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Wireline Distributed Temperature Measurements and Permanent Installations Behind Casing.

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ABSTRACT

Quasi-continuous temperature profiles can be measured in boreholes deploying fibre-optic distributed temperature sensing technology. In this paper, two different experimental designs using this technology are presented within case studies. For temporary installations, the sensor cable is lowered into the borehole, and after data acquisition the sensor cable is again retrieved. In the In-situ Geothermal Lab Groß Schönebeck a wireline DTS installation has been performed up to a depth of 4265 m and temperature of 143 °C. For long-term monitoring, or in cases when full access to the interior of the borehole is needed, the sensor cables are installed behind the borehole casing. The deployment of distributed temperature sensing technology proved to be successful for temperature monitoring in boreholes under a wide range of conditions, and it favors the observation of dynamic subsurface processes involving temperature changes. With wireline DTS installations, the open-hole and cased-hole sections of a borehole can be measured and multiple deployments can be performed with a single sensor cable. With the permanent installation behind casing, even abandoned and sealed wells can be monitored, which makes this method especially suitable for long-term thermal monitoring.

1. INTRODUCTION

Temperature measurements have long been recognized as an important tool for the monitoring of dynamic processes in the subsurface both in academia and industry. Within recent years, fibre-optic distributed temperature sensing (DTS) has been introduced as a new technology for the measurement of temperature in boreholes (e.g. Hurtig et al., 1993; Förster et al., 1997). Lately intricate installation procedures for the monitoring of flow conditions in oil and gas wells are under development, involving hydraulic injection of the optic fibre into small diameter control lines (e.g. Laurence, 2000). Within this paper two different experimental designs using DTS technology are presented within case studies and current developments are discussed.

Through the deployment of DTS technology, quasi-continuous temperature profiles can be measured with high temporal resolution. The principle of distributed temperature sensing is described in Hartog and Gamble (1991); Wisian et al. (1998) compare DTS to other conventional temperature logging methods.

Within previous projects, basically two different application methods for DTS have been used at GFZ Potsdam: For temporary installations, the sensor cable is lowered into the borehole, and after data acquisition the sensor cable is again retrieved. Following general wireline logging practice, this method will be referred to as the "wireline DTS installation". Nevertheless, in contrast to conventional wireline logging, where the logging tool is moved along the section of the borehole to be scanned, the DTS cable remains in place during the measurement of the temperature profiles. For long-term monitoring or in cases when full access to the interior of the borehole is needed, the sensor cables are installed behind the borehole casing. The specific procedures and advantages are highlighted within three case studies of temperature monitoring within the Hawaii Scientific Drilling Project (HSDP-2), the In-situ Geothermal Lab Groß Schönebeck, and the Mallik 2002 Gas Hydrate Production Research Well Program.

The DTS systems deployed within the studies presented here (opto-electronic units manufactured by Sensa, United Kingdom) enable the simultaneous online registration of temperature profiles along up to four different boreholes with an accuracy of ±0.3 °C. Prior and during the field experiments, individual calibrations of the deployed sensor cables were performed at the GFZ Potsdam and on site.

2. TEMPORARY WIRELINE DTS INSTALLATIONS

2.1 The Hawaii Scientific Drilling Project (HSDP-2)

In the framework of the International Continental Drilling Program (ICDP) various temperature measurements were carried out in the HSDP2 borehole (Hilo, Hawaii, see Fig. 1) using wireline DTS installations.

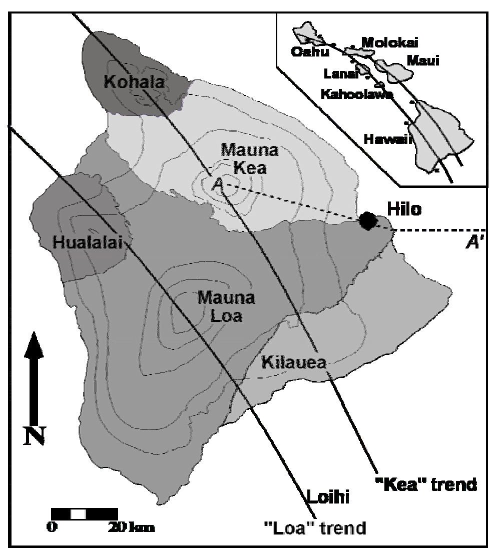

Figure 1: Map of the location of the HSDP2 borehole. The dotted line represents the profile (A-A') from the 2-D modeling (details in Büttner and Huenges, 2003). The inset shows all Hawaiian Island including the Island of Hawaii (adapted from DePaolo et al., 2001).

The main objective was the fundamental understanding of the thermal and hydraulic field of that ocean island (Big Island of Hawaii). We expected to get new insights to the unsolved questions of the effect of hydraulic conditions in the vicinity of the borehole. The result was a reliable model of the thermal-hydraulic field (Büttner and Huenges, 2003; Dannowski, 2002). In addition, a hydraulic experiment was performed in 2001 to enhance the understanding of the hydraulic field and its driving forces.

2.1.1 Installation of the sensor cable

The experimental set-up is displayed in Fig. 2. The set-up includes a packer in order to investigate pressure and temperature changes of the lower, open-hole section of the borehole. The DTS cable is guided through the packer. Below the packer a downhole pump is located. Since the HSDP2 well is a flowing artesian well, it was not used within the experiments described here.

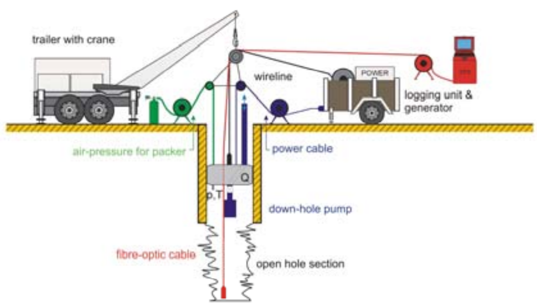

Figure 2: Experimental set-up of the wire-line installation of the sensor cable.

2.1.2 Temperature measurements

Fig. 3 shows the temperature profiles of the first measurement campaign in 1999 with a final depth of 600 m (Büttner and Huenges, 2003). Conventional temperature - depth plots at different times are displayed on the left side of Fig. 3. The mid part shows a time versus depth profile of temperature with a color image. The lithological column with the stratigraphic sequence of various lavas is displayed on the right side.

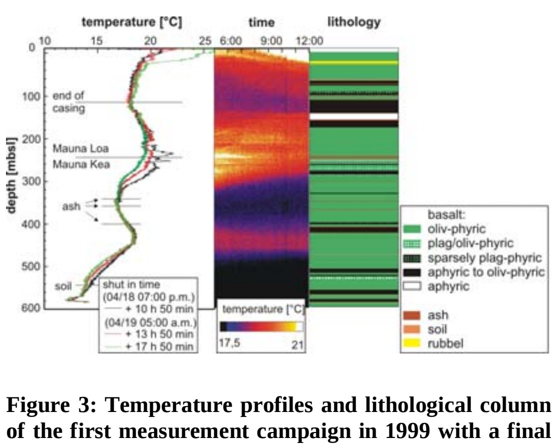

Figure 3: Temperature profiles and lithological column of the first measurement campaign in 1999 with a final depth of 600 m (modified after Büttner & Huenges, 2003).

Temperature measurements were performed to a depth of 2100 m during the last campaign in 2001. Access to the lower 1000 m of the borehole was not possible due to an obstruction. However, this obstruction did not seem to isolate the lower part hydraulically. Fig. 4 shows the temperature and pressure variation with closed packer that was installed in a depth of 380 m. The depth for the packer was chosen to omit the influence of a casing break above. The open-hole section starts below 1800 m. The temporal variation of pressure and temperature is due to tidal changes. Those were observed for the first time in this borehole. Obviously, the water column was lifted and lowered according to tidal change after the opening of the packer (Fig. 5).

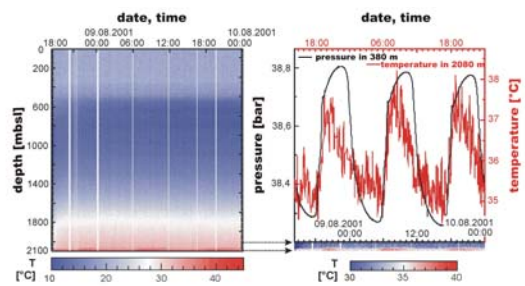

Figure 4: Temperature and pressure variation with closed packer. The open borehole section starts below 1800 m. Variation of pressure is due to tidal changes, which were observed for the first time in this borehole.

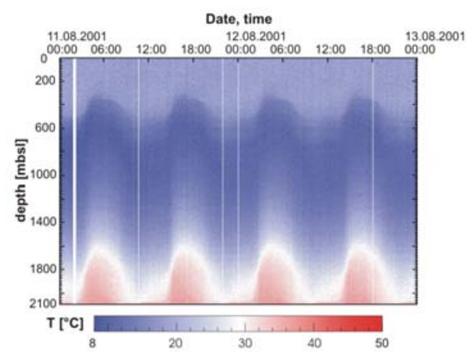

Figure 5: Temperature variation after opening of the packer. The profile shows that the water column was lifted and lowered according to tidal changes.

2.2 In-situ Geothermal Lab Groß Schönebeck, Germany

Wireline DTS temperature measurements were applied to characterize hydraulic active, stimulated horizons in a depth greater than 4 km and temperatures above 143 °C in highly saline formation fluids (TDS up to 256 g/l).

The well Groß Schönebeck 3/90, a former gas exploration well (Fig.6), was selected as geothermal laboratory because the geological setting is characteristic for many sedimentary basins worldwide: temperatures necessary for geothermal power generation are given but permeabilities of the sedimentary rocks are too low for a direct exploitation (Holl et al., 2005).

The site is used to develop hydraulic stimulation techniques to enhance permeability in siliciclastic sediments and volcanic rocks of the Permian Rotliegend formation. In this context DTS measurements shall serve to localize stimulated zones of enhanced permabilities during and after hydraulic tests.

Figure 6: Location of the well Groß Schönebeck 3/90, Germany

The target horizon was completed with a slotted liner in the interval between 4135 m and 4268.7 m. In December 2003 a massive hydraulic fracturing experiment was performed for several days with injection rates up to 80 l/s. With this treatment a significant productivity increase was achieved in the stimulated Rotliegend sandstones and the interpretation of hydraulic and pressure data proofed the presence of highly conductive fractures during injection. (Zimmermann et al., 2005) The remaining question was the distribution of the hydraulic active zones within the fractured interval.

2.2.1 Temperature measurements

To answer this question, 3 months after the massive stimulation experiment about 100 m³ cold fluid was pumped into the well and subsequent temperature measurements were carried out. A specially constructed high temperature fibre optic cable was used for the wireline DTS installation.

The DTS measurements (Fig. 7) show the internal structure of the stimulated sections and their transient temperature behavior. Two hydraulic active zones (Ia, Ib) were identified by the temperature log (B) recorded before the massive hydraulic stimulation the experiment. After the experiment a third zone (II) can clearly be distinguished within the slotted interval. This third zone was created as a result of the stimulation within the conglomerates and the volcanic rocks underlying the Rotliegend sandstone units. The measured transient temperature response is an important input parameter for the thermo-hydraulic modeling of the reservoir and its mechanical behavior.

The findings for the first time prove the feasibility of wireline DTS measurements in depths below 4 km and temperatures up to 143 °C in highly saline formation fluids. Future installations will allow measurements during production/injection tests and thus give valuable information about the performance and the sustainability of waterfrac treatments in deep reservoirs.

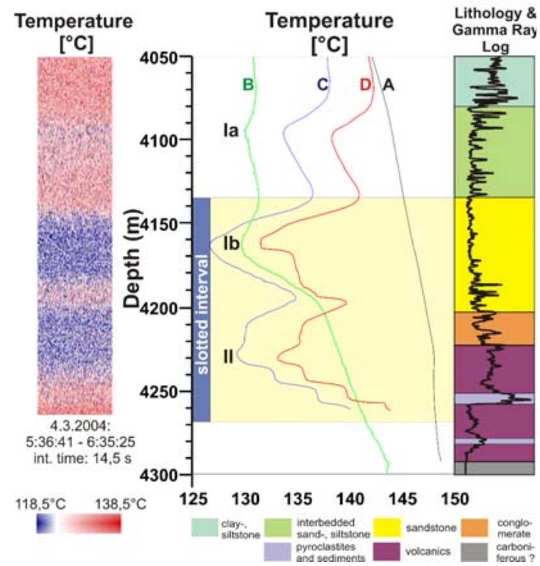

Figure 7: Temperature variations after cold-water injection into stimulated horizons. Temperature logs: A = after reopening (Oct. 2001), B = before massive stimulation (Nov. 4, 2003), C = Mar. 5, 2004, D = Apr. 28, 2004. Hydraulic active zones are denoted as Ia, Ib, II (see Text)

3. PERMANENT INSTALLATION OF SENSOR CABLES BEHIND THE BOREHOLE CASING: THE MALLIK 2002 GAS HYDRATE RESEARCH WELL PROGRAM

Within the framework of the Mallik 2002 Gas Hydrate Production Research Well Program (Dallimore et al., 2002), three 1180 m deep wells, spaced at 40 m, were equipped with permanent fibre-optic sensor cables (Fig. 8; Henninges et al., 2004). The field experiment was carried out in order to investigate the in-situ conditions of one of the most concentrated gas hydrate occurrences currently known, located at the coast of the Mackenzie Delta, Northwest Territories, Canada. Within the sedimentary succession, gas hydrate accumulations were found to occur between 810 m and 1104 m below ground level, overlain by a thick permafrost layer extending to a depth of about 600 m below ground level.

3.1 Installation of the sensor cables

In the central Mallik 5L-38 well DTS sensor cables were installed to 939 m depth, and on-line temperature monitoring during a thermal stimulation experiment was performed (Hancock et al., 2004). In the two lateral observation wells, the sensor cables were installed to a depth of 1158 m in order to determine the formation temperatures.

A special feature of the experiment design is the permanent installation of the sensor cables behind the borehole casing. After completion of the well, the sensor cables are located in the cement annulus between casing and borehole wall. The fibre-optic cables were attached to the outer side of the casing at every connector, within intervals of approximately 12 m, using custom-built cable clamps (Fig. 8 and Fig. 9).

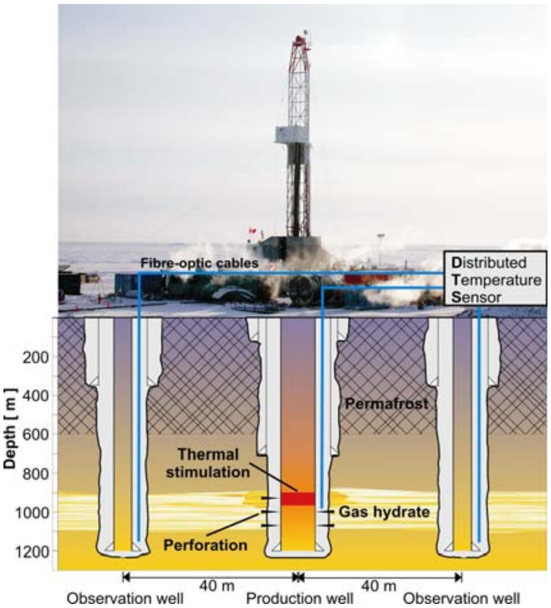

Figure 8: The Mallik 2002 Gas Hydrate Production Research Well Program drilling rig and a schematic cross section of the field experiment. After completion of the well the fibre-optic Distributed Temperature Sensing cable is embedded in the cement annulus between the casing and the borehole wall (modified after Henninges et al., 2003).

3.2 Temperature measurements

The DTS logging was started one to two days after completion of the respective well, and continuous monitoring of the well temperatures was performed over a period of up to 61 days. Government regulations for the abandonment procedure required that the wells be plugged and the casing cut below ground level. In order to enable future temperature measurements, the DTS cables were secured and left accessible during the abandonment of the wells. The surface ends of the sensor cables were stored in custom-designed steel boxes on site. Two subsequent DTS surveys were carried out for long-term temperature monitoring in October 2002 and September 2003 with a temporary set-up of the DTS equipment.

3.3 Measurement results and examples of evaluation

Excerpts of the recorded temperature data from one of the lateral observation wells are displayed in Figure 9 as temperature profiles for successive points in time after the cementing of the well. As a result of the thermal disturbance due to the drilling process, a continuous process of equilibration of the wellbore temperature to the temperature of the surrounding formation can be observed during the 21-month logging period between January 2002 and September 2003. The disturbed temperature profiles exhibit specific patterns, which are related to the mobilization of latent heat during the melting of permafrost and the decomposition of gas hydrate, as a result of the drilling and completion of the wells. These patterns were used as indicators for the location of the base of the ice-bonded permafrost and the gas hydrate occurrences (Henninges et al., 2004). A sinusoidal signature in the temperature-depth gradient marks the transition zone between the gas-hydrate-bearing and non gas-hydrate-bearing strata (Fig. 10). This "pseudo-discontinuity" of the temperature gradient and the related temperature step both gradually decrease over time as the thermal disturbance dissipates.

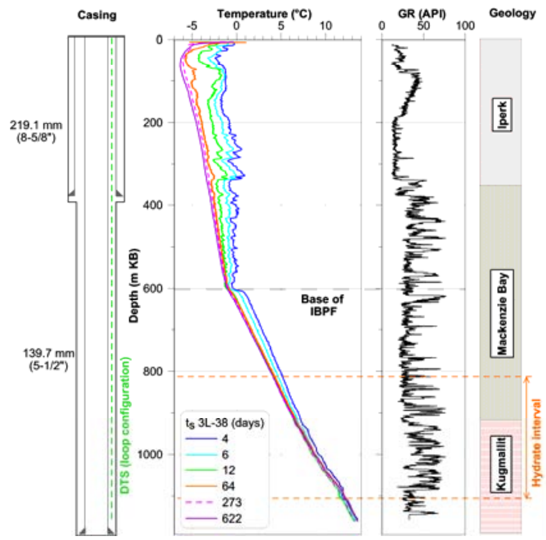

Figure 9: Temperature profiles of the Mallik 3L-38 observation well for successive times after completion of the well (t_s), cased-hole gamma-ray log (GR), well completion diagram (left) and sequence boundaries (right). IBPF = ice bearing permafrost. Modified after Henninges et al., 2004.

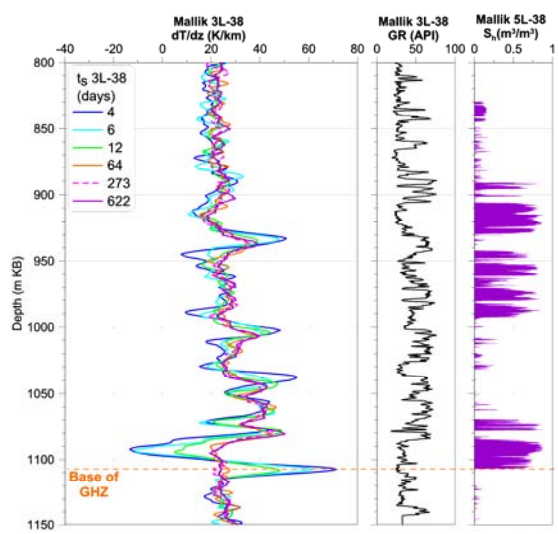

Figure 10: Detail of 10-m average temperature gradients (dT/dz), cased-hole gamma-ray log (GR), gas hydrate saturation (S_h, fraction of total porosity) for the zone of the gas hydrate occurrences (GHZ). The base of the GHZ is marked by a sinusoidal change of the temperature gradient, which gradually diminishes with time. Modified after Henninges et al., 2004.

4. CONCLUSIONS

The deployment of fibre-optic distributed temperature sensing proved to be successful for temperature monitoring in boreholes under a wide range of conditions. One of the main advantages of DTS technology is, that continuous temperature profiles can be registered with high spatial and temporal resolution. This favors the observation of dynamic subsurface processes involving temperature changes. In comparison to other conventional temperature logging equipment, a lower accuracy of the temperature data of +/- 0.3 °C has to be accepted.

The temporary installation of DTS sensor cables inside the borehole do not require that the sensor cable is moved during measurement in contrast to wireline logging. Advantages to the permanent installation behind the casing are, that the open-hole section of a borehole can be measured and multiple deployments can be performed with a single sensor cable. The permanent installation behind casing allows for full access to the well during the temperature measurement. Even abandoned and sealed wells can be monitored, which makes this method especially suitable for long-term thermal monitoring.

Borehole installations are posing high demands on the used materials. The cladding of the sensor cables has to be designed to protect the delicate optical fibre and to withstand high temperature and pressures, strongly corrosive formation fluids, as well as high mechanical stress during installation. For the well completion custom-designed fastenings, lead-throughs and optical connectors are required.

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