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Innovative Microseismic Monitoring Tools and Configurations for Geothermal Applications

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ABSTRACT

Stimulation and long term microseismic monitoring of Enhanced Geothermal System (EGS) developments must fulfil two roles; mitigation of seismic risk and imaging of the reservoir, for which the monitoring system must be both highly sensitive and accurate. In principle these aims can be achieved using a network of sensors in dedicated monitoring boreholes close to the reservoir. At the Utah FORGE (Frontier Observatory for Research in Geothermal Energy) such a network has been employed to monitor a stimulation at around 8500ft depth bGL. Innovative, high temperature 3C geophone, multi-level geophone strings were deployed in three boreholes at ~3000ft offset from the stimulation zone where the tools were at up to ~180°C. In addition, a string of fibre optic 3C sensors, wireline DAS and behind casing DAS were also deployed on a trial basis at 3-4000ft depths. An alternate approach to the installation of sensors close to the reservoir has been trialed at the Bedretto Underground Laboratory in Switzerland. There a 4 level, 3C clamped geophone string was installed in the stimulation hole beneath the injection zone. These tools enabled microseismic events of ~-3Mw to be detected and located during an experimental stimulation and demonstrated how EGS monitoring may be achieved at higher resolution and sensitivity using sensors deployed in the injection hole rather than in dedicated, deep monitoring boreholes.

1. INTRODUCTION

In Enhanced Geothermal Systems (EGS) developments seismic and microseismic monitoring has been used both to monitor the reservoir development (Evans et. al., 2005) and seismic risk. Over recent years the risk aspect of this application has become increasingly important and is now critical for public acceptance, in Europe at least (Trutnevyte and Wiemer, 2017). Typically, in EGS applications microseismic monitoring has been conducted using a network of sensors in shallow boreholes augmented by one or more deep boreholes (Dyer et. al., 2008) in conjunction with surface seismic monitoring (Pankow et. al., 2017). Here we will consider only the microseismic element of EGS monitoring.

The data from shallow, borehole based seismic networks are relatively easy to process using a mix of manual and automated methods. However, the P and S wave velocity model may be 2 or 3D and include near surface variations that must be reliably determined and combined with 3D model traveltime estimation to obtain accurate event hypocentres. If the network can be deployed closer to the reservoir and preferably in the reservoir host rock, 1D velocity models may be used and greater accuracy is possible simply due to the relative proximity of the sensors to the events.

Placing the sensors closer to the reservoir is also beneficial in increasing the sensitivity of the network which may enable the seismic risk to be reduced during an EGS reservoir stimulation. Risk mitigation measures, such as the Adaptive Traffic Light Scheme (Grigoli et. al., 2017), use the b-value to predict the risk of larger events based on the prior distribution of smaller events. Using a more sensitive network, the b-value can be estimated from a range of smaller events, for example down to -2 Mw, enabling risk models and predictions to be obtained earlier in a stimulation process than from a less sensitive, near surface network of sensitivity >-1Mw.

However, deploying sensors close to an EGS necessarily means that they will be at high ambient temperatures and pressures. At the Utah FORGE (Frontier Observatory for Research in Geothermal Energy) a network of three dedicated, deep monitoring holes were equipped with high temperature sensors to monitor a stimulation at around 8500ft depth bGL. This was possible as this site is in a remote location away from neighbours who might be disturbed by the developments, but elsewhere, drilling deep monitoring holes may be prohibitive on environmental grounds or public acceptance.

In Europe, Geo-Energie Suisse received authorisation to develop a deep EGS project at its Haute-Sorne site in early 2023. Development of this project is very sensitive, politically, environmentally and on grounds of risk and disturbance of the neighbours. Hence, drilling a network of monitoring boreholes could be contentious and less effective than deploying high temperature sensors within the stimulation borehole. In the case of a plug and perf stimulation design, the sensors would be temporarily clamped within the borehole. The alternative would be for the sensors to be permanently emplaced as an integral element in a sliding sleeve type completion. Here we describe a trial at the ETH Bedretto lab of a sensor deployment beneath packers to test the effectiveness and practicality of such a deployment.

2. UTAH FORGE HIGH TEMPERATURE GEOPHONE NETWORK MONITORING

Utah FORGE is a dedicated underground field laboratory sponsored by the US Department of Energy (DOE) for developing, testing, and accelerating breakthroughs in Enhanced Geothermal Systems technologies to advance the uptake of geothermal resources around the world. A first deep stimulation well 16A-32 was completed in January 2021 to a measured depth of 10987ft (Figure 1.) including a toe ward section of around 4000ft at a dip of ~30° within granite reaching a bottom hole temperature >220°C (380F). In April 2022 three stages in 16A were hydraulically stimulated. The first stage was within an openhole section of 200ft at the toe of the well and the second stages were conducted through perforations. Each stage commenced with a perforation shot and successive stages were isolated with temporary plugs.

The field site is underlain by granite, the top surface of which dips to the west at around 25°. The depth of the granite is at around 2616ft bGL at seismic monitoring well 78-32 and 4552ft bGL at 16A-32 (Figure 1). A compilation of articles related to the geologic setting of the Utah FORGE site can be found in Allis and Moore (2019).

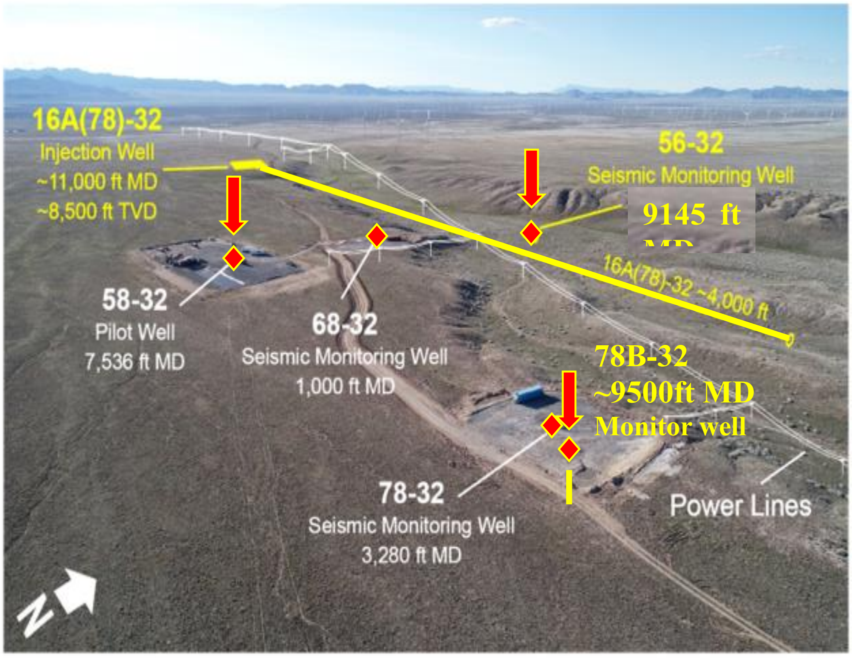

Figure 1: Utah FORGE field site with injection well 16A. Monitor wells 56-32, 58-32, 78-32(78-32A) and 78-32B were equipped with 3C-seismic tools. 78-32A had wireline DAS and 78-32A and 78-32B had cemented behind casing DAS

2.1 Microseismic monitoring

A pre-existing pilot well, 58-32 and two dedicated monitoring wells, 56-32 and 78B-32 (Figure 1) were available for microseismic monitoring during the stimulation and the tools that were deployed are shown in Figure 2. The initial intention had been to deploy an eight level, 3C digital geophone string in each of the monitor wells. However, the first string and backup string that were deployed into 56-32 failed and an alternate two-level analogue system was deployed instead. It was found that the eight level strings in 78B-32 and 58-32 had a maximum internal temperature limit of 160°C above which the tools would shut down. This corresponded to an ambient well temperature of ~180°C.

In addition to these geophone systems a three level, 3C fibre optic tool was deployed on a trial basis in the well 78A-32 which also had DAS within its wireline. There were also fibre optic DAS systems cemented behind casing in both 78A-32 to TD and in 78B-32 to 3993ft bGL. Whilst these tools were all at relatively low temperatures, 125°C or less, it is notable that they were all reliable throughout the whole ten days period of the monitoring.

In contrast, there were a number of failures during the deployment of the geophone strings such that during Stage 1 only the eight-level string in 58-32 was available, during Stage 2 the two-level string in 56-32 was also active and during Stage 3 the eight level strings in both 58-32 and 78-32B as well as the two-level string in 56-32 were active. Whilst only the 58-32 string was active in Stage

1 the microseismic events were located using hodograms in addition to P and S arrival times. The groups were oriented using a perforation shot in the openhole prior to Stage 1 to enable the events during the subsequent stimulation to be located in realtime.

Typical trace data of a Stage 3 event are shown in Figure 3 from the whole 3C network. The background noise level of the tools is around ±0.01µm/s, increasing to more than ±0.02µm/s during the injection suggesting that the noise is real rather than system generated. The noise floor limited the sensitivity to around -2Mw whereas the largest events were ~0.5Mw. To date ~3500 events have been located (Figure 4.). However, at the peak injection rate of 50barrels/minute there were up to 2000 triggers per hour most of which were very small events that could not be reliably located.

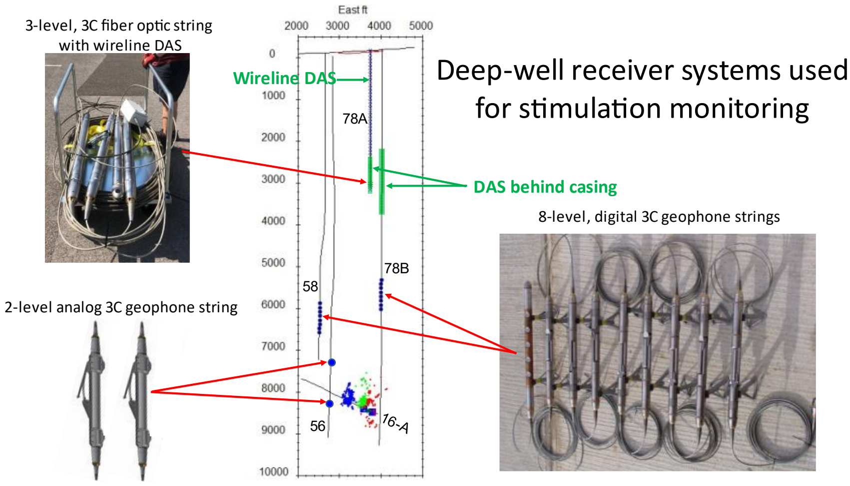

Figure 2. 3C tool strings used for the FORGE monitoring together with the wells and depth ranges of the 3C and DAS monitoring systems. Note the well names have been shortened to the first two digits and letter.

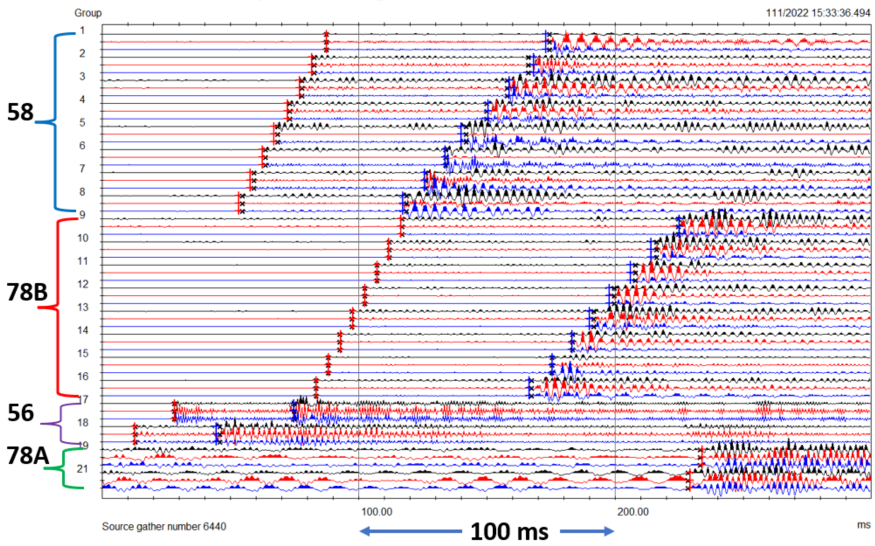

Figure 3. Mid-sized event from Stage 3, -1.1Mw. Symbols: red + P pick, blue + S pick, black x model P or S time. Group by group scaling. No filters except a common mode filter applied to 78A-32. Note, the mid group of 78A-32 is not displayed as this group was consistently noisy. The well names have been shortened to the first two digits and letter.

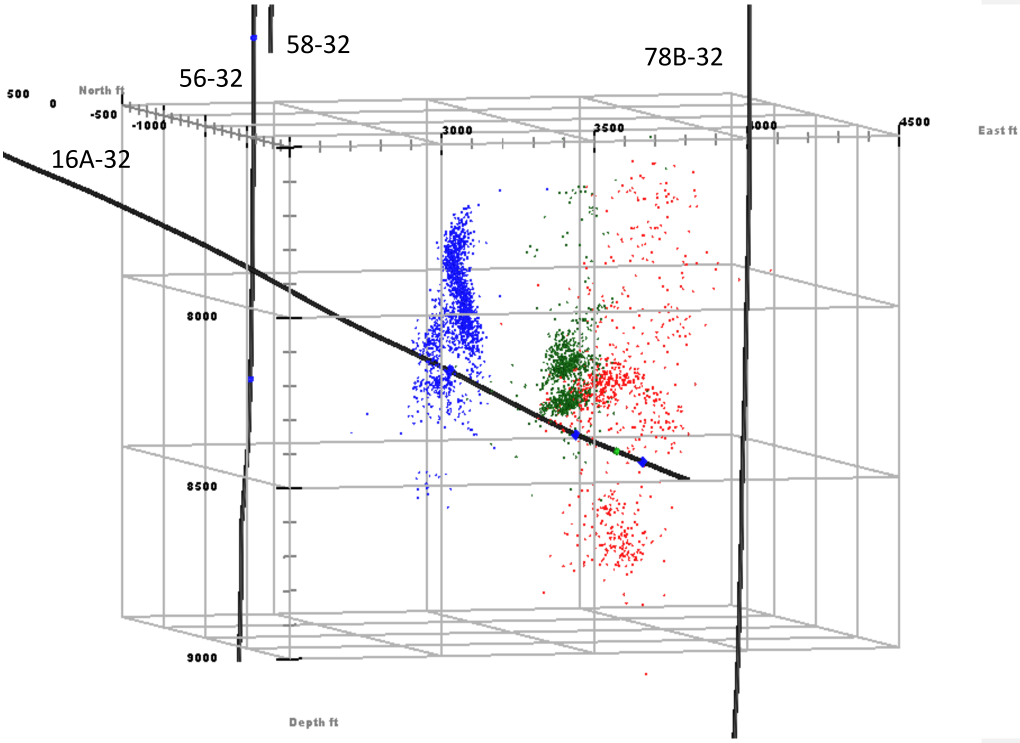

Figure 4. 3D view of the event distribution of Stages 1, 2 and 3, red, green, blue respectively. In 16A-32 the perforation shots are indicated by blue diamonds and the casing shoe by a green disk.

2.2 Discussion

In this application it was found that the digital geophone strings could be deployed for a relatively short period, in this case 10 days, at up to an ambient well temperature of ~180°C which was around 20°C less than expected. Nonetheless, it was demonstrated that reasonable locations could be obtained from a single string using hodograms which is an important consideration for applications such as Haute-Sorne where it is planned to perform the monitoring using a single string in the stimulation well. A more fundamental limitation was also found in that high temperature wirelines from three different vendors all suffered failures during these trials and subsequent attempts to deploy tools for long term monitoring in autumn 2022. It was not possible to derive definitive results but overall, it seemed that over the longer term none of the wirelines could be relied upon at greater than 150°C downhole.

3. BEDRETTO SUB PACKERS GEOPHONE TRIAL

The Bedretto Underground Laboratory for Geosciences (BULG) is located in a dis-used railway service tunnel leading from the Furka railway tunnel to the Bedretto valley in the Canton of Ticino in the south of Switzerland. The BULG has been developed by the Swiss federal, public university of ETH Zurich to host experiments into drilling and completion, hydraulic stimulation, monitoring and seismic risk mitigation related to EGS.

The lab is located within the Rotondo Granite of the Gotthard Massif in an enlarged portion of the Bedretto service tunnel that is 2000-2100m from the entrance in the valley and approximately 1100m beneath the surface (Figure 5). A number of boreholes have been drilled to the south-west at varying dips from the 100m portion of the tunnel comprising the lab. Hydraulic experiments in these boreholes have been performed by Geo-Energie Suisse (GES) to prove the concept of multi-stage EGS reservoir development at a scale of 10s of metres. It is also essential for GES to monitor microseismicity due to these hydraulic experiments and demonstrate innovative sensors and techniques that are applicable to its deep EGS project at Haute-Sorne. A key aspect of the monitoring was to investigate the potential for monitoring using sensors beneath the completion.

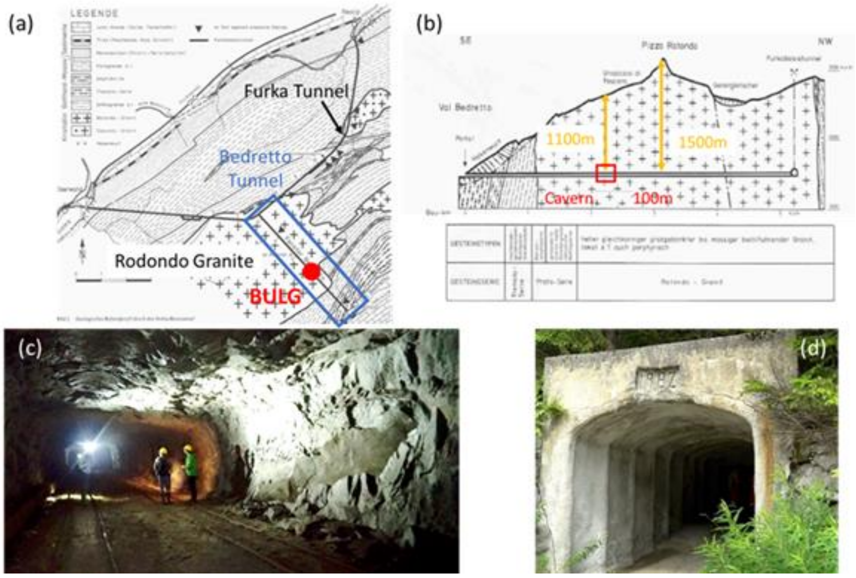

Figure 25. (a) Geological map of the surroundings of the Bedretto tunnel (blue inset) and location of the BULG (red circle); (b) NW-SE profile along the Bedretto tunnel, depicting the location of the cavern hosting the BULG; the approximate depth is depicted by yellow arrows (panels a and b modified from Keller and Schneider, 1982); (c) inner view of the tunnel; (d) south entrance to the tunnel.

3.1 Sub packer geophone design

In order to perform hydraulic tests of a limited depth interval in a borehole inflatable packers may be used to hydraulically isolate the top and bottom of the interval of interest. The packers in turn are connected to a tubing string for deployment purposes and through which water may be injected into the interval. A ¼" hydraulic line is used to inflate the packers once they are on depth. This system was modified to include up to four special seismic sections beneath the injection interval. Each of these sections contained one, 3 component (3C) geophone sensor and two dummies for radial symmetry (Figure 6). Along the axis of each of the seismic sections there is a packer that can be inflated using a separate hydraulic line to clamp the geophone tool to the borehole wall and deflated to release the geophone.

3.2 Packer geophone calibration

Initially this system was deployed at shallow depth (20m) to test the clamping/releasing mechanism and also that the geophone was adequately clamped to the borehole wall to provide a good seismic response. The seismic response was assessed using a sparker source in a nearby borehole from 10-120m depth to obtain a range of azimuths and inclination of the direction of energy propagation through the geophone (Figure 7). As it is planned to use this configuration to locate seimicity from a linear string at Haute-Sorne it is essential that the geophone/clamp system provides good vector fidelity so that the hodogram azimuths may be used to locate the events radially about the string. This test demonstrated that the direction of energy propagation derived from the hodograms correctly follows the ray paths from the source to the geophone as shown in Figure 7.

3.3 Microseismic monitoring

The last step in the trials of the packer clamping system was to deploy it during an hydraulic test to monitor seismicity. Up to four packer geophones could be deployed beneath the packed off interval but due to the limited depth of the borehole the number had to be reduced for deeper hydraulic trials. Here data are illustrated from an hydraulic test in stimulation borehole ST2 over an interval from 327.5 to 331.5m with two packer geophones at 339.1 and 344.1m (Figure 8.). The stimulation was monitored using the two packer geophones in ST2 and a further string of eight geophones of the same type as the packer geophones in monitoring borehole ST1 (Figure 8). The 8-level string was deployed on wireline and clamped using electrically powered arms in the conventional way. The event locations were derived by simultaneously fitting the observed P and S arrivals times at the combination of the packer geophones and the 8-level string to the geometrical times for a constant P and S velocity model using a grid search. A subset of the last 25% of the events are shown in Figure 8 for clarity. The events ranged in magnitude from -3.3 to -1.6Mw.

Trace data from one of the larger events, -2.6Mw, is shown in Figure 9 and this event is also highlighted with a green box in Figure 8. In this case the P and S arrivals are clear on the two packer geophones although the relative amplitudes of the P and S phases vary between the strings and within the 8-level string as would be expected. As the packer geophones are mechanically coupled to the injection tubing the noise level is significantly higher than on the 8-level string. The noise is thought to be due to a combination of flow within the tubing, ~48 litres per minute, and mechanical noise passing down the tubing from surface pump vibrations that are coupled through the tubing connections.

For the same event as in Figure 9, the calibrated trace levels are shown in Figure 10 for the deeper packer geophone. From the unfiltered trace data the noise level is ~±20microns/second. However, the noise is predominantly at <200Hz whereas the microseismic energy is concentrated in the band 400-1200Hz. Hence it is practical to simply high pass filter the trace data from the packer geophones as is illustrated in the lower display of Figure 10 and Figure 9 to enhance the signal to noise.

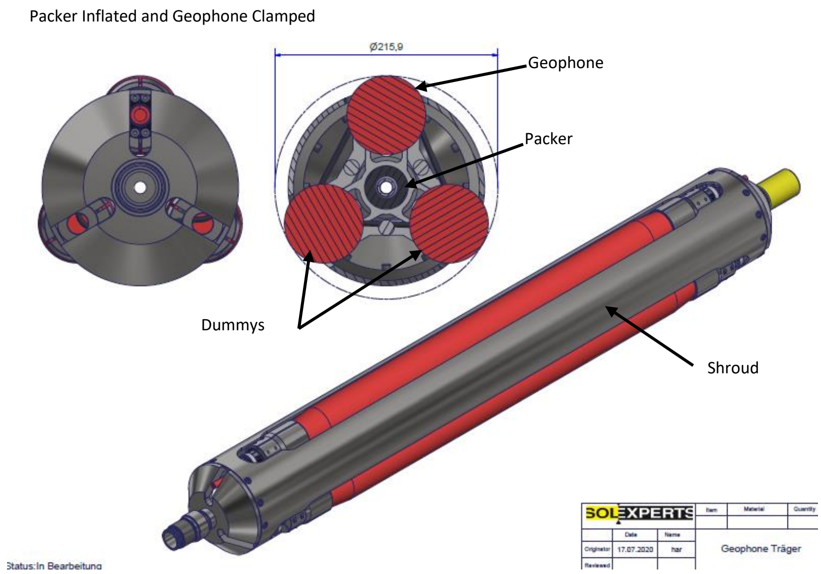

Figure 6. Seismic element of a multi-packer completion. The section is deployed beneath the rest of the completion. Each section contains one 3 component geophone tool which is clamped to the borehole wall by inflating the axial packer. During deployment and recovery the packer is deflated and the seismic tool and dummies are withdrawn by elastic elements into the shroud for protection.

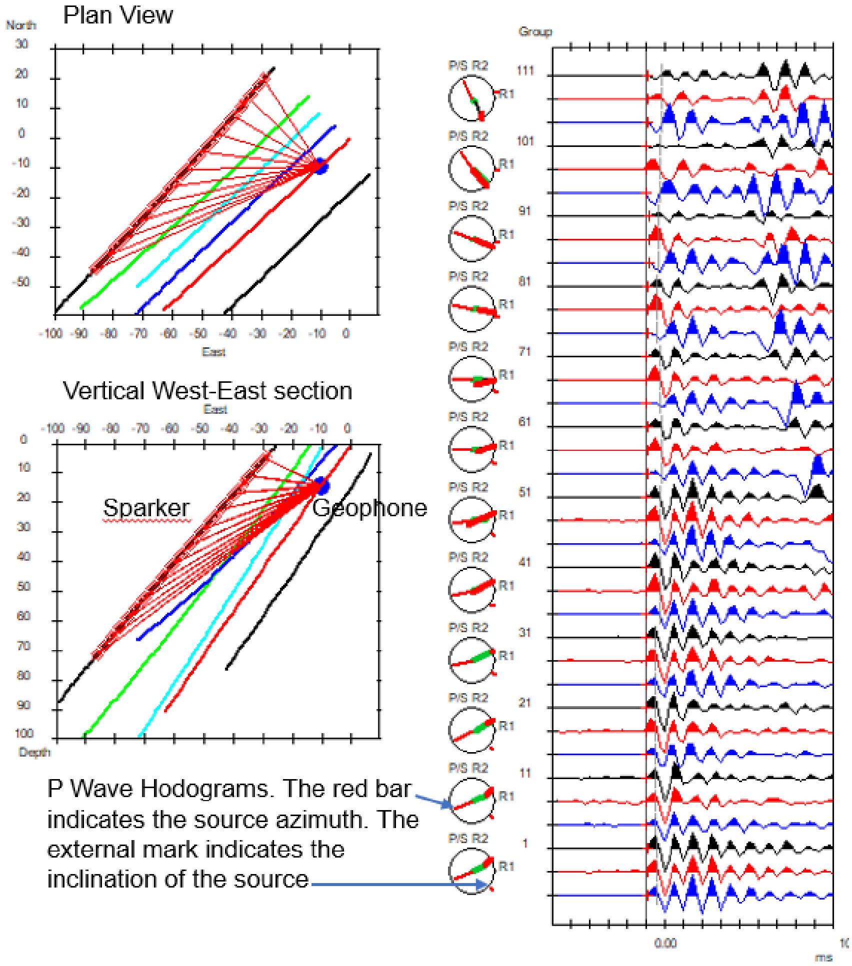

Figure 7. Vector fidelity test of the geophone and packer clamping system. The red bars within the hodogram dials indicate the azimuth of the source derived from the hodogram and the tick mark on the periphery of the dials indicates the inclination of the source. The trace data of each 3-component group are rotated to the directions Vertical, East, North corresponding to the black, red, blue traces respectively. From top to bottom of the section, each group corresponds to the source positions from East to West in the plan view and top to bottom of the depth section.

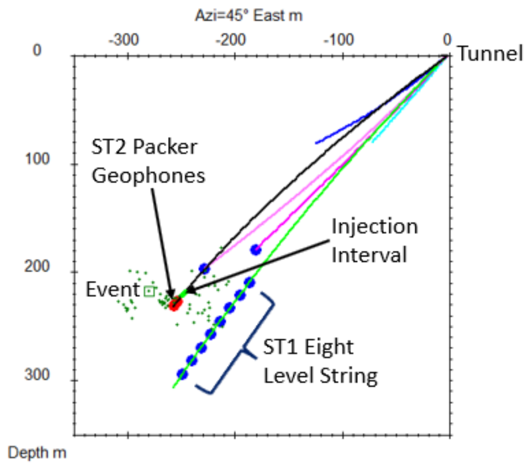

Figure 8. Vertical section, south-west to north-east in the plane of the boreholes ST1 and ST2. The tunnel, top right, extends into the mountain in a north westerly direction, into the plane of the figure. There are two geophones clamped by packers beneath the injection interval. Above the geophones are two packers that seal the top and bottom of the injection interval. The whole assembly is deployed on tubing that is used to inject into the packed off interval. For clarity only a small portion of the events that were detected are shown and have a moment magnitude range of -3.3 to -1.6Mw. The microseismicity was monitored using the eight-level, 3-component string in ST1 and two level 3-component packer clamped geophones in ST2.

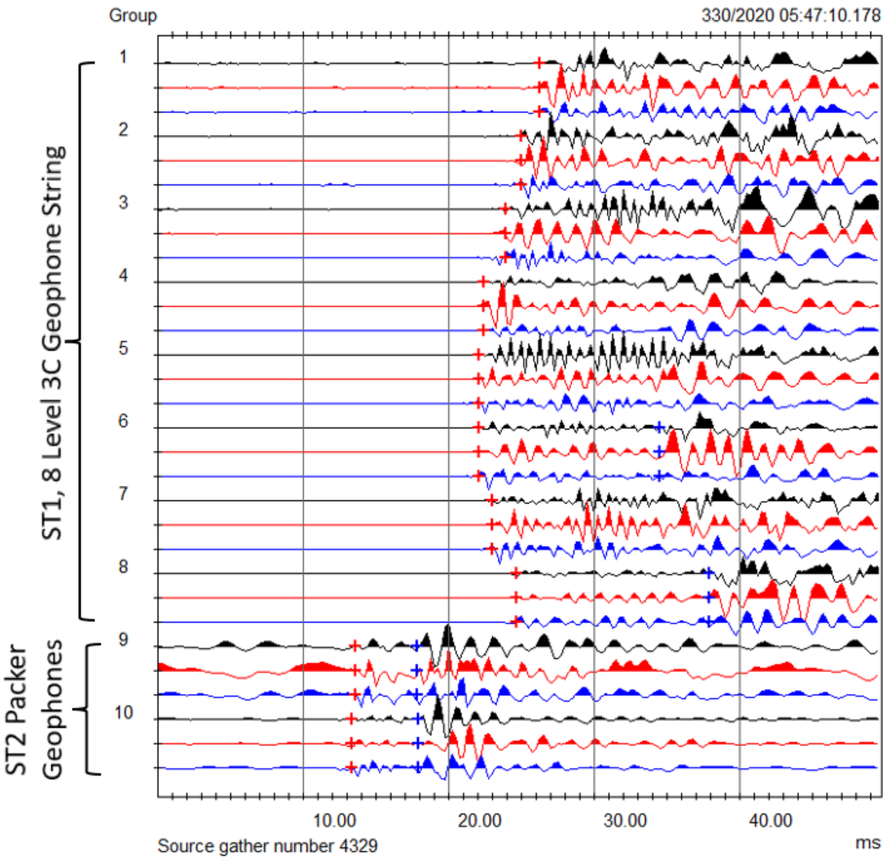

Figure 9. Three component trace data for a -2.6Mw event indicated by the green box around it in Figure 8. The data have been high pass filtered at 200Hz and are shown with group-by-group scaling. The traces are not oriented. Black traces are the axial component and red/blue traces the radial components.

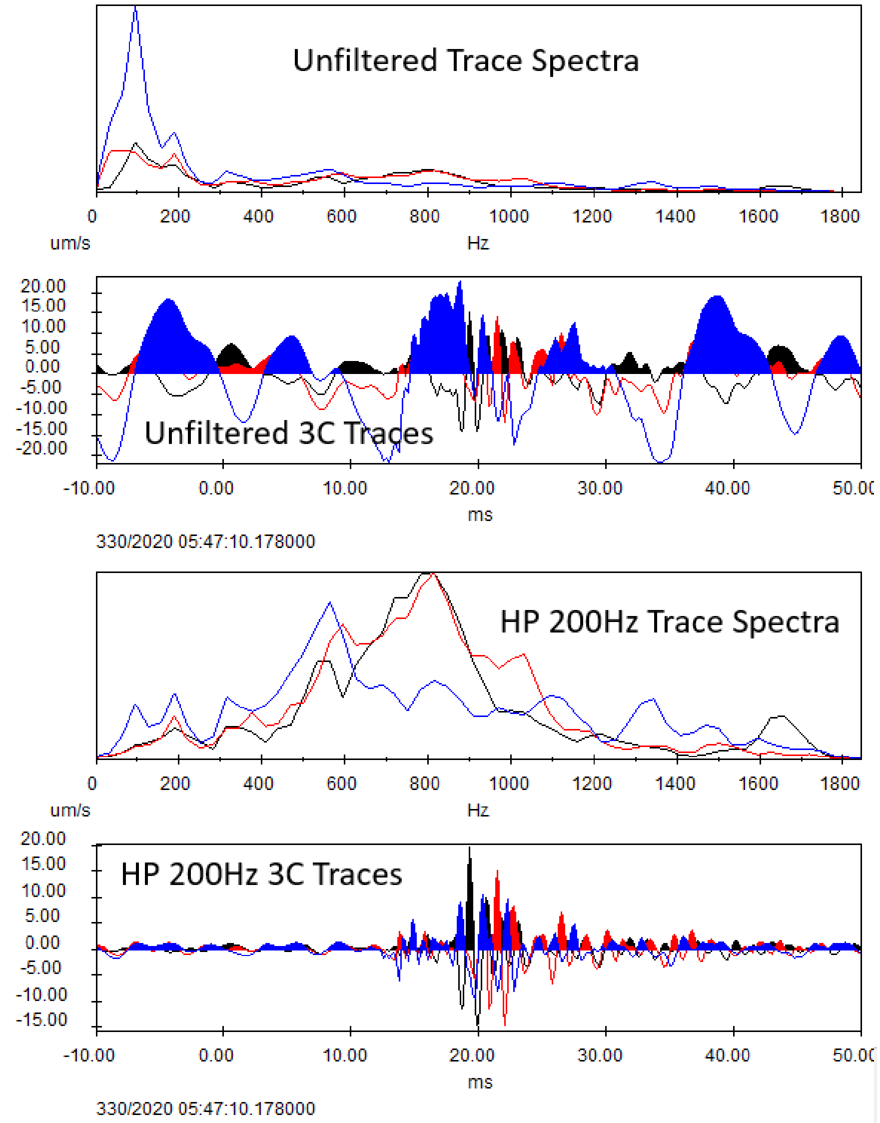

Figure 10. Trace data from the lower packer geophone for the same -2.6Mw event as in Figure 9 where black is the axial trace and red and blue the radial traces. Low frequency pumping noise in the top, unfiltered, spectra and trace displays are removed with a 200Hz high pass filter in the lower displays.

3.4 Discussion

The sub-packer geophone system was also deployed at the bottom of a multi-packer system installed into ST1 in April 2021 and the geophone remains operational. It may be that the long-term reliability of this tool is in part due to the electrical connections being entirely encapsulated in ¼" metal tubing and a metal-to-metal seal at the tool rather than the conventional connection using a wireline and elastomer seals. Whilst these trials have shown the feasibility of placing a seismic sensor beneath a multi-packer completion, the approach in general depends on the availability of reliable high temperature packers. In this case, a digital geophone tool was deployed which was important due to the high levels of electrical noise in the Bedretto lab. However, the design is equally applicable to any tool that can be connected using a metal tube and the higher temperature specifications of an analogue sensor or fibre optic sensor are likely to be required for EGS monitoring.

4. CONCLUSION

The high temperature geophone string deployments at Utah FORGE demonstrated that the particular system employed was reasonably reliable for short-term monitoring at up to 180°C ambient well temperature. In this respect it may be concluded that such a system could be used for monitoring within an EGS stimulation well where the peak rock temperatures are moderated by the injected flow. A more critical and unexpected observation has been the limited reliability of high temperature wirelines. This factor will significantly limit the utility of digital geophone strings for long term monitoring to temperatures less than the tools themselves are capable of withstanding.

The second trial at Bedretto demonstrated that it is practical to deploy 3C geophones as part of a multi-level completion and that the noise levels do not unduly affect the sensitivity. A similar permanent deployment at the bottom of a multi-packer completion system at Bedretto has also demonstrated that the electrical connections within a ¼" tubing with a metal-to-metal type seal at the seismic tool provides long term reliability, having been installed for 18 months at the time of writing and still fully functional.

None the less, these electronic sensor systems seem to have little scope for development towards greater reliability over the longer term at higher temperatures. As such, it appears a better option is to pursue the development of 3C fibre optic sensors and DAS, particularly for geothermal applications where ambient temperatures of 200°C or more are to be expected.

REFERENCES

Allis, R., and Moore, J.N., editors, 2019. Geothermal characteristics of the Roosevelt Hot Springs system and adjacent FORGE EGS site, Milford, Utah: Utah Geological Survey Miscellaneous Publication 169, 245 p., 8 appendices, 2 plates, scale 1:24,000, https://doi.org/10.34191/MP-169.

Dyer, B.C., Schanz U., Ladner F., Haring M.O. and Spillman T., 2008. Microseismic Imaging of a Geothermal Reservoir Stimulation. The Leading Edge, Vol. 27, No. 7, pages 856-869, July 2008.

K. F. Evans, H. Moriya, H. Niitsuma, R. H. Jones, W. S. Phillips, A. Genter, J. Sausse, R. Jung and R. Baria, 2005. Microseismicity and permeability enhancement of hydrogeologic structures during massive fluid injections into granite at 3 km depth at the Soultz HDR site. *Geophysical Journal International*, Volume 160, Issue 1, January 2005, Pages 388–412, https://doi.org/10.1111/j.1365-246X.2004.02474.x

Grigoli, F., S. Cesca, E. Priolo, A. P. Rinaldi, J. F. Clinton, T. A. Stabile, B. Dost, M. G. Fernandez, S. Wiemer and T. Dahm, 2017. Current challenges in monitoring, discrimination, andmanagement of induced seismicity related to underground industrial activities: A European perspective, Rev Geophys, 55(2), 310-340

Keller F., Schneider T.R., 1982. Geologie and Geotechnik. Schweizer Ingenieur und Architekt, 24: 512-520.

Pankow, K. L., Potter, S., Zhang, H., and Moore, J. (2017). Local Seismic Monitoring at the Milford, Utah FORGE Site. *RC Transactions*, 41.

Trutnevyte E. and Wiemer S., 2017. Tailor-made risk governance for induced seismicity of geothermal energy projects: an application to Switzerland. Geothermics 2017, 65, 295-312.

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