



# High variability and exceptionally low thermal conductivities in nearshore sediments: a case study from the Eckernförde Bay

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## Abstract

Heat flow measurements are a standard technique in Geophysics both onshore and offshore. Recently, such measurements became increasingly important in shallow waters. The increasing amount of offshore power installations makes it necessary to have a good knowledge about the subsurface heat flow and the thermal properties of the sediments to optimize the construction of the necessary powerlines. While the thermal properties are well studied for deep ocean sediments, only few published data exist for nearshore sediments. In this study, we investigate the sediment temperatures and thermal conductivities of nearshore sediments in the German part of the Baltic Sea. The shallow sediment temperatures reflect the interplay of the response to the seasonal cycle in connection with the sediments' thermal conductivity. We find thermal conductivity values ranging from 0.67 to 3.34 W/(m\*K) for the sediments down to ~4.2 m below seafloor. 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. Sandy sediments show thermal conductivities larger than 1 W/(m\*K) whereas organic-rich muds have lower values (< 1 W/(m\*K)). Furthermore, the thermal conductivities seem to decrease with increasing free gas content in the sediment. The latter needs to be confirmed by further investigations.

**Keywords** Coastal sediments · In-situ thermal response test · Sediment temperature · Shallow gas · Thermal conductivity

## Introduction

### Thermal properties of marine sediments

The measurement of thermal properties of marine sediments has a long history in science and technology. Hence, extensive literature is available on deep sea heat flow (Davies 2013 and references therein). The main scientific interest 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. Starting in the 1950s, Bullard (Bullard et al. 1956) developed a method to determine the thermal conductivity and the temperature gradient in the seafloor and used this to investigate the geothermal heat flow in the marine realm. The methods for measurement and calculation were further refined by Lister (1970), Hyndman et al. (1979), Goto and Matsubayashi (2008) and others.

The use of thermal conductivity data has been adopted in industrial applications. Starting in the 1970's, geothermal marine heat flow data have been used to confine basin models for the formation of hydrocarbons in the marine shelf areas (McKenzie 1978). On land and in coastal waters, in contrast, the thermal conductivities of soils and sediments are of interest for various applications such as geothermal heat pumps and the thermal isolation of underground pipelines or cables. Since the beginning of the 21st century, an increasing number of cables and pipelines were installed offshore. Specifically, for the burial of offshore (energy-) cables, the knowledge of the thermal properties of the sediments is essential since offshore energy cables are designed for certain maximum core temperatures during load (Anders

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and Brakelmann 2018). Exceeding the maximum core temperature leads to a permanent damage of the energy cable. The thermal conductivity and sediment temperature directly affect the thermal loss (cooling) of buried energy cables and, consequently, their temperature. 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 conductivity of sediments along designated electrical underground cable routes is also measured by the offshore industry and the demand for these measurements will increase in the future due to the fast-paced widespread development of offshore renewable energy.

### Knowledge on coastal sediment conductivities

Today, a vast number of thermal conductivity data exist in coastal regions for the upper 6 m of the sediments, but only few of them are published as their acquisition was mostly done by the industry. Furthermore, thermal properties of nearshore sediments are not yet in focus of the science community. Some industrial data are available through the web portal of the Netherlands Enterprise Agency, for instance, Brijder (2022) reports thermal conductivity values for sandy sediments in the North Sea ranging between 1.04 and 3.32 W/(m<sup>3</sup>K). Similar values were published by Müller et al. (2016) who investigated thermal conductivities in shallow, sandy sediments in the Baltic Sea. Müller et al. (2016) report values in a range between 1.36 and 2.02 W/(m<sup>3</sup>K). The range in thermal conductivity values in both publications can be explained by a highly variable, local sediment composition. For example, lab-studies for water saturated sands show that the thermal conductivity depends on grain size and degree of consolidation of the sand. The lab values range between approx. 1.2–4.2 W/(m<sup>3</sup>K) (Cortes et al. 2009; Lee et al. 2016). In contrast, thermal conductivities of organic-rich sediments are generally found to be very low (< 1 W/(m<sup>3</sup>K)). These values were investigated in organic-rich sediments, e.g., in the Black Sea (Poort et al. 2007) or in the Saanich Inlet, Canada (Hyndman 1976). On the basis of laboratory experiments, He et al. (2021) found that thermal conductivities of organic-rich soils (> 5% organic content) are smaller than 1 W/(m<sup>3</sup>K) and decrease with increasing organic content.

The sediments of the Baltic Sea are generally of large heterogeneity, both, laterally and with depth. This is not surprising since during its geological history most of the area often fell dry due to sea level variations and/or were modified/eroded/deposited during advances and retreats of the Scandinavian ice sheet during several glacial/interglacial cycles. Organic rich muds prevail in the deeper basins of the Baltic Sea (> 20 m water depth) while sands of variable grain size, gravel, till and lag sediments irregularly stand out in the shallow coastal areas. Grainsize variations from clay to sand/gravel at relatively short distances are common (Tauber 2012).

The particulate organic content in the surface sediments in the Baltic Sea ranges from less than 0.1% in shallow sandy areas to 16% in deeper muddy basins (Leipe et al. 2011 and references therein). In sediments of very high organic content, shallow gas may form by the consumption of organic material in an anoxic environment resulting in the reduction of sulfate and methanogenesis (Floodgate and Judd 1992). The presence of free gas may further influence the bulk thermal properties of the sediments since the thermal conductivity of free gas (i.e., bubbles) is very low. For example, the thermal conductivity of methane at a temperature of 20 °C and 1 bar is just 0.034 W/(m<sup>3</sup>K) (Friend et al. 1989). If the methane concentration exceeds solubility in the pore water, discrete gas bubbles and gas-filled voids will form (Abegg and Anderson 1997), which will effectively reduce the bulk thermal conductivity of the sediments.

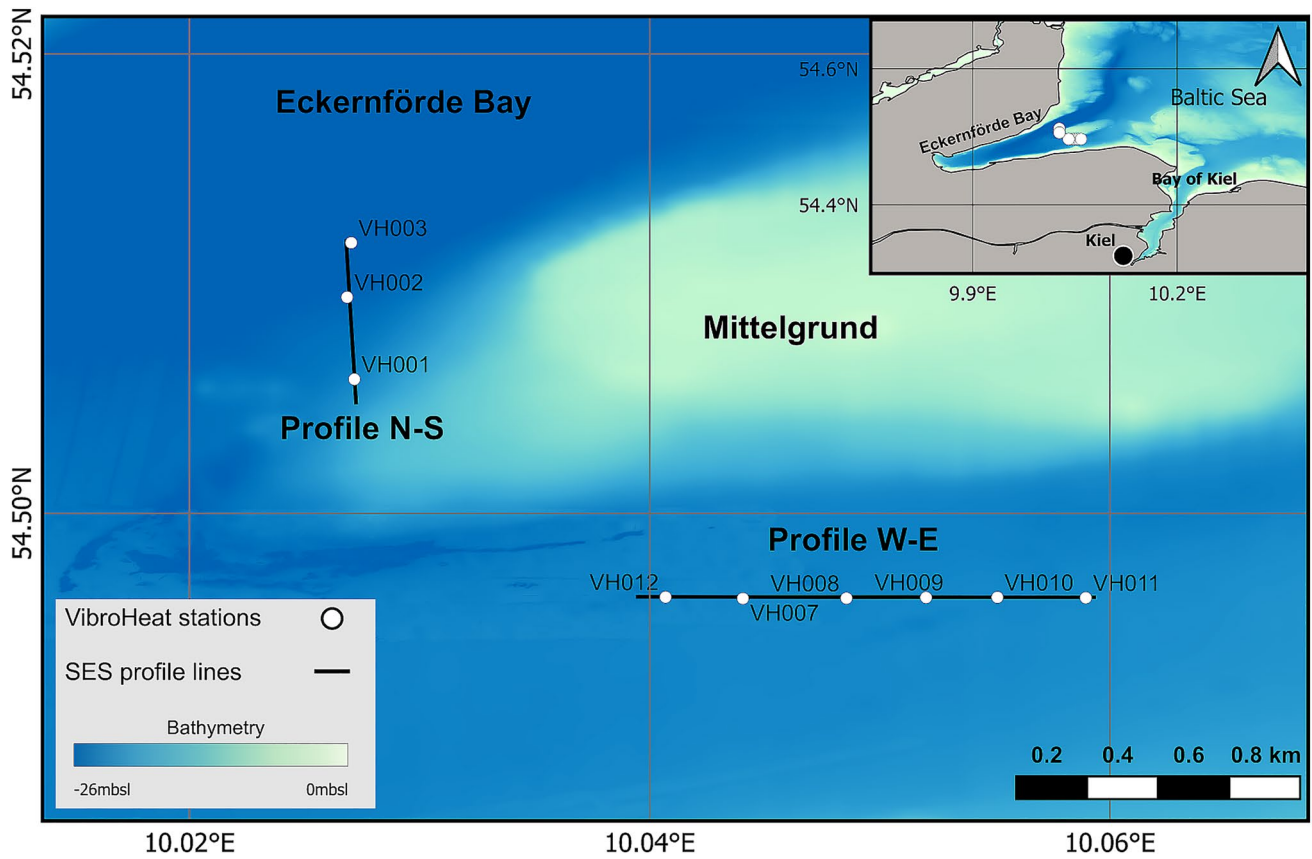
In this study, we show results of in-situ thermal conductivity measurements in shallow nearshore sediments of the Baltic Sea. The data illustrate the occurrence of considerable changes in thermal conductivities at short distances depending on the different soil types in the nearshore sediments ranging from sands to gas-bearing soft muds.

Due to the scarcity of published data on nearshore thermal conductivities, their high variability is not yet acknowledged but is essential for e.g., dimensioning of power cables. Our data, therefore, add to the published data and show that even conservative assumptions about minimum thermal conductivities may not be sufficient for a safe planning and design of power cables.

## Methods and data acquisition

### Survey overview

This study was carried out with the German research vessel “Alkor” during the cruise AL584 in November 2022. The survey area (Fig. 1) was selected around Mittelgrund, a shallow shoal of glacial origin. Based on published hydroacoustic profiles by Hoffmann et al. (2020), Lohrberg et al. (2020) and Jensen et al. (2002), the survey profiles were chosen to cover sandy sediments as well as organic-rich muds, specifically including regions with free gas in the sediments. One profile (Fig. 1, profile N–S) was acquired along the Western margin of Mittelgrund from South to North to investigate the thermal properties of the sediments along the transition from sandy to muddy sediments. A second profile (Fig. 1, profile E–W) south of Mittelgrund was chosen based on the presence of free gas in the muddy sediments indicated by acoustic turbidity or its absence, respectively. Gas-bearing sediments are commonly mapped using acoustic methods. Acoustic signals cannot penetrate through the gas horizons, but rather excite the natural frequency of the gas bubbles due to effects of resonance and reverberation (Wilkens and Richardson 1998).



**Fig. 1** Map of survey area in Eckernförde Bay west and south of Mittelgrund. Solid black lines present profiles N–S and W–E, with marked white circles for the location of thermal measurements. Bathymetric data are taken from Schneider von Deimling et al. (2020)

This phenomenon is commonly known as ‘acoustic turbidity’ or ‘acoustic blanking’ in sub bottom profile data and is used as a strong proxy for the presence of free gas in the sediment.

In the Baltic Sea, acoustic turbid sediments have been detected in acoustic profiles since the 1950s for instance by Schüler (1952), Wever et al. (1998), Hoffmann et al. (2020) and Lohrberg et al. (2020). In the Eckernförde Bay, (Abegg and Anderson 1997) found significant free methane contents of up to 4.5 Vol.-% in muds with acoustic turbidity.

Parametric sediment echo sounding profiles were obtained along the transects in order to confirm the presence or absence of free gas in the sediments. The data were recorded with the INNOMAR sediment echo sounder SES-2000 at a frequency of 6 kHz, which translates to a vertical resolution of approx. 12.5 cm. All figures of sub-bottom profiles were created using the *IHS Markit Kingdom Seismic Interpretation Software*®. They are shown with full amplitude and with a linear time-to-depth conversion of 1500 m/s. On the base of the acoustic information in-situ thermal properties measurements were conducted at the 9 locations summarized in Table 1.

**Table 1** List of VibroHeat locations

Station	Lon [°E]	Lat [°N]	Water depth [m]
VH001	10° 1.630'	54° 30.350'	– 22.5
VH002	10° 1.611'	54° 30.565'	– 25.9
VH003	10° 1.622'	54° 30.707'	– 27.3
VH007	10° 2.643'	54° 29.777'	– 23.3
VH008	10° 2.913'	54° 29.778'	– 23.2
VH009	10° 3.121'	54° 29.780'	– 23.1
VH010	10° 3.307'	54° 29.780'	– 23.6
VH011	10° 3.537'	54° 29.779'	– 22.8
VH012	10° 2.441'	54° 29.781'	– 23.5

### In-situ temperatures and thermal conductivities

In principle, marine thermal properties are measured with a heat flow probe which consists of a sensor string and a strength member. The sensor string is a thin and several meter long metal tube with a set of temperature sensors and a heating wire aligned within the tube. The sensor string is then connected parallel and with a distance of some centimeters to the several meter long strength member which

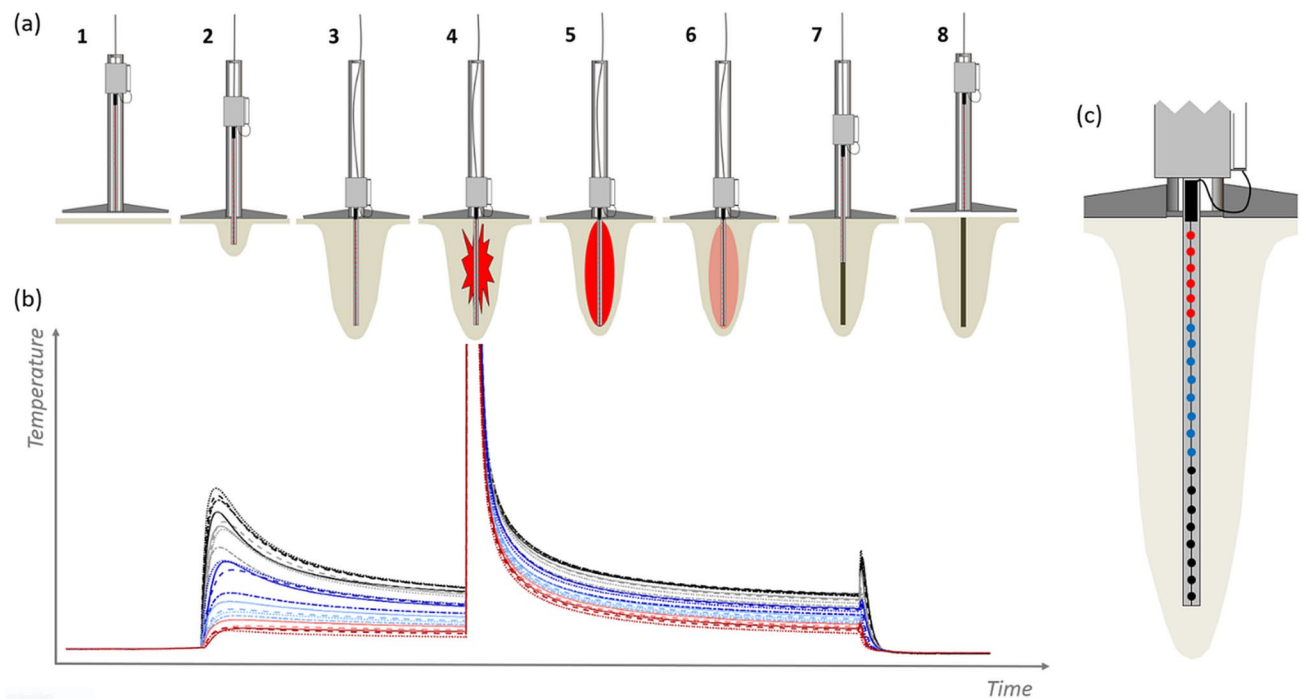
is needed to insert the string into the soil. The ‘classical’ heat flow probe usually penetrates the soft deep-sea sediments driven by gravity, i.e., by its own weight. However, the heterogeneous and often shear-resistant sediments in coastal regions do not allow an efficient penetration by gravity alone. Thus, for the measurement of the thermal properties, we used the VibroHeat system designed by FIELAX GmbH, in which the sensor string is combined with a VKG type Vibrocorer (Dillon et al. 2012; Müller et al. 2016). The VibroHeat system records temperature as a function of time. The temperatures are recorded with 22 thermistors that are placed within a sensor string. The sensor string also contains a heating wire with which a distinct amount of energy is released into the sediments (Fig. 2). To calculate the in-situ temperature and thermal conductivity of the sediment, the inversion method is used according to Hartmann and Villinger (2002). The main assumption of the method is that the heat transport is caused by heat conduction only. The mathematical uncertainty calculated propagating the full Hesse-Matrix is generally less than 1%. 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 2 mK are accepted. Although sediment cores were obtained by the vibrocorer in our research area, no serious attempts were made to describe the core material in detail, because sediment successions in the Eckerförde Bay are well known (Jensen et al. 2002).

## Results

### N–S transect, western margin of Mittelgrund

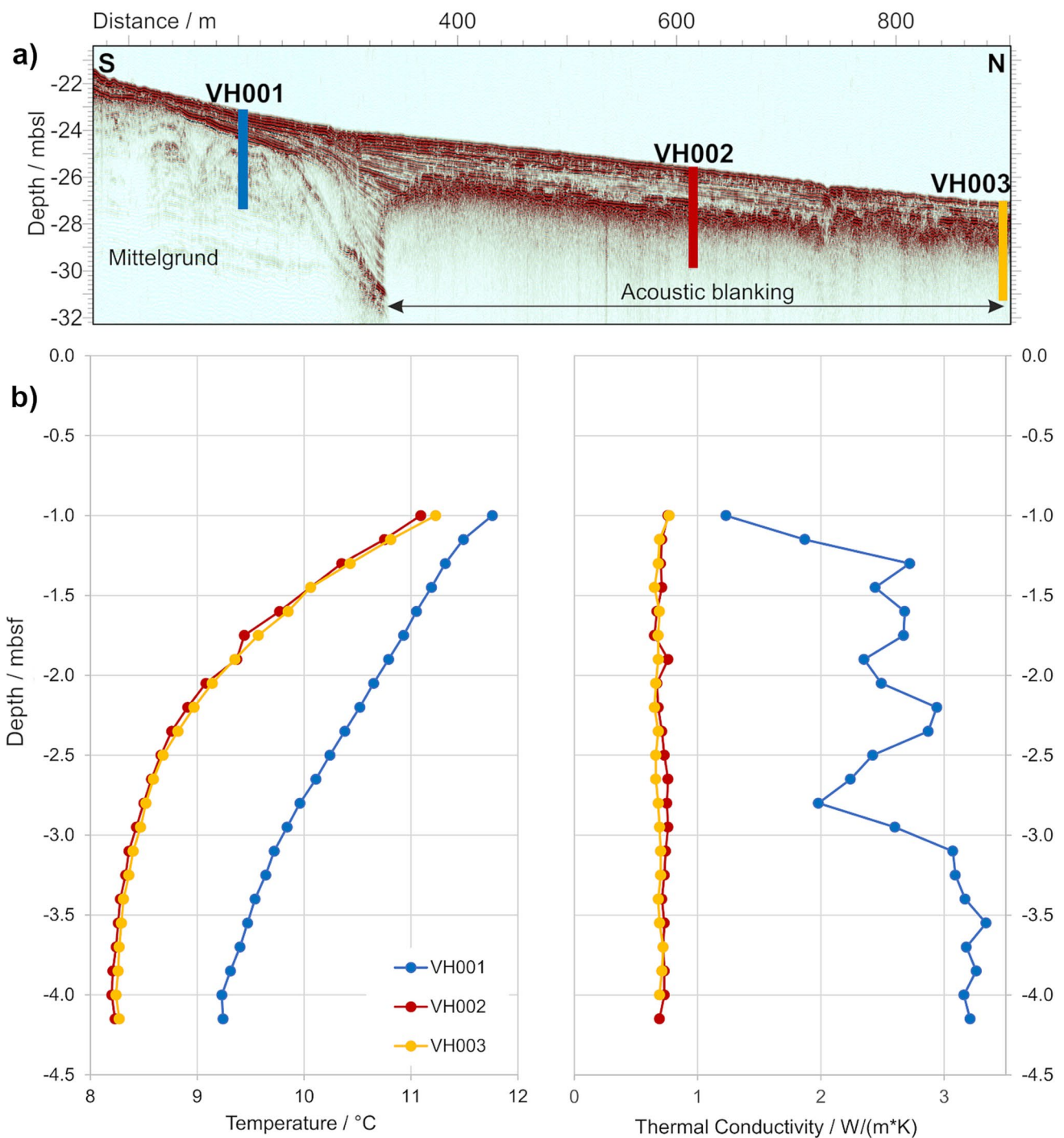
The N–S transect starting at the western margin of Mittelgrund is about 850 m long. Three measurements of temperatures were conducted along this transect. Within the first 250 m, the acoustic data image the sediments down to approx. 7 m below seafloor (mbsf), while on the remaining part of the transect sediments below 1.5 mbsf are hidden by acoustic turbidity (Fig. 3a). As suggested



**Fig. 2** **a** Schematic illustration of a thermal properties’ measurement in combination with a vibrocorer: 1: VibroHeat lowering to the seabed. 2: Penetrating into seabed. 3-7: Recording temperatures of thermal decay of the frictional heat, heat pulse, and heat pulse decay for the determination of ambient (undisturbed) temperatures and thermal conductivities. 8: Pullout and retrieval to surface. **b** Corresponding temperature recordings of the 22 thermistors. **c** Illustration of the dis-

tribution of the individual NTC (Negative Temperature Coefficient) thermistors. The colors of the NTC correspond to the colored curves in (b). The total length of a measuring cycle (penetration to extraction) can be adjusted to the specific sediment type but is typically 35 to 40 min. The evolution of the temperatures depends on the energies during deployment and sediment type. Typically, the temperature rises between 5 and 10 °C during the heating (4)





**Fig. 3** Location and results of VibroHeat measurements along profile N–S. **a**: Depth section profile of sub-bottom profile with marked locations and acoustic blanking as an indicator for free gas. **b** Results

of thermal properties for locations VH001, VH002 and VH003. The graphs show the temperature and thermal conductivity versus depth

earlier (Jensen et al. 2002), this profile crosses the transition from sandy sediments to organic-rich muds. The vibrocorer was able to penetrate down to a depth of 4.4 mbsf, which results in a deepest temperature test at 4.15 mbsf. The lower panel of Fig. 3b shows the temperature

and thermal conductivities vs. depth. Sandy material has been obtained at location VH001 only (blue). The ambient temperatures measured over the probed depth range at location VH001 vary from 11.8 to 9.2 °C top-to-bottom. Thermal conductivities are in the range of 1.23–3.34 W/

( $\text{m}^*\text{K}$ ) with the smallest values at the top of the profile, which is well within expectations for sandy sediments.

At locations VH002 and VH003 (orange, yellow), organic-rich muds were recovered by the vibrocorer. Degassing was evident by muddy material being squeezed out due to pressure release through small holes in the core liner (Fig. 4). The temperatures vary from 11.2 to 8.2 °C top-to-bottom and the thermal conductivity values are very low between 0.65 and 0.77  $\text{W}/(\text{m}^*\text{K})$ . Such low values have not yet been published for nearshore sediments.

### E–W transect, south of Mittelgrund

The E–W transect has a length of 1300 m (Fig. 1). The acoustic data penetrate down to approx. 7 mbsf in the eastern part of the profile, while in the western part the acoustic penetration is only 1–2 mbsf with acoustic blanking below (Fig. 5a). VH009, VH010 and VH011 are placed in the eastern part of the profile in absence of acoustic turbidity, while VH007, VH008 and VH012 are located in the western part in presence of acoustic turbidity. Organic-rich muds were recovered by the vibrocorer at all locations with very soft dark grey material at the top of the cores and more stiff greenish clayey material at the bottom of the cores.

The temperature data of all stations show a very similar curved profile from approx. 12.3 °C at 0.60 mbsf to –8.3 °C at 3.75 mbsf (Fig. 5b, left panel). The thermal conductivities at all locations are very low and range between 0.67 and 0.81  $\text{W}/(\text{m}^*\text{K})$  with an overall mean of 0.73  $\text{W}/(\text{m}^*\text{K})$  and slight increase with depth (Fig. 5b, right panel). Please note that the scale for the thermal conductivities is much smaller compared to Fig. 3b right panel.



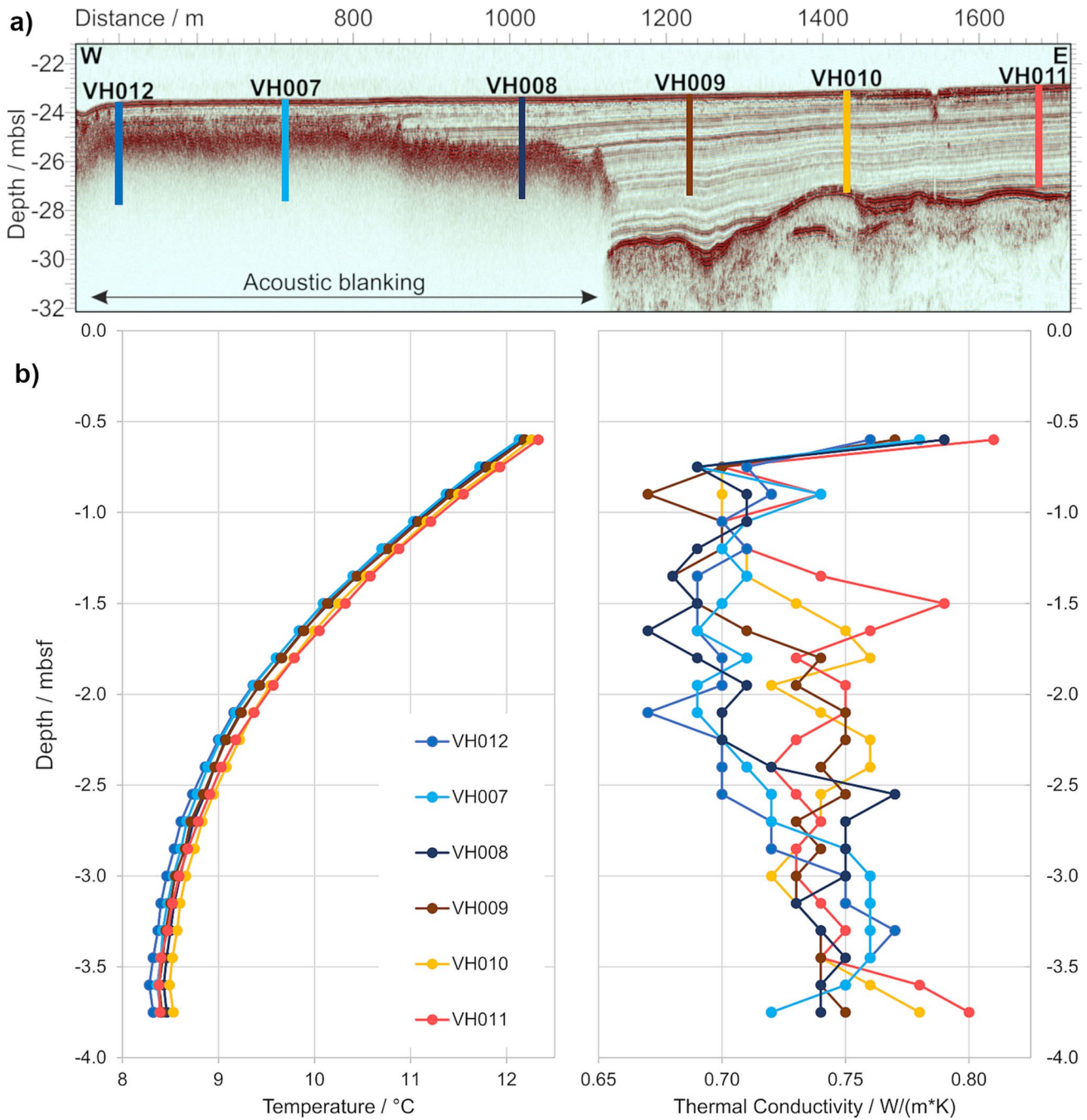
**Fig. 4** Discharge of muddy material through boreholes in the core liner at location VH002 may be attributed to degassing upon pressure release (Photo taken by R. Usbeck)

In the shaded grey depth range between –1.6 mbsf and 2.3 it seems that the reddish profiles show systematically higher thermal conductivities (–0.71–0.76  $\text{W}/(\text{m}^*\text{K})$ ) than the blueish profiles (–0.67–0.71  $\text{W}/(\text{m}^*\text{K})$ ). The reddish values are all located in the eastern part while the blueish are located in the western part where the acoustic signal is blanked. The depth of the blanking (1–2 mbsf) roughly coincides with the shaded depth range.

### Discussion

Our measurements add new information to the few published data of thermal conductivities in offshore sediments in coastal regions. We found a large difference in the thermal conductivities between the sandy material found at location VH001 (up to 3.34  $\text{W}/(\text{m}^*\text{K})$ ) and the organic-rich muds at all other locations (down to –0.67  $\text{W}/(\text{m}^*\text{K})$ ). At a distance of only 400 m between locations VH001 and VH002 (Fig. 3a), the thermal conductivity changes from less than 1  $\text{W}/(\text{m}^*\text{K})$  to more than 2  $\text{W}/(\text{m}^*\text{K})$ . This demonstrates the large variability of the thermal properties in coastal sediments even in small areas within short distances compared to the sediments of the deep oceans, where the data vary less. For instance, an average value of 0.820  $\text{W}/(\text{m}^*\text{K})$  with a standard deviation of 0.117  $\text{W}/(\text{m}^*\text{K})$  has been calculated for the entire North Pacific (Stein and Abbott 1991). Values of less than 0.7  $\text{W}/(\text{m}^*\text{K})$  as found in the Eckernförde Bay rarely occur in deep ocean sediments. Obviously, the large range of thermal conductivities in our study is due to the variability in the sediment composition which is typical in coastal regions as they have been formed by very different sedimentary processes compared to the open ocean where the sedimentation processes change very slowly both, horizontally and with depth over geological time scales.

The sediment temperatures show a curved depth-dependence which is not observed in deep ocean sediments. In the deep sea, bottom water temperatures and consequently temperature of sediments can be assumed to be nearly constant. Thus, temperature profiles in deep sea sediments usually show a linear increase with depth towards the geothermal gradient as e.g. in Davis and Fisher (2011). In contrast, in the investigated Eckernförde Bay, the bottom water temperatures vary seasonally from approx. 3 to 13 °C (Lennartz et al. 2014). The amplitude and depth of a seasonal imprint of temperature into the sediment depends on the sediment's thermal diffusivity  $\kappa$  of the sediment, which is closely related to the thermal conductivity via the specific heat capacity ( $\rho c$ ) of the sediment ( $\kappa = \lambda/(\rho c)$ ). If a thermal diffusivity is high, the seasonal signal imprints itself deeper into the sediment. The measurements of this study were conducted in late autumn. At this time of the year, the submarine sediment temperatures are rather high because the



**Fig. 5** Location and results of VibroHeat measurements along the E–W transect. **a:** Depth section profile of sub-bottom profile with marked locations and acoustic turbidity as an indicator for gas-bearing sediments. **b** Results of thermal properties for stations VH007–

VH012. The graphs show the temperature and thermal conductivity versus depth. The shaded area indicates the depth range where the thermal conductivity values differ along the profile

sediment response is delayed towards the seasonal cycle by the slow vertical conductive temperature migration through the water column and the sediments (Hansen 1993). That is why VH001 shows a higher sediment temperature and different curve shape than its neighbors VH002 and VH003 (Fig. 3). After a cold period, the profiles should bend to

the left with a reversed effect. At the location with higher thermal conductivities, the temperatures will then generally be lower as the cooling of the sediments will be more effective. The cumulated effect of seasonal variability of bottom water temperatures and different thermal conductivities is described and modelled in Müller et al. (2016).



Müller et al. (2016) conclude that both, the thermal conductivity and the naturally occurring seasonal variation of the sediment temperatures, are crucial information for the design of electrical power cables as described in the DNV GL guidelines “DNVGL-RP-0360- Subsea power cables in shallow water” (DNV GL 2016).

Knowing about the high range of variability of thermal conductivity as presented in this study is important as it demonstrates that it is not possible to generalize sediments in coastal regions. Thus, no ‘typical’ thermal conductivity can be assigned to larger areas as it is often done by industry who then use assumed thermal conductivities for their cable design calculations Anders and Brakelmann (2018) or Zhang et al. (2020).

The very low thermal conductivities smaller than 0.7 W/(m<sup>2</sup>K) presented in this study demonstrate that typical conservative estimates for the thermal conductivity of generally 1.4–2.0 W/(m<sup>2</sup>K) for coastal sediments used in calculations for offshore power cables (Brakelmann and Richert 2005; Anders and Brakelmann 2018) may be inappropriate if organic-rich, fine-grained sediments are present. The presence of organic rich sediments in the Baltic Sea is not unusual (Leipe et al. 2017). Consequently, it increases the range of values that should be considered for thermal conductivities in the Baltic Sea.

Besides the dependence of the thermal properties on different sediment types, we suppose a dependence of the thermal properties on the gas content in the sediment as indicated on the E–W profile at –1.6 to 2.3 mbsf (Fig. 5). Here, a small change of thermal conductivity values coincides with the depth of blanking in the corresponding sediment echosounder profile. It is assumed that free gas in the form of gas bubbles and gas-filled voids would have an insulating effect since gas is a poor heat conductor (Friend et al. 1989). As a consequence, we suggest that the thermal conductivity of identical sediment packages is decreased in areas displaying acoustic turbidity (i.e., contain free gas) compared to areas in absence of acoustic turbidity. The data presented suggest that the free gas indeed reduces thermal conductivity, but the reduction is very small compared to the overall variability and is not clearly detectable statistically. Also, it cannot be excluded that the small but distinct differences in the thermal conductivity values along the E–W transect are simply a matter of the rock physical properties of the sediments, e.g., density or water content. However, the observed difference should not be over-interpreted but requires further investigation. The observation of a possible influence of free gas on the thermal conductivity is important because it is to our knowledge not yet incorporated in standard cable design.

## Conclusions

We presented in-situ temperatures and in-situ thermal conductivities in the Eckerförde Bay. The sediment temperatures show a curved depth-dependence, which is accounted to the seasonal heating and cooling of the sediments by the temperature variation of the bottom water. The thermal conductivities show a large range from 0.67 W/(m<sup>2</sup>K) to 3.34 W/(m<sup>2</sup>K) that vary with sediment composition. First indications were found that free gas in the sediment lowers the thermal conductivity due to an insulating effect of gas bubbles.

In summary, the large variability of the thermal conductivity in the small area of the Eckernförde Bay exceeds by far that of sediments of the deep oceans ( $0.820 \pm 0.117$  W/(m<sup>2</sup>K) (Stein and Abbott 1991) that are valid for vast regions. Thus, thermal properties of sediments in coastal regions have a much higher variability than deep ocean sediments.

The results show that no generalized assumption can be made about sediment temperatures or thermal conductivities and also the conservative approach for thermal conductivities in the Baltic Sea does not cover the whole range of values observed in this study. However, both parameters, sediment temperature and thermal conductivity, are needed for calculating and dimensioning offshore power cables.

A verification of the seasonal cycle is planned by a re-test of the same sites in April when the seasonal cycle has imprinted the cold winter temperatures into the sediment. This will also provide an opportunity to confirm if the horizon of free gas and reduced thermal conductivity significantly depends on temperature.

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**Author contributions** All authors participated in the on-board data collection, reviewed the manuscript, and approved the publication. RU and NK are the project leaders. RU and MD processed the TRT data and wrote the main text of the manuscript in collaboration with FN, NK and AP provided valuable comments on the manuscript content. AL edited the SES data and provided the figures in the upper part of Figs. 3 and 5. He also thoroughly read and substantially improved the main structure of the manuscript. FN and AP prepared the figures, corrected the text, and prepared the manuscript for publication (references, etc.).



**Data availability** Thermal conductivity data as well as raw data of the Innomar sub-bottom profiler have been handed in to PANGAEA repository for publication and are available under: <https://doi.pangaea.de/https://doi.org/10.1594/PANGAEA.962163> (thermal data). <https://doi.pangaea.de/https://doi.org/10.1594/PANGAEA.961650> (acoustic data).

## Declarations

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

**Ethics approval and consent to participate** All authors accept the ethical responsibilities as stated for the journal.

**Consent to participate** Informed consent was obtained from all individual participants included in the study

**Consent for publication** Informed consent was obtained from all individual participants for whom identifying information is included in this article.

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