

# Locating the Nordstream explosions using polarization analysis

S. C. Stähler  \* <sup>1</sup>, G. Zenhäusern  <sup>1</sup>, J. Clinton  <sup>2</sup>, D. Giardini  <sup>1</sup>

<sup>1</sup>Institute for Geophysics, ETH Zürich, Switzerland, <sup>2</sup>Swiss Seismological Service, ETH Zürich, Switzerland

**Author contributions:** *Conceptualization:* S. C. Stähler. *Software:* G. Zenhäusern. *Formal Analysis:* S. C. Stähler, G. Zenhäusern. *Writing - original draft:* S. C. Stähler. *Writing - Review & Editing:* S. C. Stähler, G. Zenhäusern, J. Clinton, D. Giardini. *Visualization:* G. Zenhäusern. *Supervision:* D. Giardini.

**Abstract** The seismic events that preceded the leaks in the Nordstream natural gas pipelines in the Baltic Sea have been interpreted as explosions on the seabed. We use a polarization-based location method initially developed for marsquakes to locate the source region without the need for a subsurface velocity model. We show that the 2 largest seismic events can be unambiguously attributed to the methane plumes observed on the sea surface. The two largest events can be located with this method, using 4 and 5 stations located around the source, with the uncertainties in elliptical bounds of  $30 \times 30$  km and  $10 \times 60$  km, respectively. We can further show that both events emitted seismic energy for at least ten minutes after the initial explosion, indicative of resonances in the water column or the depressurizing pipeline.

**Zusammenfassung** Die Lecks in den Röhren der beiden Nord-Stream-Pipelines wurden von zwei signifikanten Seebeben begleitet. Der Charakter dieser Seebeben spricht gegen einen tektonischen Prozess und für eine Explosion, gefolgt von schneller Dekompression des Gases. Wir verwenden eine Polarisationsanalyse, die die Richtung der Bodenbewegung analysiert, um die Beben zu lokalisieren. Diese Methode wurde ursprünglich entwickelt, um die Epizentren von Beben auf dem Mars mit einem einzelnen Seismometer zu bestimmen. Wir zeigen, dass mithilfe von 5 Stationen in der Nähe der westliche Ostsee die beiden Explosionen sicher den an der Oberfläche beobachteten Methan-Strudeln zugeordnet werden können. Darüber hinaus können wir zeigen, dass auf die Explosionen ein mindestens zehnminütiger energiereicher Dekompressionsprozess folgte. Mehrere Resonanzfrequenzen in den analysierten Signalen deuten auf Reverberationen in der Wassersäule oder den geplatzten Leitungen hin.

**Non-technical summary** The leaks in the Nordstream pipelines, which transport natural gas from the Siberian gas fields to central and western Europe have been accompanied by seismic events consistent with underwater explosions. Seismic network operators located these explosions using the arrival times of different seismic wave types (P-waves, S-waves), that travel with different velocities. However, these velocities depend on the geological structure of a region and are often not well known, specifically in locations without many earthquakes. We therefore apply a method that uses the polarization, i.e. the direction, in which the ground is moving to determine the direction towards the seismic events. Using 5 stations around the Western Baltic Sea, we show that the two seismic events are located next to the observed gas leaks. We also show that the seismic events consisted of an initial explosion followed by an at least ten minute long process near the source, likely related to the rapid decompression of the pipeline and sound reflections between the sea floor and the surface.

## Introduction

The catastrophic leakage events that occurred in the Nordstream 1 and 2 natural gas pipelines in the Baltic Sea on 26 September 2022 generated global interest due to their significance for the European gas supply and the relationship between the Russian Federation and the Western European nations at each end of the pipeline. Shortly after 02:00 local time, a pressure drop was noticed at the German (western) end of the pipeline by the operators. Later, Danish military intelligence reported large methane plumes at the sea surface and restricted the area to marine traffic (Navigational warning NW-230-22 by the Danish Marine Authority). A sec-

ond larger event occurred that evening shortly after 19:00 local time (17:00 UTC) and resulted in a second methane plume at the surface (NW-237-22). Despite the fact that the pipelines were not transporting any gas at the time of the leak, they were fully pressurized and thus several million tons of methane were released after the leak. A few hours after the initial leak, the Swedish national seismic network SNSN at Uppsala University (Lund et al., 2021) reported an earthquake of  $M_L = 2.7$  near the now-confirmed location of the leak, based on picking arrival times of seismic waves (SNSN, 1904, event 2022092603\_Y4GNpS). The second event was also reported by SNSN as  $M_L = 3.1$  (SNSN, 1904, event 20220926135\_nj3BWW), close to the location of the second leak, clearly on the Nordstream 2 pipeline. Since

\*Corresponding author: mail@simonstaehler.com

Production Editor:  
Kiran Kumar Thingbaijam  
Handling Editor:  
Ryo Okuwaki  
Copy & Layout Editor:  
Théa Ragon

Received:  
October 7, 2022  
Accepted:  
October 26, 2022  
Published:  
October 28, 2022

	Event 1		Station	P arrival	S arrival	Back-azimuth [deg]
Origin time	00:03:24		UP.DEL	00:03:55	00:04:25	153 (142-165)
Local time	02:03:24		PL.GKP	00:04:37	00:04:48	-
Latitude	54.768		DK.BSD	00:03:32	-	125 (111-139)
Longitude	15.431		DK.LLD	00:04:00	-	100 (71-125)
Magnitude	2.7		KQ.PEEM	00:03:50	00:04:08	54 (20-81)
	Event 2A	Event 2B	Station	P arrival	S arrival	Back-azimuth [deg]
Origin time	17:03:50	17:03:58	UP.DEL	17:04:15	17:04:37	135 (128-143)
Local time	19:03:50	19:03:58	PL.GKP	17:04:27	-	325 (265-2)
Latitude	55.6	55.617	DK.BSD	17:04:03	17:04:11	55 (37-70)
Longitude	15.71	15.745	DK.LLD	17:04:30	-	85 (46-113)
Magnitude	3.1	3.1	KQ.PEEM	17:04:20	17:04:45	33 (356-79)

**Table 1** Summary of key parameters from open accessible nearby stations. P and S-wave arrival times for each station with estimated back-azimuth. Back-azimuth uncertainty ranges are given in parentheses. All times are on 2022-09-26 (UTC), local time is in CEST. Event location, origin time and magnitudes are taken from the SNSN catalog (SNSN, 1904)

the Baltic Sea is a region of very low seismicity (Grünthal et al., 2008), it is plausible to identify these seismic events with the leaks and attribute them to an explosion. The localization was facilitated by the relatively high amplitude of the signal, so that its arrival time could be observed on tens of stations. We here present an approach that uses a minimum number of stations and does not require a prior velocity model.

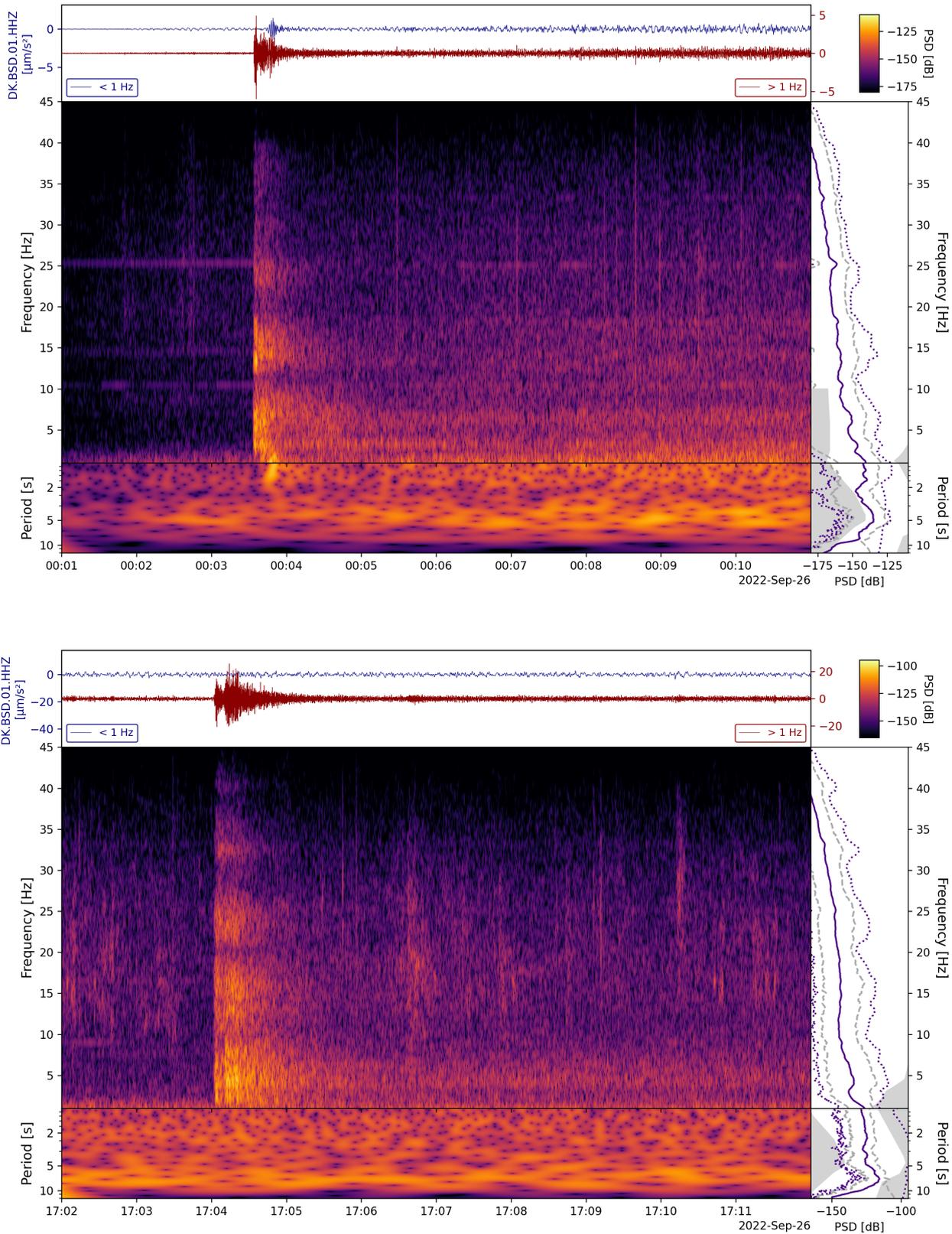
Seismic detection of man-made explosions is a task that dates back to the mid-20th century, when nuclear explosions were monitored by both super-powers. Coincidentally, the Norwegian Seismic Array (NORSAR), which first reported the Nordstream seismic events considered in this study, was set up precisely for this task (Schweitzer et al., 2021). In the early period for seismology, event detection and location was not done using global networks but rather by single arrays that determined the back-azimuth and incident angle of seismic body waves by measuring the apparent horizontal slowness, i.e. the difference in arrival times, over a network of 10–100 km aperture. The main motivation for using single arrays was that in the 1970s and 1980s, near real-time communication, as well as clock synchronization was not guaranteed in a global seismic network, so local arrays provided a more robust way to observe nuclear test signals from regional to teleseismic distances. Based on differential arrival time of seismic phases, the incident angle and the back-azimuth, an event could be located within the territory of a Nuclear power and attributed to a known test site, and its magnitude estimated to obtain the yield of a nuclear test. Improvement came with the installation of a global seismic network of digital recorders connected via satellite, by using arrival times at different stations and triangulate the source location. This however requires a reasonable model of seismic velocities. In many regions of the world such models do not exist, coincidentally also in the Baltic Sea, a mostly aseismic region. The Baltic sea basin itself is an eroded basin created during the the Pleistocene glaciation (Hall and van Boeckel, 2020), similar to the Great Lakes in Northern America. The sea floor is covered with several 100 m of soft quaternary sediments but does show a surprising complex-

ity. Specifically south of Bornholm, a system of graben faults points SW/NE, and the shallower Arnager block has exposed cretaceous bedrock at the surface. Hence the seismic velocity profile in the uppermost kilometers is complex (Ostrovsky et al., 1994; Vejrbæk et al., 1994). The low slope however makes landslides unlikely.

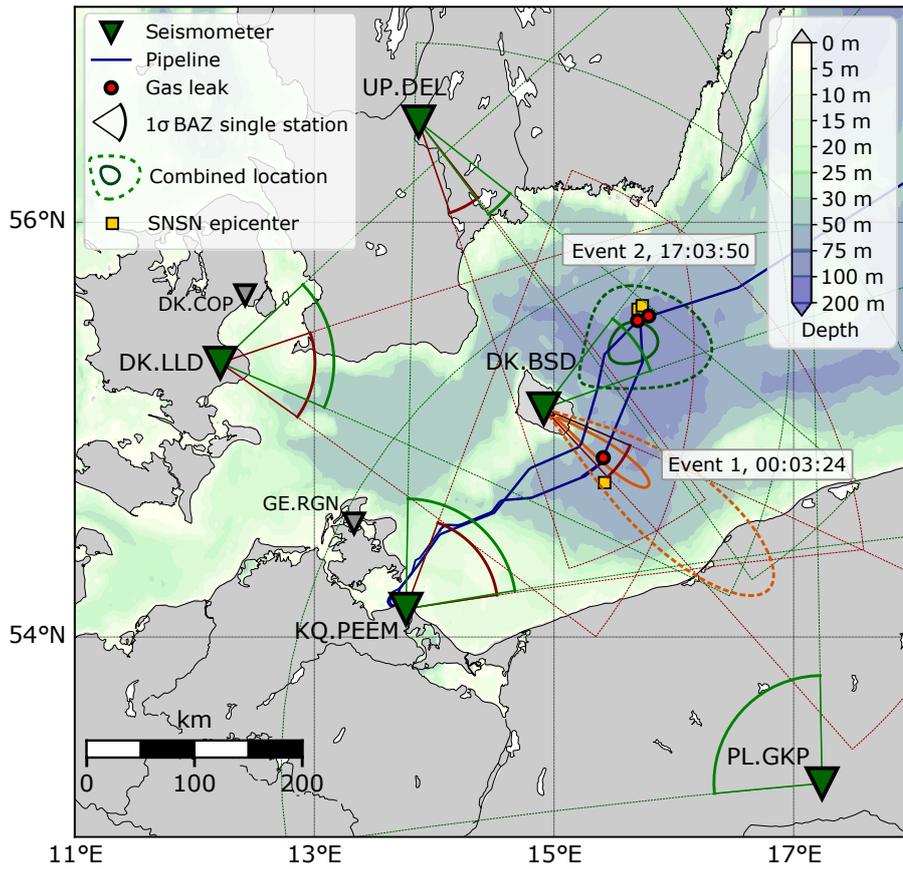
We therefore apply a method for event localization that does not require a seismic velocity model and which was initially developed to locate seismic events on Mars (Zenhäusern et al., 2022a). On Mars, we separately determine the distance and direction of the marsquake as seen from a single seismic station (Böse et al., 2016). The direction (back-azimuth) is determined based on the polarization of the main body waves: P and S. Since the P-wave is a compressional wave, its particle motion is in the direction of propagation, i.e. on a line pointing away from the epicenter. The S-wave is transversally polarized, i.e. orthogonal to the direction of polarization, which helps to determine the back-azimuth if the P-wave is not sufficiently polarized (e.g. low signal amplitude, scattering effects). The method is described in Zenhäusern et al. (2022a), where successful application to teleseismic events on Earth is demonstrated. It is now routinely applied by the InSight Marsquake Service (MQS, Clinton et al., 2021; Ceylan et al., 2022) to locate seismic events on Mars, where only a single seismometer (Lognonné et al., 2019) operates and thus classical multi-station methods cannot be applied.

## Method

We apply a complete polarization analysis of P and S body waves to determine the back-azimuth of seismic events. The three-component seismogram is transformed into time–frequency domain using a continuous wavelet transform (Kristekova et al., 2006) to produce a time–frequency dependent complex spectral matrix. For each time–frequency pixel, the matrix is decomposed into eigenvectors to obtain information on the instantaneous polarization of the seismic signal. This method is based on the work of (Samson, 1983) and was first applied to seismic data by Schimmel and Gallart



**Figure 1** Seismograms and spectrograms of both seismic events from station DK.BSD. The top subplot in each combined figure shows seismograms filtered above (red) and below (blue) 1 Hz. For better visibility of long-period energy, the spectrogram is plot on a logarithmic scale below 1 Hz. In the right subplot, the median (solid purple line) and 5th, and 25th (purple dotted and dashed grey), as well as 75th and 95th percentiles (dashed grey and purple dotted) of acceleration are plot together with the NLNM and NHHM as grey areas (Peterson, 1993). The 95th percentiles of the spectrogram shows the continued excitation of several bands after the event.



**Figure 2** Overview map of the Western Baltic Sea. We could obtain clear back-azimuths from four stations for event 1 (generally marked by red colors) and five for event 2 (marked by green colors). The grey triangles are stations where we detected an arrival, but could not obtain a clear polarization. Solid lines mark the 1 sigma location for each event combined from all usable stations, dashed lines the 2 sigma location. Event 1 is located less well, mainly due to the less favourable geometry of UP.DEL and DK.BSD, the two stations with best azimuth constraints. Squares mark epicenters from the SNSN catalog, leak locations (circles) are based on navigational warnings NW-230-22 and NW-237-22 by the Danish Maritime Authority. The bathymetry map uses the SRTM30\_PLUS dataset (Becker et al., 2009), the pipeline can be obtained from OpenStreetMap (relation 2006544).

(2003). We use all open access stations from the European Integrated Data Archives (EIDA, Strollo et al., 2021) within 3° (333 km) great-circle-arc distance around the reported position of the leaks. We download all HHZ, HHN, and HHE channels (high-sensitivity seismometer, typically sampled at 100 Hz) and correct the data to displacement using EVALRESP as implemented in ObsPy (Krischer et al., 2015). We then manually scan the data of days 2022-09-25 and 2022-09-26, i.e. including the day before the leaks were reported, for signals of nearby, seismic events with energy above 10 Hz using daily spectrograms. As reported by SNSN, one event was found on 2022-09-26 00:03:24 UTC and a second event around 2022-09-26 17:03:50 UTC (see figure 1 for seismograms and spectrograms of both events.). Table 1 has an overview over all stations on which the events were clearly detectable. For each of these stations, we identify a P-wave arrival window and apply our back-azimuth analysis to it in a 15 second time window starting 5 seconds before the arrival. See figure 3 for an example of our polarization analysis plot (Zenhäusern et al., 2022a). Polarization plots for all investigated stations can be found in the supplement. To locate the event, we combine the probability  $p_i(\alpha)$  of multiple sta-

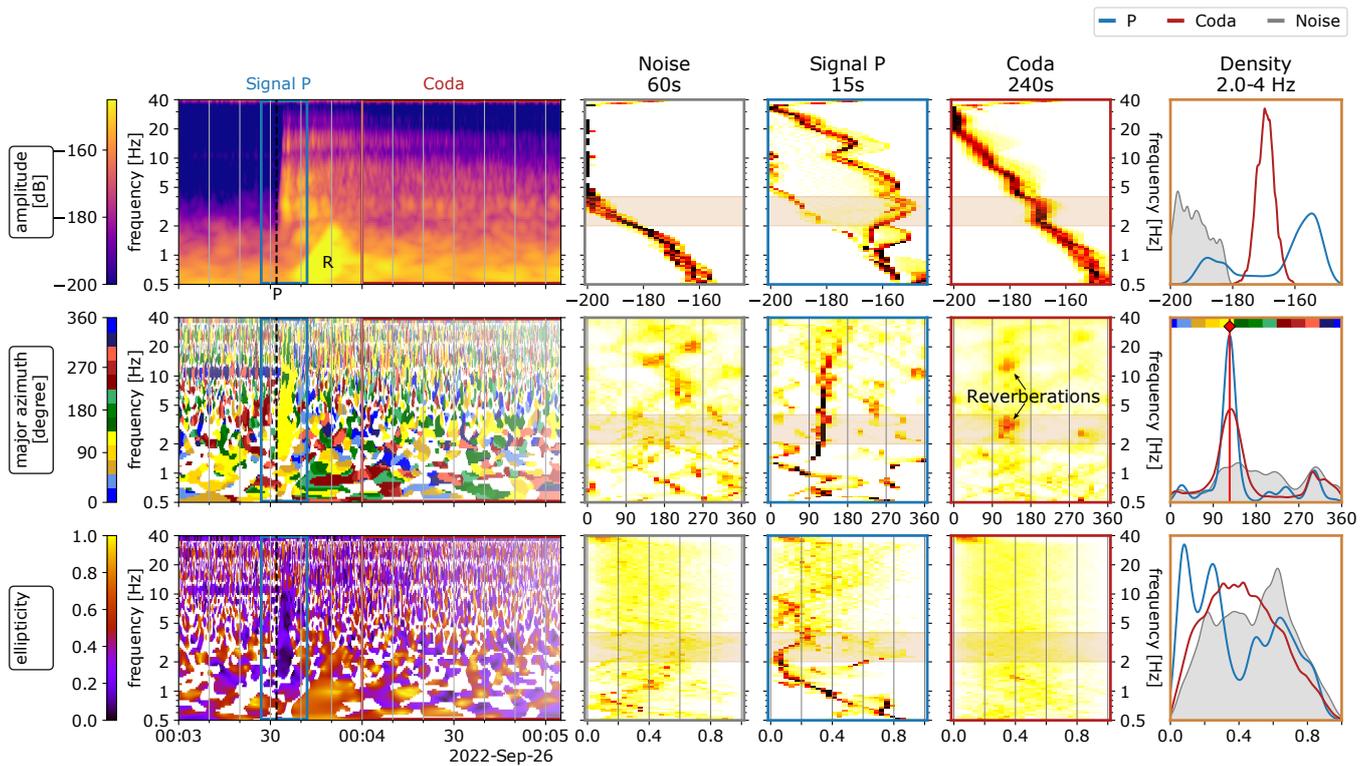
tions  $i$  as a function of backazimuth  $\alpha$  by multiplication

$$p_{\text{total}}(\varphi, \theta) = \prod_{i=1}^N p_i(\alpha(\varphi, \theta)), \quad (1)$$

to obtain a probability density function for latitude  $\theta$  and longitude  $\varphi$ . From this density function, a maximum likelihood value and an error ellipse is obtained and plotted in figure 2.

## Results

We find clearly polarized P-waves at 4 (event 1) and 5 (event 2) stations in a distance range from 50 to 250 km. The clearest observation is on station DK.BSD located on Bornholm Island (see figure 3 for the first explosion), with a mostly marine path. For both events, the back-azimuth is constrained to less than 30° (table 1). The energy in the seismograms ranges from 0.2 to 40 Hz, with a clear P-wave but no obvious S-wave. A Rayleigh wave with clear elliptical polarization arrives 10 seconds after the P. The overlap between S and Rayleigh is consistent with other quakes in distances of 50-100 km. The lack of a Love wave or transversally polarized S-waves (SH) supports an isotropic source, such as an explosion. The



**Figure 3** Polarization analysis of event 1 (2022-09-26 00:03:24 UTC) for Station DK.BSD. Shown are the amplitude in  $(m/s)^2/Hz$  [dB] (top row), azimuth (middle row), and ellipticity (bottom row). A linear signal corresponds to a low ellipticity. (left) Time-frequency plots for the different parameters, with marked time windows. The noise window is from 2 min to 1 min before the P pick (outside of depicted time range). (columns 2-4) Histogram depiction of the time windows seen on the left. The x-axis corresponds to the scale of the respective colorbar on the left. (right) Kernel density estimate (KDE) calculated from the time window between 2–4 Hz (shaded area in histogram plots). The x-axis again corresponds to the colorbar scale. The KDE peak of the P-wave is marked with a red vertical line and diamond. The signals from this first event shows a clearly polarized P-wave up to 20 Hz, a Rayleigh wave between 0.5 and 2 Hz and sustained polarization after the event. The back-azimuth is estimated to  $125 \pm 14$  degree from the P-wave. After the P-wave, polarization in the same direction is seen at 3.5 and 15 Hz, estimated as a continued pulsation at the source location. This is visible in the coda of the event, where there are distinct clusters (row 2, column 4; marked with 'Reverberations'). Further, the KDE of the coda shows a similar azimuth distribution as the P-window, albeit with lower signal amplitude.

signal has an overall duration of at least 10 minutes before falling to pre-event noise levels. SNSN reported two separate explosions for the second seismic event, separated by 8 seconds, which we find to be consistent with the observation that the second pulse has the same polarization attributes as the first.

The second-closest station KQ.PEEM in Peenemünde, Germany, in 100 (event 1) and 150 km (event 2) distance has clearly visible signals as well. Both P and S-arrivals are visible, but back-azimuths are less constrained ( $60^\circ$  uncertainty for event 1,  $80^\circ$  for event 2). The reduced amplitude is possibly due to the extended shallow sea over half of the distance to the events. The third station, UP.DEL in Southern Sweden, is significantly clearer in signal and shows a comparable back-azimuth constraint to DK.BSD. Surprisingly, this works even for the first event, which is located behind the Bornholm island as seen from the station. The fourth station, DK.LLD, shows a similarly bad constraint as KQ.PEEM, which is plausible given a low amplitude and paths that cross the Bornholm island and the lands of Southern Sweden. A signal is visible on several other openly accessible stations in Germany, Denmark, and Sweden (e.g. DK.COP,

DK.LLD, GE.RGN, GR.BSEG, UP.VIKU), but the polarization analysis did not obtain any additional constraints on the source locations. Polarization plots for these stations can be found in the supplement. Multiplication of the probability density functions for all "good" stations results in source regions close to the reported leaks. The first event has a very elongated uncertainty ellipse. For this event, the stations DK.BSD and UP.DEL are almost located in a line. The actual leak, as given by the navigational warning NW-230-22 is located inside the  $1\sigma$  region. For the second event, the stations are better positioned to constrain the location of the event very closely. The navigational warning NW-237-22 is just outside the  $1\sigma$  region, mainly due to the broad uncertainty from DK.BSD. Together with the known geometry of the Nordstream pipelines and the locations of the methane plumes on the sea surface, an identification of the explosions with the seismic events seems plausible.

On stations DK.BSD, which is the closest station to either event, and UP.DEL, we find sustained polarization after the first event: The P-wave polarization is present in the coda for several minutes. This is a clear indication that the signal duration is not caused primarily

by scattering but that seismic energy was radiated from the source over an extended period, at least 15 minutes. An explanation for this could be continued release of gas under high pressure. We can further investigate the peaks in the spectrogram (fig. 1) at about 3.5, 8, 15 and 24 Hz for event 1 and about 4, 15, 23 and 32 Hz for event 2. The two peaks at 3.5 and 15 Hz are confirmed to be consistently polarized for event 1, while the others are difficult to resolve. Assuming a speed of sound of 1470 m/s (typical for the Western Baltic Sea in September, see Grelowska, 2016), these two peaks would correspond to wave lengths of about 98 and 420 meter, respectively. The water depth at the source is 70 meter, so this suggests that the 15 Hz signal could be an actual reverberation within the water column, and the one at 23 and 32 Hz overtones. The 3.5 Hz signal (with the longer wavelength) is more likely an effect of the leak itself, potentially the Minnaert resonance of rising gas bubbles (Devaud et al., 2008).

Additional stations like GE.RGN on the Rügen island (Germany) or DK.COP near Copenhagen were tried, but had poorer azimuth constraints than neighbouring stations. We thus did not include them in this analysis and figure. The SNSN operates several more stations in Southern Sweden that might give additional constraints and which were used for their location, but data from these was not publicly available at the time of writing.

## Conclusion

The analysis of P-wave polarization on the signal of the Nordstream pipeline explosions shows the strong potential of the method for a model-agnostic location of seismic events. We clearly associate both leaks with the separate seismic events. Location uncertainties from 4 and 5 stations' polarization were larger than those based on travel time methods, but the latter used significantly more stations. As opposed to travel time methods, our approach does not need a velocity model, is robust against timing errors on stations and can easily be started from a single station, as soon as data is available there.

Both events show an absence of strong S-waves, consistent with a mostly isotropic source, such as an explosion. The closest station, DK.BSD on Bornholm, shows a clearly polarized coda, indicative of an ongoing source process over at least 10 minutes with several strong resonant peaks. This documents that polarization analysis of a small number of seismometer located onshore has the capability to locate and characterize seismic events in the water column.

## Acknowledgements

We would like to thank editor Ryo Okuwaki and Kiran K. S. Thingbaijam for providing reviews that helped improve the manuscript. We would also like to thank Alice-Agnes Gabriel for helping improve the German abstract. The authors recognise support from the ETH+ funding scheme (ETH+02 19-1: "Planet Mars").

## Data and code availability

The polarization code is available on github, the version used here on Zenodo (Zenhäusern et al., 2022b). Figure 1 was created with dailyspec (Stähler, 2022)

Seismic data were handled with ObsPy (Krischer et al., 2015). Calculations in Python were done with NumPy (Harris et al., 2020) and SciPy (Virtanen et al., 2020), and the results were visualized with Matplotlib (Hunter, 2007), seaborn (Waskom, 2021), and basemap. Seismic Data was collected using obspyDMT (Hosseini and Sigloch, 2017) from EIDA (<https://www.orfeus-eu.org/data/eida/>). We recognise the following networks for providing data: Network DK, GE (GEOFON Data Centre, 1993), PL, UP (Lund et al., 2021) and KQ (Christian Albrechts - Universität zu Kiel, 2017)

## References

- Becker, J. J., Sandwell, D. T., Smith, W. H. F., et al. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30\_PLUS. *Mar. Geod.*, 32(4):355–371, 2009. doi: 10.1080/01490410903297766.
- Böse, M., Clinton, J. F., Ceylan, S., et al. A Probabilistic Framework for Single-Station Location of Seismicity on Earth and Mars. *Phys. Earth Planet. Inter.*, 262:48–65, 2016. doi: 10.1016/j.pepi.2016.11.003.
- Ceylan, S., Clinton, J. F., Giardini, D., Stähler, S. C., et al. The marsquake catalogue from InSight, sols 0–1011. *Physics of the Earth and Planetary Interiors*, page 106943, Sept. 2022. doi: 10.1016/j.pepi.2022.106943.
- Christian Albrechts - Universität zu Kiel. Kiel University Earthquake Monitoring, 2017. doi: 10.7914/SN/KQ.
- Clinton, J. F., Ceylan, S., van Driel, M., et al. The Marsquake catalogue from InSight, sols 0–478. *Phys. Earth Planet. Inter.*, 310 (October 2020), 2021. doi: 10.1016/j.pepi.2020.106595.
- Devaud, M., Hocquet, T., Bacri, J.-C., and Leroy, V. The Minnaert bubble: An acoustic approach. *Eur. J. Phys.*, 29(6):1263–1285, Sept. 2008. doi: 10.1088/0143-0807/29/6/014.
- GEOFON Data Centre. GEOFON Seismic Network. 1993. doi: 10.14470/TR560404.
- Grelowska, G. Study of Seasonal Acoustic Properties of Sea Water in selected Waters of the Southern Baltic. *Pol. Marit. Res.*, 23 (1(89)):25–30, Apr. 2016. doi: 10.1515/pomr-2016-0004.
- Grünthal, G., Stromeier, D., Wylegalla, K., et al. The Mw 3.1–4.7 earthquakes in the southern Baltic Sea and adjacent areas in 2000, 2001 and 2004. *J Seismol*, 12(3):413–429, July 2008. doi: 10.1007/s10950-008-9096-0.
- Hall, A. and van Boeckel, M. Origin of the Baltic Sea basin by Pleistocene glacial erosion. *GFF*, 142(3):237–252, July 2020. doi: 10.1080/11035897.2020.1781246.
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. Array Programming with NumPy. *Nature*, 585(February):357–362, 2020. doi: 10.1038/s41586-020-2649-2.
- Hosseini, K. and Sigloch, K. ObspyDMT: A Python toolbox for retrieving and processing large seismological data sets. *Solid Earth*, 8(5):1047–1070, Oct. 2017. doi: 10.5194/se-8-1047-2017.
- Hunter, J. D. Matplotlib: A 2D graphics environment. *Comput. Sci. Eng.*, 9(3):90–95, 2007. doi: 10.1109/MCSE.2007.55.
- Krischer, L., Megies, T., Barsch, R., et al. ObsPy: A bridge for seismology into the scientific Python ecosystem.

- Comput. Sci. Discov.*, 8(1):014003–014003, 2015. doi: 10.1088/1749-4699/8/1/014003.
- Kristekova, M., Kristek, J., Moczo, P., and Day, S. M. Misfit Criteria for Quantitative Comparison of Seismograms. *Bull. Seismol. Soc. Am.*, 96(5):1836–1850, Oct. 2006. doi: 10.1785/0120060012.
- Lognonné, P., Banerdt, W. B., Giardini, D., Pike, W. T., et al. SEIS: Insight’s Seismic Experiment for Internal Structure of Mars. *Space Sci. Rev.*, 215(1):12–12, Jan. 2019. doi: 10.1007/s11214-018-0574-6.
- Lund, B., Schmidt, P., Hossein Shomali, Z., and Roth, M. The Modern Swedish National Seismic Network: Two Decades of Intraplate Microseismic Observation. *Seismological Research Letters*, 92(3):1747–1758, Mar. 2021. doi: 10.1785/0220200435.
- Ostrovsky, A. A., Flueh, E. R., and Luosto, U. Deep seismic structure of the Earth’s crust along the Baltic Sea profile. *Tectonophysics*, 233(3):279–292, May 1994. doi: 10.1016/0040-1951(94)90246-1.
- Peterson, J. Observations and Modeling of Seismic Background Noise. Technical report, Albuquerque, New Mexico, 1993.
- Samson, J. C. Pure states, polarized waves, and principal components in the spectra of multiple, geophysical time-series. *Geophysical Journal International*, 72(3):647–664, Mar. 1983. doi: 10.1111/j.1365-246X.1983.tb02825.x.
- Schimmel, M. and Gallart, J. The use of instantaneous polarization attributes for seismic signal detection and image enhancement. *Geophys. J. Int.*, 155(2):653–668, 2003. doi: 10.1046/j.1365-246X.2003.02077.x.
- Schweitzer, J., Köhler, A., and Christensen, J. M. Development of the NORSAR Network over the Last 50 Yr. *Seismological Research Letters*, 92(3):1501–1511, Jan. 2021. doi: 10.1785/0220200375.
- SNSN. Swedish National Seismic Network. Uppsala University, Uppsala, Sweden. Other/Seismic network, 1904. doi: 10.18159/SNSN.
- Stähler, S. C. *dailySpec: V0.2*. Zenodo, Oct. 2022. doi: 10.5281/zenodo.7220311
- Strollo, A., Cambaz, D., Clinton, J., et al. EIDA: The European Integrated Data Archive and Service Infrastructure within ORFEUS. *Seismological Research Letters*, 92(3):1788–1795, Mar. 2021. doi: 10.1785/0220200413.
- Vejbæk, O. V., Stouge, S., and Poulsen, K. D. Palaeozoic tectonic and sedimentary evolution and hydrocarbon prospectivity in the Bornholm area. *Dan. Geol. Unders. Ser. A*, 34:1–23, Sept. 1994. doi: 10.34194/seriea.v34.7054.
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nat. Methods*, 17(3):261–272, 2020. doi: 10.1038/s41592-019-0686-2.
- Waskom, M. L. Seaborn: Statistical data visualization. *J. Open Source Softw.*, 6(60):3021, 2021. doi: 10.21105/joss.03021.
- Zenhäusern, G., Stähler, S. C., et al. Low-Frequency Marsquakes and Where to Find Them: Back Azimuth Determination Using a Polarization Analysis Approach. *Bulletin of the Seismological Society of America*, May 2022a. doi: 10.1785/0120220019.
- Zenhäusern, G., Stähler, S. C., and van Driel, M. Polarisation analysis for seismic data. Zenodo, Oct. 2022b. doi: 10.5281/zenodo.7220543.