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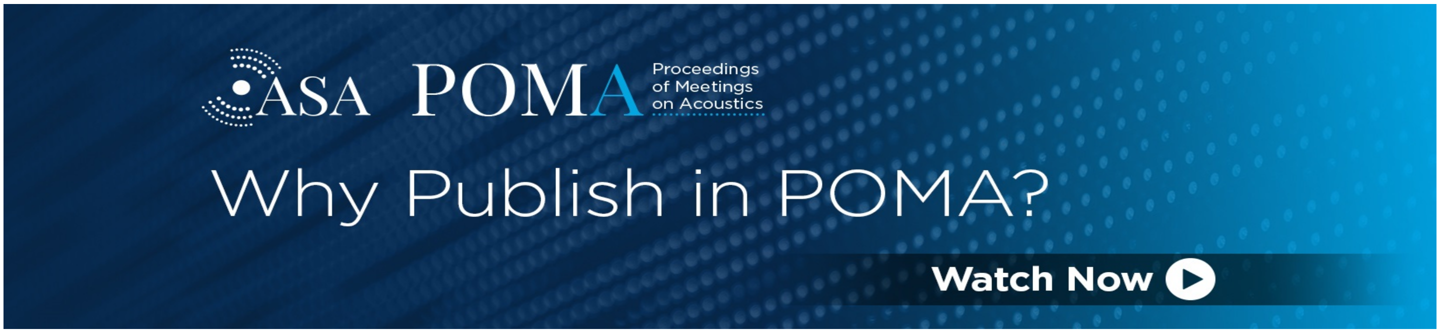

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Underwater Acoustics: Seabed and sediment classification

Correlations between sound speed and density in seabed sediment cores collected in Norwegian waters

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In modelling of underwater sound propagation, knowledge about the seabed's acoustic properties is essential, especially sound speed and density. These two properties are highly correlated, and standard empirical regressions are often used to predict one property from the other. The Norwegian Defence Research Establishment (FFI) has a large database of sediment sound speed and density measurements from laboratory analysis of seabed gravity cores. This paper presents the results from 47 cores collected from FFI's research vessel M/S H.U. Sverdrup II on the Norwegian continental shelf and in the Barents Sea. The densities measured in the cores range from 1.35 to 2.4 g/cm^3 and sound speeds from 1410 to 1750 m/s (corrected to 23°C, and 1 atm. pressure). An empirical regression between density and sound speed derived from FFI's data set deviates significantly from standard empirical regressions found in the literature, as bulk densities are higher and sound speeds lower than expected. Another study from the Barents Sea also reported high bulk densities in seabed sediments and suggested that clay mineralogy might be the cause.The importance of applying an appropriate sound speed-density relationship will be demonstrated using the acoustic ray tracer Lybin developed by the Royal Norwegian Navy and FFI.

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1. INTRODUCTION

In modelling of underwater sound propagation and seabed classification, knowledge about the seabed's acoustic properties is essential, especially sound speed and density. These two properties are highly correlated, and standard empirical relationships are often used to predict one property from the other.

The Norwegian Defence Research Establishment (FFI) has a large database of sediment sound speed and density measurements from laboratory analysis of seabed gravity cores. The gravity cores were collected from FFI's research vessel M/S H.U. Sverdrup II on the Norwegian continental shelf and in the Barents Sea. This paper presents and discusses the results from 47 gravity cores with top surface sediment layer classified from clay to muddy gravel, and compares our empirical relationship between sound speed and density with results from other published studies.

2. REGIONAL SETTING

The study area encompasses four subregions along the Norwegian coast, from the Oslo Fiord in the south to the Barents Sea in the north (Figure 1). The seafloor topography has been shaped by repeated glaciations, and large amounts of glacigenic sediments have been deposited off shore (e.g. Svendsen et al. 2004, Olsen et al. 2013, Ottesen et al. 2022). Typical characteristics of glacigenic sediments, such as tills, is poor sorting and inclusion of larger clasts. After the deglaciation of Norwegian waters at about 14 ka before present (e.g. Patton et al. 2017), a variable amount of glaciomarine and marine sediments have been deposited.

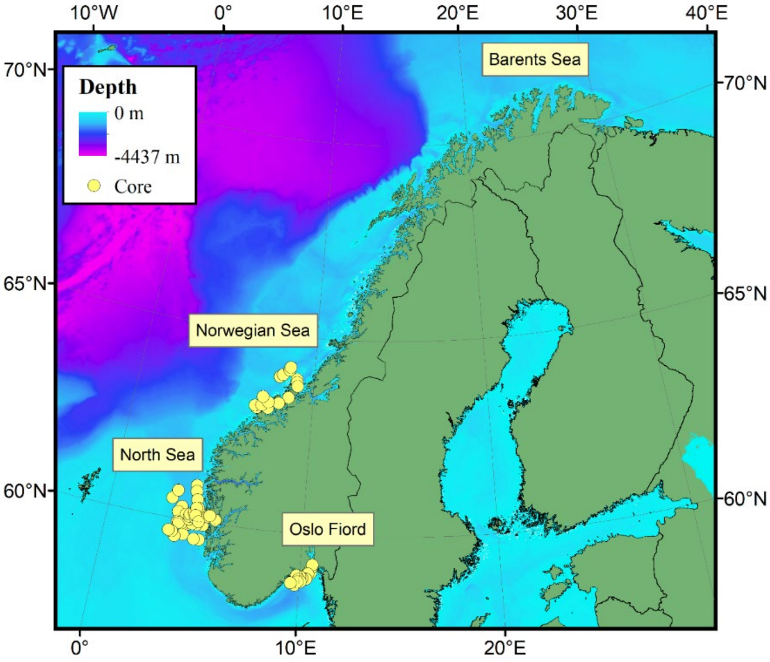

Figure 1. Map showing the four subregions in the study area and locations of the sediment cores collected along the Norwegian coast. The bathymetry is from EMODnet (2016).

In the Barents Sea, marine sedimentation has been limited during the Holocene (~11.7 ka), and the thickness of these recent sediment deposits is usually below ~1 m (Rise et al. 2016). Longer cores from the Barents Sea might therefore sample sediments from past glaciomarine or glacial environments. In contrast, the Norwegian Channel, which runs from the outer Oslo Fiord to the North Sea (Figure 1), has been a significant sediment trap since deglaciation (Rise et al. 2008). At the North Sea core sites, the thickness of marine Holocene sediments is typically 4–9 m thick (Eidem and Landmark 2008), and the cores probably recovered marine sediments exclusively. The sediment maps in Rise et al. (2008) do not cover all the core sites in the outer Oslo Fiord, but it is likely that the cores mainly sampled Holocene marine sediments. The Norwegian Sea core sites are not as well covered by geological maps, and the amount of recent Holocene sedimentation is therefore uncertain.

3. MATERIAL AND METHODS

Originally, 77 sediment cores collected in Norwegian waters between 2005 and 2013 from the research vessel M/S H.U. Sverdrup II were included in the study (Figure 2). Three types of gravity corers of diameter 63 mm or 110 mm were used. Two of the corers have unknown origin, the last is produced by KC Denmark.

All the sediment cores were analyzed by the University of Bergen (UiB), Department of Earth Science. The cores were sent through a GEOTEK Multi Sensor Core Logger, for measurements of mainly wet bulk density derived from gamma ray attenuation, fractional porosity, p-wave velocity and p-wave amplitude at certain intervals, usually every 0.5 cm (Eidem and Landmark 2013, Eidem 2017a, Eidem 2017b). For calibration of density, a water-filled core with a stepped aluminum block of known dimensions was used. At least for the cores collected late 2013, an empty core liner from the same batch was used in the calibration process. We will refer to p-wave velocity as sound speed from here on. The analysis results were tabulated versus depth. Some of the cores were split before analysis, others afterwards. The different layers were described and reported. Sub-sampling for grain size analyzes was carried out with at least one sample for each core.

Figure 2. The cores were collected from the research vessel M/S H.U. Sverdrup II. The gravity corer from KC Denmark with a tube of length 2.5 m was used in the Norwegian Sea in 2013. Photos: FFI.

The sediments in the cores from 2005 and 2006 did not always fill up the core liners, making the continuous sound speed measurement problematic. The data from these 24 cores are therefore excluded from the study. FFI collected 13 gravity cores with diameters 63 mm and 110 mm in the Barents Sea in 2009. The 63 mm cores had air in the sediment and space between the sediment and the core liner, and we have therefore only included the seven 110 mm cores from the Barents Sea in the analysis.

In total, 47 single gravity cores with lengths between 0.3 and 2.7 m acquired at water depths of 45–670 m are included in the study (Table 1):

- 14 sediment cores with diameter 63 mm collected in the Oslo Fiord, early 2013
- 16 sediment cores with diameter 63 mm collected in the North Sea, 2007
- 10 sediment cores with diameter 110 mm collected in the Norwegian Sea, late 2013
- 7 sediment cores with diameter 110 mm collected in the Barents Sea, 2009

With core lengths of up to 2.7 m, the cores from the four subregions mostly sample recent marine sediments, but might also sample sediments from a glaciomarine or glacial environment in some locations.

UiB reported the p-wave amplitudes, which give the significance of every sound speed measurement. Only data with p-wave amplitudes above a given threshold are included in the study. The sound speed was especially difficult to measure in the upper 10–30 cm of the cores due to weak contact between the sediment and the core liner. A substantial part of the data from this interval is excluded due to low p-wave amplitudes. In order to compare sound speed and density at the same depth, density values were excluded as well when the p-wave amplitude was below the threshold, or when the sound speed value was lacking.

To avoid outliers representing or indicating measurement errors, data with lower sound speed than 1410 m/s, density lower than 1.3 g/cm^3, shift in sound speed of more than 30 m/s between two following depths (1 cm or less difference in depth) and shift in density of more than 0.4 g/cm^3 were excluded. The consequence of removing outliers is shown in Figure 3 for the North Sea cores. The density and sound speed against depth after removal of outliers from the Norwegian Sea cores are also shown in Figure 3. The sound speed values were corrected to 23°C and 1 atm, as recommended in Hamilton (1971), before removing the outliers which counted less than 4 % of measurements. The sound speed at in-situ sea conditions is 30–40 m/s lower, mainly due to lower temperatures (Lurton 2002, Kim et al. 2018).

Sediment samples from the cores in the Oslo fjord (top-surface samples) and North Sea (subsampled at different depths), and for nine of the ten cores in the Norwegian Sea (top-surface samples) were analyzed at UiB with respect to grain size distribution (GSD), using sieving to separate coarse and fine sediments (Eidem and Landmark 2013, Eidem 2017a). The mud fraction (grain size < 63 µm in diameter) was analyzed with Micrometrics Sedigraph III 5120 or Malvern Mastersizer 3000. The content of gravel (> 2 mm), sand (63 µm–2 mm), and mud (< 63 µm) was calculated for all the samples, and the content of silt (2–63 µm) and clay (< 2 µm) for the samples from the two southern subregions.

Table 1. Minimum, mean and maximum core length included a potential oasis layer for the sediment cores collected in each subregion (Oslo Fiord (O), North Sea (N), Norwegian Sea (H) and Barents Sea (B)) and altogether.

	O	**N**	**H**	**B**	**ONHB**
Min core length (cm)	36	44	28	40	28
Mean core length (cm)	145 ± 59	144 ± 63	121 ± 71	152 ± 93	140 ± 67
Max core length (cm)	256	233	228	273	273
Number of cores	14	16	10	7	47
Number of GSD samples[1]	14	16	9	0	39
Additional GSD samples[2]		62			

[1] Top-surface samples

[2] Samples at additional 2–5 depth intervals

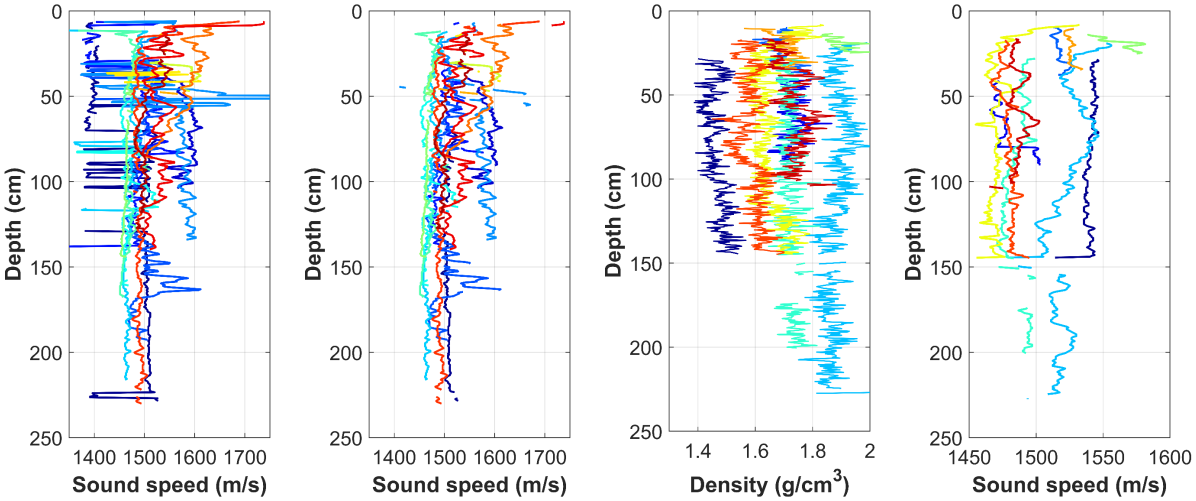

Figure 3. Sound speed against depth before and after removing outliers from the North Sea cores (two left panels). The density and sound speed against depth after removing outliers from the Norwegian Sea cores (two right panels).

4. RESULTS

The sound speed against density is plotted for each of the four subregions in Figure 4–Figure 7. All the accepted measurements are included in the figures, with different colors for each core. Overall, the data points from 2007, 2009 and 2013 agree, as shown in Figure 8. However, the measurements from the Oslo Fiord are in general low in both sound speed and density, indicating very soft sediments. In addition, the Norwegian and Barents Sea cores have somewhat higher sound speeds compared to sediments from both the North Sea and the Oslo Fiord. Only a few data points are close to the two lower thresholds 1410 m/s and 1.3 g/cm^3. A second order polynomial regression between sound speed and density is calculated to be

$$v_p = 2025 - 715\rho + 230\rho^2, \tag{1}$$

where v_p is the sound speed in m/s and ρ is the density in g/cm^3.

One of the cores from the Norwegian Sea (Core 01/13) deviates significantly from other cores in the subregion due to high sound speed and low density (dark blue dots in Figure 6). The density and sound speed profiles are displayed as dark blue lines in the right panels of Figure 3, and both appear realistic. There is no obvious explanation for the high sound speed and low density, but the core contains abundant shell fragments and gas bubbles.

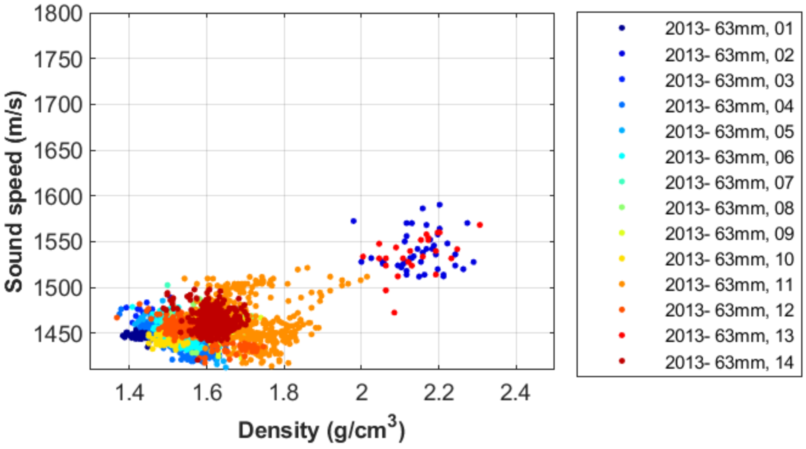

Figure 4. Sound speed versus density for the 14 sediment cores collected in the Oslo Fiord, in total 2889 measurements.

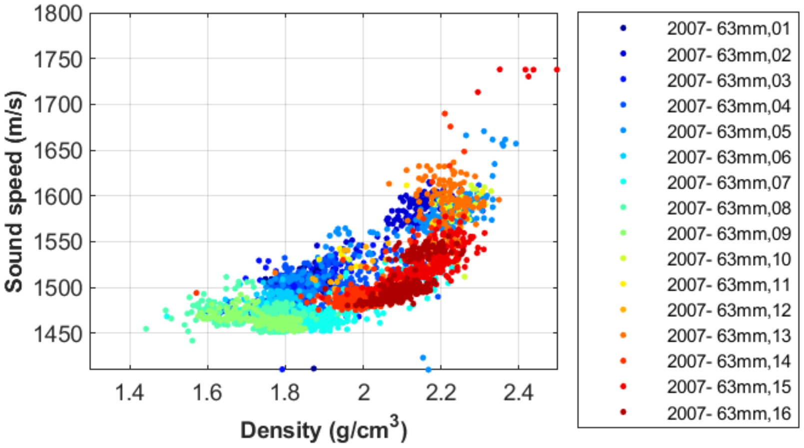

Figure 5. Sound speed versus density for the 16 sediment cores collected in the North Sea, including three cores in Korsfjorden, in total 3330 measurements.

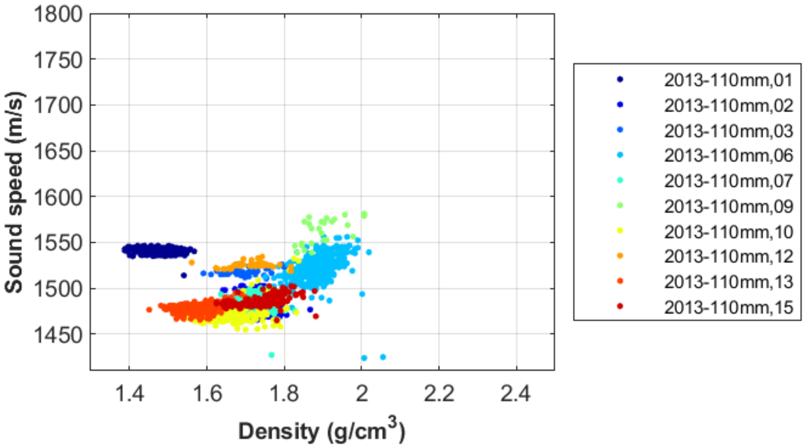

Figure 6. Sound speed versus density for the 10 sediment cores collected in the Norwegian Sea, in total 1866 measurements.

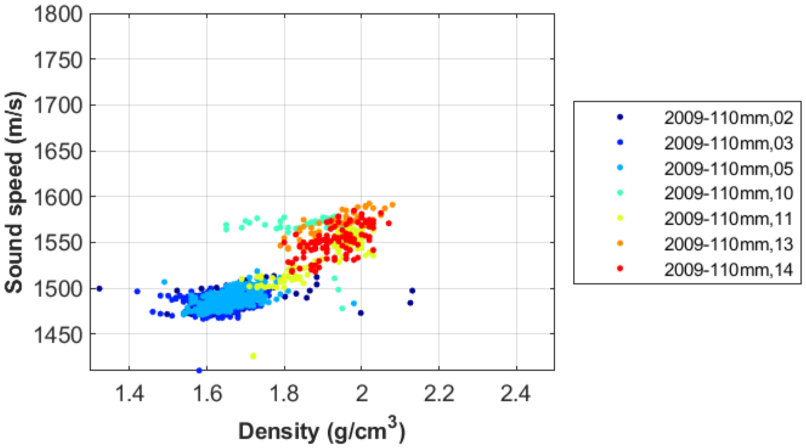

Figure 7. Sound speed versus density for the 7 sediment cores collected in the Barents Sea, in total 1341 measurements.

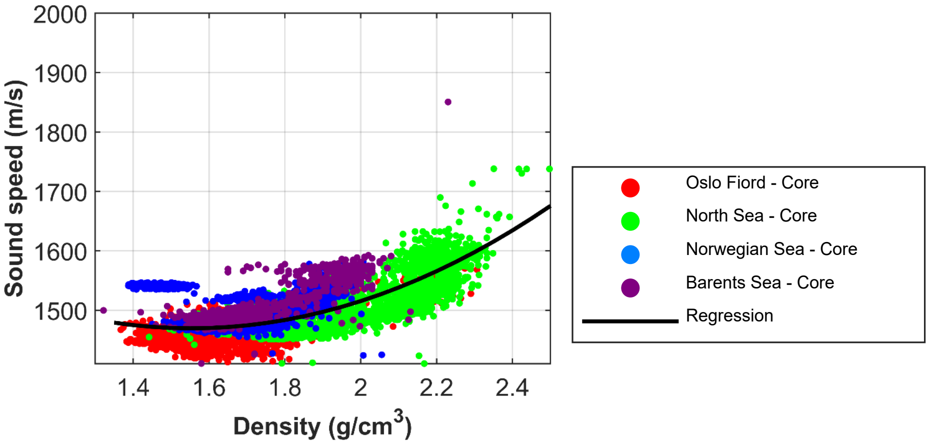

Figure 8. Sound speed versus density for the 47 sediment cores, in total 9426 measurements.

The gravel, sand and mud content were on average 4, 24 and 72 % respectively, for the 39 top surface sediment samples from the three southern subregions (Figure 9). The 30 top surface samples from the Oslo Fiord and North Sea contained 38 % silt and 37 % clay on average. Only 10 of the 39 sediment samples contained more than 1 % gravel. Hence, the top surface sediment of the sediment cores consisted of mainly fine-grained sediments. The depth of the top surface samples were in general less than 10 cm.

The gravel, sand, silt and clay content were on average 0.7, 14, 39 and 46 % respectively, for 78 subsamples from the 16 sediment cores in the North Sea. The cores were subsampled between 3 and 6 times at increasing depths dependent on the core length. Except for 5 of the 16 top surface samples, the subsamples did not contain gravel.

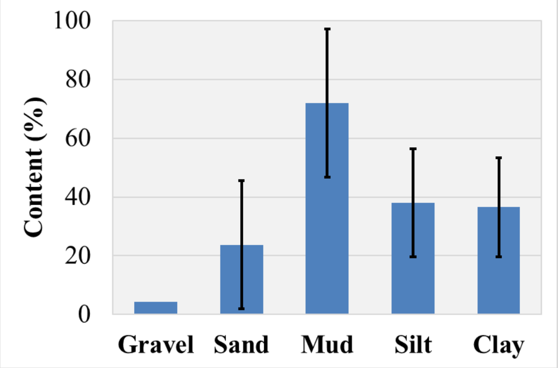

Figure 9. The content of gravel, sand, and mud in the top surface samples from 39 of the 47 sediment cores, incl. standard deviation in percentage points. The mud in the 30 top surface samples from the Oslo Fiord and North Sea cores consisted on average of equal amounts of silt and clay.

5. DISCUSSION

A. METHODOLOGICAL SHORTCOMINGS AND POSSIBLE ERRORS

The use of gravity cores to measure geoacoustic parameters as sound speed and density has been, and still is, a common method for collecting ground truth data, despite the possible errors due to disturbance of the sediments during collection, storage, handling, transport and measurements in the laboratory. One disadvantage is also the limited number of sediment cores from coarse-grained sites.

Common for the cores in the study is the collection platform (M/S H.U. Sverdrup II) and analysis laboratory (UiB). However, the cores were collected by different operators over a span of several years using three gravity corers with dimensions 63 mm and 110 mm. The handling, storage time and the transport to the laboratory varied. This has probably resulted in difficulties measuring the sound speed in the upper parts of the cores, and problems with space between liner and sediment, especially for the 63 mm cores. Despite the efforts to filter the density and sound speed data based on p-wave amplitudes, and to only include depths were both parameters are measured, outliers are still present in the data.

Wet bulk density measurements were performed on 41 discrete subsamples with volume between 5 and 9 ml from the 16 sediment cores collected in the North Sea in 2007. The subsamples had on average 0.30 ± 0.16 g/cm^3 lower density than the MSCL gamma density at the same depth (Eidem 2008). According to the laboratory, the exact volume was difficult to measure, and this may explain some of the difference. Wet bulk density measurements on 15 discrete subsamples with volume between 7 and 11 ml from the 14 sediment cores collected in the Oslo Fiord in 2013, show on average only 0.04 ± 0.07 g/cm^3 lower density than the MSCL gamma density. All these 15 subsamples were less than 12 cm from top of the sediment.

B. COMPARISON TO EMPIRICAL REGRESSIONS

In the literature, different empirical regressions are given for various sediment physical and geoacoustic properties. In general, the measured sound speeds against densities in this study are lower than a selection of published regressions, and the difference increases with increasing density as shown in Figure 10. Even if the wet bulk density is potentially 0.30 g/cm^3 lower than the gamma density, the empirical regressions from the standard literature are above the measured data in our study.

According to Jackson and Richardson (2007), the most widely used regressions are compiled by Hamilton and Bachman (1982), who measured sediment properties in cores from the Bering Sea, North Sea, Mediterranean Sea, equatorial Pacific and other regions. Most of the samples were from the upper 30 cm of the seabed. The regression of sound speed against density for the continental terrace is given separately in Hamilton and Bachman (1982). It is unknown for the authors how many of the samples were from the North Sea, but according to Orsi and Dunn (1991), many of the samples were from the North Pacific. A later version of this regression, compiled by Bachman (1985), is valid on the continental terrace (shelf and slope), abyssal hill and plain, based on sediment samples restricted to the upper 20 cm of sediment. The two regressions by Hamilton and Bachman (1982) and Bachman (1985) give significantly higher sound speed against density than the measured data in our study.

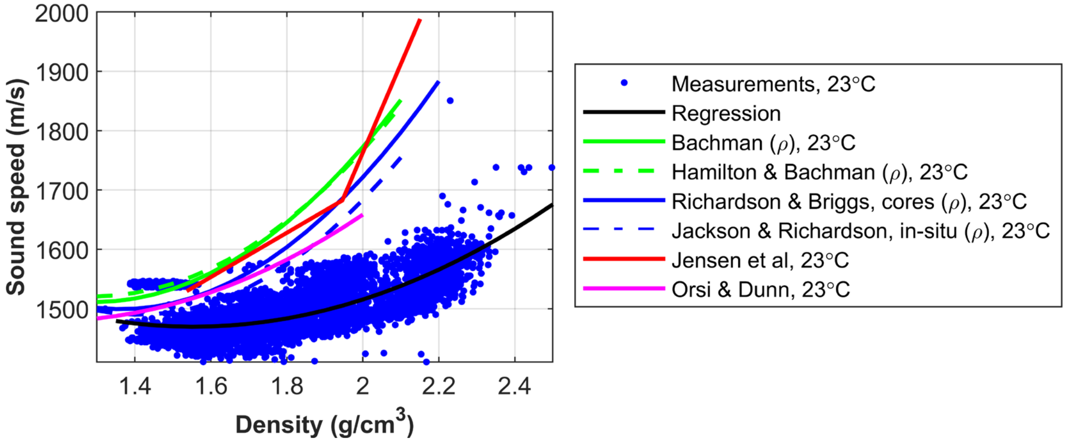

Figure 10. Sound speed versus density for the 47 cores collected in the four subregions. The data is compared with empirical regressions from Bachman (1985), Hamilton and Bachman (1982), Richardson and Briggs (2004), Jackson and Richardson (2007), Jensen et al. (2000) and Orsi and Dunn (1991). A second order polynomial regression to our measurements is plotted in black.

Richardson and Briggs (2004) present a regression for sound speed against density based on nearly 800 cores with maximum length 45 cm from 69 shallow-water sites around the world. Jackson and Richardson (2007) present a regression for in-situ measurements of sound speed against density for 88 sites, yielding lower sound speed for a given density than the other three (Figure 10). The in-situ sound speed ratio was only slightly lower than determined from laboratory measurements of cores taken from 78 of the 88 sites. These two regressions predict a lower sound speed than Hamilton and Bachman (1982) and Bachman (1985), but still higher than measured in our study.

Jensen et al. (2000) lists sound speed and density of different seafloor materials of relevance (clay, silt, sand, gravel, and morraine), compiled from work by Hamilton published in 1980 and 1987. These values are equal or higher than the regressions by Jackson and Richardson (2007).

Orsi and Dunn (1991) present regresssions for 54 sediment cores from the Barents Sea (Figure 10), where only the upper 10 cm was used. The sound speed against density is equal or lower than the four above regressions, but still above our measurements.

C. CLAY MINERALOGY

The relatively low sound speeds compared to density, or the relatively high density compared to sound speed, is not straightforward to explain. One factor, which may explain some of the increased density against sound speed, is the clay mineralogy. Orsi and Dunn (1991) also measured higher bulk densities than reported by Hamilton and Bachman (1982), and suggest that clay mineralogical differences between the data sets is the cause:

"*The relative absence of smectite from the clay mineral assemblage in Barents Sea sediments may explain their lower porosities and higher densities than surface sediments from other continental shelves.*"

Smectite has the capacity to bind water, and is able to absorb significantly more water than other clay minerals (Orsi and Dunn 1991, Schulz and Zabel 2006). Hence, smectite has low density, ranging from 2.0–2.6 g/cm^3, whereas other common clay minerals such as illite, chlorite and kaolinite all have densities higher than 2.6 g/cm^3 (e.g. Totten et al. 2002 and references within). Chlorite also occurs in coarser grain sizes than 2 µm (Windom 1976).

Vogt and Knies (2009) present the clay mineral assemblange of 158 samples from the western Barents Sea and along the northern part of the Norwegian coast. The content of illite, chlorite, kaolinite and smectite are on average 49 %, 21 %, 17 %, and 13 % respectively (Figure 11). According to Fagel (2007) and Windom (1976), the amount of smectite is much larger in the Pacific than in the other regions of the world seas, which agrees well with the low concentrations found by Vogt and Knies (2009). It is therefore possible that the high densities in our measurements are to some degree caused by clay mineralogy.

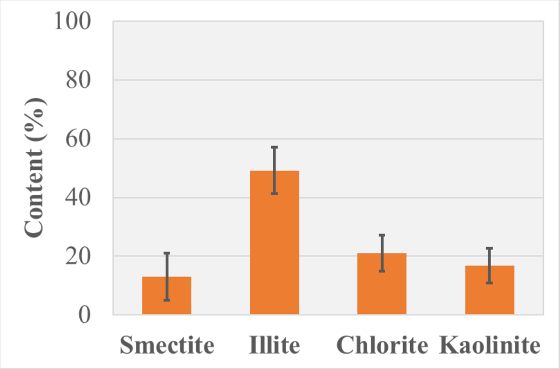

Figure 11. The content of the four clay mineral groups incl. standard deviation in percentage points for 158 samples from the western Barents Sea and along the northern part of the Norwegian coast. The dataset behind the figure is copied from Vogt and Knies (2009).

6. THE EFFECT OF LOW SOUND SPEED AGAINST HIGH DENSITY

In order to evaluate the effect of low sound speed and high density compared to values in standard literature, a simple scenario was set up using Lybin with a semi-infinite and range-independent seabed, water depth 300 m and a downwards refracting sound speed profile. Lybin is a ray trace model developed by the Royal Norwegian Navy and FFI (Dombestein and Jenserud 2010). The source was placed at 50 m depth and sent an FM pulse of length 1s, bandwidth 1000 Hz and frequency 2 kHz. The seabed sound speed and density was varied in three different cases (Table 2). The wind speed was set to 6 m/s and had a random component, which produced slightly different propagation loss with equal settings.

Case 1 corresponds to standard values of density and sound speed from the literature, with density ratio (DR) 1.5 and sound speed 1550 m/s. In Case 2, the sound speed is decreased to 1470 m/s and the density ratio of 1.5 is kept. This corresponds to values measured in our study in the low-density range (Figure 10). In Case 3, the initial sound speed of 1550 m/s is kept, but the density is increased to 2.1 m/s, corresponding to our data in the high-density range (Figure 10).

The propagation loss of Case 1 is plotted from 0 to 30 km in Figure 12. In Case 2, the lower sound speed of 1470 m/s increased the propagation loss with more than 20 dB in the given scenario (Figure 13, upper panel). In Case 3, the increased density ratio of 2.1 had only minor effect on the propagation loss (Figure 13, lower panel). In this scenario, an increase in density has less effect on propagation loss than a decrease in sound speed close to the sound speed of seawater. Hence, if sound speed is estimated from measurements of density (from e.g. cores or grab samples) using an ill-suited empirical regression, it might affect predictions of propagation loss with some significance.

Table 2. A summary of three cases used to model the effect of low sound speed and high density. Attenuation was 0.9 dB/λ and wind speed 6 m/s in all three cases.

	Density ratio	**Sound speed (m/s)**
Case 1, standard literature values	1.5	1550
Case 2, our low-density range	1.5	1470
Case 3, our high-density range	2.1	1550

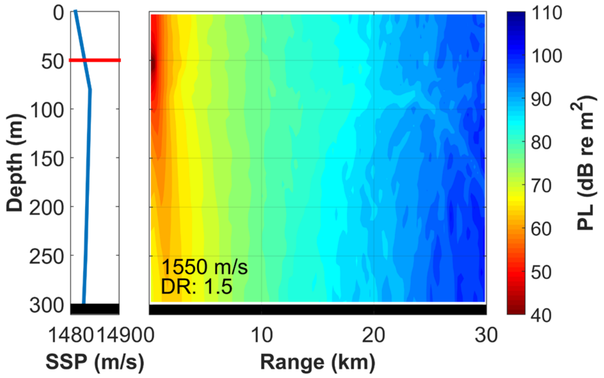

Figure 12. Propagation loss for the Case 1.

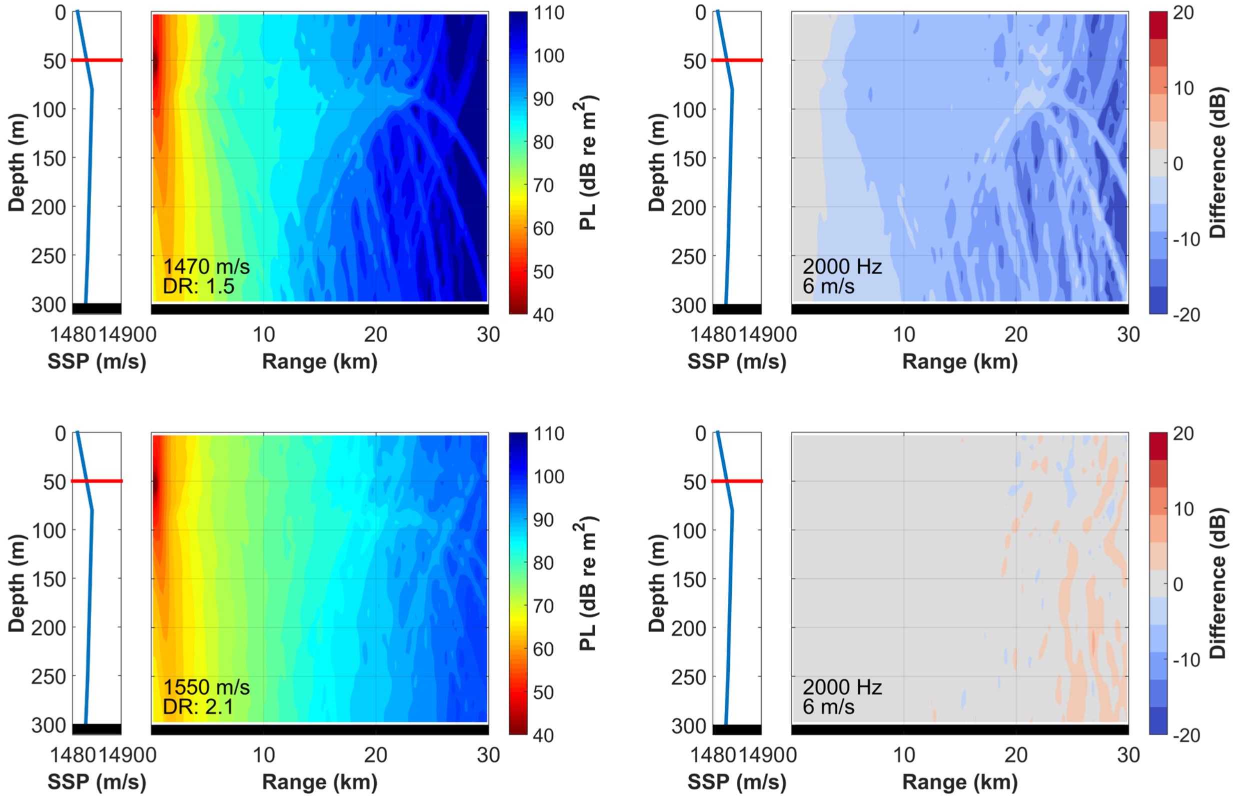

Figure 13. Propagation loss for Case 2 (upper left panel) and Case 3 (lower left panel). The right panels show the propagation loss differences for Cases 2 and 3 computed with respect to Case 1.

7. CONCLUSION

Analysis of 47 gravity cores with lengths between 0.3 and 2.7 m collected along the Norwegian coast and in the Barents Sea, and measured using a GEOTEK Multi Sensor Core logger, shows higher density against sound speed compared to standard empirical regressions found in the literature. Generally, cores from this region contain substantial amounts of clay. A speculation, assuming the results are not dominated by methodological errors, is that the relatively low amount of the clay mineral group smectite in this region increases the density. Smectite absorbs water and thus decreases the density of a sediment. We therefore need more information about the clay mineralogy groups and silt content in our study area.

The low sound speed measured compared to the empirical regressions is also unexpected. Additional measurements of sound speed and density in this region using other methods are necessary to evaluate, explain or at best validate the results in this study.

Simple simulations using the ray trace model Lybin indicates that the higher density has less effect on propagation loss than the lower compressional sound speed, which is close to the sound speed of seawater.

REFERENCES

Bachman, R. T. (1985). "Acoustic and physical property relationships in marine sediment." Journal of the Acoustical Society of America **78**(2): 616-621.

Dombestein, E. and T. Jenserud (2010). Improving underwater surveillance: Lybin sonar performance prediction. MAST 2010.

Eidem, E. J. (2008). Tolkning av sedimentprøver fra Forsvarets øvingsfelt i nordlige Nordsjøen innsamlet 2004-2008. FFI-rapport 2008/02041, Forsvarets forskningsinstitutt.

Eidem, E. J. (2017a). Correlation between sediment properties and seafloor characterization maps based on multibeam backscatter data from three regions off the coast of Norway. Proceedings of the 4th Underwater Acoustics Conference & Exhibition (UACE), 2017, Skiathos, Greece.

Eidem, E. J. (2017b). Klassifisering av havbunnen i prioriterte områder langs Norskekysten (CD&E 1446). FFI-rapport 2017/00323, Forsvarets forskningsinstitutt.

Eidem, E. J. and K. Landmark (2008). Seabed classification of the Navy's exercise area in the northern North Sea. FFI-rapport 2008/02135, Forsvarets forskningsinstitutt.

Eidem, E. J. and K. Landmark (2013). "Acoustic seabed classification using QTC IMPACT on single-beam echo sounder data from the Norwegian Channel, northern North Sea." Continental Shelf Research **68**: 1-14.

EMODnet (2016). EMODnet Bathymetry Consortium (2016): EMODnet Digital Bathymetry (DTM). https://doi.org/10.12770/c7b53704-999d-4721-b1a3-04ec60c87238. **2016**.

Fagel, N. (2007). Clay Minerals, Deep Circulation and Climate. Developments in Marine Geology, Elsevier. **1**.

Hamilton, E. L. (1971). "Prediction of in-situ acoustic and elastic properties of marine sediments." Geophysics **36**(2): 266-284.

Hamilton, E. L. and R. T. Bachman (1982). "Sound velocity and related properties of marine sediments." Journal of the Acoustical Society of America **72**(6): 1891-1904.

Jackson, D. R. and M. D. Richardson (2007). High-Frequency Seafloor Acoustics. New York, Springer.

Jensen, F. B., W. A. Kuperman, M. B. Porter and H. Schmidt (2000). Computational ocean acoustics. New York, Springer.

Kim, S., G. S. Lee, D. Kim, J. Hahn and W.-H. Ryang (2018). "Variation of temperature-dependent sound velocity in unconsolidated marine sediments: Laboratory measurements." Marine Geosources & Geotechnology **36**.

Lurton, X. (2002). An Introduction to Underwater Acoustics: Principles and Applications, Springer-Praxis.

Olsen, L., H. Sveian, D. Ottesen and L. Rise (2013). Quarternary glacial, interglacial and interstadial deposits of Norway and adjacent onshore and offshore areas. Quaternary Geology of Norway. L. Olsen, O. Fredin and O. Olesen, Geological Survey of Norway Special Publications. **13:** 79-144.

Orsi, T. H. and D. A. Dunn (1991). "Correlations between sound velocity and related properties of glacio-marine sediments: Barents Sea." Geo-Marine Letters **11**: 79-83.

Ottesen, D., C. Batchelor, L. R. Bjarnadottir, D. H. Wiberg and J. Dowdeswell (2022). "Glacial landforms reveal dynamic ice-sheet behaviour along the mid-Norwegian margin during the glacial-deglacial cycle." Quaternary Science Reviews **285**.

Patton, H., A. Hubbard, K. Andreassen, A. Auriac, P. L. Whitehouse, A. P. Stroeven, C. Shackleton, M. Winsborrow, J. Heyman and A. M. Hall (2017). "Deglaciation of the Eurasian ice sheet complex." Quaternary Science Reviews **169**: 148-172.

Richardson, M. D. and K. B. Briggs (2004). Relationships among sediment physical and acoustic properties in siliciclastic and calcareous sediments. ECUA.

Rise, L., R. Bøe, D. Ottesen, O. Longva and H. A. Olsen (2008). "Postglacial depositional environments and sedimentation rates in the Norwegian Channel off southern Norway." Marine Geology **251**: 124-138.

Rise, L., J. Knies, N. Baeten, H. A. Olsen, V. Bellec and M. Klug (2016). Sedimentkjerner fra Barentshavet Øst tatt på MAREANO-tokt med G.O. Sars i 2014. NGU-rapport 2016.021.

Schulz, H. D. and M. Zabel, Eds. (2006). Marine geochemistry, Springer.

Svendsen, J. I., H. Alexanderson, V. I. Astakhov, I. Demidov, J. A. Dowdeswell, S. Funder, V. Gataullin, M. Henriksen, C. Hjort and M. Houmark-Nielsen (2004). "Late Quaternary ice sheet history of northern Eurasia." Quaternary Science Reviews **23**(11-13): 1229-1271.

Totten, M. W., M. A. Hanan, D. Knight and J. Borges (2002). "Characteristics of mixed-layer smectite/illite density separates during burial diagenesis." American Mineralogist **87**: 1571-1579.

Vogt, C. and J. Knies (2009). "Sediment pathways in the western Barents Sea inferred from clay mineral assemblages in surface sediments." Norwegian Journal of Geology **89**.

Windom, H. L. (1976). Lithogenous material in marine sediments. Chemical oceanography. J. P. Riley and R. Chester. **5:** 103-135.