

Fibre-optic temperature measurements in boreholes

J. Henniges, G. Zimmermann, G. Büttner, J. Schrötter, K. Erbas, and E. Huenges
GeoForschungsZentrum Potsdam

Paper presented at the 7th FKPE-Workshop “Bohrlochgeophysik und Gesteinsphysik”
October 23-24, 2003, GeoZentrum Hannover, Germany.

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. Following general wireline logging practice, we refer to this method as the “wireline-type installation”. Nevertheless, in contrast to conventional wireline logging, where the logging tool is moved along the section of the borehole to be scanned, the sensor 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 deployment of distributed temperature sensing technology proved to be successful for temperature monitoring in boreholes under a wide range of conditions, and it favours the observation of dynamic subsurface processes involving temperature changes. With “wireline-type” 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.

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). 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 this paper two different experimental designs using DTS technology are presented within case studies and current developments as well as planned applications are described.

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-type” 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 two case studies of temperature monitoring within the Hawaii Scientific Drilling Project (HSDP-2) and 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.

Temporary “wireline-type” installation of sensor cables: The Hawaii Scientific Drilling Project (HSDP-2)

In the framework of the International Continental Drilling Program (ICDP) various field experiments were carried out with DTS wireline-type measurements in the HSDP2 borehole in Hilo, Hawaii (Fig. 1). The main objective of these experiments was the fundamental understanding of the thermal and hydraulic field of an ocean island (Big Island of Hawaii). We expected to get new insights to the unsolved questions of the hydraulic conditions in the vicinity of the borehole and hence a reliable model of the island hydrology (Büttner and Huenges, 2003; Dannowski, 2002).

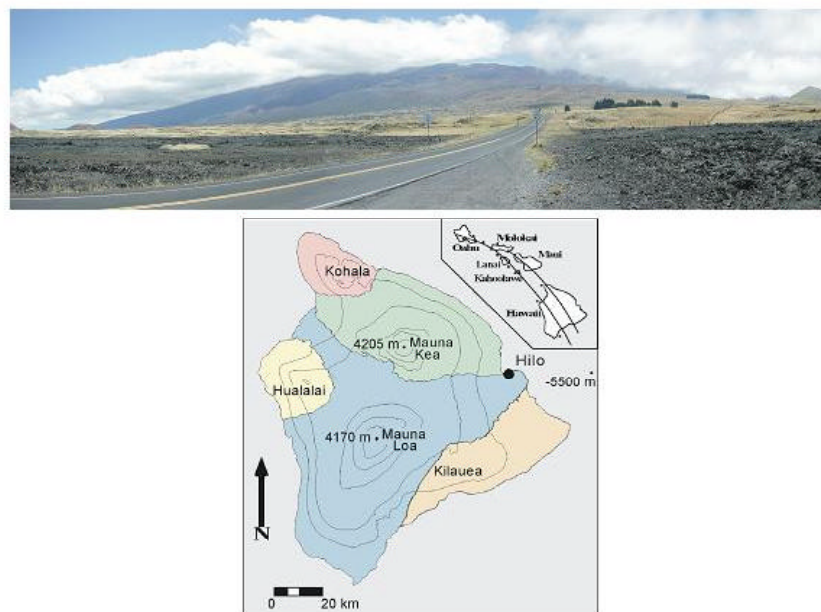


Figure 1: Map of the location of the HSDP2 borehole

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.

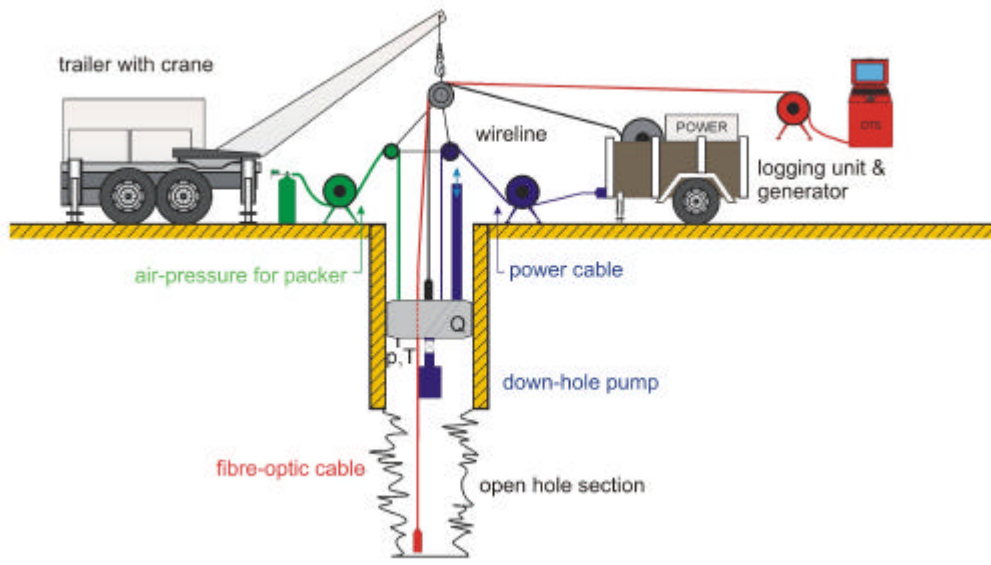


Figure 2: Experimental set-up of the wire-line installation of the sensor cable

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 colour image. The lithological column with the stratigraphic sequence of various lavas is displayed on the right side.

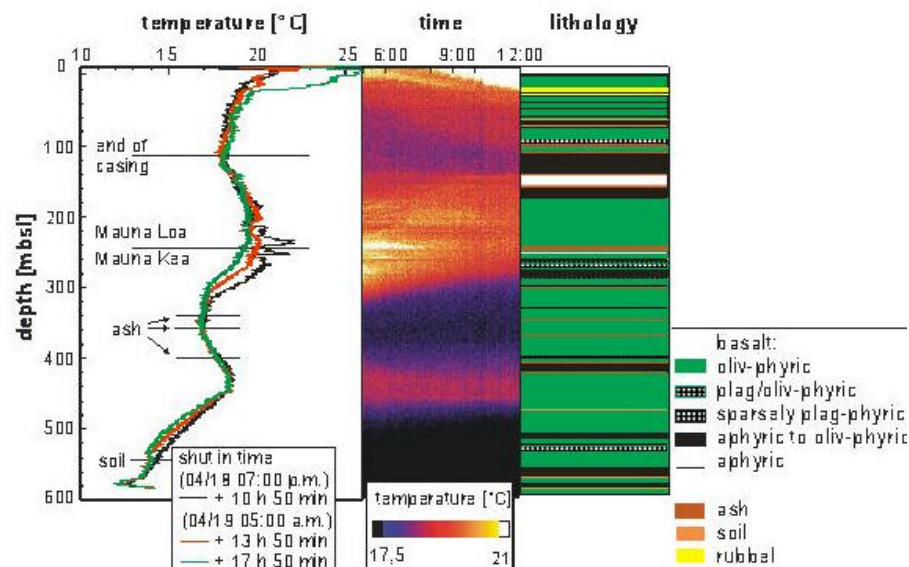


Figure 3: Temperature profiles and lithological column of the first measurement campaign in 1999 with a final depth of 600 m (from Büttner & Huenges, 2003).

During the last campaign in 2001 measurements were performed to a depth of 2100 m. Access to the lower 1000 m of the borehole was not possible due to an obstruction, which

nevertheless did not seem to isolate the lower part hydraulically. Fig. 4 shows the temperature and pressure variation with closed packer, which was installed in a depth of 380 m. This 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, which were observed for the first time in this borehole. After that the packer was opened and the water column was lifted and lowered according to tidal change (Fig. 5).

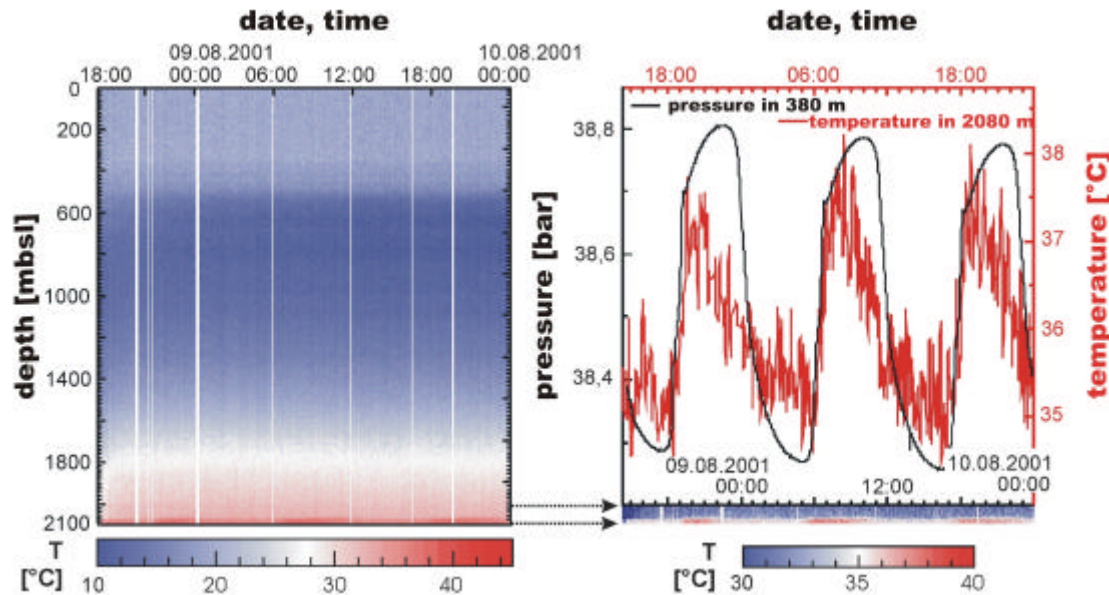


Figure 4: Temperature and pressure variation with closed packer. The open borehole section starts below 1800 m. Variation of pressure is due to tidal changes which were observed for the first time in this borehole.

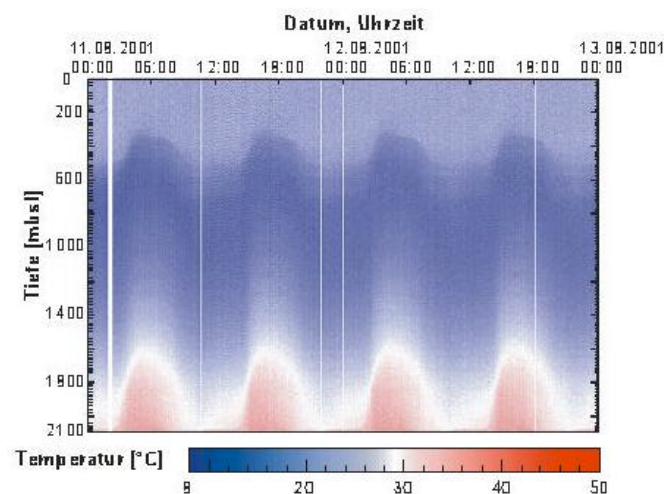


Figure 5: Temperature variation after opening of the packer. The profile shows that the water column was lifted and lowered according to tidal changes.

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 1200 m deep wells, spaced at 40 m, were equipped with permanent fibre-optic sensor cables (Fig. 6; 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 ~800 m and 1100 m below ground level, overlain by a thick permafrost layer extending to a depth of ~600 m below ground level.

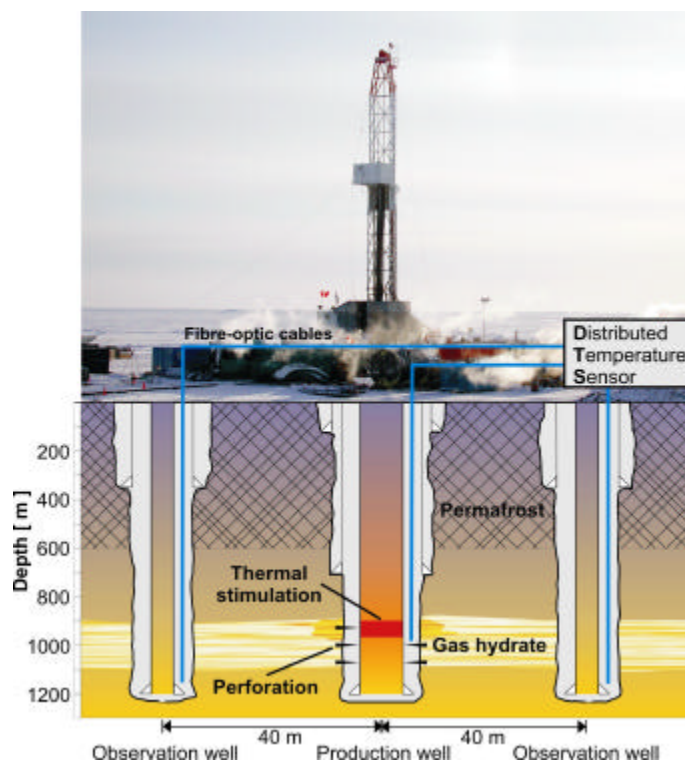


Figure 6: The Mallik 2002 Gas Hydrate Production Research Well Program drilling rig and a schematic cross section of the field experiment. After completion of the well the fibre-optic Distributed Temperature Sensing cable is embedded in the cement annulus between the casing and the borehole wall (modified after Henninges et al., 2003).

Installation of the sensor cables

In the central Mallik 5L-38 well DTS sensor cables were installed to ~940 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 ~1160 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. 7).



Figure 7: Permanent installation of the fibre-optic DTS cables: The sensor cables were attached with custom-built cable clamps during the installation of the borehole casing (modified after Henninges et al., 2003).

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 (Fig. 8).



Figure 8: Temporary set-up of the DTS-logging equipment at the flooded and partially frozen Mallik site in October 2002. Foreground: shelter for DTS instrument, background: steel boxes accommodating surface ends of sensor cables (modified after Henninges et al., 2003).

Measurement results and examples of evaluation

Excerpts from the recorded temperature data are displayed in Figure 9 as temperature profiles and temperature gradients for successive points in time after the cementing of the wells. 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 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 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. This “pseudo-discontinuity” of the temperature gradient and the related temperature step both gradually decrease over time as the thermal disturbance dissipates.

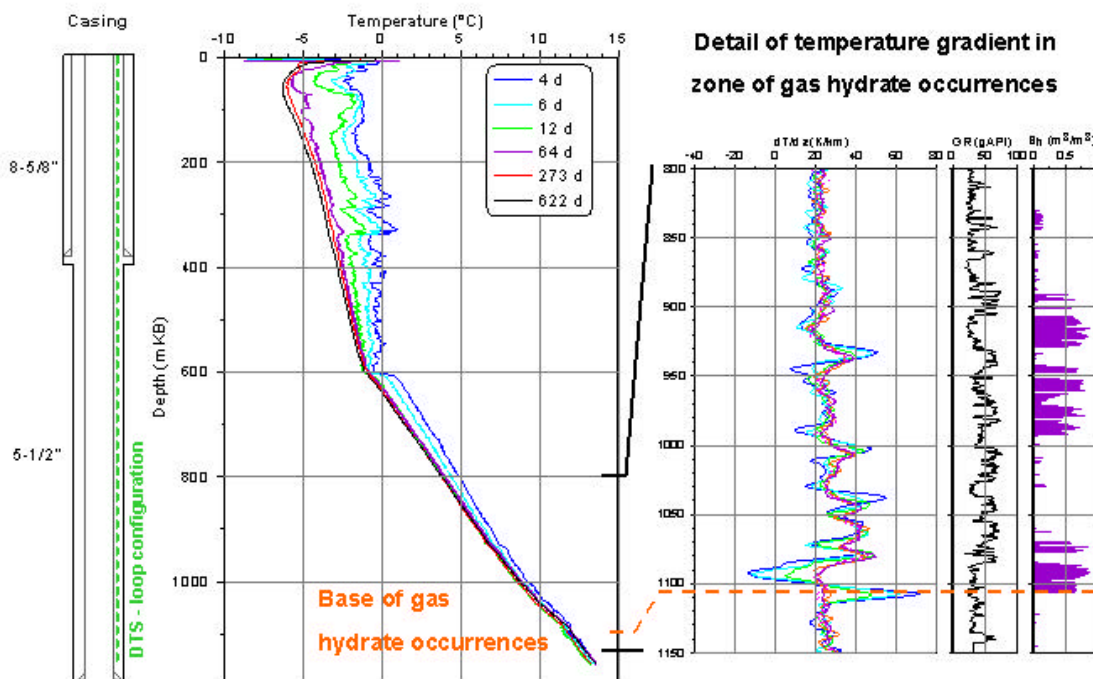


Figure 9: Temperature profiles and temperature gradients of the Mallik 3L-38 observation well for successive times after completion of the well (t_s). Detail shows profiles of 10-m average temperature gradients (dT/dz), gamma-ray log (GR), gas hydrate saturation (S_h , fraction of total porosity) for 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.

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 favours 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.

Acknowledgements

The Mallik project was funded by the German Ministry of Education and Science (BMBF) within the framework of the GEOTECHNOLOGIEN program, No. G0556A. The Mallik program participants include 7 partners (Geological Survey of Canada (GSC), Japan National Oil Corporation (JNOC), GeoForschungsZentrum Potsdam (GFZ), United States Geological Survey (USGS), United States Department of the Energy (USDOE), India Ministry of Petroleum and Natural Gas (MOPNG), BP-Chevron-Burlington joint venture group) and was supported by the International Continental Scientific Drilling Program (ICDP).

The Hawaii project was funded by the Deutsche Forschungsgemeinschaft (DFG) under grant HU 700/2.

References

- Büttner, G., and Huenges, E., 2003. The heat transfer in the region of the Mauna Kea (Hawaii) – constraints from borehole temperature measurements and coupled thermo-hydraulic modeling, *Tectonophysics*, 371, 1-4, 23-40
- Dallimore, S.R., Collett, T.S., Weber, M., and Uchida, T. (2002): Drilling program investigates permafrost gas hydrates; EOS, Transactions, American Geophysical Union, Vol. 38, No. 18, Pages 193, 189.
- Dannowski, G., Untersuchung des thermo-hydraulischen Feldes und der Wärmeflussdichte in der Nähe eines aktiven Mantelplumes (Insel Hawaii) mit Hilfe von Bohrlochtemperaturmessungen, Scientific Technical Report STR02/03, GeoForschungsZentrum Potsdam
- Förster, A., Schrötter, J., Merriam, D.F., and Blackwell, D.D. (1997): Application of optical-fiber temperature logging – An example in a sedimentary environment; *Geophysics*, 62 (4), p. 1107-1113.
- Hancock, S., Collett, T.S., Dallimore, S.R., Satoh, T., Huenges, E., and Henninges, J. (2004): Overview of thermal stimulation production test results for the Japex/JNOC/GSC Mallik 5L-38 Gas Hydrate Research Well.- In: Dallimore, S.R., and Collett, T.S. (eds.), *Scientific Results from Mallik 2002 Gas Hydrate Production Research Well Program*, Mackenzie Delta, Northwest Territories, Canada, Geological Survey of Canada Bulletin 585 (in press).
- Hartog, A., and Gamble, G. (1991): Photonic distributed sensing; *Physics World*, 3, p. 45-49.

- Henninges, J., Schrötter, J., Erbas, K., and Huenges, E. (2004): Temperature field of the Mallik gas hydrate occurrence – implications on phase changes and thermal properties.- In: Dallimore, S.R., and Collett, T.S. (eds.), Scientific Results from Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, Geological Survey of Canada Bulletin 585 (in press).
- Henninges, J., Böde, S., Schrötter, J., Erbas, K., Huenges, E., and the Mallik Working Group (2003): Permanent installation of fibre-optic DTS-cables in boreholes for temperature monitoring (abst.); EGS-AGU-EUG Joint Assembly (Nice, France), EGS Geophys. Research Abstracts, v.5 (CD).
- Hurtig, E., Schrötter, J., Großwig, S., Kühn, K., Harjes, B., Wieferig, W., and Orrell, R.P. (1993): Borehole temperature measurements using distributed fibre optic sensing; Scientific Drilling, 3 (6), p. 283-286.
- Wisian, K.W., Blackwell, D.D., Bellani, S., Henfling, J.A., Normann, R.A., Lysne, P.C., Förster, A., and Schrötter, J. (1998): Field comparison of conventional and new technology temperature logging systems; Geothermics, 27 (2), p. 131-141.