DISTRIBUTED TEMPERATURE MEASUREMENTS AT AN ACTIVE PLATE-BOUNDING FAULT USING FIBRE OPTIC SENSORS

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ABSTRACT

New Zealand attracts people for its liveliness, but its geography produces more seismic events and the Southern Alpine Fault is one of the largest sources of such activities. Deep fault drilling project -2B was commissioned to explore and understand the geophysical properties of the fault at depth. This involves the distributed temperature monitoring along the depth of the boreholes in the Whataroa valley. Here, we report the development and field deployment of the Raman based distributed fibre optic temperature sensor. The temperature profiles and its gradient are estimated using the indigenous interrogator and results compared to those of the commercial DTS interrogator.

1. INTRODUCTION

The Alpine Fault, located at the boundary between the Pacific and Australian tectonic plates, is a unique natural laboratory for researchers across multiple countries. At 850 km long, this transform fault spans the entire length of the South Island and poses one of the greatest sources of seismic risk to NZ (Figure. 1). Paleo-seismic records at the central section of the fault reveal that a great earthquake of Mw (Moment magnitude)> 8 occurs on interval of 330 ± 60 years, and that an event is due. An event of this magnitude would propagate hundreds of kilometres uninhibited, causing significant impact to both land and community [1-2].

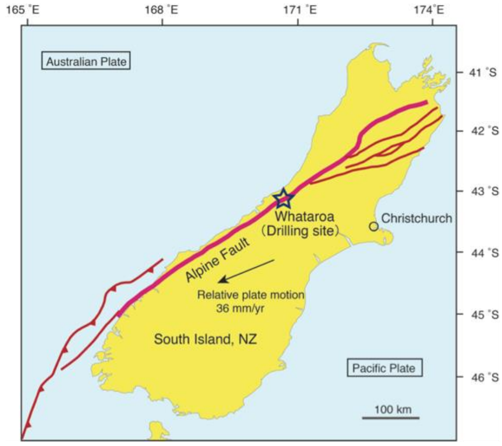

Figure 1: The Alpine fault at the boundary between the Australian and Pacific tectonic plates. Location of DFDP-2B borehole drilling site is highlighted. ***(Courtesy: Phys.org)***

Aiming at investigating the ambient and geophysical conditions before large earthquakes, the Deep Fault Drilling Project scientific borehole (DFDP-2B) was drilled in the Whataroa valley to a depth of 893 m. As part of this campaign, a fibre-optic cable was installed in the borehole for distributed temperature profiling and to better understand the fault at depth (Figure. 2). Downhole temperature monitoring is of paramount importance as it is important to understand the petro-physical properties and the rupture behaviour of the active faults [3]. In this paper, we present our developed Raman based fibre-optic distributed temperature sensor (Raman DTS) for continuous monitoring of temperature using the existing fibres in the borehole. This method relies on measuring the spectral shift in light scattered in fibre optic cable (Raman scattering).

In 2016, the DFDP-2B borehole was surveyed by a commercial DTS over a two month interval. Five years after the initial survey, in March 2021, we resurveyed the borehole temperature with the developed DTS. The mean temperature and corresponding gradient shows less variation in first 200-300 m, but shows significant change with increasing depth. Permanent continuous monitoring of such temperature profiles at depth is critical to develop a better understanding of conditions present around major fault. Owing to its unique capability of operating at high temperature environments over tens of kilometres depth, the developed sensor can offer a permanent solution for real-time, distributed and spatially localised temperature monitoring of geothermal-resources, without interrupting normal operations of the geothermal powerplant throughout its life-time.

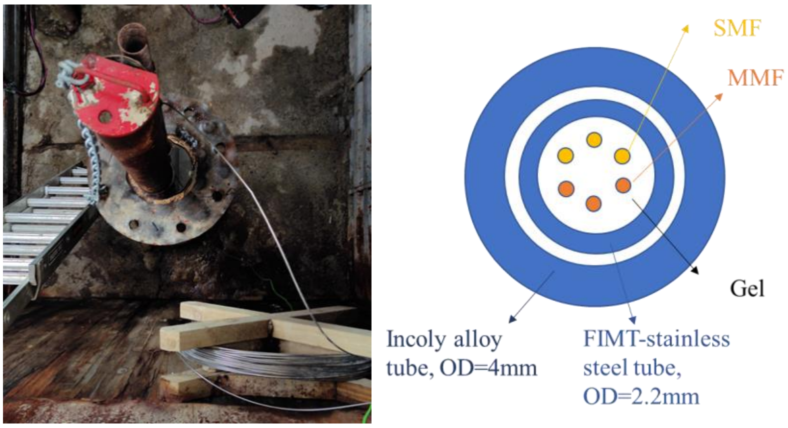

Figure 2: (a) Fibre optic cable in the borehole (b) Cross section of fibre in metal tube (FIMT) from Draka

2. THEORY AND TEMPERATURE CALIBRATION

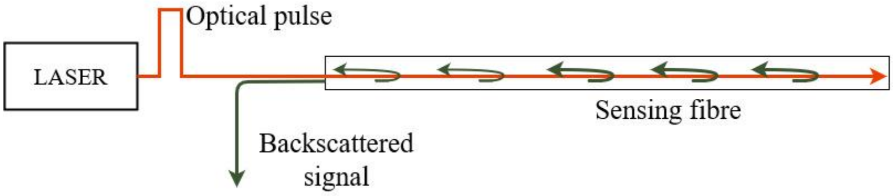

Figure 3: Schematic representation of Optical time domain reflectometry scheme. A light pulse from the laser source interacts with the optical fibre as it propagates down the fibre and this generates the back-scattered signal

Raman based DTS interrogators rely on the optical time domain reflectometry using the Raman back-scattered signal, an attractive choice for temperature characterisation from photons shifted to longer wavelength and shorter wavelength than Raleigh scattering respectively due to the differential dependence of the Stokes and anti-Stokes scattering on temperature. Raleigh scattering is predominantly elastic scattering of light by particles much smaller than the wavelength of the radiation [4-6]. Anti-Stoke signal intensity strongly depends on the temperature, whereas Stokes scattering exhibits weak temperature dependence. Hence, the temperature at any point can be estimated by taking the ratio of anti-Stokes (P_{AS}) to Stokes (P_S) intensity. The Stokes and anti-Stokes power P_S, P_{AS} can be expressed as

$$P_s(T,z) = K_s\lambda_S^{-4}P_0\rho_S\exp[-(\alpha_0+\alpha_S)z] \tag{1}$$

$$P_{As}(T,z) = K_{As}\lambda_{As}^{-4}P_0\rho_{As}\exp[-(\alpha_0+\alpha_{As})z] \tag{2}$$

Where P_0 is the launch power, K_{AS} and K_S the scattering co-efficient of Stokes and anti-Stokes, $\alpha_{0,S,As}$ is the attenuation coefficient of pump, Stokes and anti-Stokes, λ_S and λ_{AS} are the Stokes and anti-Stokes wavelengths and ρ is the temperature dependent Bose-Einstein probability distribution of phonons.

Raman DTS can be deployed in many different configurations, including single ended, double ended and loop configurations [7-9]. In our case, we focus on the single ended measurement configuration as we have access to only one end of the fibre installed in the borehole. In such a scheme, the temperature can be estimated using the expression given in Equation 3 [10].

$$T(z) = \frac{\gamma}{\ln\left(\frac{P_S(z)}{P_{aS}(z)}\right)+C-\Delta\alpha z} \tag{3}$$

Where γ represents the shift in energy between a photon at the wavelength of the incident laser and the scattered Raman photon, *C* is a dimensionless calibration and *Δα* is the differential attenuation between the anti-Stokes and Stokes signals in the fibre. The three key parameters γ, C and $\Delta\alpha$ are determined using the ratio of Stokes and anti-Stokes signal intensity at the reference fibre sections. Three independent measurements are necessary to estimate the three constant parameters. This can be experimentally achieved by keeping known lengths of spatially separated fibre sections in three known temperatures. The explicit steps involved in the estimation of the above parameters can be obtained from [10]. The DTS interrogator follows a dynamic calibration routine, in which the above calibration parameters are estimated during each data acquisition.

3. EXPERIMENTAL SETUP

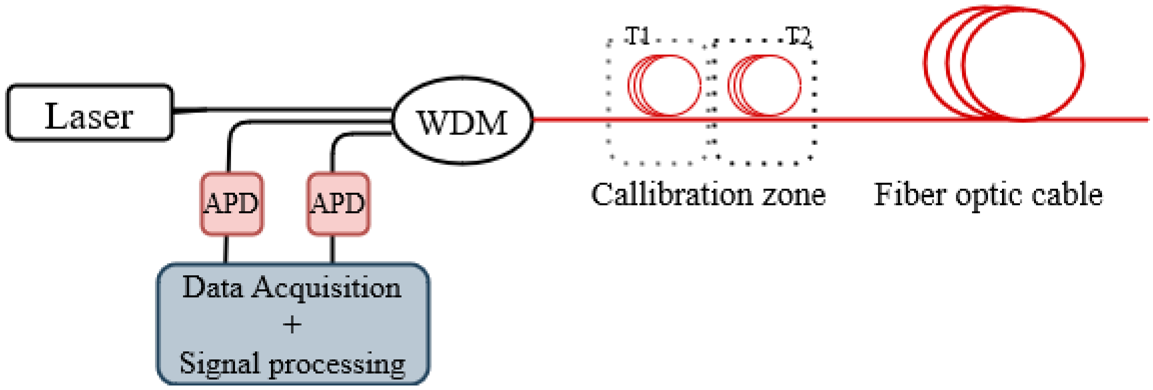

Figure 4: Schematic of the Raman DTS interrogator. WDM: Wavelength division multiplexer, APD: Avalanche Photodiode.

A schematic of the developed Raman DTS interrogator is shown in Figure. 4. It consists of a high-power laser with an operating wavelength of 1550 nm, a Wavelength division multiplexer (WDM), avalanche photodiodes (APDs) at Stokes and anti-Stokes wavelengths, and data acquisition and processing units. In order to estimate the temperature profile along the sensing fibre, the laser source is amplitude modulated using pulses with a duration of 10 ns at a repetition rate of 20 kHz. The amplified signal initiates the scattering processes in the sensing fibrer and the Stokes and anti-Stokes Raman components in the back-scattered signal are filtered using the WDM and detected using the respective APDs.

A temperature calibration zone with two temperature-controlled water-baths at arbitrarily chosen temperatures are used for the thermal characterization of the DTS interrogator. The temperatures of the water-baths are simultaneously monitored using PT-100 thermocouple probes. Fibre in metal tube (FIMT) installed in the borehole includes three strands of single mode fibres and three strands of multimode fibres enclosed in a gel-filled metal tube. Temperature characterisation of the borehole has been conducted using the DTS interrogator over the multimode fibres in the FIMT, which has an effective length of 893 m. Single–ended Raman optical time domain reflectometry configuration has been used for the measurement as the interrogator has access to only one end of the fibre cable in the borehole.

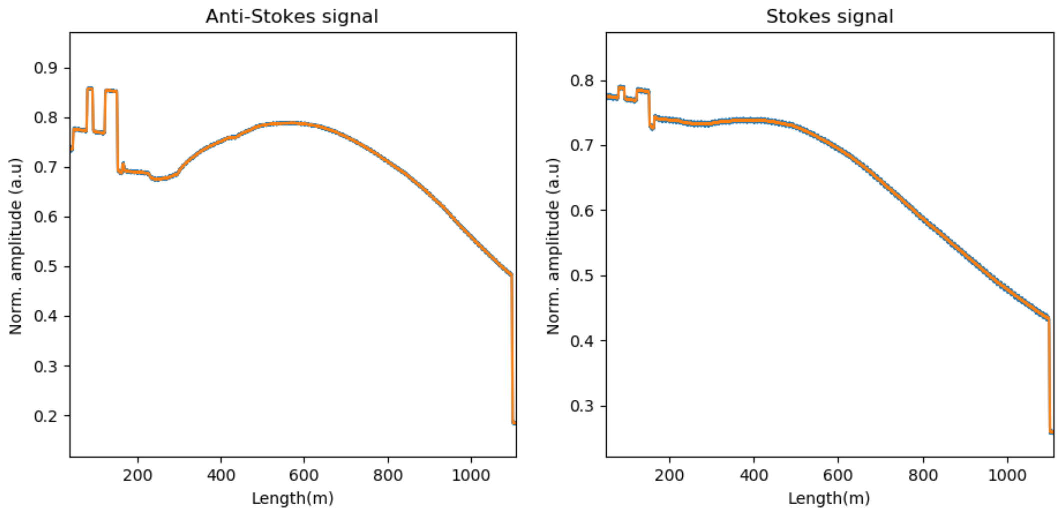

Figure 5: (a) Anti-stokes and (b) Stokes intensity along the sensing fibre

As mentioned in the previous section, this configuration demands three calibration zones for accurate temperature estimation, and this is achieved by using three fibre sections of the sensing fibre kept in the calibration baths (two sections at T1 and one section in T2) alternatively. The calibration baths are assumed to maintain constant temperature throughout the measurement time. The Stokes and anti-Stokes signals measured along the length of sensing fibre is shown in Figure. 5. This includes the fibre sections at the calibration baths, a 50 m section in the borehole cellar followed by 893 m along the borehole.

Temperature of the reference fibre sections are 60^{0}C, 30^{0}C and 60^{0}C respectively. The intensity of the Stokes and anti-Stokes signals are captured using oscilloscopes after 200k averages to filter out the spurious spikes in the signal and thereby improve the signal to noise ratio (SNR). In order to further improve the SNR, a first order Savitzky-Golay filter (a digital filter that can be applied to a set of digital data points for the purpose of smoothing the data) is applied on the averaged signal.

4. RESULTS AND DISCUSSION

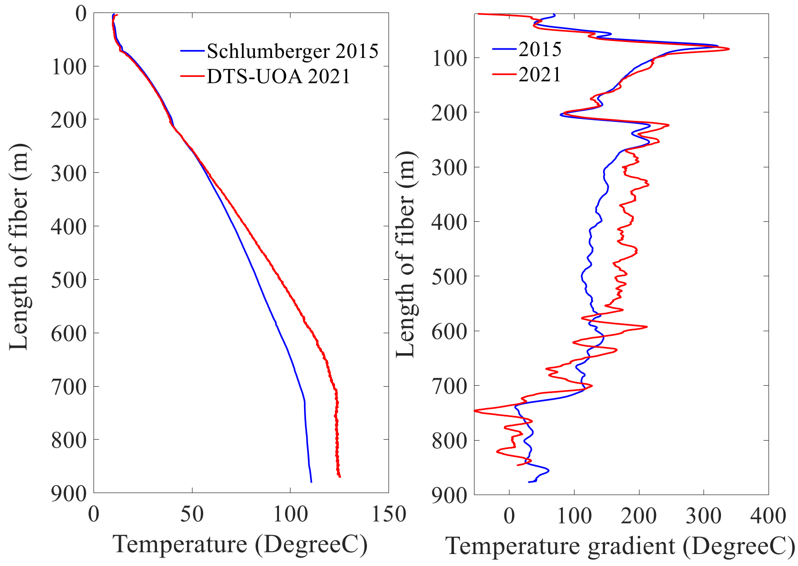

Figure 6: (a) Estimated temperature profile along the length of the borehole measured during the initial campaign using the commercial DTS from Schlumberger is shown along with that estimated in March 2021 using the DTS interrogator developed at UoA. (b) Depicts the gradient of temperature along the borehole.

Temperature and its gradient are critical parameters which reveal the thermal characteristics such as thermal conductivity, heat transfer etc. and are used to infer the locations of aquifers and aquitards. Compared to the conventional wire-line logging method, a distributed fibre optic sensor enables a cost-`effective permanent solution for real-time, distributed and spatially localized temperature information along the downhole. The calibration parameters are calculated using the reference fibre sections kept in the known temperature water baths and are used to estimate the temperature (Figure.6a) and its gradient (Figure.6b) along the borehole. Temperature measurements taken during 2015 using the commercial DTS interrogator are also depicted.

5. FUTURE DIRECTIONS

New Zealand is well-endowed with geothermal resources due to its geographical position along the pacific-Australian tectonic plate. With more than 60 years of geothermal power generation, NZ has gained a significant increase in power generation capacity. Longevity and sustainability of geothermal power generation solely rely on the local resource characteristics such as downhole temperature and pressure. There is a rapidly expanding need for continuous monitoring of the temperature gradient of the reservoir, which provides valuable information on the location of aquifers and their relative permeability. Owing to their unique capabilities, distributed fibre optic temperature sensors (DTS) offer a continuous real-time logging tool, and thereby reduce the complexity and cost by an order of magnitude compared to traditional sensors.

Apart from temperature sensing, the optical fibre can also be used as an acoustic detector, detecting seismic waves. Distributed acoustic sensors rely on the Rayleigh back scattered signal from the sensing fibre. Optical fibre can also be used for Distributed strain sensing (DSS) which opens up possibilities for acquiring high-resolution static and quasi-static strain profiles of deformations and provide insight to newly discovered slow-slip events that acts to relieve stress on the plate boundary.

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