A European endeavour for optimizing Zonal Isolation, Drilling and Exploitation of EGS projects

WELLTEC – ZONAL ISOLATION

WORK PACKAGE 2.2 2.3 AND 3.3

Authors: Welltec Completions

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1. Introduction to Welltec's work packages

Welltec's contribution to ZoDrEx has been to enhance its zonal isolation equipment for high enthalpy usage in EGS. EGS holds the ability to provide non-metrological dependent renewable energy at over 90 percent capacity factor. However, development of EGS is expensive in part due to the long development periods and geological uncertainties associated with geothermal energy in general. The full potential of EGS can only be achieved if wells can be divided into multiple zones that allows for access to larger heat exchange surfaces, thus making the wells more effective. To achieve this zonal isolation is required to support both zonal isolation during stimulation to allow for effective propagation and help reduce the effects of shadow stress. But also, to isolate different sections of the well, while eliminating the effects of undesirable sections of the wells from the desirable sections.

Due to formation pressures, weaknesses around the borehole and sometimes drilling mishaps, many geothermal wells struggle with breakout and ovalization of the borehole, which can compromise the potential of well and lead to vast additional costs. To mitigate this Welltec's contribution is the development and testing of a high expansion External Casing Packer (ECP) and flow control to provide zonal isolation and control for EGS capable of managing geothermal conditions for use in crystalline formations, based on its metal expandable packer technology.

To demonstrate viable zonal isolation and the potential of using all metal multistage lower completion in EGS, Welltec will demonstrate it's potential in the Bedretto rock laboratory in collaboration with international consortium partners to support the development of a multistage geothermal systems in granite in order to facilitate the future development of EGS projects.

2. Analysis of existing hardware capability

The Welltec Annular Barrier (WAB) builds on metal expandable packer (MEP) technology. MEPs are used worldwide in oil and gas to improve well integrity in both cased and holes. The MEP provides enhanced integrity to wells by allowing for a close-off metal-to-metal sealing of annuli when relining or in irregular boreholes.

The WAB is basically a metal membrane with seals, which is mounted onto a liner; and once deployed, it is hydraulicly expanded, causing it to plastically deform and create an effective annular seal in minutes. The WAB design allows for low expansion pressure with high differential pressure capabilities. Depending on need the expansion system can be configured to isolate the expansion port, maintaining the collapse and burst ratings of the casing. The integrated compensation system allows for the WAB to be compensated to the annulus above or below, so that no pressure may collapse it when applied to the sleeve. As the WAB is non retrievable it becomes part of the well construction and has historically been used for zonal isolation and cement assurance application, or as a standalone barrier replacing cement within the reservoir.

The robust nature of the WAB enables it seal in both open or closed hole, with or without cement, and provide anchoring capability. With its robust design the WAB is as such ideal for geothermal application.

However, to enhance the WAB for EGS application we identified that they key to updating the WAB for EGS application would be material selection both to manage high temperatures and corrosive fluids, including sulfide(H2S) and CO_2, but also to ensure the longevity of the well.

As the objective was also to improve the expansion ratio of the WAB to improve the management of borehole deformation, it was also evident that we would also have to develop a new seal design unlike the pre-existing design.

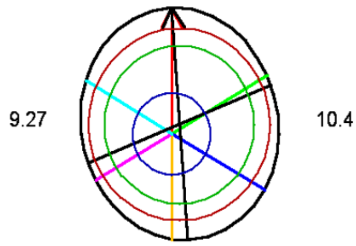
For the WFV material selection is also of importance, but the key to optimizing the flow valve was to ensure that it can manage a sufficient mass flow as is required in geothermal application.

3. Enhancement of Welltec Annular Barrier and Flow Valve

To ensure the quality of our product line it was a prerequisite that both the WAB and WFV be designed for ISO 14310 qualification.

3.1 Enhancement of Welltec Annular Barrier for High Expansion

Initially three new and very different high expansion packer designs were modelled and simulated to find the design best for managing ovalization and breakout. The target was to develop an 8 ½ ECP for EGS capable of managing high breakout boreholes capable of managing minimum temperatures of 200°degree Celsius with a 30-year lifespan, allowing it to be used in wells for both heating and power generation application. Making it ideal for EGS deployment in European crystalline formations, but also with the ability to function in the mid-temperature range hydrothermal systems elsewhere in the world.



Fehler! Verweisquelle konnte nicht gefunden werden.: An example of a borehole diameter profile from a calipher log of an 8.5” borehole where the effects of ovalization has caused the borehole to deform to 9.27¨ by 10.4¨ inches. The new ECP will make it possible to seal deformed bore holes of this size.

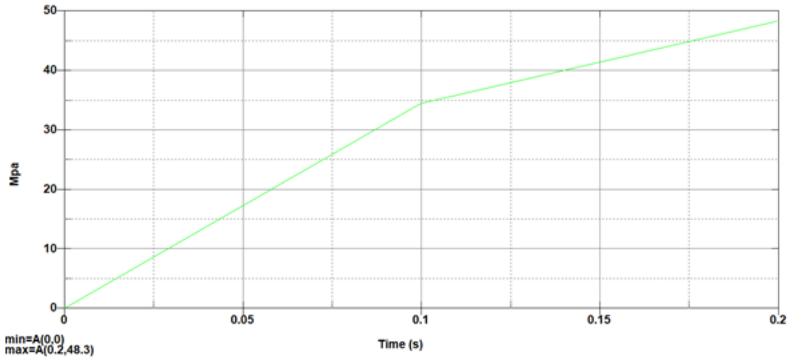
Welltec’s MEP technology is a permanent, non-retrievable packer which is mounted onto the liner and hydraulicly expanded through the casing, causing the packer elements to plasticly deform into either the open bore hole or casing, sealing of the annulus. Because of the robustness, it also supplies anchoring power, allowing it to function in a variety of ways when it comes to providing zonal isolation.

Based on the MEP technology, a new sleeve design developed to improve setting in a crystalline setting and making breakout. To ensure it could also manage long term high temperature geothermal fluids, it was combined with an ultralow carbon, nickel alloy cable of managing both high temperatures and hydrogen sulfide(H2S), as often seen in hydrothermal systems. As importantly it was selected to withstand repeat thermal stress, as associated with geothermal workovers over life span, where wells are cooled to allow for maintenance work.

To ensure the best possible standard the packer had to be qualified to ISO 14310 V6 (V3 leak criteria), to ensure optimal sealing conditions for life of well. To ensure this standard, the design, and as a result the expansion ratio was limited to the maximum stress that the material around the minimal properties of its construction.

Based on its history of working with it, Welltec has high confidence in expansion using FEA modelling with years of fine tuning the mechanical material models with experimentation and testing. The design expansion limit was evaluated as the maximum stresses that the materials can support based on the minimum material properties of the packer's design.

LS-Dyna was used to simulate expansion in two steps, first at expansion pressure increase from 0 to 5KPSI at .1 seconds, then expansion from 5 to 7Kpsi at .2 seconds.



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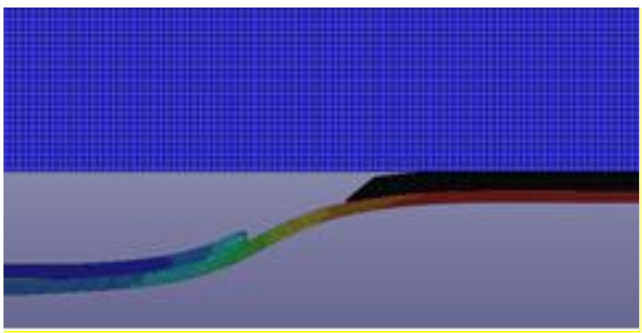
Ultimately limiting the expansion ratio of the packer design materials maximum acceptable stress. This was based on extensive laboratory testing performed with the material with UTM values above 800 Mpa.



Fehler! Verweisquelle konnte nicht gefunden werden.3: FEA screenshot of contouring of effective plastic strain of the new packer design.

The model assembled for test was a full scale 8 1/2¨ model with an expansion ratio up to 27 percent. A smaller version that would have allowed for a greater expansion rate was also modelled but not manufactured, as smaller diameters are not commonly used in geothermal systems.

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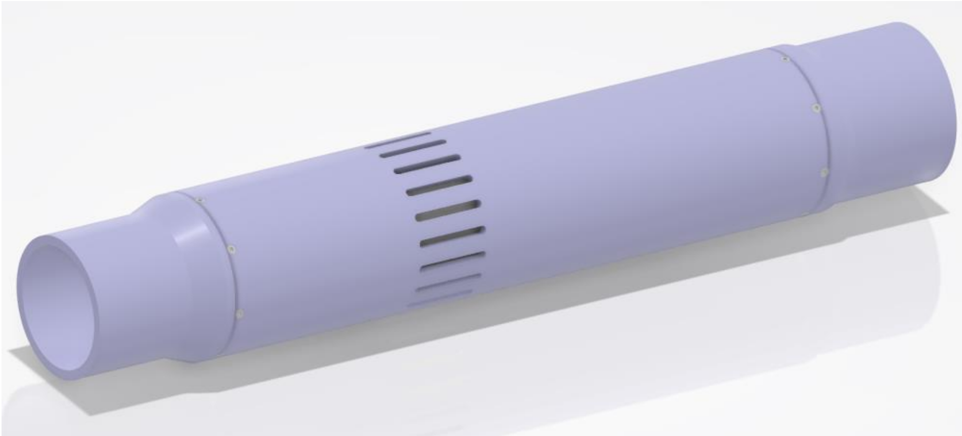
Despite, the improved expansion ratio, it was concluded that to ensure a robust high temperature design with minimal leakage to ensure zonal isolation at the required qualification standard, packers should be set in less affected areas, above or below, to ensure an efficient seal to isolate that section of the borehole from the rest of the borehole. As some examples of breakout studied (see example below) were so extreme that that the material could be expected to handle the elongation let alone sealing the borehole's annulus.

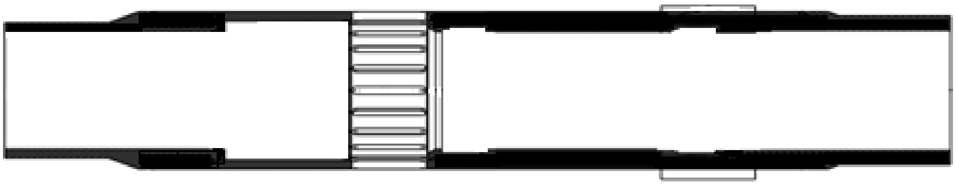
3.2 Enhancement of Welltec Flow Valve

The work included the development of a 7" flow valve to function as both inflow and as stimulation gate. Historically valves have not been used in geothermal wells, as the instalment of valves was though to reduce and restrict the flow of fluids to the well. However, valves provide a means for taking control of the formation, while providing a fixed access point to the formation that can be stimulated directly and closed off if the zone should prove to have a negative effect on the rest of the well, be it a lose zone or if there is any sign of stress clusters that is threating to short-circuit the heat exchange surface system.



Fehler! Verweisquelle konnte nicht gefunden werden.5: A 3D model rendering of the 1250mm long flow valve with a diameter of 208 mm (8.19¨) with closed ports.

For the demonstration and test a valve with a 110 percent capacity flow was used, although this could be increased, either by number of number or size or ports. Adjustments to the designs were made to the open/close mechanism to suit geothermal, primarily it was a question of adjusting the alloy managing hydrogen sulfide (H_2S) conditions rather than temperature. A successful test of the mechanism was carried out to ensure it could be manipulated prior to deployment.



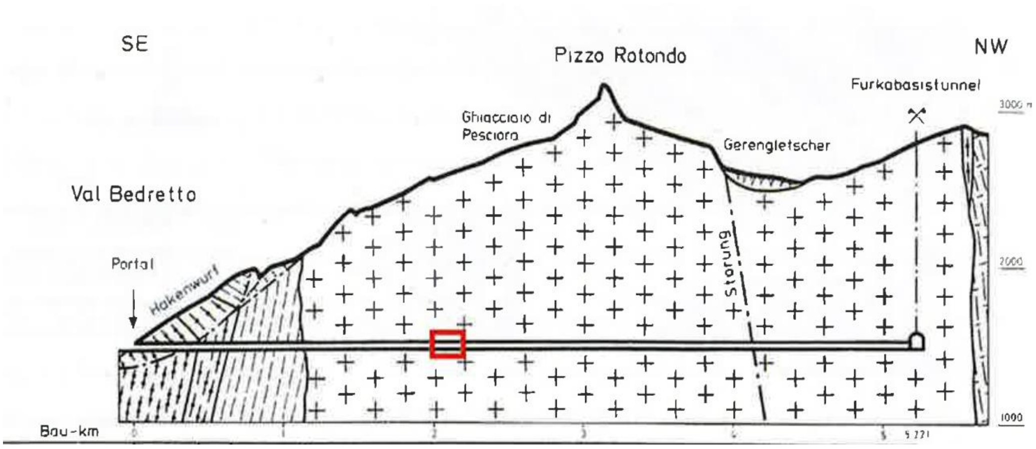
Fehler! Verweisquelle konnte nicht gefunden werden.6: Schematic of the 8.19¨ flow valve with ports open to be mounted on a 7¨ liner for full bore access for both injection and production.

With the flow valve designed to withstand upwards of 300° Celsius and the high expansion packer being able to manage 260° Celsius, the two should easily be able to be implemented in multistage EGS systems, with the packer also being able to function as a standalone to assist line hangers or function as cement assurance/replacement.

Material selection was done on a generic geothermal basis, as ultimately each formations and fluids will have unique properties, that will threaten the life span of any equipment installed in it. However, the selected material should outlive the K55 and L80 liners that have commonly been used in geothermal systems.

4. Testing of zonal isolation in Bedretto

The Bedretto rock laboratory or Bedretto Underground Laboratory for Geoenergies (BULG) is an abandoned train service tunnel, drilled in 1982, that has been repurposed into a rock laboratory by Eidgenössische Technische Hochschule Zürich (ETH Zurich), to study various aspects of rock mechanics, hydrology, and drilling technologies. The estimated stress components of the rock laboratory is he vertical stress of Sv = 26.5 MPa, the maximum horizontal stress of SH max = 0.8 − 1 × Sv oriented approximately along N100E, the minimum horizontal stress of Shmi n = 13 − 16 MPa[1]



Fehler! Verweisquelle konnte nicht gefunden werden.7: A cross-section of the Bedretto RockLab or gallery where the testing took place is a little over 2000 meters inside the mountain and has approximately 1100 to 1200 metres of mountain above it (overburden9.

An 8½” (220mm) borehole horizontal borehole with a 6°degree decline was drilled to a total depth of 120 meters in the spring of 2021, but a video log run in June showed that the borehole was blocked at 99 meters. According to ETH Rock laboratory team this was likely because the borehole had prematurely intercepted a section of the formation affected by another wise well documented fault line in the formation informally known as the “bad boy”. Already when drilled a water flow of 2.5 l/m was detected coming from the borehole, which kept flowing throughout installation and testing.

[1] David, Christian; Nejati, Morteza; Geremia, Davide (2020) On petrophysical and geomechanical properties of Bedretto Granite - Research Collection (ethz.ch) Retrieved: 15/11/2021

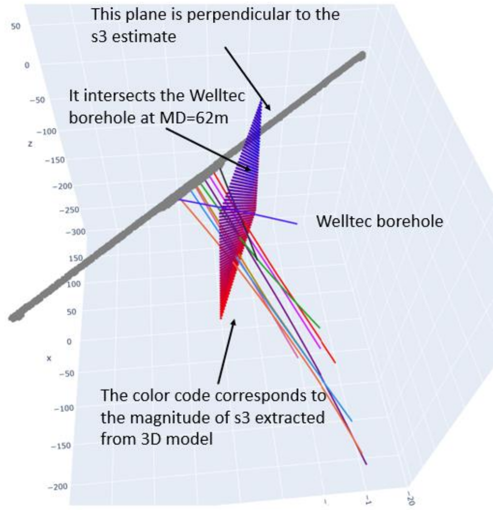
Fehler! Verweisquelle konnte nicht gefunden werden.8*: A screenshot from a camera of the originally 120-meter-long test borehole blocked at 99 meters.*

Nevertheless, it was decided to proceed with what remained and a caliper log was later run in the well and based on the readings the two sections in the wells with the most competent borehole characteristics were selected, centralizing the zones at 62 and 76 meters.

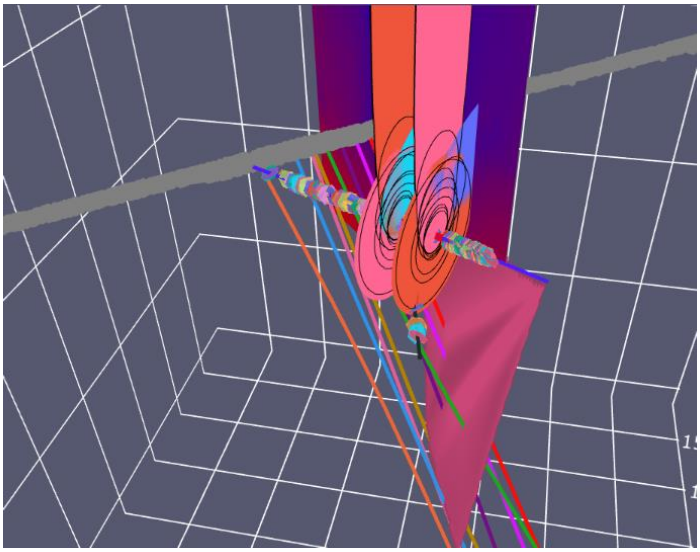
Fehler! Verweisquelle konnte nicht gefunden werden.9*: Part of the 8 ½" hammer-drilled borehole where the most upper packer was set at 60 meters.*

With the assistance of Geo Energie Suisse and ETH Zurich, an injection protocol was developed based on the known properties of the formation stress values to test the completion system. These properties include vertical and horizontal stress overburden in the formation to determine suitable pressure, flow rates and shut-in periods to test the completion system.

![ZoDrEx]

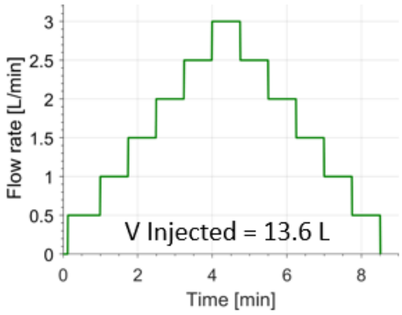


Fehler! Verweisquelle konnte nicht gefunden werden.10: A 3D oblique stress gradient model prepared by Geo Energie Suisse, showing the Welltec borehole (the short blue one) with neighbouring wells below. The colour code that intersects Welltec borehole shows the stress plane at 62 meters which is where the upper zone would later be installed.



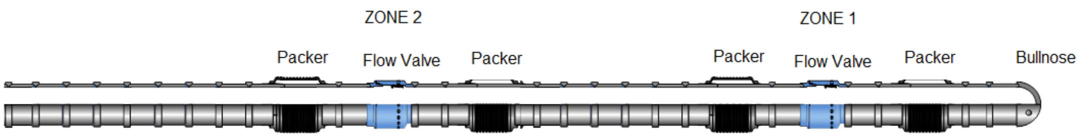
Fehler! Verweisquelle konnte nicht gefunden werden.11: This 3D model as prepared by Geo Energie Suisse shows the same as the previous model, but it also shows part of the fault line known as the “bad boy”, in the form of the pink plane, which all the neighbouring wells intersects below. Additionally, it shows the expected vertical hydro migration stress patterns by the planned zones at both the 62and 76 meters zones. The stress plane from the tunnel which would later effect the tests can be seen in the background.

The stimulation protocol developed by ETH dictated a constant 1-1.5 l/m injection flow rate, after which a clear pressure peak should be visible and a allow for fracturs to propagate until a constant pressure was observed. After which shut-in periods should abided by. From here repetition of cycles with increasing injection flow rate would be carried out. Lage stimulation cycles of maximum 35 MPa were also planned with shut-in periods between cycles.



Fehler! Verweisquelle konnte nicht gefunden werden.2: The step-rate protocol with step up and stepdown protocol as prepared by ETH Zurich

Prior to drilling the borehole, it was decided that given the low temperatures and pressures of the Bedretto laboratory, a different packer and different material should be used for the flow valve in the same 8 1/2¨ size as the new designs would use to save on high temperature material costs. Before shipping the equipment to Bedretto, the 125 cm long flow valve and 250 cm long packer were mounted on 7¨ 32ppf VAM TOP 2- and 3-meter pup-joints and a detailed tally was prepared detailing the exact setting depths of the packers and flow valves.



Fehler! Verweisquelle konnte nicht gefunden werden.: Bedretto test well completion schematic with zone 2 (upper) at 61.25m to 63.98m and zone 1 (lower) at 75.03m to 77.76m. The upper was set at 59 meters.

In August 2021, the completion system consisting of the four ECP's and two flow valves were deployed. Prior to deployment the packers were mounted on 7¨ pup-joints. In the Bedretto the toe pup-joint, fitted with a bullnose was slowly pushed into the nearly horizontal borehole, after which the next piece of pup-joint was torqued up, one at a time till the whole system with packers and valves were pushed into place.

Fehler! Verweisquelle konnte nicht gefunden werden.: A picture from Bedretto, where a flow valve, already connected to a packer, temporally wrapped in blue packaging is about to be connected to a 7¨ pup-joint with a packer already partially in the well.

Fehler! Verweisquelle konnte nicht gefunden werden.: Flow valve (black, left) and packer (right) installation in Bedretto (August 2021)

Once fully in place in place, the casing was hydraulicly pressurized in steps. The system was slowly pressurized in steps of 500 psi with 3-5 minutes between steps, allowing all four packers to slowly plastically deform into the borehole, thereby sealing off the annulus. Once fully expanded the expansion pressure was perfectly held for 10 minutes before pressure was bleed off. Throughout the installation and expansion, the well kept producing water at 2.5 l/m, indicating the inflow came from above the upper packer installed 59 meters.

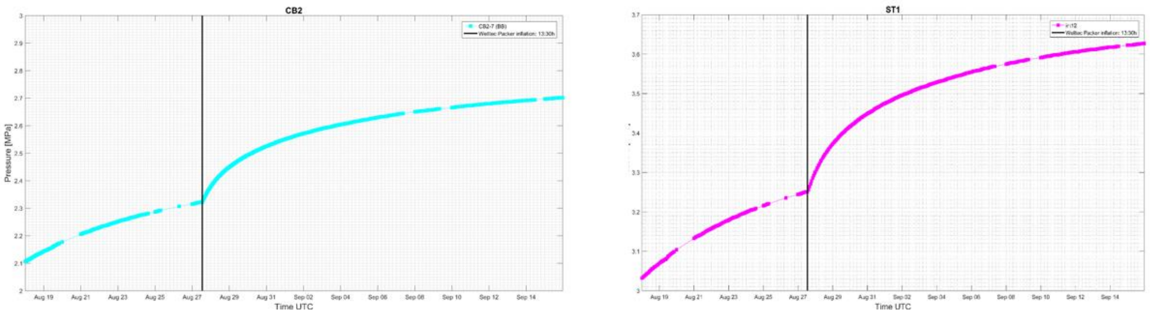
5. Conclusions

As explained above the new high expansion ECP design, had to go on compromise with the expansion rate to ensure that it could live up to qualification standards. Although based on the same MEP technology as other Welltec packers the result was a much different looking packer, as the seals were changed, but with the same robustness made in a ultralow carbon, nickel alloy and with a 260° Celsius temperature capability and a 5.000psi Delta P, designed for ISO 14310 V6 (3V leak criteria) qualification. With an expansion rate of 27 percent, the new ECP will be able to seal off breakout section or ovalized borehole, with deformities as large as the example shown on page 3. However, installation of permanent packers should rather be installed above and below such sections with serve cases of breakout of opalization to thoroughly isolate them.

Only minor adjustments were made to the flow valve adjustment. Although the valve used has a flow capacity of 110 percent, some may prefer to see an even greater inflow sections, as the conventional geothermal industry has grown accustomed to using perforated liners with large inflow area, in which case future work could incorporate more or even larger flow gates.

The Bedretto tests were not as extensive as hoped, but it was demonstrated that the system could help change the flow and pressure in its section of the formation. The completion systems consisting of valves and packers were installed in the 8 ½" diameter and 99 meter long bore hole in August 2021. The borehole had intercepted the nearby fault line earlier than expected. The pre-existing flow of 2.5 l/m that had becoming from the well since it was drilled and continued during installation continued to flow throughout testing and after. The system was successfully run and set hydraulicly, plastically deforming all 4 packers into the borehole simultaneously to ensure a seal annulus. As this did not change the flow, it was evident that the inflow came from somewhere above the upper packer set at 59 meters.

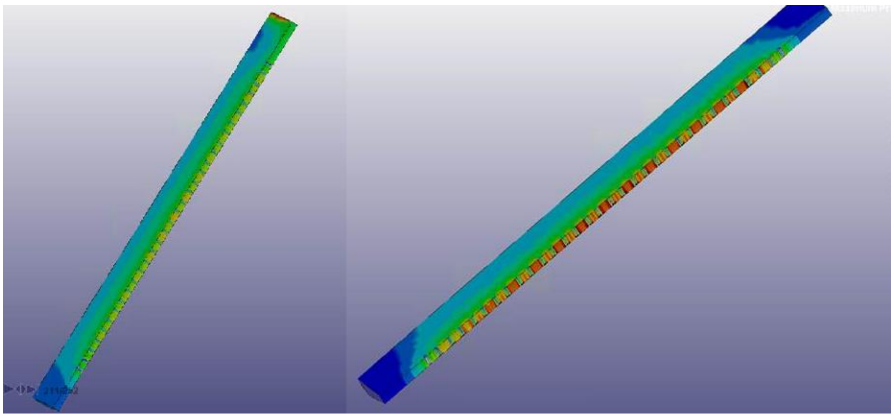
The setting and effect of the packers were confirmed over the next 20 days, as sensors (pressure and flowmeters) in the neighbouring wells, ST1 and CB2 registered a 50psi increased indicating a change in fluid flow in the formation following setting, indicating the system successfully created a new seal inside the borehole causing the pressure in a part of the formation to formation. This was reconfirmed during shut-in, as the system held pressure over an 11-day period.



Fehler! Verweisquelle konnte nicht gefunden werden.: GeoMonitor data from sensors in CB2 (left and ST1 (right) captured a change consistent change in pressure in the formation following the installation of the system.

Despite attempts running multiple stimulation cycles in the upper zone results were inconclusive. Upon opening lower zone, water was immediately detected coming through the casing/valve in rates of 2.83 to 2.95 l/m, which stopped immediately once the zone was closed again, indicating the system's ability to isolate separate zones with different flows.

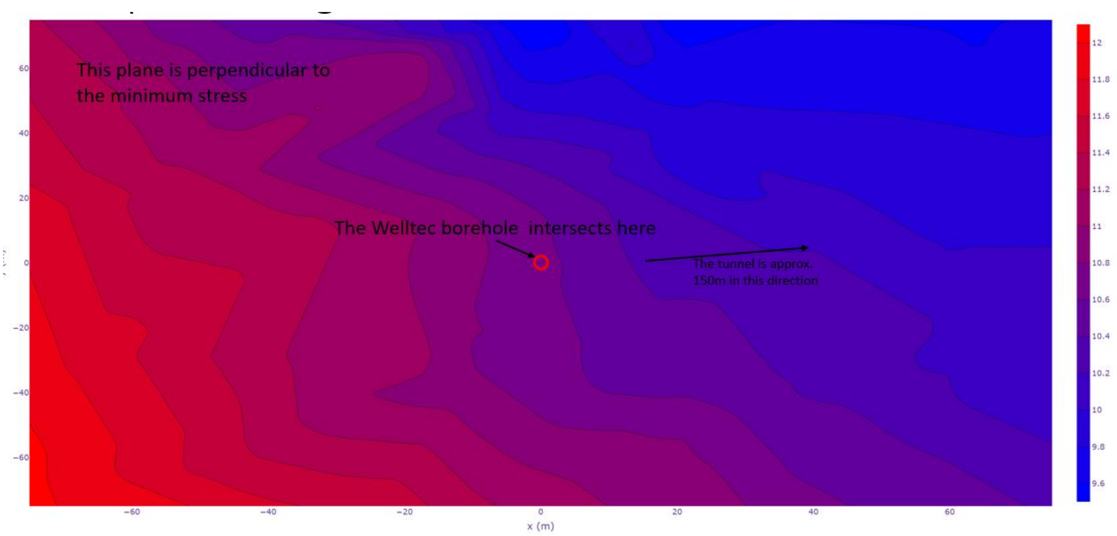
A five-step step-rate-test was carried out with initial rate of 0.5 and finally 7.5 l/m showed that the zone was in communication with an existing network, very likely dominated by the large nearby fault. This made further testing of the completion system difficult, as there was an indication of a cross-over flow in the formation, which pressed water across the formation around the bore hole. Nevertheless, the effects of the step rate test in the lower zone were detected by ETH's micro-seismic sensors on a single channel in MB7.



Fehler! Verweisquelle konnte nicht gefunden werden.: FEA model showing the packer to rock contact stress without (left) and with (right) overburden stress. The pressure applied to the formation changes as the rock mechanical pressure changes. Interestingly, the squared darker elements along the seals, are not where the micro-localized contact stress is applied, but the areas in between them.

To obviate effects of potentially causing mini fractures along the system the expansion was carried out in steps with time intervals between pressure increases. Likewise, prior to, and after testing, FEA modelling incorporating the formation’s vertical and horizontal overburden stress only indicated minimal contact stress on the borehole, rendering the probability of borehole bypass low. However, to further eliminate doubt micro-localized stresses and expansion procedure could be further investigated when it comes to setting the packers in highly competent rock formations. Additionally, further tests could in the future be caried out in the upper zone.

Although the rock laboratory offered a unique opportunity to test the equipment in a granite formation, the test was likely affected by the proximity to the tunnel, after the section of the borehole that was left for testing after the well was cut short to 99 meters, which meant the stress plane gradient overburden was overshadowed by the stress perturbation caused around the tunnel, thus those making the results difficult to transfer.



Fehler! Verweisquelle konnte nicht gefunden werden.: The oblique stress gradient plane at 76 meters, the red circle indicates where the borehole intersects the plane with the wellhead located behind the plane. The gradients from the increase of overburden are heavily overshadowed by the stress perturbating from the tunnel 150 meters away. The plane intersecting at the 62-meter zone showed a similar overburden effect on the area around the borehole.

Although the developed hardware has yet to see deployment in a real well, the test in the Bedretto laboratory has offered a unique opportunity to test the equipment in the actual dimensions. Over the cause of the material selection process, we have also learned that some of the geothermal material selection choices can to a degree also be implemented in carbon capture storage (CCS) well solutions, especially when it comes to ensure long-term durability.

The developed result will aid in ensuring better control of both EGS and hydrothermal resources by allowing for better control of the well borehole through improved zonal isolation, thereby allowing wells to function optimally to its individual geological circumstances.