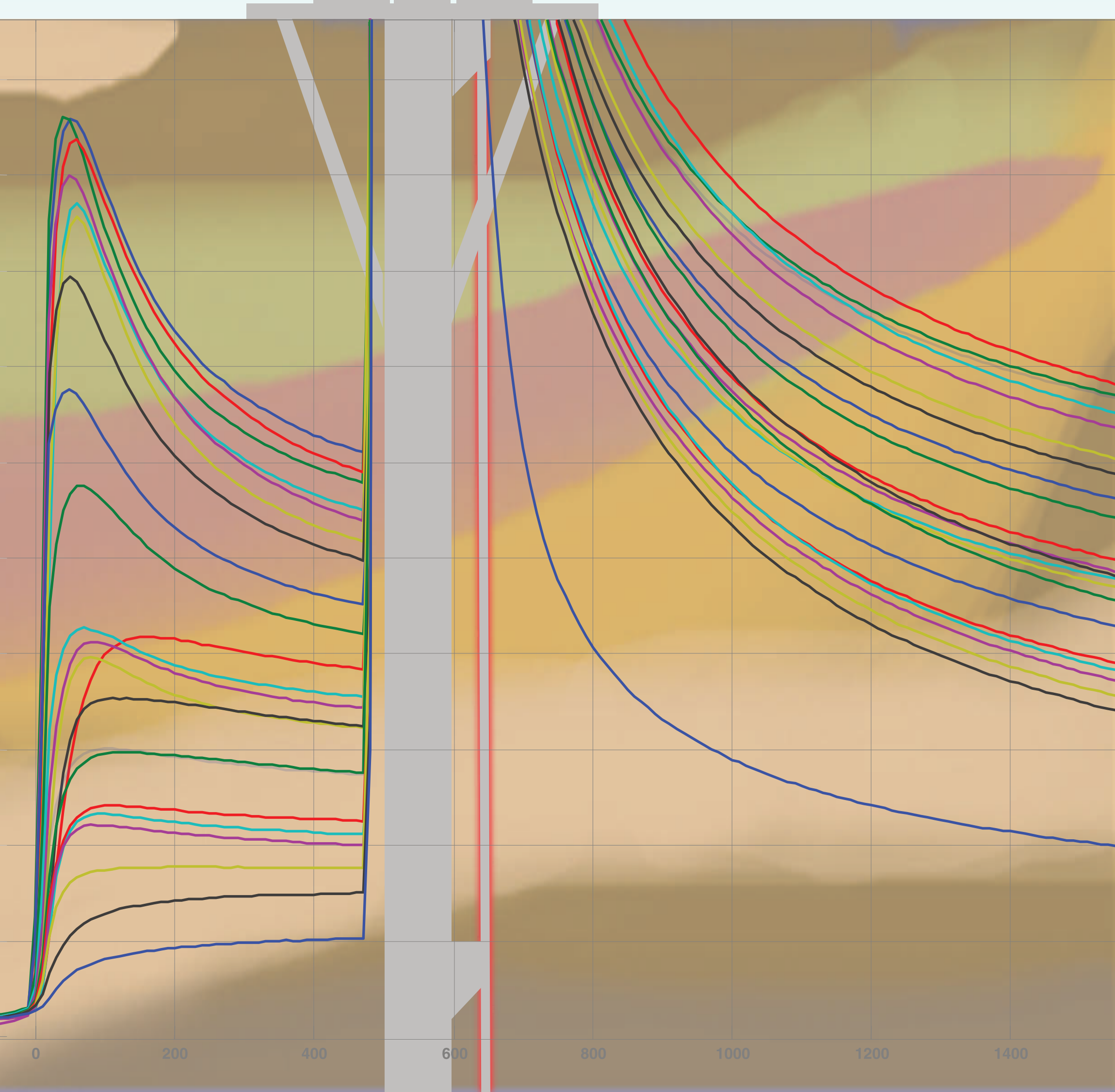
FIELAX

In-situ Thermal Testing



In-situ
Thermal Testing

Origin and development

Measuring the thermal properties of marine sediments has a long history in science and technology. The main scientific interest was originally focused on the determination of the geothermal heat flow of deep-sea sediments and its implication for the evolution of the Earth's crust. From the 1950s onwards, *Bullard* developed a method to determine the thermal conductivity and the temperature gradient in the seabed and used this to investigate the geothermal heat flow in marine environments.

Over time, the use of thermal conductivity data was adopted for industrial applications. Since the 1970s marine geothermal heat flow data have been used to constrain basin models for the formation of hydrocarbons in marine shelf areas. On land and in coastal waters, however, thermal conductivities of soils and sediments are of interest for several applications such as geothermal heat pumps and the thermal insolation of underground pipelines or cables.

Since the beginning of the 21st century, more and more cables and pipelines have been laid at sea. Especially for the burial of offshore (energy-) cables, knowledge of the thermal properties of sediments is of crucial importance, as offshore energy cables are designed for certain maximum core temperatures during load. The need for these measurements will increase in the future due to the rapid, widespread expansion of offshore renewable energy.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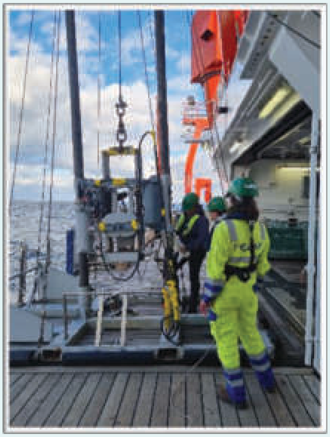


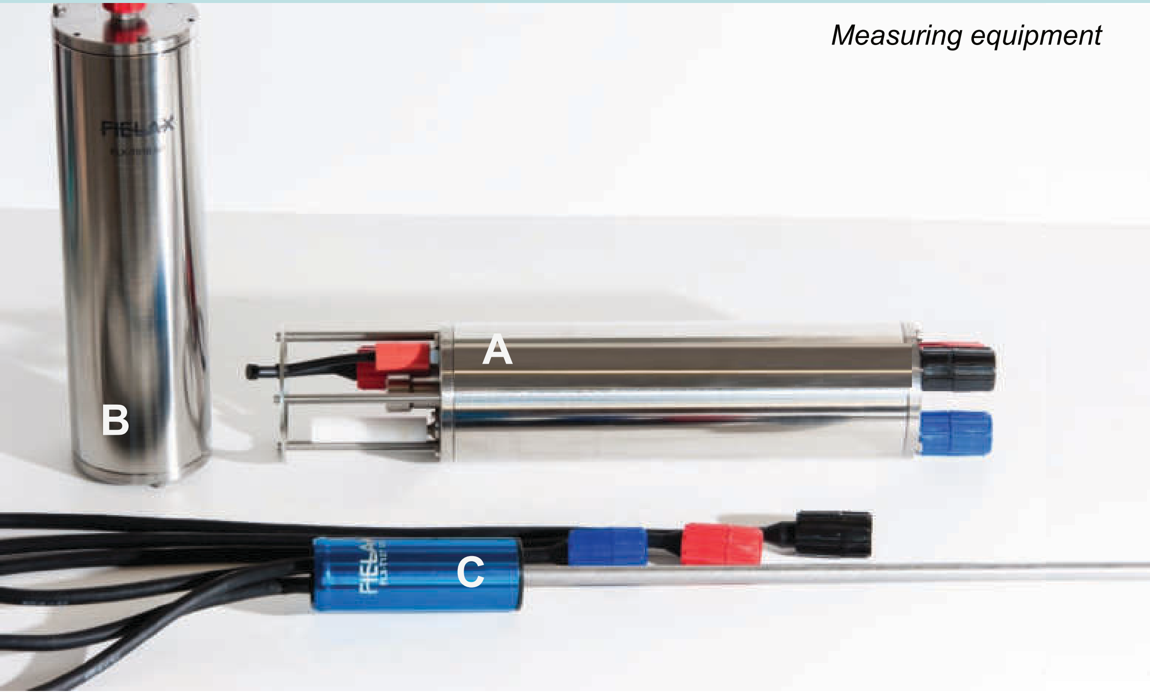
About us

FIELAX GmbH was founded in 2002 and is based downtown the German North Sea port Bremerhaven. The founders previously worked as scientists within Germany's polar and marine research and for a shipping company with strong commitment to research vessels. FIELAX offers scientific technical services and products for research and shipping. Our highly qualified team of scientists and engineers has longstanding experience in surveying operations on land and sea. Our clients benefit from this experience and from our expert knowledge in physics, geophysics, chemistry, mathematics, hydrography, information technology and electronics.

Over the last two decades, FIELAX has gained a wealth of experience in in-situ thermal measurements in various marine environments. Starting with classical heat flow probe measurements in soft deep-sea sediments, FIELAX has not only further developed its instrumentation to enable measurements in shallow water regions, but also the knowledge base and understanding of thermal transport processes in marine sediments from both natural and artificial sources.

The worldwide experience with thermal measurements in different marine environments makes FIELAX a pioneer in conducting in-situ thermal measurements and sets standards for data processing and interpretation.

Measuring equipment



Processing Software

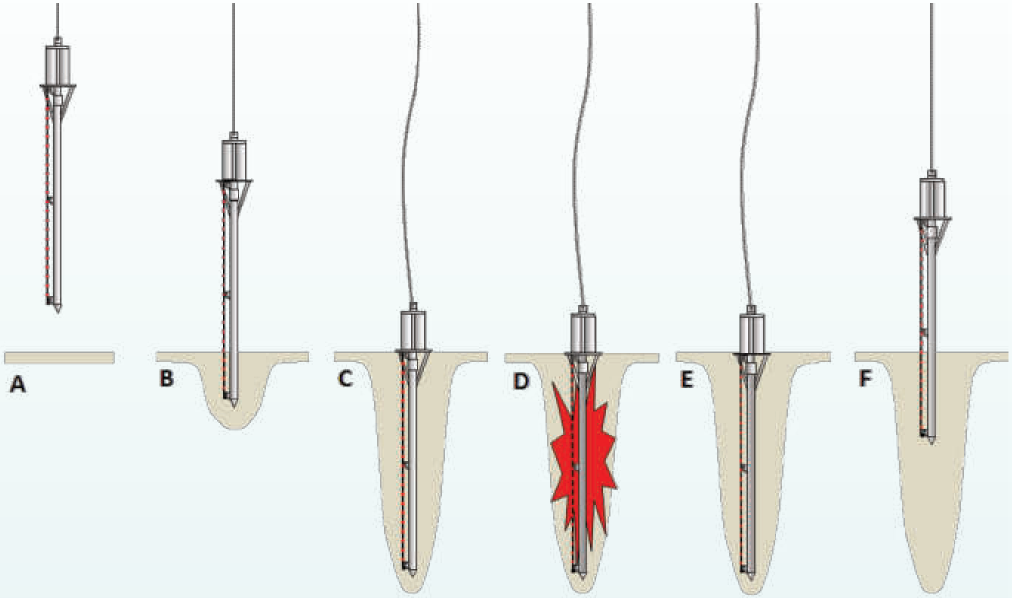
Heat Flow Temperature Data

- Quality Control
- Data Management
- Processing Tool

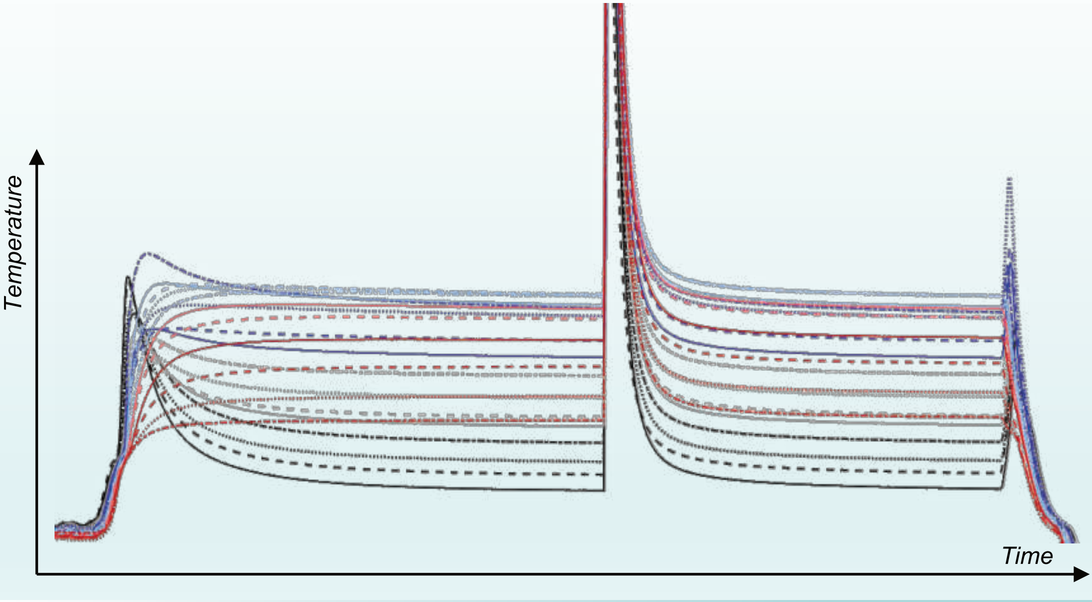
Instrumentation & Software

The thermal measurement equipment consists of three components. The data acquisition (**A**) and power supply (**B**) units are build in Grade-5 titanium pressure housings. Online or memory-based data recording with a frequency of 1 Hz is possible, which enables continuous recording for 2000 minutes. The temperature is recorded with thermistors that are arranged within a sensor string (**C**). The length of the sensor string is adjustable to the customer´s requirements, but the maximum number of thermistors is limited to 22. The sensors are designed for temperature ranges of -2°C to 60°C, with a resolution better than 1 mK and an accuracy of 2 mK. The sensor string also contains a heating wire, which is used to deliver a certain amount of energy to the sediments. The amount of energy delivered by heating is determined by precise voltage and current measurements. The measured temperature data are evaluated using specially developed software.

Schematic illustration of a thermal properties' measurement



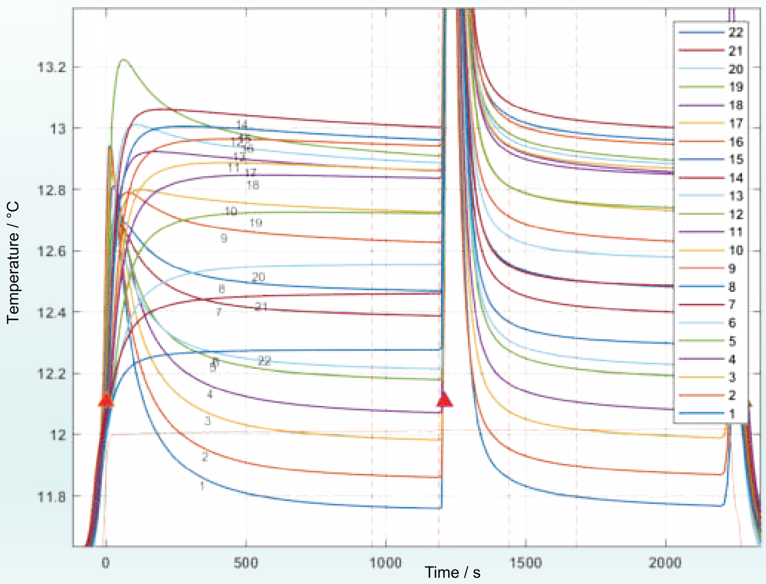
Corresponding temperature recordings of the 22 thermistors



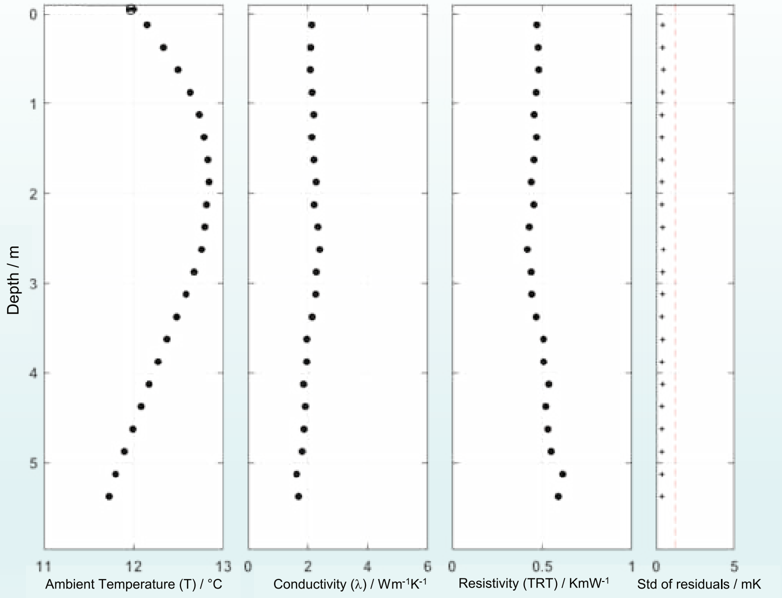
Temperature recording

The FIELAX system records temperature as a function of time. The data acquired are used to calculate the depth-dependent ambient temperatures and the sediment´s thermal conductivity. A full measuring cycle starts with the penetration process. The probe is lowered to the seafloor (**A**) and penetrates the sediment, causing the temperature to rise due to frictional heating (**B**). After a certain period of stability time (**C**), a heat pulse is released and heats up the sensor tube and the surrounding sediment (**D**). Typically, the temperature rises between 5 and 10 °C during the heating. The probe remains in the sediment to measure the thermal decay of the heat (**E**). The cycle ends with the retrieval of the probe (**F**). The total length of a measuring cycle (penetration to extraction) can be adjusted to the specific sediment type but is typically 35 to 40 minutes. The evolution of the temperatures depends on the energies during deployment and sediment type.

Temperature recording for each sensor



Depth dependent thermal parameters and quality marker



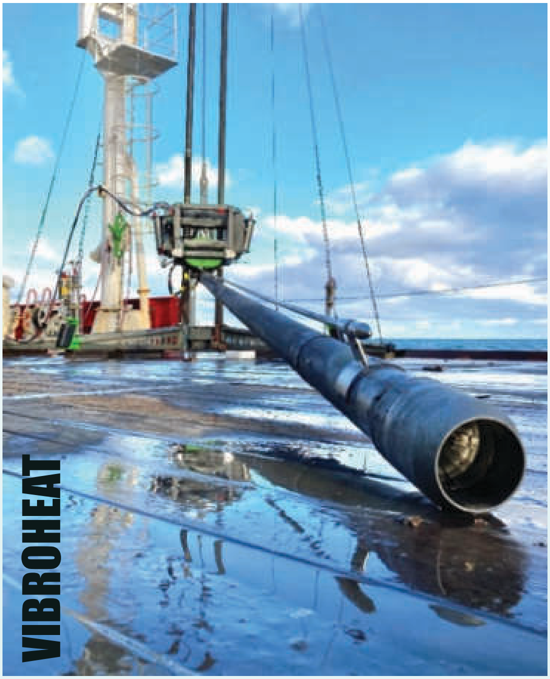
Data Processing

To calculate the in-situ temperature and thermal conductivity of the sediment, the inversion method is used according to *Hartmann & Villinger* (2002). In a simplified view, the in-situ temperature is determined by an asymptotic closure to equilibrium temperatures, the thermal conductivity is calculated from the decay of the exactly known heat pulse. FIELAX has examined both, synthetic and real data, to find the best time intervals for data evaluation with minimal mathematical error resulting in pre-set time intervals only to be changed if very high / very low conductivities are present.

The main assumption of this method is that the heat transport is caused by heat conduction only. The validity of this assumption is tested as follows: The calculated thermal conductivities and the known heat pulse are used to jointly calculate a theoretical temperature decay curve for each sensor. Each curve is then compared to the corresponding measured temperature vs. time data. The standard deviation of the residuals between these two curves provides an estimate of the quality of the results. Only values with a residual smaller than 1.2 mK are accepted.

Hartmann, A. & Villinger, H. (2002), Inversion of marine heat flow measurements by expansion of the temperature decay function, Geophys J Int 148:628–636.


HEATFLOW

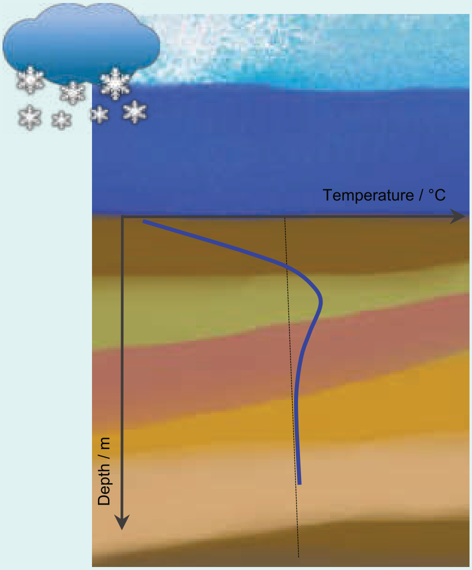

VIBROHEAT

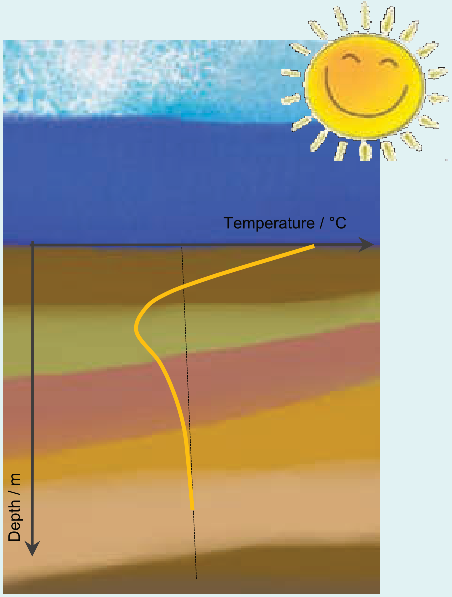

PUSHHEAT

Measurement Systems

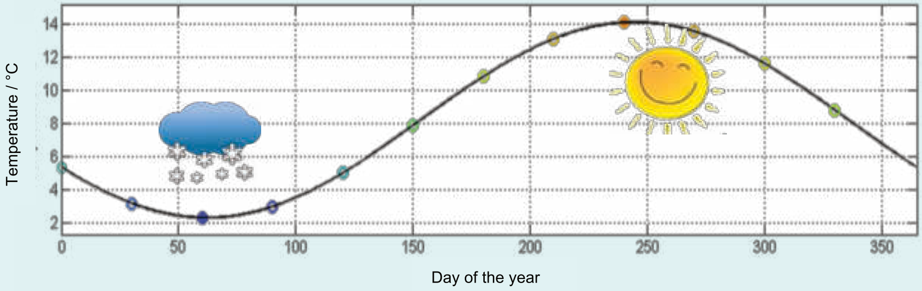
FIELAX system combined with geotechnical equipment

Sediment temperatures in shallow coastal regions

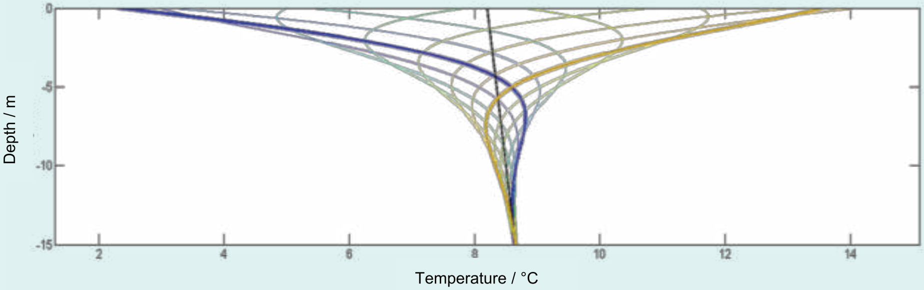




Annual bottom water temperature variations



Analytical solution



Sediment Temperatures

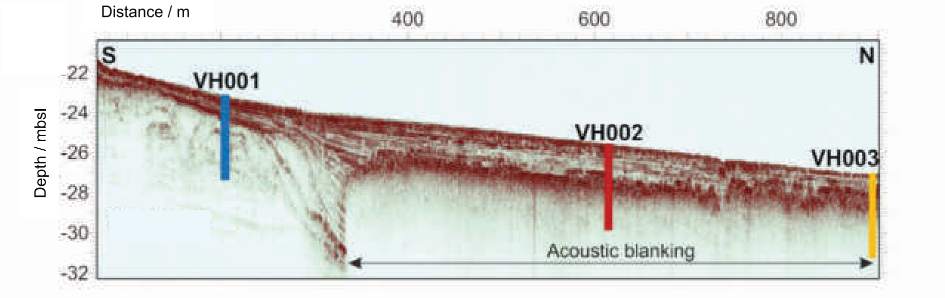
The effect of bottom water temperature variations

Sediment temperatures in shallow coastal areas are mainly driven by bottom water temperatures, which usually follow a seasonal cycle. Knowing the time of the maximum/minimum temperatures in the marine sediment at the burial depth can be important for e.g. the dimensioning of offshore energy cables.

The dimensioning and costs of power cables depend not only on the robustness and technical feasibility of cable installation, but also to a large extent on the thermal properties and the ambient temperature of the sediment. A realistic assumption about the bottom water temperature variations can significantly improve the assumptions for cable dimensioning and thus help to avoid considerable economic damage.

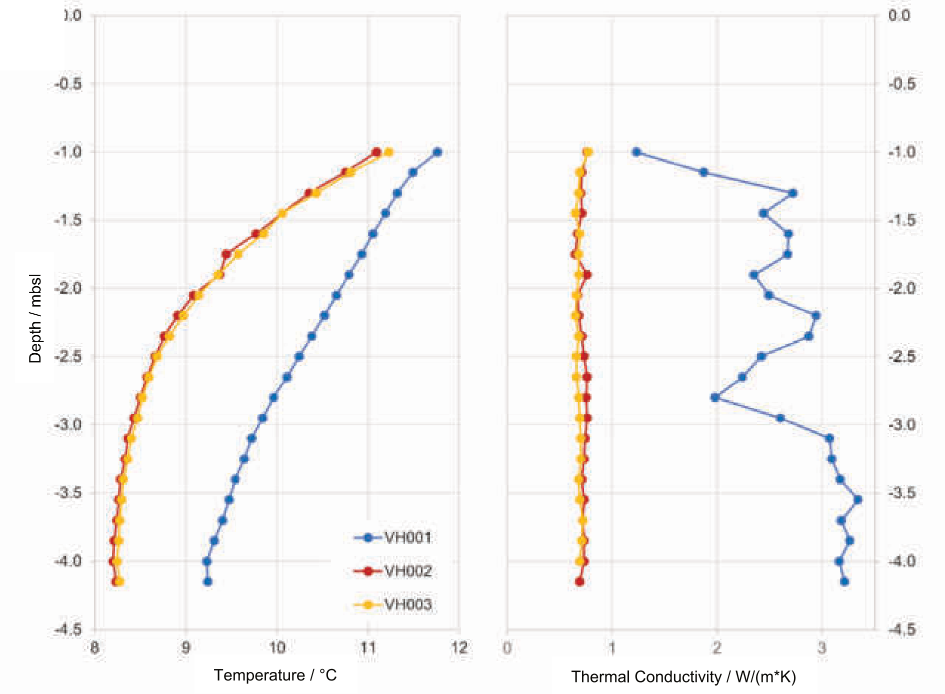
Left: (Top) Sediment temperatures in shallow coastal regions (e.g. Baltic and North Seas) naturally vary with season. In winter sediment temperatures increase with depth, with the higher temperatures reflecting the influence of the summer before. The temperatures in the summer decrease with depth with the lower temperatures reflecting the influence of the winter before. (Middle) Bottom water temperature variations approximated by a sinusoidel wave. (Bottom) Sediment temperatures as a function of depth with seasonal forcing from the surface for a homogenous sediment.

Depth section profile of sub-bottom profile with marked locations



(Usbeck et al., 2023)

Thermal properties measured in the German part of the Baltic Sea



(Usbeck et al., 2023)

Sediment Thermal Conductivity

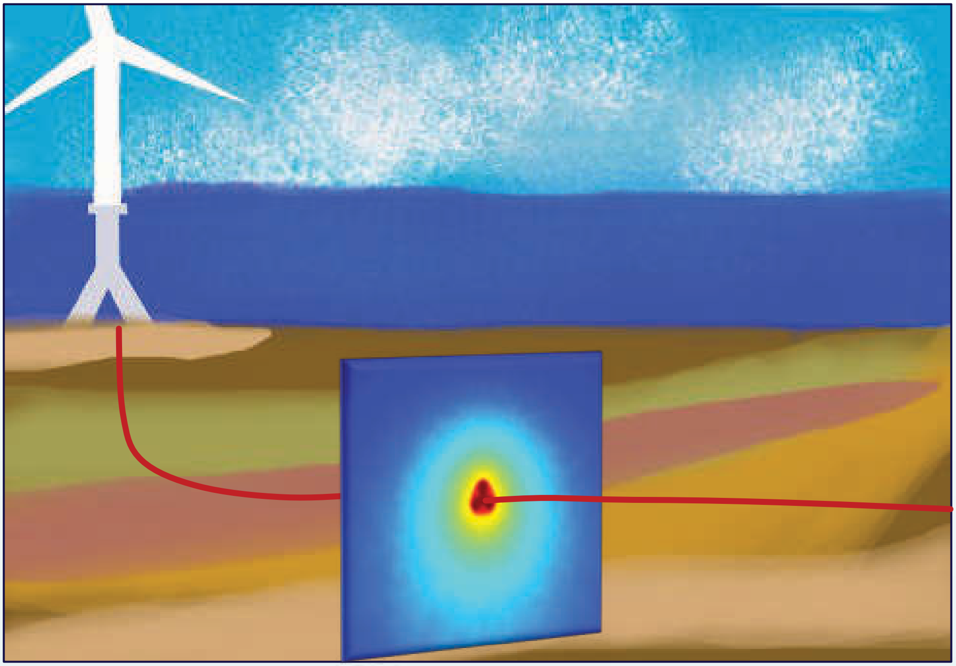
High variability in nearshore sediments

While thermal properties of deep ocean sediments are well studied, there is little published data for coastal sediments. In 2022/2023, FIELAX investigated the sediment temperatures and thermal conductivities of nearshore sediments in the German part of the Baltic Sea. The sediment temperatures nicely reflect the interplay of the response of the sediment to the seasonal cycle in connection with the sediments' thermal conductivity.

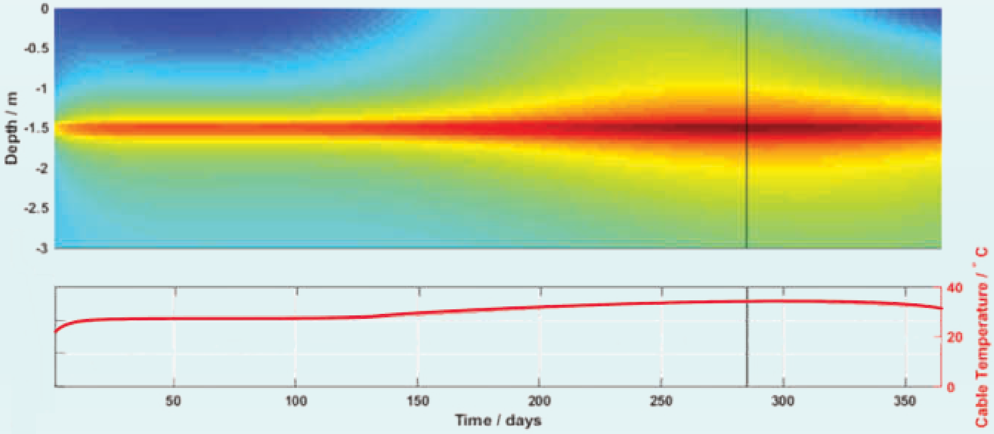
Usbeck et al. (2023) found that thermal conductivity values are ranging from 0.67 to 3.34 W/(m K) for the sediments down to approximately 4 meters below seafloor and within short distances. This variability exceeds that of conservative estimates widely used for coastal sediments and is also much higher than the variability found in the deep oceans. While sandy sediments typically show thermal conductivities larger than 1 W/(m K), organic-rich muds have lower values (< 1 W/(m K)). Hence, knowledge of the thermal properties of coastal sediments is becoming increasingly important due to the expanding offshore energy industry.

Left: (Top) Depth section profile of sub-bottom profile with marked locations and acoustic blanking as an indicator for free gas. (Bottom) Results of thermal properties for locations VH001, VH002 and VH003. The graphs show the temperature and thermal conductivity versus depth.

Temperature evolution in and around an energy cable



Temporal evolution of sediment temperatures



(modified after Müller et al., 2016)

Thermal Modelling

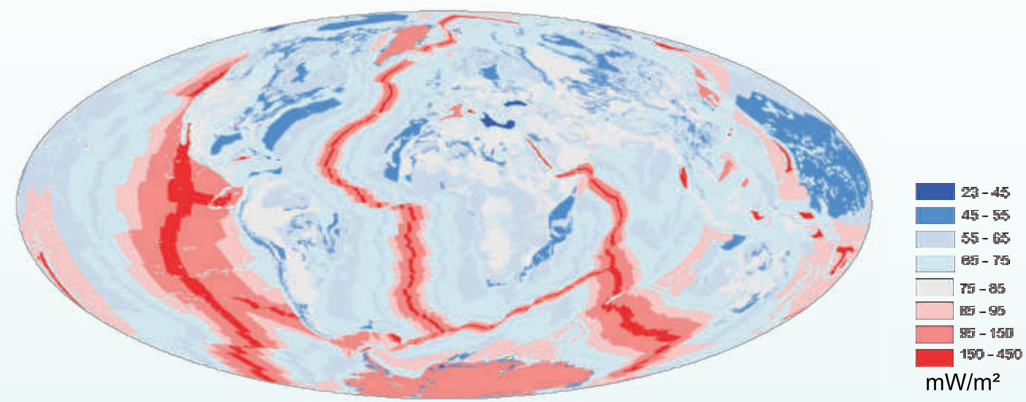
Offshore Cable Design

Offshore power cables laid in sediments are designed for certain maximum core temperatures during load and exceeding these temperatures can lead to permanent damage to the power cable. The ambient temperatures and the thermal conductivities of the sediments have a direct effect on the heat loss (cooling) of buried cables and consequently on their core temperatures. If the sediments do not allow sufficient cooling of the cables, their critical temperatures may be reached already during a regular power transmission and not only under full load.

Therefore, the thermal conductivities of sediments along proposed routes for underground power cables are of interest to the offshore industry, and the demand for these measurements is steadily increasing due to the rapid development of offshore renewable energy. FIELAX offers computer modelling based on in-situ measured sediment properties and water temperatures to estimate the thermal energy dissipation mechanisms and the environmental impact of submarine cables.

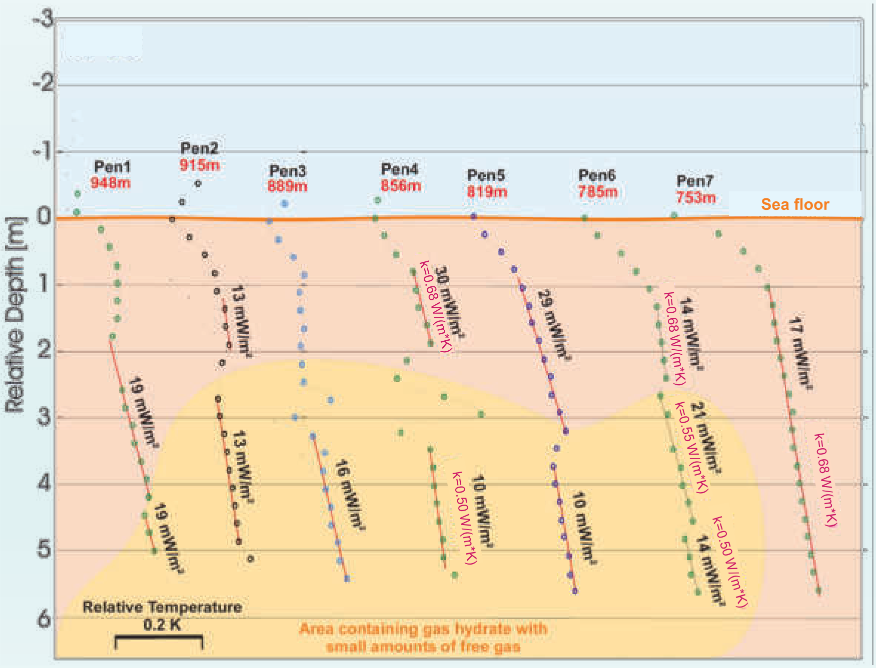
Left: (Top) Finite element method (FEM) based 2D-model for the temperature field in and around a subsea cable. The model calculates the temperature in and around the buried power cable in a vertical plane perpendicular to the cable. (Bottom) Annual variations of the sediment temperatures: The example shows the temporal evolution for a submarine power cable buried in 1.5 m depth and a constant power loss of 50 W/m, turned on at day 1. The temporal evolution is caused by seasonal forcing.

Global heat flow model



Davies, J.H. & Davies, D.R. (2010), Earth´s surface heat flux, Solid Earth, 1: 5-24.

Temperature profiles across a gas hydrate reservoir



Geothermal Heat Flow

Scientific Applications

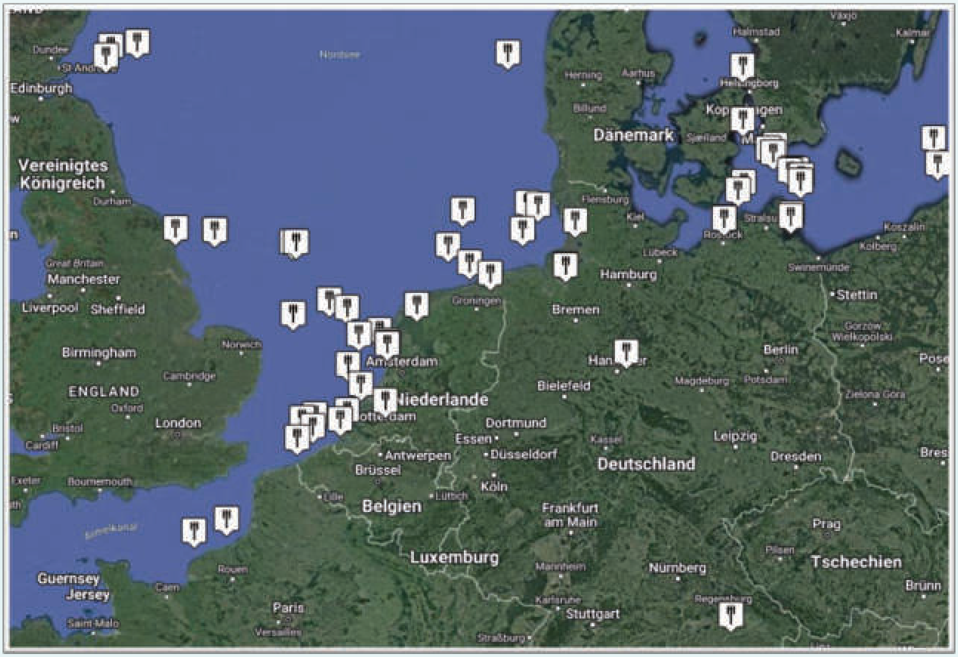
The term ‘geothermal heat flow’ refers to the thermal energy that dissipates constantly from its sources within the earth to the surface, either by convection or conduction. Geothermal heat is the driving force for a variety of multi-scale geologic processes taking place in the Earth’s crust and lithosphere e.g. plate tectonics. The internal temperature of the earth increases with depth. Near the surface, the average geothermal gradient is relatively constant with on average 30 K for every kilometer of depth.

Heat flow measurements enable stability analysis of gas hydrate deposits. Gas hydrates have been found to occur naturally in large quantities in ocean sediments, deep lake sediments, and permafrost regions. The amount of methane potentially trapped in natural gas hydrate deposits is significant, which makes them of major interest as a potential energy resource for the future.

In the field of petroleum geology, heat flow measurements are essential in the exploration of new oil and gas reservoirs, as they provide critical constraints for sedimentary basin modeling and aid in thermal maturity calculations. In order to determine the probability of oil and gas formation it is decisive to unravel the thermal history of potential source beds, as the generation of hydrocarbons strongly depends on the temperature the sedimentary source rock has experienced since deposition.

Furthermore, many experts see geothermal power also as an essential component of the world’s green-energy future.

FIELAX's worldwide experience with thermal measurements



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