DISTRIBUTED TEMPERATURE SENSING IN FRACTURED LOW-TEMPERATURE RESERVOIRS — LESSONS LEARNED IN NEW ZEALAND AND CENTRAL EUROPE

Lucie Janků-Čápová[1,3], Petr Dědeček[2], Tomáš Fischer[3], Rupert Sutherland[1] and John Townend[1]

[1]School of Geography, Environment and Earth Sciences, Victoria University of Wellingon, Kelburn Parade, Wellington 6012

New Zealand

[2] Institute of Geophysics of the Czech Academy of Science, Boční II/1401, Prague 4, 141 31, Czech Republic

[3] Faculty of Science, Charles University in Prague, Albertov 6, Prague 2, 128 43, Czech Republic

luciel@janku.rocks

Keywords: *DTS, fibre-optic cable, geothermal gradient, heat flux, permeable fractures*

ABSTRACT

DFDP-2B is a ~900 m-deep borehole drilled in 2014 in the hanging-wall of the Alpine Fault, in the South Island of New Zealand. PVGT-LT1 is a 2 km-deep hole drilled in 2007 in the Bohemian Massif, in the town of Litoměřice, Czech Republic. Both boreholes intersect foliated metamorphic rocks and are equipped with a fibre-optic cable that has been used for temperature monitoring and locating permeable fracture zones. By comparing data from the two boreholes we identify common problems and develop best practices for downhole applications of Distributed Temperature Sensing (DTS).

DTS measurements are sensitive not only to intrinsic properties of the optical fibre and the measuring unit, but also to ambient temperatures surrounding the measuring unit. A drift may occur in the recorded data if the temperature of the logging unit is not uniform, and here we describe different corrections (linear, polynomial) to this drift. The resulting data are also sensitive to filtering and time-averaging. Results from the two boreholes suggest that setting a longer sampling interval in the DTS unit generates less noise, although longer durations of measurement (1 hour or more) and averaging can effectively reduce the noise.

Our results highlight how different filtering techniques are appropriate depending on the scale of interest. For example, a 5 m moving window is useful for identifying individual fractured zones whereas a 100 m moving window enables zones of conductive heat transfer to be distinguished.

We show that DTS can provide reliable continuous downhole temperature measurements in fractured metamorphic rocks with accuracy ±0.5°C and <5 m spatial resolution, provided that the temperature of the measuring unit is kept stable or appropriate corrections made to correct for drift. This is sufficient for monitoring dynamic temperature changes in boreholes and more convenient than conventional logging for acquiring data on an on-going basis.

1. INTRODUCTION

Distributed Temperature Sensing (DTS) is becoming increasingly popular across industries, including geological disciplines, as fibre-optic cables are widely available, versatile and can be used for long-term monitoring. Here we compare measurements from two different boreholes, DFDP-2B and PVGT-LT1, which are both equipped with a fibre-optic cable and a distributed sensing technology, and discuss lessons learned during these measurements.

1.1 DFDP-2B

DFDP-2B (Sutherland et al., 2015) was drilled in the Whataroa Valley, South Westland, New Zealand, in late 2014, inersecting 240 m of Quaternary sediments further into the metamophic basement in the hangingwall of the Alpine Fault, consisting of Alpine Schist, protomylonite and mylonite, to the total drilled depth of 893 m (815 m true vertical depth). Due to a casing damage, the hole is only accessible to 400 m. The main purpose of the borehole was to study the condition of the Alpine Fault, which is late in its earthquake cycle and expected to rupture in a major eathquake wihin the next decades (e.g. Howarth et al., 2021). Key findings of the drilling project are described elsewhere (e.g. Rupert Sutherland et al., 2017; Townend et al., 2017; Toy et al., 2017). A fibre-optic cable is installed in a double-ended configuration along the full 893 m length of the hole and cemented in a BQ casing tube, with additional 147 m-long section of the cable at each end on the surface. The cable and site setup is shown in Figure 1.

Figure 1: DFDP-2 drillsite. The site office is located in the shipping container placed over the borehole (wellhead is accessible through a cellar under the container floor). The measuring equipment, as well as the surface part of the cable, are placed inside the container.

The fibre-optic cable was used for distributed acoustic sensing (DAS) during a VSP experiment in early 2016 (Townend et al., 2018) and for repeated distributed temperature sensing (DTS) measurements in 2015 and early 2016 (Janků-Čápová, 2018).

1.2 PVGT-LT1

PVGT-LT1 was drilled in Litoměřice, Czech Republic, Europe, in 2007 (Burda et al., 2007) to the total depth of 2111 m. It was the first (and only) primarily geothermal exploration well in the Czech Republic. It intersected 780 m of sedimentary rocks (Quaternary, Cretaceous and Permo-Carboniferous), 120 m of ignimbrite and metamorphic basement composed of phyllite and mica schist (Burda et al., 2007). Immediately after drilling, the lower part of the hole collapsed and is accessible to only ~1750 m. Currently, the hole is cased to 853 m (additional perforated casing that had originally been in the hole was removed in late 2019 (**Error! Reference source not found.**A)). More details and findings from this borehole have been described elsewhere (e.g. Šafanda et al., 2020).

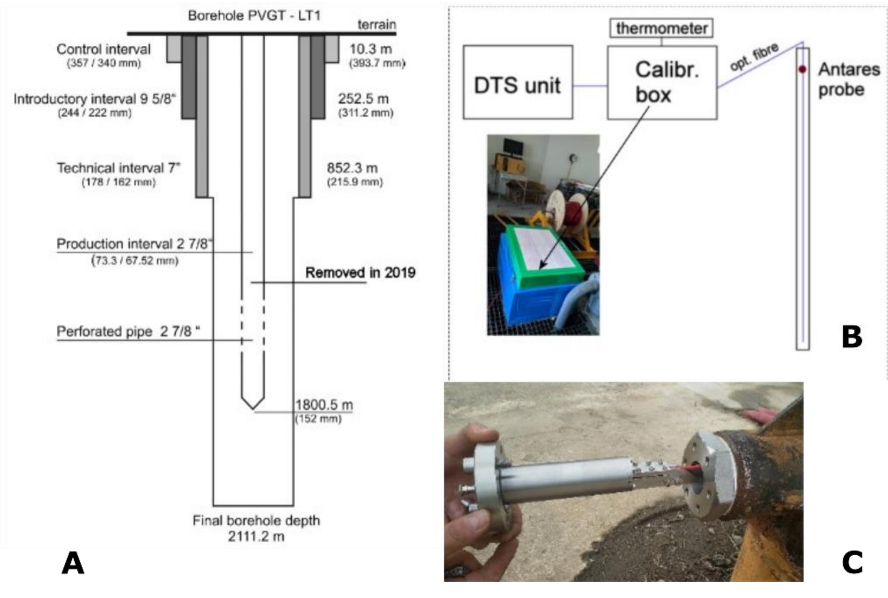

Figure 2: Construction of the PVGT-LT 1 borehole (A).Arrangement of DTS system with isothermal box, precise thermometer and independent temperature probe (Antares) (B). Pressure bushing for optical fiber connection (C).

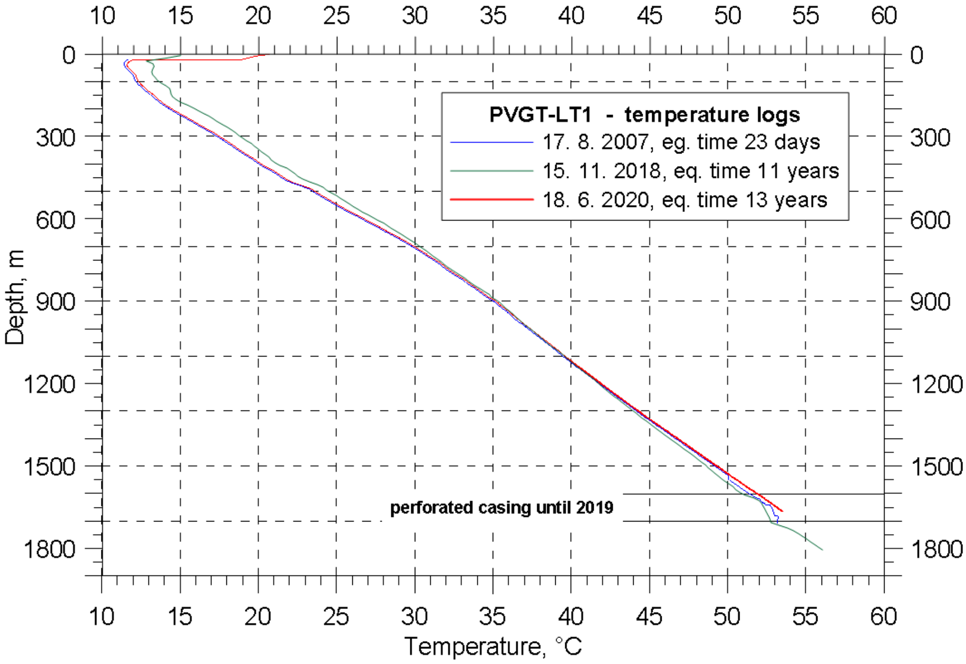

Figure 3: Temperature logs of borehole PVGT-LT1

Over the years, repeated temperature logs show gradual thermal equilibration, as well as the effect of the casing removal. Until the first hydraulic stimulation testing in 2020, the borehole was mildly overpressured with minimum fluid discharge.

A fibre optic cable was first installed together with a downhole seismometer in early 2020 after the removal of perforated inner casing to the depth of 1608 for temperature measurements during hydraulic testing in January-February 2020. To sustain the high pressures during testing and for attachment o the casing, a special pressure bushing vessel was developed for the fibre (Figure 2C). After the tests, the seismometer and cable needed to be removed. The cable was then reinstalled in mid-2020 to the depth of 1716 m for additional measurements. During the hydraulic tests, the DTS unit was placed in a building 40 m away from the borehole (Figure 2B). During the second campaign, the unit was placed in a mobile cabin next to the wellhead along with other equipment.

2 DISTRIBUTED TEMPERATURE SENSING

2.1 Technical overview of method

The optical fibre is composed of a core of silica glass 5–50 µm in diameter and a silica cladding with accessory elements that improve optical properties (Brown, 2009). In addition to an optical fibre, the complete measuring system is assembled of laser source, optical splitter, an opto-electric signal processing unit and a display unit (e.g. a personal computer).

The process is based on Optical Time-Domain Reflectometry (OTDR). Since the cladding has a lower refractive index than the core, a laser pulse that is released into the optical fibre is guided back towards the source (and the measuring unit), but a small proportion of this signal gets scattered in dependence on the temperature in which the fibre resides (Brown, 2009). The heat in the fibre material has the form of vibrations of particles of the fibre that cause Raman scattering (Hartog, 2017). The frequency of the scattered photons provides an information on how the photon interacted with the fibre material – the low-frequency band of the spectrum (Stokes) represents the case where energy has been transferred from the light to the fibre, the higher-frequency (anti-Stokes) band represents the case where photon gained energy from the fibre. The ratio of the Stokes and anti-Stokes bands is a function of temperature.

Based on the arrival time of each of the back-scattered photons to the measuring unit, the point of measurement can be determined anywhere along the length of the cable. In practice, this depends on the operating wavelength of the light source and a type of cable based on "modes" (interference patterns of scattered light in the optical fibre). Different operating wavelengths and modes are suitable for different lengths of the cable and manufacturers will generally supply equipment with the optimal parameters for a particular purpose (such as measurements in a borehole versus along an embankment). For borehole applications, multi-mode cables operating at lower wavelengths (900 or 1064 nm) provide the best spatial resolution of 1-3 m (Hartog, 2002).

2.2 Data acquisition and processing at DFDP-2B

DTS measurements in DFDP-2B were acquired with a multi-mode Draka 6 cable and a Schlumberger Fibre Monitoring Suite (FMS) DTS unit. Data were processed with Ultra Studio software. Measurements were performed in a campaign mode, as the DTS unit did not have a stable power supply (mobile generator was used each time). This cable provides spatial resolution of 1 m and additional points are interpolated by the unit every 0.5 m.

Several measurements were performed during each campaign, with a duration usually between 30 minutes and 2 hours. During each measurement, the source sends and receives a light signal to both ends of the cable approximately every 15 s, and records the measured two-way temperature profile. The first step of processing involved flopping the inverse half of the profile and averaging with the other half. Flipped profiles of every measurement were then averaged together to further reduce noise. Thus, a single temperature-depth profile is acquired for a time interval of each measurement.

Even following this procedure, data still appears noisy and for temperature and geothermal gradient analysis (Janků-Čápová, 2018), additional averaging and more advanced smoothing was required. Measurements for each day and then for each campaign were averaged, so that there is a single temperature profile for each month of measurement.

2.3 Data acquisition and processing at PVGT-LT1

For the both campaign the single channel Sentinel DTS unit (Sensornet co.) together with heavy-duty optical cable with steel reinforcement and protection was used. Temperature resolution depends on time step of recording and can be as fine as 0.004°C, spatial resolution is 1 m. The first campaign took place in January and February 2020, the second from the end of August to January 2021. The measurement was always performed continuously with a step ranging from 10 minutes to 4 hours depending on the dynamics of hydraulic tests in the well.

Different unit calibration method and setup was used for each campaign. During the first campaign, the setup was as shown in Figure 2B. An isothermic box was placed between the unit and the borehole with 15 m of the optical fibre and an independent high-precision temperature logger. Additionally, the Antares temperature logging tool was lowered 30 m down the borehole. Such setup allowed for potential temperature drift of the fibre optic cable, but due to the borehole depth (cable length) did not allow corrections for the slope of the temperature profile. During the hydraulic tests, a fracture was opened at 880-890 m and below this level, temperature field remained unaffected. Therefore, precise independent temperature log run in June 2020 was used for calibration of the setup during the second campaign. DTS measurements were fixed to this temperature log at depth interval 1100 – 1700 m where temperature field remained stable. Data from January and February 2020 were retrospectively calibrated the same way.

3 CHALLENGES ENCOUNTERED

3.1 DFDP-2B

3.1.1 Physical measurement

The cable is rated for 85°C, but the downhole temperatures exceed 100°C. Exposing the cable to higher temperatures than it had been designed for may lead to degradation of the fibre. Some optical losses have been encountered during the measurements, indicating minor degradation may indeed be taking place.

The lack of stable power supply and telemetry option has disabled permanent monitoring of downhole temperatures. Due to laboursome logistics of dispatching a field expedition to the relatively remote location in the West Coast of the South Island of New Zealand, measurements could only be caried out on a two-monthly basis.

3.1.2 Filtering and smoothing

Geothermal gradient from DFDP-2B was filtered using a Savitzky-Golay filter with sliding window size varying from 5 m for tracing local inhomogeneities (such as permeable fractures) to 200 m for analyzing geothermal gradient in each geological unit (Figure 4).

The Savitzky-Golay filter is a type of a moving average filter upgraded by fitting a polynomial by least-squares method to a defined number of points (window length). The optimal window length and polynomial order is achieved if the fitted function has a single inflexion point in the window. Therefore, lower orders of polynomial are better suited for larger window lengths. Janků-Čápová (2018) used a third order polynomial for the analysis of geothermal gradient.

The purpose of geothermal gradient analysis was to divide the drilled interval into sections where heat transfer is dominated by conduction or by advection, and to determine the conductive heat flux from Fouier's Law for each section, so that the amount of heat transferred conductively in a vertical direction could be determined and lateral advective heat fluxes could be estimated. The zones identified using a Savitzky-Golay filter with a third order polynomial and a 200 m moving window are shown in Figure 5. The zone boundaries were defined by locating inflexion points in the geothermal gradient (second derivative of temperature).

The problem of the Savitzky-Golay filter lies in finding optimal parameters, so that the filtered profile is an accurate representation of the geological and geophysical situation without imposing author's subjective biases in the data.

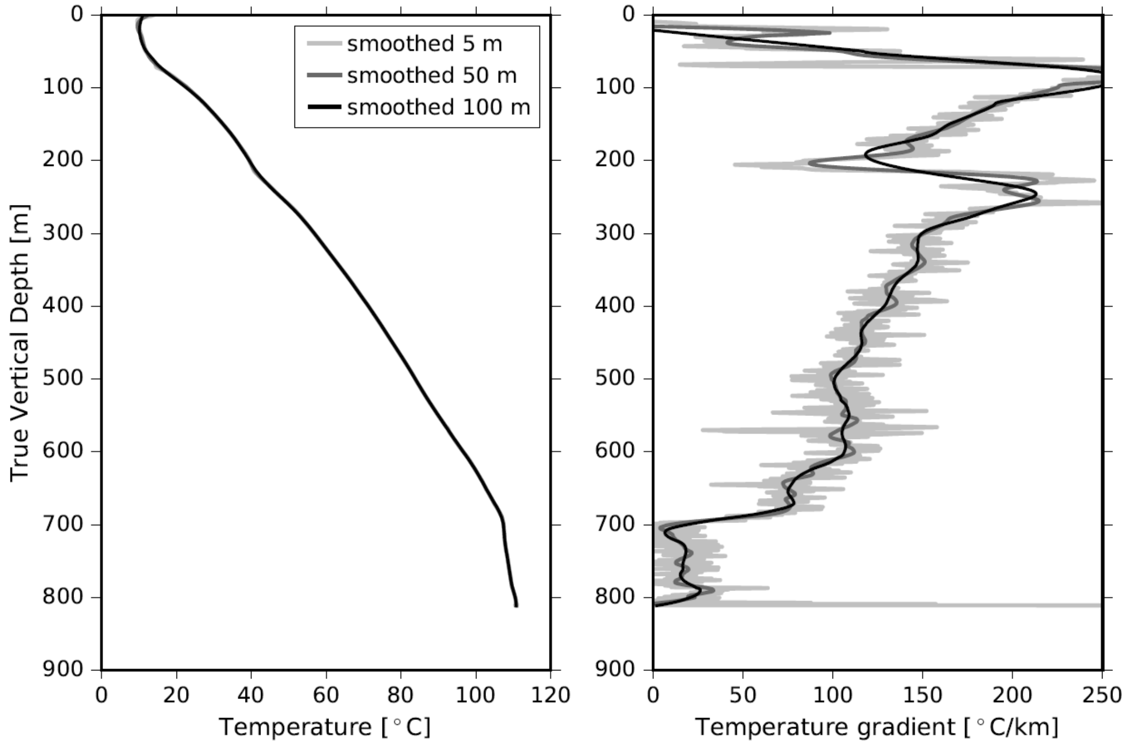

Figure 4 Applying a Savitzky-Golay filter with a 5 m, 50 m and 100 m moving window, progressively reducing noise and enhancing the signal representing the rock mass rather than individual inhomogeneities. (Janků-Čápová, 2018)

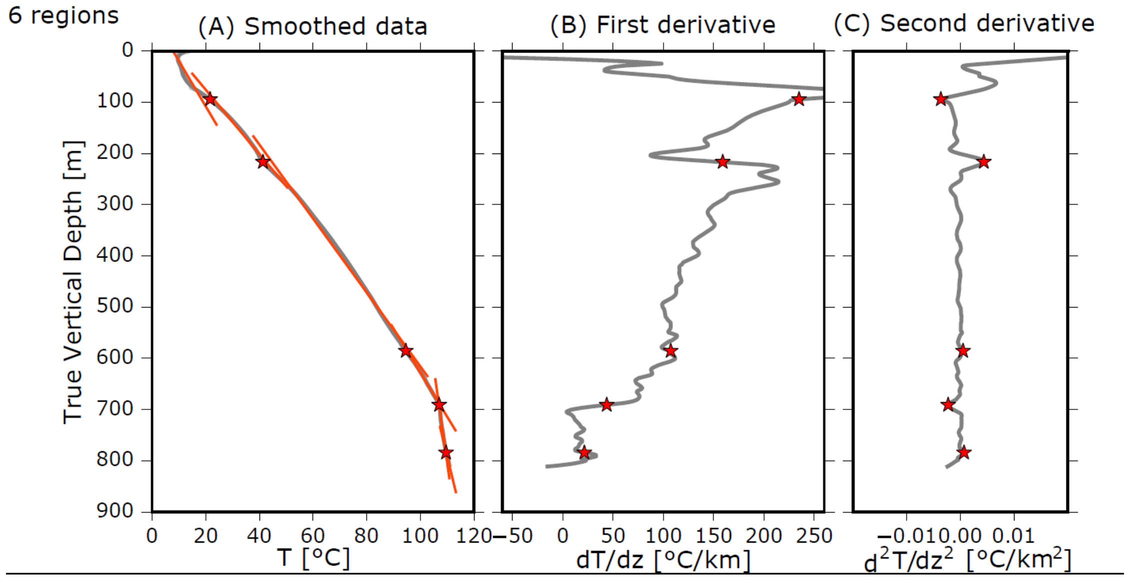

Figure 5 Example of thermal gradient analysis with Savitzky-Golay filter. The red lines in panel A represent the linear geothermal gradient for each section extrapolated 50 m each way for visibility. Stars represent the zone boundaries. (Janků-Čápová, 2018)

3.2 PVGT-LT1

3.2.1 Physical measurement and data correction

Measurements during both campaigns had a time step of 30 minutes with the exception of the time immediately following fracture opening when dynamic tests were taking place, this time step was reduced to 10 minutes. Since the DTS unit launches a measurement every 10 s and time averaging over the pre-set time step is automated, the resulting data were without noise and no further filtering was required. What appeared to be a serious problem was temperature dependence of the DTS unit itself. During the second campaign, when the unit was placed inside the mobile cabin, ambient temperature during summer days fluctuated between 10 and 40°C. As shown in Figure 6, these ambient temperature variations resulted in the increase of measurement error of the DTS system, gradually deviating the measured temperature with depth, and the deviation from the wireline-determined baseline reached several °C at 1700 m. This implies that it was not only an absolute shift of the measured temperatures, but the slope of the temperature curve was distorted too. At 20 m, these variations are not as apparent as they are overprinted by water flowing into the hole.

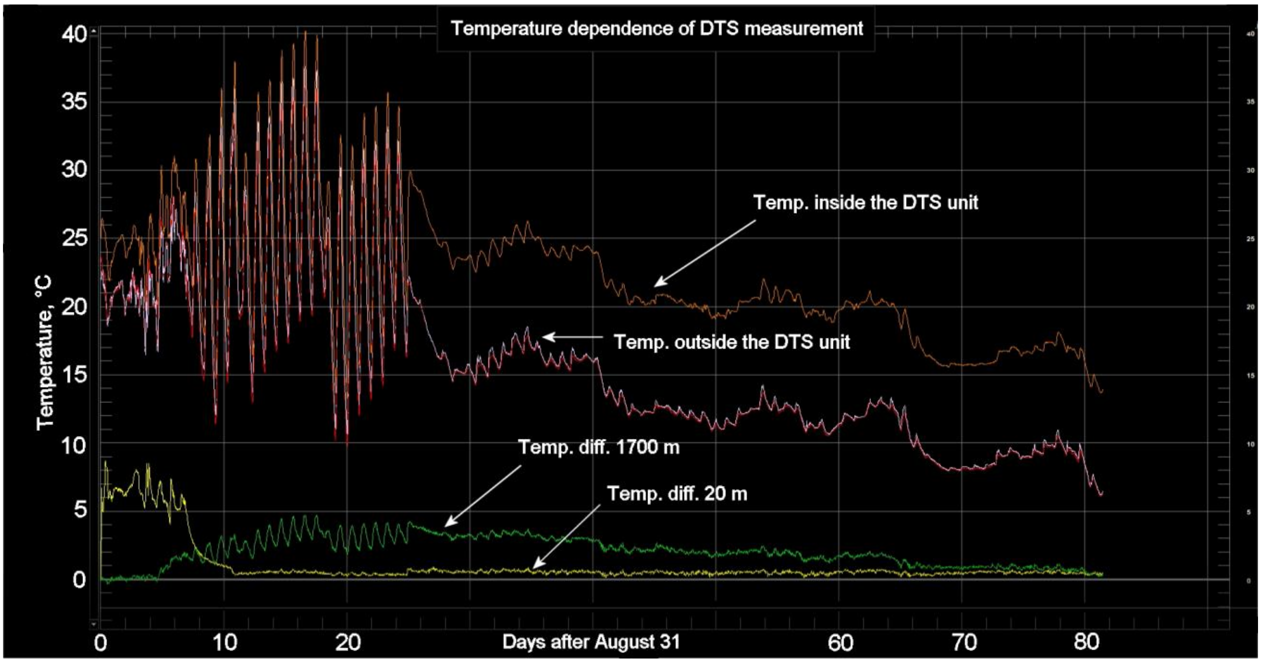

Figure 6: The effect of temperature variations around the unit on the measured data in the borehole.

Measured data were corrected using the temperature log from June 2020 at 1200 – 1700 m. Figure 7 shows an example of the measured and corrected data at 1000 m, just over a 100 m below the open fracture. Two corrections were tested – one when the reference geotherm was approximated by a line and another, when it was approximated by a polynomial, which had a closer match to the shape of the temperature curve. Thus, the measured data were stabilised and the deviation at all depth intervals of the unaffected temperature field was kept under 0.5°C.

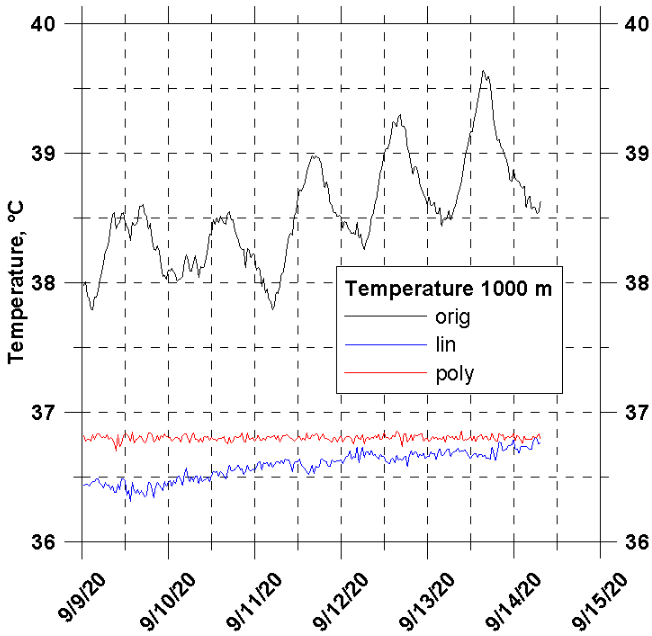

Figure 7: Corrected data at the depth of 1000 m

3.2.2 Measured data

The primary purpose of the DTS was monitoring during hydraulic testing in PVGT-LT1. Figure 8 illustrates the timeline of hydraulic stimulation in January 2020, with the moment of fracture opening marked with a star, and the thermal response of the formation to cold borehole fluid injected into the newly formed hydraulic fracture.

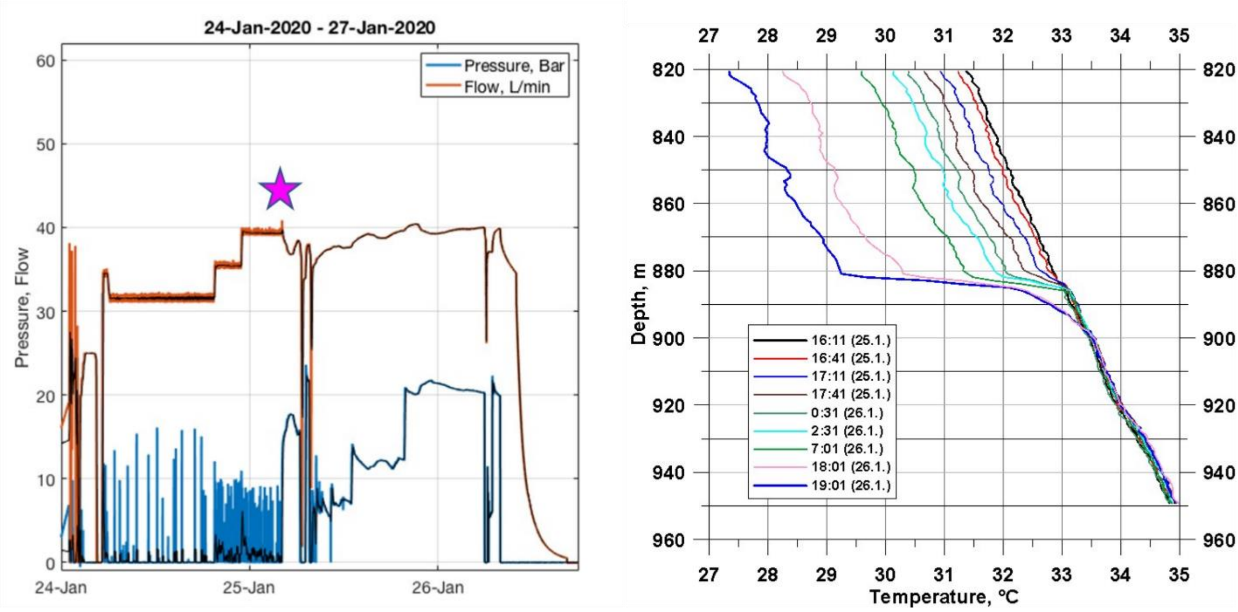

Figure 8: Injection history during January 2020 (left). Temperature field during fracture opening in January 2020 (right).

4. CONCLUSION

Challenges and uncertainties we encountered may serve as a valuable lesson for future applications. It is essential to have the correct estimate of bottom hole temperature prior to drilling and obtain a cable with high enough temperature rating, as the fibre degrades after a long exposure to excessive temperatures. Stable temperature of the environment in which the measuring unit resides is also important, because excessive temperatures or extreme temperature fluctuations introduce drift to the measured values. Corrections discussed in this paper may be applied to mitigate this effect.

To increase signal to noise ratio, sufficiently long measurement times need to be set and additional filtration may be needed during post-processing, depending on the desired application of the data.

Distributed Temperature Sensing provided valuable data in boreholes where access with traditional logging tools is limited (DFDP-2B is only accessible to the depth or 400 m) or continuous temperature monitoring during operations such as hydraulic stimulation is required (as in PVGT-LT1). Within the spatial resolution of the cable, the data generally shows the accuracy of ±0.5°C over repeated averaged data at equilibrium state, and thus proves to be a reliable tool for measuring temperatures in geothermal wells.

ACKNOWLEDGEMENTS

Measurements in the DFDP-2B borehole were a part of the international Deep Fault Drilling Project (multiple funding organisations) and a PhD project funded by the Earthquake Commission Student Grant E2568/3185. Measurements in PVGT-LT1 were funded by RINGEN - research infrastructure upgrade grant No CZ.02.1.01/0.0/0.0/16_013/0001792. We thank Schlumberger for providing the DTS unit for DFDP-2B, Arthur Hartog for assistance with the setup, Friend family for site access in Whataroa, and Calum Chamberlain and Laura-May Baratin from Victoria University of Wellington for making the measurements in March and September 2015. We also thank Robert Kincler from the Institute of Geophysics of the Czech Academy of Sciences for technical assistance with processing the data from PVGT-LT1.

REFERENCES

Brown, G. (2009). Downhole Temperatures from Optical Fiber. *Oilfield Review, Winter 200*(4), 34–39.

Burda, J., Žáček, V., Mlčoch, B., Lojka, R., & Valečka, J. (2007). *Závěrečná zpráva za léta 2006-2007: Geologické a hydrogeologické poměry ověřovacího vrtu PVGT-LT 1 v geotermální struktuře Litoměřice pro energetické využití*.

Hartog, A. H. (2017). *An Introduction to Distributed Optical Fibre Sensors*. Taylor & Francis Group. https://doi.org/10.1201/9781315119014

Hartog, A. H. (2002). Progress in distributed fiber optic temperature sensing. In M. A. Marcus & B. Culshaw (Eds.), *Proc. SPIE 4578, Fiber Optic Sensor Technology and Applications 2001* (pp. 43–52). International Society for Optics and Photonics. https://doi.org/10.1117/12.456092

Howarth, J. D., Barth, N. C., Fitzsimons, S. J., Richards-Dinger, K., Clark, K. J., Biasi, G. P., Cochran, U. A., Langridge, R. M., Berryman, K. R., & Sutherland, R. (2021). Spatiotemporal clustering of great earthquakes on a transform fault controlled by geometry. *Nature Geoscience*, *14*(May 2021), 314–320. https://doi.org/10.1038/s41561-021-00721-4

Janků-Čápová, L. (2018). *Thermal and hydraulic characterization of the hanging-wall of the central Alpine Fault* [Victoria University of Wellington]. https://researcharchive.vuw.ac.nz/xmlui/handle/10063/7648

Šafanda, J., Verner, K., Franěk, J., Peřestý, V., Holeček, J., & Fischer, T. (2020). Geology and geothermal potential in the eastern flank of Eger Rift (Litoměřice area, Czech Republic). *Geothermics, 86* (September 2019). https://doi.org/10.1016/j.geothermics.2020.101808

Sutherland, R., Townend, J., Toy, V., Allen, M., Baratin, L., Barth, N., Beacroft, L., Benson, A., Boese, C., Boles, A., Boulton, C., Capova, L., Carpenter, B., Celerier, B., Chamberlain, C., Conze, R., Cooper, A., Coussens, J., Coutts, A., … Zimmer, M. (2015). *Deep Fault Drilling Project (DFDP), Alpine Fault Boreholes DFDP-2A and DFDP-2B Technical Completion Report: Vol. 2015/50* (GNS Science Report, Issue 50).

Sutherland, Rupert, Townend, J., Toy, V. G., Upton, P., & DFDP-2B Science Team. (2017). Extreme hydrothermal conditions at an active plate-bounding fault. *Nature*. https://doi.org/10.1038/nature22355

Townend, J, Kellett, R., & Eccles, J. (2018). *Whataroa 2016 Seismic Experiment Acquisition Report* (Issue May). https://doi.org/10.21420/G2TK9T

Townend, John, Sutherland, R., Toy, V. G., Doan, M.-L., Célérier, B., Massiot, C., Coussens, J., Jeppson, T., Janku-Capova, L., Remaud, L., Upton, P., Schmitt, D. R., Pezard, P., Williams, J., Allen, M. J., Baratin, L.-M., Barth, N., Becroft, L., Boese, C. M., … Zimmer, M. (2017). Petrophysical, Geochemical, and Hydrological Evidence for Extensive Fracture-Mediated Fluid and Heat Transport in the Alpine Fault's Hanging-Wall Damage Zone. *Geochemistry, Geophysics, Geosystems*. https://doi.org/10.1002/2017GC007202

Toy, V. G., Sutherland, R., Townend, J., Allen, M. J., Becroft, L., Boles, A., Boulton, C., Carpenter, B., Cooper, A., Cox, S. C., Daube, C., Faulkner, D. R., Halfpenny, A., Kato, N., Keys, S., Kirilova, M., Kometani, Y., Little, T., Mariani, E., … Team, D.-2 S. (2017). Bedrock geology of DFDP-2B, central Alpine Fault, New Zealand. *New Zealand Journal of Geology and Geophysics*, 1–22. https://doi.org/10.1080/00288306.2017.1375533