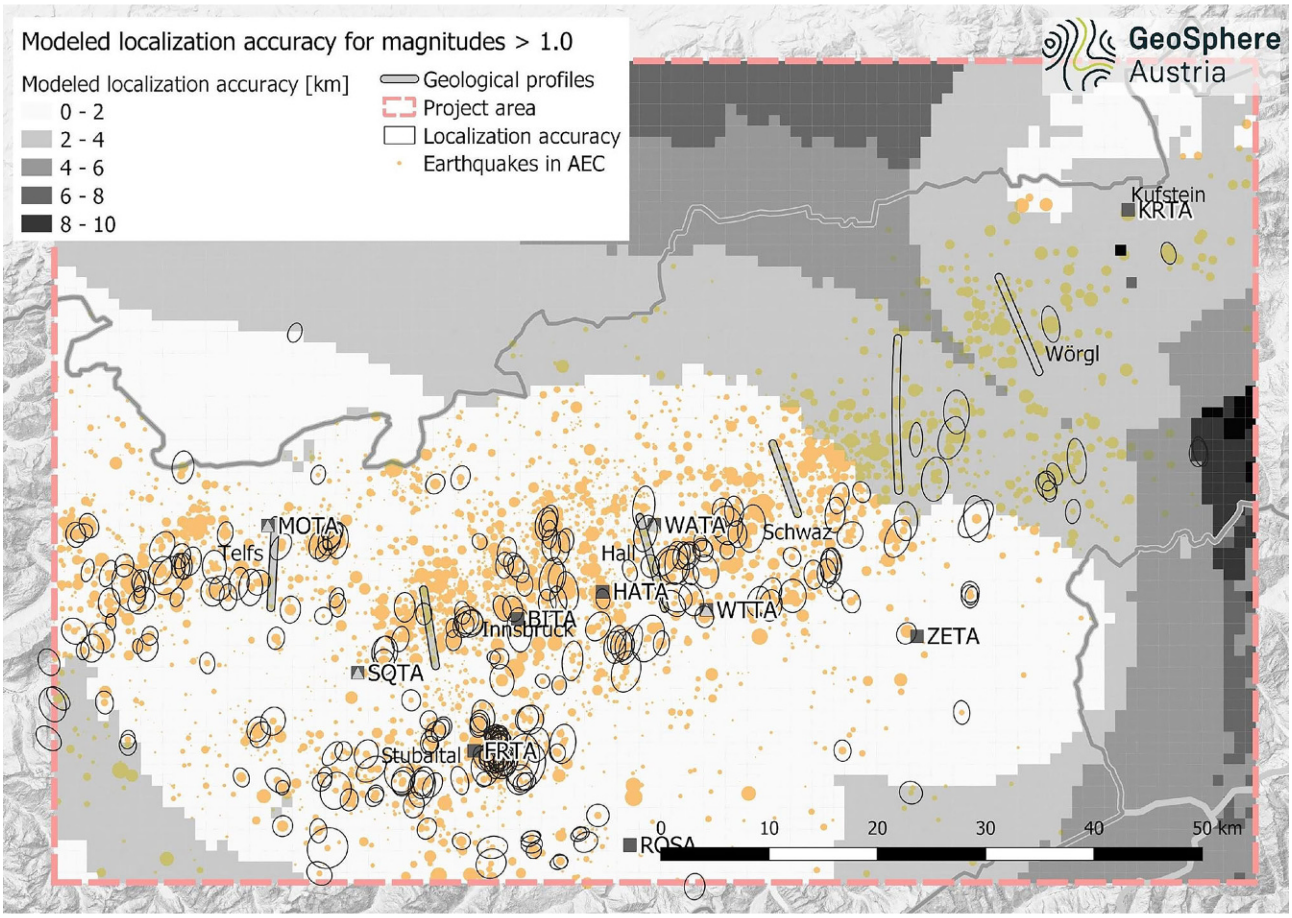


Fig. 7: Modelled localization accuracy in the project area for magnitudes > 1.0 with a 1 km grid in comparison to localization accuracy from AEC data

Conversely, this could be unfavourable by posing a risk of wellbore damage or induced seismicity arising from even minor changes in the pore pressure during fluid extraction and injection [32].

## 8. Summary and Outlook

With the help of existing seismic data in the Inn Valley, as well as geological outcrops at the northern and southern Inn Valley margins, six geological conceptual models were generated across the Inn Valley (oriented approximately north-south). In particular, the seismic profile TRANSALP in Kramsach was reprocessed to a section of 40 km length for this project, which is overlaid with a possible drilling proposal in Fig. 9. The positioning of this drilling proposal and the intended drilling target resulted from:

- The certainty of the prognosis, which is significantly higher north of the Inn Valley,
- The distribution of possible reservoir rocks,
- The optimal drilling direction to ensure borehole stability,
- The modeled water circulation

At this point it is explicitly pointed out that this drilling proposal is only one exemplary proposal of many. It is recommended to obtain large core sections at least in the potential reservoir horizons in order to ensure a correct lithological description and to be able to determine geomechanical rock parameters from the obtained cores. Furthermore, an extensive geophysical in-situ and ex-situ measurement program and temperature measurements in the borehole are recommended. In case thermal water is found, the water should be sampled and analyzed for hydrochemical risks, corrosivity, and precipitation.

Further geophysical surveys are required for the planning of exploration wells for potential areas of interest outside of Kramsach. New seismic profiles should be positioned fundamentally transverse (approx. northwest-southeast orientation) to the Inn Valley and have a minimum ground surface exposure length of 6 km. Longer exposures, with up to 20 km, are preferred. Only with such a large length can a reliable interpretation be made about the calcareous alpine subsurface or its southward boundary at depths of up to 5000 m. In order to significantly increase the informative value of two-dimensional seismic profiles, several (at least two to three seismic profiles) intersecting profiles per area of interest are strongly recommended. Only in this way can the complex three-

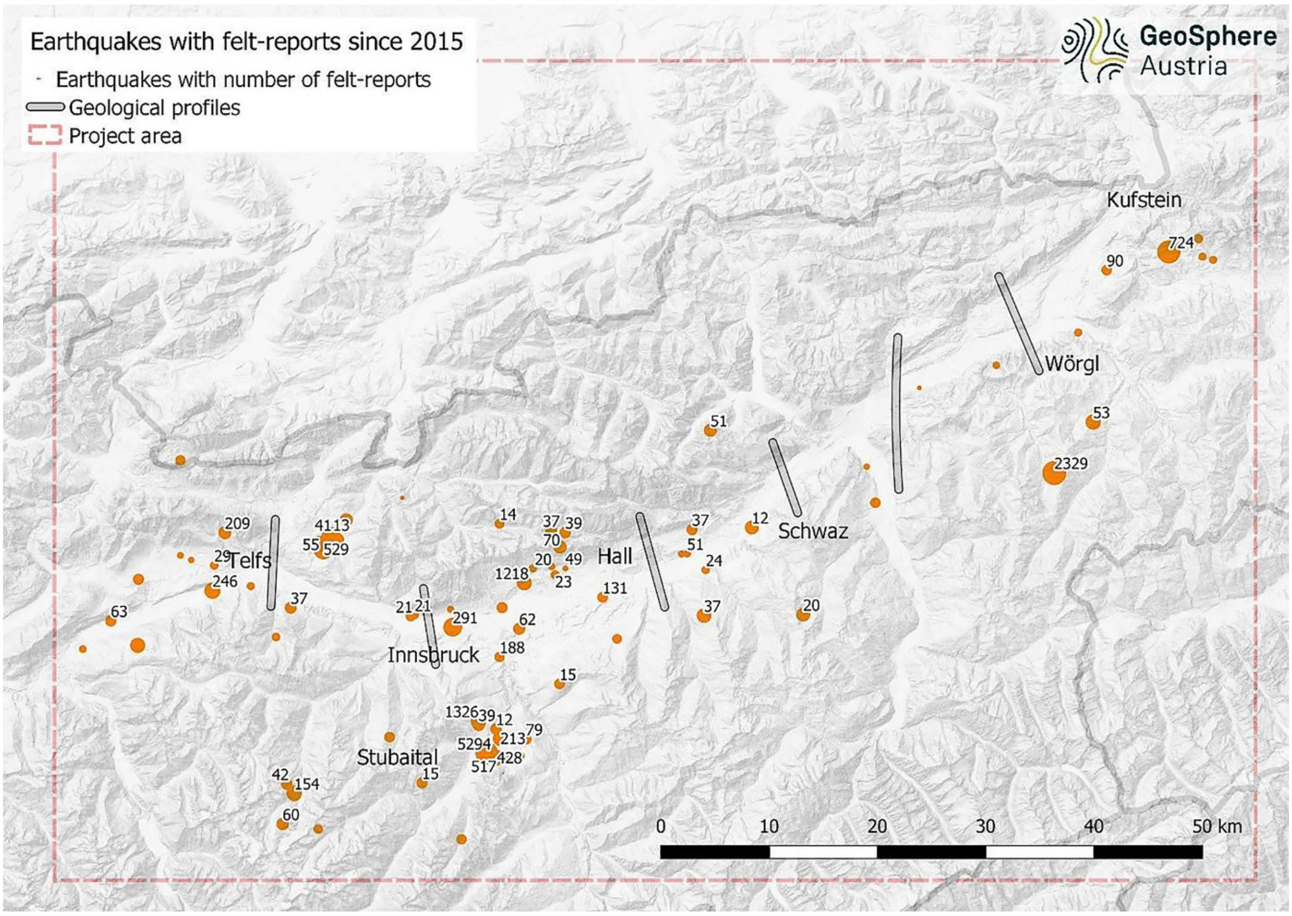


Fig. 8: Earthquakes and number of macroseismic (felt) reports from the population since 2015 in the project area

dimensional subsurface structure beneath the "young" Inn Valley fill be adequately visualized.

The acquisition of three-dimensional data (3D seismic), which is internationally common practice for planning production and reinjection wells in order to minimize the geological risk of discovery, is recommended after drilling an exploration well to prove the presence of carbonate reservoir rocks at a geothermally relevant depth (hydrothermal aquifer).

Drillings of any design—less expensive exploration wells or more costly production wells—should be planned and drilled exclusively "directly" on modern seismic data (2D or 3D) corresponding to the target depth in order to minimize geological risk.

The analysis of the project area with regard to known seismicity shows that, according to ÖNORM EN 1998-1, the seismic hazard for the area between Innsbruck and Hall is in zone 4 and thus in the zone with the highest risk of earthquakes in Austria. Induced seismicity exists almost everywhere in the Inn Valley. The main sources are mining and tunnelling. The localization quality between Innsbruck and Hall is very high and the detection limit low. The much larger station distances east of Hall lead to lower localization quality and higher detection limits. Here, the measurement network should be compacted as far in advance as possible in order to be able to make qualitative statements about the natural seismicity. When planning deep geothermal projects, care must be taken to ensure that the accompanying seismic monitoring can distinguish between natural and induced seismicity.

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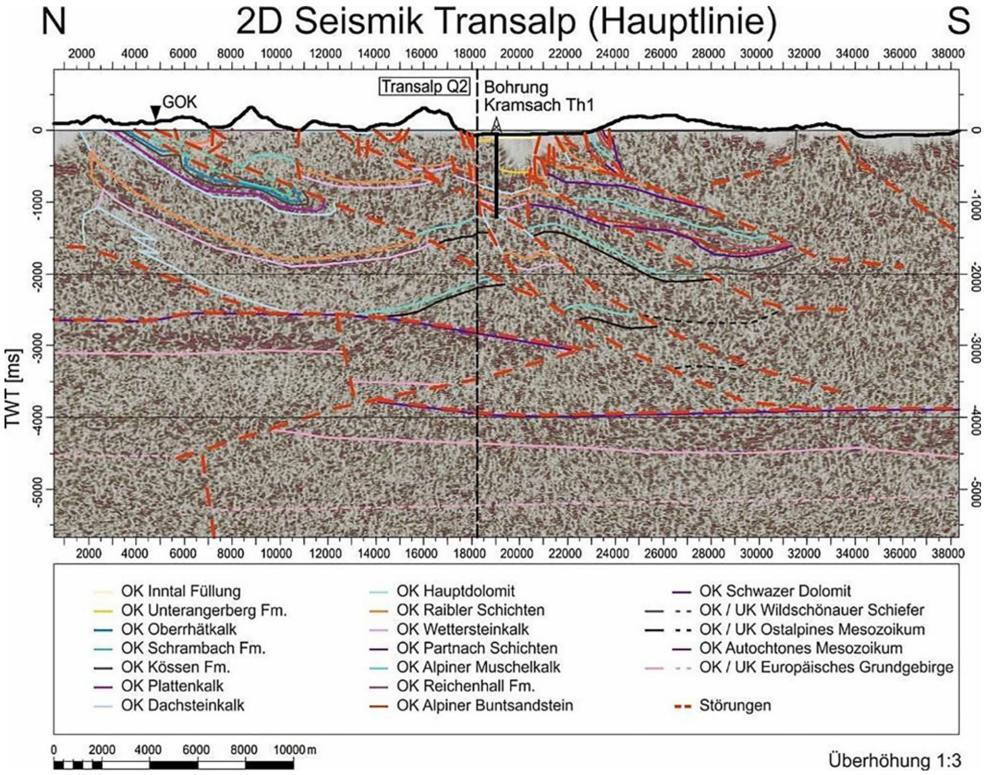


**Fig. 2:** Reprocessing of the 2D seismic "Transalp (*main line*)" in the time domain with geological horizons: The *black dashed line* indicates the intersection with the Transalp cross section. The well path of the Kramsach Th1 well (1000 m projected) is shown in *black* and a depth of 1645 m was reached. The ground elevation is also shown in *bold black line*. The *red dashed lines* are the interpreted thrust faults

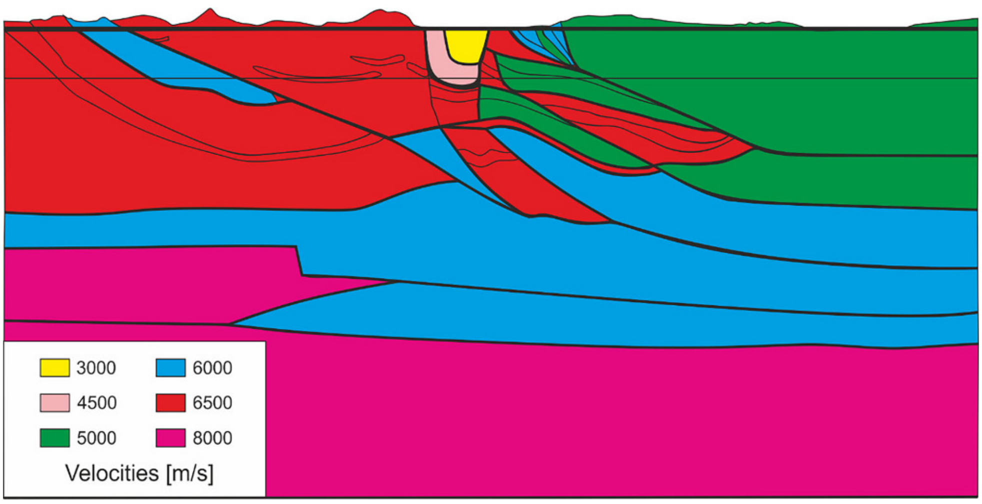


**Fig. 3:** Final velocity model for the Transalp profile. The shallow formations with velocities of 6000 m/s were modeled together with the surrounding rocks with 6500 m/s

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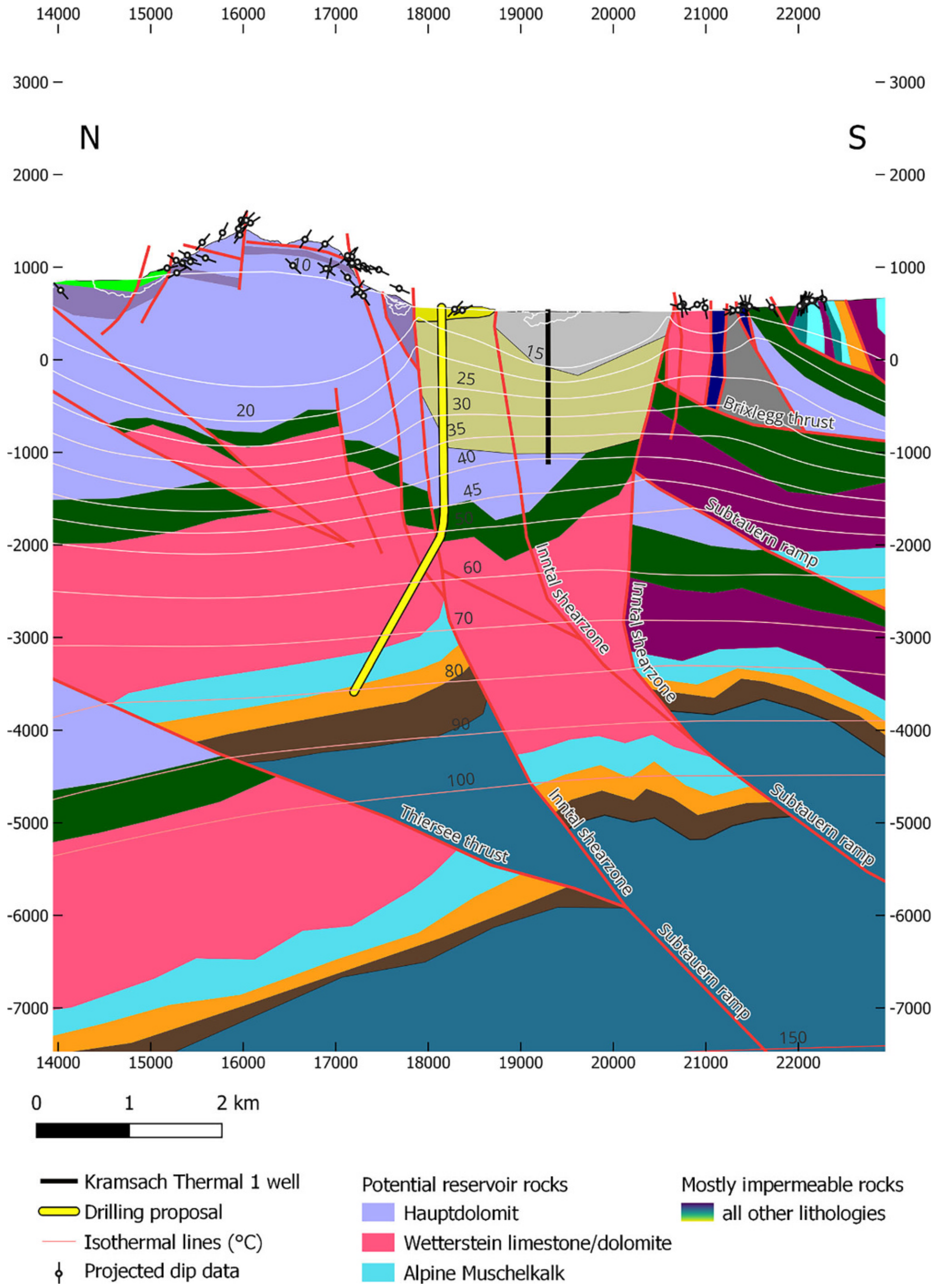


**Fig. 9:** North-south cross-section of the Transalp/Kramsach profile with drilling proposal (*yellow*) and existing Kramsach Thermal 1 well, which has reached the main dolomite. In addition, the isothermal lines of the hydrological modeling are superimposed on the profile


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