

Scientific Report MSM68

Two years after the completion of a cruise with the Research Vessels POLARSTERN, SONNE, METEOR, MARIA S. MERIAN, POSEIDON, ALKOR, HEINCKE, or ELISABETH MANN BORGESE, the scientific exploitation of the samples and data obtained have to be documented in a **Scientific Report** by the chief scientist. This includes the progress with regard to the scientific objectives as outlined in the original cruise proposal and the publication of the results in scientific journals.

Citation:

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Scientific Cruise Report

1. General Information

- MSM68
- MerMet 15-98
- Vera Schlindwein
- Alfred Wegener Institute, Helmholtz Zentrum für Polar- und Meeresforschung
- Knipovich Ridge passive seismic experiment: along-axis variations of lithospheric thickness at an ultraslow spreading ridge unraveled by passive seismology
- KNIPAS
- Longyearbyen (Norway) – Emden (Germany), October 6, 2017 to October 18, 2017
- 0

a) Publications – n.a.

Manuscripts in preparation:

Meier, M., Schlindwein, V., Scholz, J.-R., Geils, J., Krüger, F., Schmid-Aursch, M., Czuba, W. and Janik, T. Segment-scale seismicity pattern of the ultraslow-spreading Knipovich Ridge, G3, submission expected 09/2020.

Schlindwein, V., Essing, D., Hadziioannou, C., Schmidt-Aursch, M., Stähler, S., Characteristics of harmonic tremor in DEPAS OBS caused by strong bottom currents, SRL, submission expected 09/2020.

b) Book publications – n.a.

c) Other publications

Conference contributions:

- Meier, M., Schlindwein, V., Krüger, F., Czuba, W. and Janik, T. (2019). Earthquake Distribution Along an Entire Ridge Segment of the Ultraslow Spreading Knipovich Ridge, AGU Chapman Conference: Large-scale Volcanism in the Arctic: The Role of the Mantle and Tectonics, Selfoss, Iceland, 13 October 2019 - 18 October 2019.
- Schlindwein, V. (2019). Singing seismograms: Harmonic tremor signals in seismological records, IASPEI Union Lecture, 27th IUGG General Assembly, Montreal, Canada, 8 July 2019 - 18 July 2019.
- Wojcik, D., Czuba, W., Janik, T., Schlindwein, V. and Schmid, F. (2019). Seismic modelling of the lithosphere structure under Logachev Seamount on Knipovich Ridge (Greenland Sea), EGU General Assembly, Vienna, 2019.
- Schlindwein, V., Krüger, F., Schmid, F., Czuba, W. and Janik, T. (2018). KNIPAS – exploring active seafloor spreading processes at segment-scale, EGU General Assembly, Vienna, 2018.

d) Patents, arranged according to registered and issued. – n.a.

2. Summary (max. 1 DIN A4-page)

KNIPAS constitutes one of the largest ocean bottom seismometer (OBS) experiments conducted on mid-ocean ridges. A network of 26 OBS distributed over a distance of 160 km along the ultraslow spreading Knipovich Ridge recorded its earthquake activity for a period of up to 13 months. The instruments stem from the DEPAS pool (27 instruments at 23 locations) and the Polish Academy of Sciences (3 locations) and were deployed during two cruises of RV Polarstern and Horyzont II as a collaborative effort between AWI, the University of Potsdam and the Institute of Geophysics, Polish Academy of Sciences. MSM68 on RV Maria S. Merian successfully recovered all 27 DEPAS OBS in October 2017 and conducted comprehensive high-resolution mapping of the ridge topography.

The key scientific aim of KNIPAS is to understand how the little amounts of melts present at the slowest spreading mid-ocean ridges on Earth are steered towards isolated but pronounced volcanic centres and rise there through a thick lithosphere. In addition, KNIPAS investigates how a strongly oblique mid-ocean ridge is segmented and what kind of active spreading processes operate in magma controlled and in magma-starved segments to produce the anomalous oceanic lithosphere of ultraslow spreading ridges.

Since the recovery of the OBS we conducted laborious processing to determine the clock drift of the OBS recorders, the orientation of the seismometers at the seafloor and to identify, extract and pick the P- and S-phases of about 20.000 local earthquakes. 2D refraction seismic profiles of Logachev seamount gave preliminary seismic velocity profiles. A preliminary location of the 1000 best recorded earthquakes clearly indicates an undulating base of the mechanical lithosphere, with different maximum earthquake depths in different spreading segments. Deep earthquakes are in particular seen where oblique axial volcanic ridges meet the flanks of the rift valley. Logachev Seamount shows a prominent seismic gap, indicating potentially a region of melt. Two seismic swarms were recorded at Logachev Seamount that may testify to ongoing magmatic activity and open interesting research opportunities. We expect that the seismicity pattern, the amount of high-quality local and teleseismic events recorded by the network will support a comprehensive analysis of spreading processes and lithospheric structure as the project proceeds.

A problem for the KNIPAS OBS network that was not anticipated were strong ocean bottom currents that seriously affected the records. The currents reach velocities of up to 20 cm/sec and lead to Karman vortex shedding and strumming at the head buoy and the flag pole of the OBS. This produced pronounced harmonic tremor signals on all seismometer channels in a frequency band of about 1-10 Hz obscuring earthquake arrivals in times of strong tremor. We extracted the fundamental frequency of the tremor in the entire network for the duration of the survey and reconstructed ocean bottom current velocities and their variation in time and space. Measures have been taken to avoid this problem in future surveys.

3. Scientific Results (max. 20 DIN A4 Pages)

3.1 Objectives of the project

The active spreading processes at ultraslow spreading mid-ocean ridges are still poorly explored because the main representatives, the Arctic Ridge System and the Southwest Indian Ridge lie in regions with difficult working conditions. Melt is distributed very unevenly along the axis of ultraslow spreading ridges and results in contrasting magmatic and amagmatic ridge sections with different deformation styles. Reconnaissance seismicity surveys [e.g. *Schindwein and Schmid, 2016; Schindwein et al., 2013*] highlighted these differences but left many questions about detailed spreading processes open. With the passive seismic experiment KNIPAS, we study for the first time ultraslow spreading processes at the scale of entire spreading segments (Fig. 1). In particular KNIPAS seeks to find answers to the following questions as outlined in the cruise proposal:

- 1.) How does the thermal state of the lithosphere of an ultraslow spreading ridge vary along-axis? How does lithospheric thickness change along axis? Can we see more pronounced variations than on slow spreading ridges that give hints on the uneven regional melt distribution at ultraslow spreading ridges?

- 2.) Is there a seismic gap underneath Logachev Seamount and potentially its neighbouring magmatic centre that provides evidence for focussed melt supply? If yes, what are the dimensions and properties of such a gap and the adjacent earthquakes bounding this gap? Would the slope of the lithosphere-asthenosphere boundary be steep enough to allow lateral melt flow? Is the gap bounded by faults? What influence has ridge obliquity at Knipovich Ridge on the spatial extent of the seismic gap? How does it compare to the seismic gap observed at the orthogonally spreading eastern SWIR?
- 3.) Can we see variations in spreading processes along axis as on slow spreading ridges? Are there changes in the seismicity rate and pattern (symmetrical versus asymmetrical) and how are they linked to geological features? Are there differences in the seismicity of magmatic centres versus the magmatically starved sections as tentatively indicated by teleseismic data? Are detachment faults present with increased seismic activity?
- 4.) How does melt transport through the lithosphere work at a magmatic centre of an ultraslow spreading ridge? Are there signs for deep reaching faults that act as pathways, or can we identify heavily intruded regions or remnants of magma chambers?
- 5.) How representative are the detected spreading processes of ultraslow spreading ridges as a whole? What are the effects of oblique spreading? How stable in time are spreading processes at ultraslow spreading ridges? How does melt supply vary with time?

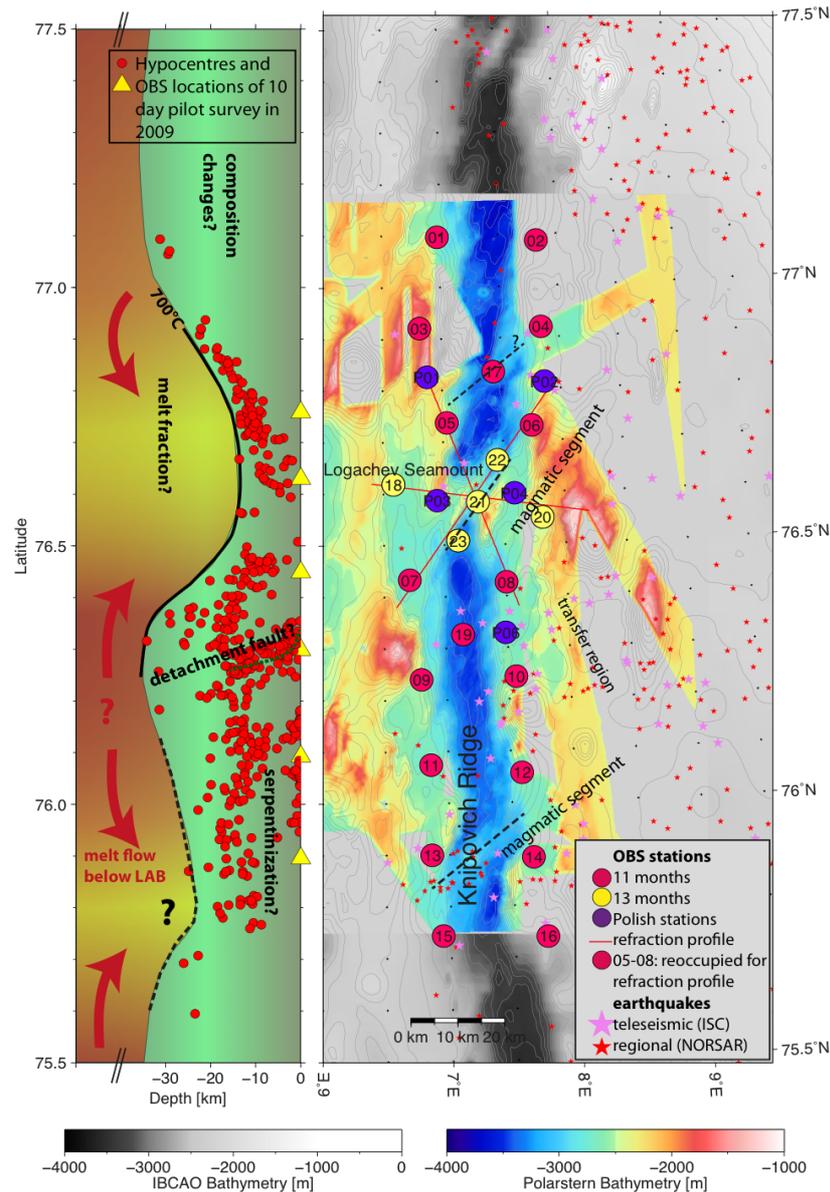


Fig. 1: The survey area with regional seismicity (stars) and earthquake locations (left) from a reconnaissance survey [Schlindwein et al., 2013]. Circles and lines represent OBS locations and seismic refraction lines as deployed. OBSs P01 and P06 could not be recovered.

3.2 Development of the work carried out including deviations from the original concept, potentially scientific failures, problems in the project organization or the technical implementation

3.2.1 Preparation of the data set and state of processing

The implementation of the project went fully according to plan. In January 2018, we exchanged data with our collaborators at the Institute for Geophysics, Polish Academy of Sciences, Warsaw, Poland. We obtained continuous records from their 3 OBS and provided them with the seismic refraction data acquired over Logachev Seamount for processing (see conference contribution Wojcik et al. 2019). We successfully applied for a DFG grant to process the valuable data set acquired during MSM68. The project was granted in April 2018 (SCHL 853/5-1, KR 1935/17-1) and could start in July 2018. It

consists of funding for a Phd student at AWI and a Phd student and 6 months of Postdoc at the University of Potsdam. The Postdoc funding was used to conduct fundamental processing of the data set. The clocks of 8 out of 27 DEPAS OBS could not be synchronized upon recovery as their batteries had expired. We used the ambient noise cross-correlation technique [Hannemann *et al.*, 2014] to determine clock drift for all instruments. Likewise, the orientation of the seismometers at the seafloor had to be determined. This was done during a practical training by a student at the University of Potsdam. Since some sensors encountered failures or saturation of one horizontal component, we could only reconstruct the orientation of 17 instruments. However, sensor orientation is not critical for many applications. By April 2019, we had a consistent data set of continuous waveforms in mseed format available along with all relevant information including instrument responses, station noise (probabilistic power spectral density plots, PPSD), time drift and sensor orientation. After that, the Phd position in Potsdam could be filled. This part of the project has just recently started. The position could not be filled earlier due to a lack of suitably qualified candidates with a solid background in geophysics.

The PhD at AWI could already start by mid 2018 to screen the KNIPAS data set for local earthquakes generated on Knipovich Ridge. We manually examined an equivalent of about 4 weeks of data distributed over the entire recording period and then determined suitable parameters and detection thresholds for an automatic event detection using Lassie algorithm (<https://gitext.gfz-potsdam.de/heimann/lassie>). 20256 earthquakes were identified. Earthquake phases were manually picked in the test data set and subsequently the picks were compared to automatic picks by pspicker [Baillard *et al.*, 2013], a kurtosis picker that is adapted for ocean bottom seismometer records. However, our data set turned out to be fairly noisy even for marine data sets, such that all earthquake picks had to be manually checked and partly refined, erroneous picks removed and missing picks added. The DFG grant included funding for student helpers as we anticipated this problem. Additional timing errors for some stations that entered the dataset during conversion of the raw data onboard only became apparent after initial earthquake location in late 2019 and required a new conversion of the raw data and a time correction of already picked phases. Meanwhile a consistent earthquake catalog of 14000 located earthquakes exists as basis for all subsequent studies of spreading processes at Knipovich Ridge. We currently work on the optimal visualization of this large data set and its geological interpretation. Focal mechanisms for about 45 earthquakes were determined. A subset of the best recorded 1000 earthquakes was picked ahead of the complete data set and was used to derive a velocity model for the location procedure. This dataset is discussed in section 3.3.1.

3.2.2 Regional seismicity at Knipovich Ridge

As an additional use, we planned to use the Knipovich Ridge OBS network also to refine earthquake locations of stronger regionally recorded seismic events that appear to be off-axis between Knipovich Ridge and the Barents Shelf. It is uncertain, whether these events are truly occurring off-axis or whether the regional seismic networks are unable to locate these events properly due to a sparse station cover and highly heterogeneous velocity structure. Unfortunately, only very few earthquakes off-axis of the network occurred during the recording period (Fig. 2). Phase arrivals of earthquakes north and south of the network were usually found to be of poor quality, potentially damped by the shallow asthenosphere at the active ridge. A comparison of earthquake locations using land stations only with earthquake locations using land stations and our OBS network was made in the framework of a bachelor thesis [Kramer, 2018]. No significant improvement could be attained and the analysis of regional earthquakes was therefore not pursued any further at the present moment. It appears that the timing errors detected in late 2019 may have contributed to poor earthquake locations although timing errors were less than 1 sec and within the picking uncertainty of regional S phases.

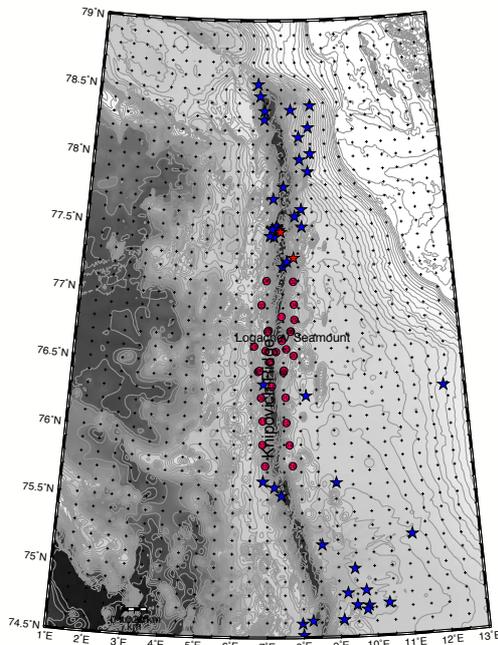


Fig. 2: Regional seismic events (blue stars) from unreviewed ISC catalog occurring during the recording time of our seismic network (red circles). Note that hardly any events occurred within the network or off-axis in the area of the network compared to the long-term seismicity (c.f. Fig. 1)

3.2.3 Unexpected, strong ocean bottom currents

Upon recovery of the ocean bottom seismometers, we already realized that stations on the eastern rift flank typically surfaced considerably north of their deployment position, indicating strong ocean currents (Fig. 3). Calculation of probabilistic power spectral density plots [McNamara and Buland, 2004] and inspection of wave form data (Fig. 4) revealed high noise levels and tremor-like signals in a frequency range between about 1 and 7 Hz, affecting a majority of the stations. It quickly became clear that this signal is produced by strong ocean bottom currents acting on the OBS, restricting the detection of local earthquakes to frequencies above 7 Hz, although S-phases typically have their main energy between about 3 Hz and 10 Hz. This current noise considerably contributed to the slow progress in picking of local earthquakes and the poor performance of automatic

picking algorithms, and eventually it also affected the detection threshold of earthquakes during the strongest phases of current noise. To avoid problems with ocean currents acting on the OBS in future surveys, we immediately analysed this phenomenon in detail in a master thesis. The results are described in section 3.3.3 below. We further used modified OBS head buoys in a follow up experiment on the Knipovich Ridge Bend to amend this problem.

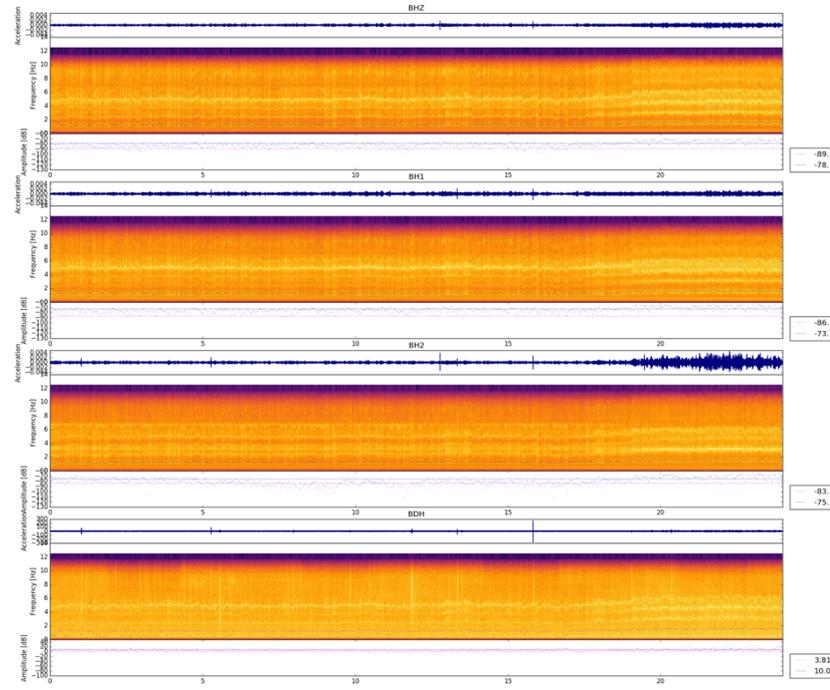


Fig. 3: Spectrograms of 24 hours of data from station KNR12 showing the 4 OBS channels. The harmonic tremor signal caused by currents acting on the OBS is clearly visible. An increase in tremor amplitude is particularly evident on channel BH2 around 20:00 connected also with different frequencies that may point to an additional vibrating source. Dots and panels with dots indicate the performance of the tremor detection algorithm in finding the fundamental frequency of harmonic tremor signals.

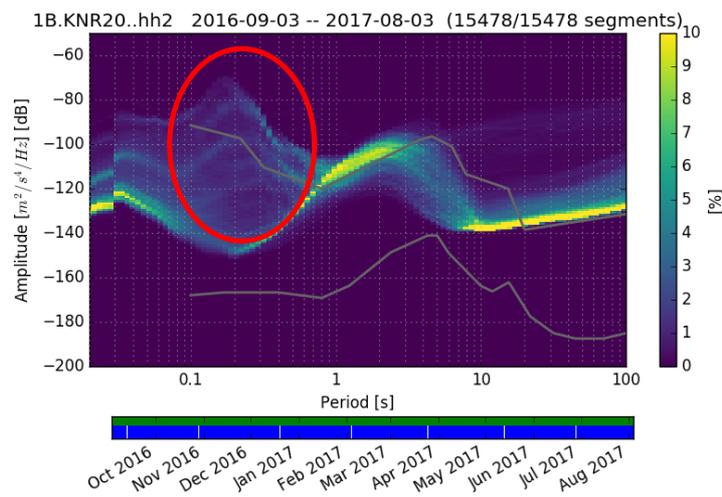


Fig. 4: Power spectral density plot of station 20. The red circle marks the frequency range affected by the tremor signal that shows amplitudes in excess of the microseismic noise peak at 2s period.

3.2.4 Unexpected acquisition of extensive multibeam bathymetry data

A pleasant development during MSM68 was that OBS recovery went very well due to very calm sea conditions. We could refrain from risky OBS recovery during darkness and used the nights for multibeam bathymetry surveying. We managed to close data gaps to a bathymetry dataset on northern Knipovich ridge acquired during MSM57 and filled gaps in existing high-resolution bathymetry data acquired during MSM67 and by RV Polarstern, extending the bathymetry cover along the ridge to south of 75°N. The entire bathymetry data set was processed in the framework of a bachelor thesis to yield a consistent topography grid of Knipovich Ridge. The grid was analysed for spreading dependent topographic features. The results are presented in section 3.3.2.

3.3 Presentation of the achieved results and discussion with regard to the relevant state-of-the-art, possible application perspectives and conceivable follow-up examinations

Large seismological data sets as KNIPAS require extensive processing as prerequisite for any geological interpretation, such that 2 years after the recovery of the OBS no final results that allow for a discussion with the regard to the relevant state-of-the-art can possibly be presented. Instead, we show here some preliminary results and indicate which objectives (3.1) will be possibly be reached. We expect further 2 years until first published papers.

3.3.1 Seismicity of Knipovich Ridge

Fig. 5 shows earthquake locations based on the Hyposat location algorithm [Schweitzer, 2001]. The 1000 best recorded events give a first impression of the seismicity pattern. In the following we address the individual objectives (3.1) and discuss the perspectives on the basis of this preliminary results.

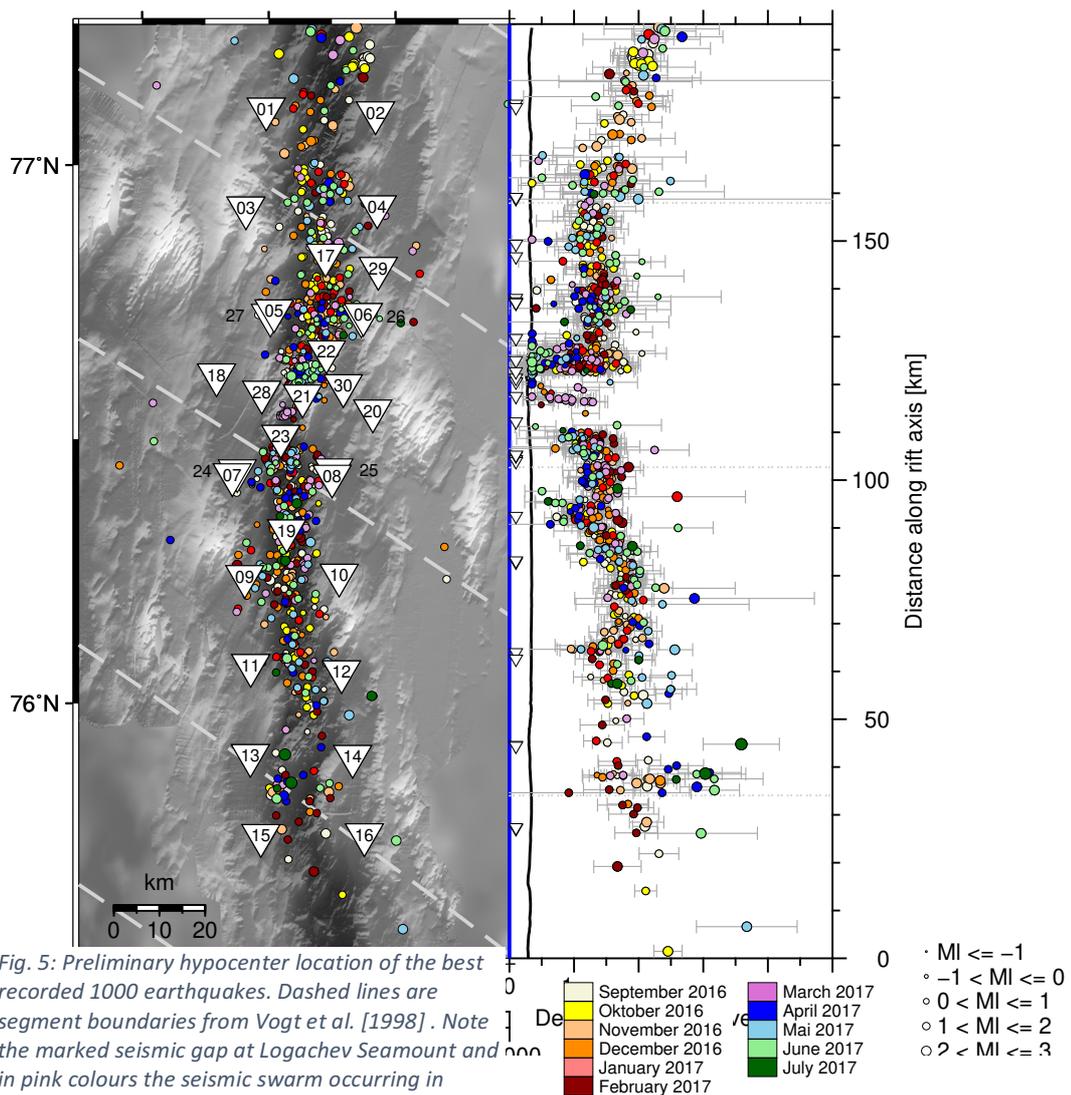
Objective 1: We can clearly see changes in the along axis depth of the seismicity that can be interpreted in terms of thermal structure and lithospheric thickness. Differences between segments (dashed lines in Fig. 5) and within segments can be seen. We currently work on a redefinition of the segmentation based on the complete seismicity image. The data set is of sufficiently high quality to support a comparison to faster spreading ridges.

Objective 2: A seismic gap at Logachev Seamount is clearly visible. It is bounded by seismically active area with many well recorded events, such that we expect to resolve, whether this gap is thermally controlled or partially fault bounded, at least towards the end of the segment. A relative relocation of the seismic events, eventually with a 3 D velocity model, will sharpen the seismicity pattern. Fault plane solutions of some stronger events near Logachev surprisingly indicate some strike-slip motion, potentially a sign for some extent of tectonic control on the seismic gap. The current seismicity pattern appears rather flat-bottomed such that it remains questionable, whether the topography of the lithosphere-asthenosphere boundary at deeper levels may be steep enough to guide melts towards the volcanic centres. However, both the northern and southern end of the survey area show deeper reaching earthquakes.

Objective 3: The network geometry was designed to allow for a comparative analysis of seismicity rates in relation to the magma supply of different spreading segments. However, due to malfunctioning seismometers that prematurely exhausted the OBS batteries, the sensitivity along the network varied both spatially and as a function of

time. In addition, the problematic noise caused ocean bottom currents affected the seismic stations to different extents, with for example station 06 frequently suffering from disturbed records. Therefore, the completeness threshold above which we can reliably compare seismicity rates may be quite high. However, a first estimate based on the complete catalogue gives a magnitude of completeness of about M_L 0.9, with lower values regionally (around 0.6 for Logachev Seamount), which is surprisingly low such that we can expect to reliably capture also weak seismicity. The preliminary seismicity patterns give indications that towards the ends of magmatic segments, deep and shallow earthquakes with some separation in depth are present. Whether these earthquakes are part of detachment faults or potentially belong to transform system is currently being clarified. Fault mechanisms indicate a consistent regime of compression in the southernmost segment and point to significant regional complexity.

Objective 4: Our data set turned out to present an excellent basis to study melt ascent and plumbing of a volcanic centre at an ultraslow spreading ridge. A large number of seismic events along with extensive refraction seismic data, that are currently being processed by our Polish colleagues, will form the basis for a detailed tomographic image of Logachev. The seismic gap along with consistent S-phase delays at station 21 potentially indicate the presence of a melt reservoir as we found in a comparable



geological setting at the Southwest Indian Ridge [Schmid *et al.*, 2017]. Particularly intriguing is a seismic swarm in March 2017 that appears to occur in the otherwise earthquake free area underneath Logachev. A further seismic swarm occurred in June at shallower levels. Both swarms may point to ongoing magmatic activity, thus we can monitor magma ascent and depths of melt reservoirs. We will have to find out, how seismic energy can be released during a swarm in an area that otherwise appears not to support brittle failure of rocks.

3.3.2 Topography of Knipovich Ridge

Fig. 6 shows the bathymetry grid over Knipovich Ridge as compiled by Geils [2018]. This bathymetry grid was subsequently submitted to an automatic detection of broad- and finescale ridges and troughs using the Benthic Terrain Modeller toolbox (Fig. 7). These patterns were statistically analysed and compared among segments as defined by Vogt *et al.* [1998]. Segments 3 and 5 clearly stand out as magmatically robust spreading segments with elevated topography, the elevation varying in time off-axis. Other areas clearly showed complex pattern related to the complicated interaction between the N-S trending rift valley and obliquely oriented magmatic ridges. A further discrimination between the segments based on their topographic characteristics was not possible. The seismological network mainly spans segments 2-4. We will analyse the seismicity pattern

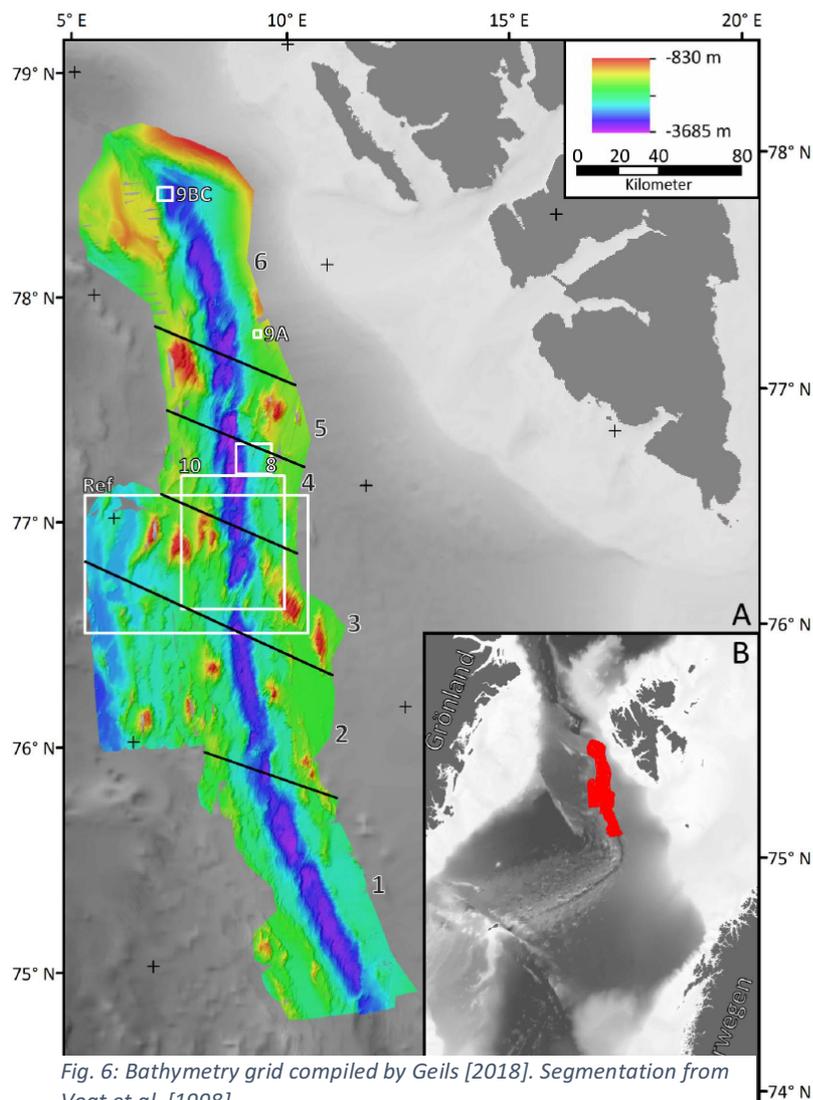


Fig. 6: Bathymetry grid compiled by Geils [2018]. Segmentation from Vogt *et al.* [1998].

segment-wise and relate it to the typical topographic signatures of the segments. To meet **objective 5**, we will assess to what extent the segments and their seismicity and topography are representative for Knipovich Ridge as a whole and for ultraslow spreading ridges in general, the topographic characteristics serving as a linking element in absence of extensive seismicity surveys on all ultraslow ridge segments.

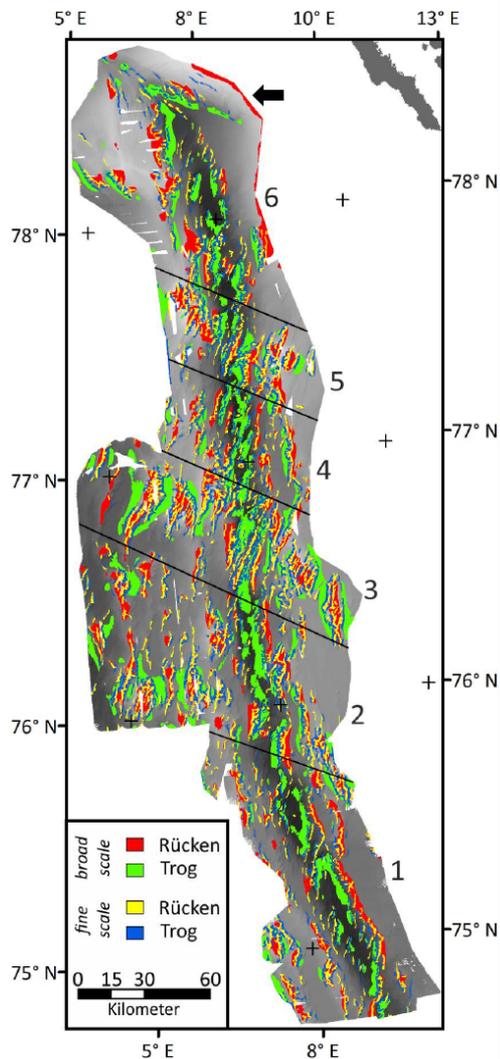


Fig. 7: Result of the topographic classification of Knipovich ridge [from Geils, 2018].

3.3.3 Ocean bottom currents at Knipovich Ridge

Fig. 3 already showed the kind of harmonic tremor produced most likely by strumming of the head buoy and potentially also by an involvement of the flag pole that might produce higher frequencies (after 20:00 in Figure 3). Comparable observations were made in a shallow water experiment [Stähler *et al.*, 2018]. Stähler *et al.* [2018] could show, how current velocities can be estimated from the tremor fundamental frequency. We used a modern tremor detection algorithm [Roman, 2017] to extract the tremor fundamental frequency of all stations during the entire recording period. Tremor occurred in 6-40% percent of the recording time of the stations, meaning that current velocities reached a threshold necessary to excite tremor (Fig. 8). Tremor frequencies then increase with current velocity until eigenfrequencies of the oscillating systems are reached and mode locking occurs (Fig. 9). In these cases, the tremor

frequency remains constant although current velocities may further increase, such that the values in Fig. 8 likely underestimate peak current velocities. The Güralp OBS of the Polish Academy of Sciences also showed tremor although at different frequencies than the KUM LOBSTER OBS. This confirms the nature of the tremor signals.

We investigated the OBS orientation relative to the assumed current direction as well as the strength of the signal on the individual seismometer components to find out how the vibrations couple so strongly into the OBS system, but this work is still in progress. For the follow-up survey on southern Knipovich where we likewise expect strong ocean bottom currents, we attached the head buoy in a kind of bag firmly to the OBS, such that there are no free ropes. The head buoy will only ascent freely after release of the OBS.

The occurrence of tremor episodes on long time scales (longer than days) was similar between OBSs 12,14 and 16, and we could see, how a water mass with strong currents “moved” from south to north along the eastern flank of Knipovich ridge.

We currently compile our observations that are only partly contained in the master’s thesis of Essing [2019] and prepare a manuscript for publication.

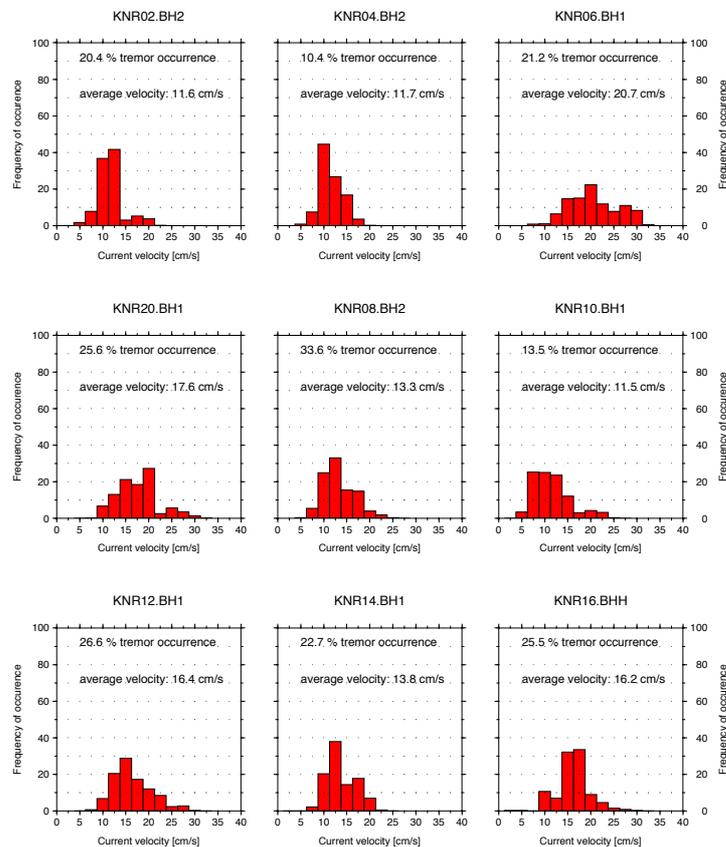


Fig. 8: Histograms of current velocities estimated from the tremor fundamental frequency. Stations on the eastern rift flank are displayed to exhibit the highest current velocities.

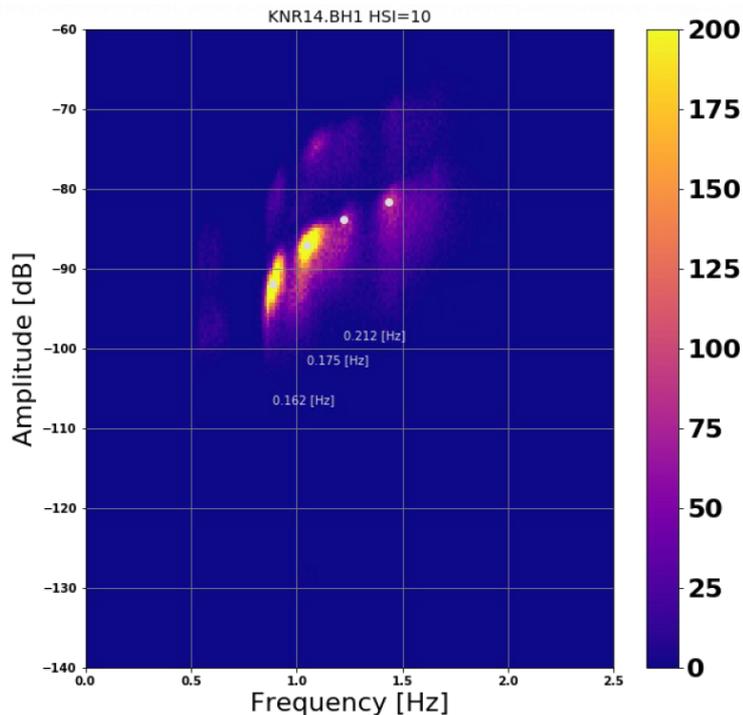


Fig. 9: Mode locking of tremor observed at station KNR14. Certain pairs of frequency and amplitude are preferred as can be seen from their frequent occurrence (yellow colours). Amplitudes of the tremor generally rises with increasing frequencies. Note that certain frequencies are generally avoided.

3.4 Who contributed to the project (the most important national and international cooperation partners involved in the dissemination of the cruise data)

Our main partners in the project are the University of Potsdam with Prof. Dr. F. Krüger as co-proponent and Prof. W. Czuba and Prof T. Janik, Geophysical Institute, Polish Academy of Sciences, Warsaw, Poland. We further collaborate with T. Barreyre, University of Bergen, with whom we currently operate an OBS network at the southern end of Knipovich Ridge around Loki's Castle vent field. This data set will become available in 2020 and we expect that it will complement KNIPAS data and enable a comparative analysis of seismicity pattern. Likewise, we have established collaboration with Dr. A. Faverola, Centre for Arctic Gas Hydrates, University of Tromsø, in project SEAMSTRESS. For that project we will jointly operate an OBS network at the northern termination of Knipovich Ridge on Vestnesa Ridge in an off-axis setting. This project will also serve to understand the KNIPAS seismicity data in a regional framework.

Nationally we collaborated with Prof. C. Hadziioannou, University of Hamburg, on noise signals in the OBS records.

3.5 Qualification of undergraduates and graduates in context with this project (e.g.

bachelor thesis, master thesis, as well as PhD thesis etc.) by listing the number of theses, which based on samples and data obtained during the cruise

Number of bachelor theses: 2

Number of master theses: 1

Number of PhD theses: 2 in progress

3.6 Status of the data and sample availability

OBS raw data are available through Pangaea:

<https://doi.pangaea.de/10.1594/PANGAEA.896635>.

Bathymetry raw data are available through Pangaea:

<https://doi.org/10.1594/PANGAEA.892679>

4. References

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