Scientific report for ECORD/IODP
MagellanPlus Workshop Series program

Carbon Cycling at the Ultraslow Arctic Spreading Ridge System

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ECORD European Consortium for Ocean Research Drilling

IODP INTEGRATED OCEAN DRILLING PROGRAM

K.G. Jebsen Centre for Deep Sea Research

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1. Rationale

The Arctic Ocean stores a significant amount of carbon in form of sedimentary organic carbon and methane hydrates beneath the ocean floor (McGuire et al., 2010, Stein et al., 1994). Our current understanding of the sources and sinks of carbon in this marine setting as well as their sensitivity to external forcing, such as volcanic/tectonic activity or climate change, is inadequate. A number of recent findings suggest that the sedimentary carbon pool is strongly affected by tectonic and hydrothermal processes: (1) Seismic studies have revealed the presence of gas hydrate deposits on ultraslow-spreading sedimented ridges in the Arctic Ocean and suggested that methane is predominantly derived from abiotic serpentinization of ultramafic rocks (Johnson et al., 2015; Rajan et al., 2012). (2) Hydrothermal vents on the southern Knipovich Ridge (SKR) show very high methane and ammonia concentration owing to pyrolysis of sedimentary organic matter (Pedersen et al., 2010). (3) A tight link between the distribution of organic carbon, and overall microbial abundance and community structure has been shown (Kallmeyer et al., 2012, Jørgensen et al., 2012). (4) Organic carbon has been shown to be extremely reactive under hydrothermal conditions, with important ramifications for global cycling of carbon (Hawkes et al., 2015). The relative roles of microbial, thermogenic, and abiotic carbon reactions and methane generation remain unknown. In addition, it remains unclear how much of the generated methane is stored as gas hydrates and how much is oxidized to carbon dioxide. CO_2 released through thermal degradation or microbial respiration of organic matter can be trapped in the basement, but the role of basement as a sink of carbon is also unclear, although there are indications of intense interactions between sediment and basement in both basaltic ridge flanks (Wheat and Fisher 2008) and ultramafic rifted margin settings (Barnes et al., 2009).

Here, we propose to start a new drilling initiative aimed at investigating the relative importance of abiotic and biotic cycling of carbon at the sediment-covered and ultraslow-spreading (8 mm/yr half rate) SKR and its flanks in the Norwegian-Greenland Sea. *We argue that the SKR area is particularly well suited for addressing first-order questions about the pathways and processes of tectonically and hydrothermally induced subseafloor carbon cycling*. Firstly, the high heat flow across the SKR will lead to thermal degradation of organic matter, which will release low-molecular weight organics that stream up and potentially support sub-seafloor life (Parkes et al, 2007). Secondly, detachment faulting is taking place in the area and the associated serpentinization reactions and fluid conduits will generate a flux of methane and other organics into the overlying sedimentary pile. Thirdly, hydrothermal solutions upwelling from a sedimented axial volcanic ridge will cause reactions with sedimentary carbon that result in a reflux of organics into the oceans. All three processes result in reactions and mobilization of sedimentary organic carbon, which is often considered passively stored away for very long time scales. We hypothesize that the organic carbon pool in large parts of the Arctic Ocean may actually be more reactive than commonly assumed. Drilling will enable us to test this hypothesis and determine the nature and extent of carbon cycling and its consequences for deep life. The proposed research is directly relevant to the *Biosphere Frontiers*, *Earth Connections* and *Earth in motion* Themes of IODP's New Science Plan, particularly Challenges 5, 6, 8, 9, 10, 13 and 14. (Due to the complex sedimentation history of the SKR addressing Challenges within Theme 1 is less relevant).

2. Meeting structure

The purpose of the proposed workshop was to bring together a team of scientists from multiple disciplines, ranging from geophysics to petrology to biogeochemistry and microbiology, to plan and draft up an IODP proposal for JR-style drilling of a series of holes on and off axis of the SKR to assess the cycling of carbon and consequences for life in sediments and shallow basement. The workshop consisted of participants with an extensive knowledge and experience in planning and leading previous IODP drilling expeditions, which along with the invaluable guidance from IODP assistant director of science services and manager of science operations, helped elucidating the operational constraints and acted as mentors for the younger and less experienced scientists.

Fig. 1. Meeting facility at the K.G. Jebsen Center for Deep Sea Research.

A guided tour to the Norwegian Ocean Observation Laboratory facility provided workshop participants the opportunity to learn about the technological infrastructure that is available from the University of Bergen for surveying targets for the upcoming IODP proposal.

Fig. 2. Site visit to the Ocean Laboratory facility examining the Ægir 6000 ROV

Lectures were given on the following topics during the first day and the following morning.

- *Structural evolution of ultra-slow spreading ridges.*
- *Knipovich Ridge and geological history of the Norwegian-Greenland sea.*
- *Seismicity and lithosphere structure at slow/ultraslow ridges.*
- *The role of water-rock reactions for cycling of buried carbon.*
- *Carbon cycling by subseafloor microbial life.*
- *Implications of deep-reaching serpentinization for the deformation mode.*
- *Gas sources in the Norwegian-Greenland sea.*
- *Challenges of drilling the SKR.*
- *Structural evolution of ultra-slow spreading ridges.*
- *Possibilities and challenges by deploying CORKs.*

Discussions were initiated after each lecture throughout the workshop and a more focused discussion in the afternoon of the second day and the morning of the third. The following main topics were discussed:

- Identify scientific objectives and questions.
- Identify/select potential drill sites to achieve the objectives.
- Identify missing site survey data.
- Identify potential risks.

3. Discussion results and recommendations

3a. Science questions

The likelihood of sedimented active core complexes at the SKR, thereby providing optimal drilling conditions allowing access to ultramafic rocks and potential active serpentinization processes with minimal risk, quickly lead to the consensus that the overarching science objective for a drilling proposal will be the prospect of drilling into a presumable active serpentinizing system.

With this in mind the four IODP research themes and the 14 underlying challenges were used as a roadmap for discussion in order to identify specific scientific objectives within the IODP framework.

Theme 2. Biosphere Frontiers

Challenge 5: *What are the origin, composition, and global significance of deep subseafloor communities?*

A thick and firm sediment layer covers the “zero-age” basalt in the rift valley and allow for drilling an otherwise inaccessible region of the deep subseafloor habitat with clear relevance for the origin of deep subseafloor communities. The type of material that can be recovered represents a novel habitat of which there is no prior knowledge with respect to microbial ecology and its potential impact on the surface world. Further, If the assumed difference in heat flux between the east and west side of the ridge valley is correct then we can investigate the effect of temperature on the microbial communities and there activity and hence their significance on the carbon cycle. Further, the drilling into the crust at the SKR will be the second operation focused on recovering deeply buried crustal material for microbial analysis and thereby help to constrain if the relatively homogenous lithology will be reflected in a similar microbial community structure.

Challenge 6: *What are the limits of life in the subseafloor realm?*

A recent expedition set out to address this exact challenge (IODP exp. 370) and the preliminary results indicate that a temperature around 70-90 degrees Celsius is the limit at the investigated sites. However, it is speculated that energy availability is an important factor influencing the temperature limit for life. The combination of high temperatures and relatively high-energy flux in terms of organic matter availability and potential serpentinization at the SKR allow us to investigate this issue in greater details.

Theme 3. Earth Connections

Challenge 8: *What are the composition, structure and dynamics of Earths upper mantle?*

It was proposed that transect drilling across the ridge from top to basement would give the opportunity to check if geochemical signature at the ridge changes over time. Needs a number of holes on the East side. Could potentially address the extent of serpentinization. I would however require quite a number of holes to be drilled, and thereby time consuming.

Challenge 9: *How are seafloor spreading and mantle melting linked to ocean crustal architecture?*

The fact that this ridge is sedimented gives an opportunity to date a number of relevant events, e.g. rotational and volcanic events that hasn't been possible previously. Would be beneficial to drill different holes at different distances from axis to investigate the timing and evolution of fault rotation. Mostly focus on sediment on western side of P21 line for this objective (unit 3 on seismic lien). This could be a low hanging fruit and only needs sediment recovering and dating. It was argued that this might need better seismic data than what we currently have.

Due to the relatively high sedimentation rate, the axial volcanic ridge (AVR) on the seismic line (P21) could be drilled to get timing of volcanic events, by focusing on basalt glass in sediments interbedded in extrusive basalt. It would answer questions related to eruption frequency and relate this to major global events, such as glaciation. Additionally the fact that the setting allows for "Zero-age" rock drilling facilitates the investigation of the crustal architecture at ultraslow spreading ridges in a broader sense.

Challenge 10: *What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?*

In principle we could drill sediment holes in one of the isolated sediment ponds to do something like what was done on exp. 336 to North Pond. A number of candidate sites to the west could be relevant. However, it would need more seismic and heat flow data to pinpoint and evaluate if interesting. It was agreed that this objective should be re-evaluated once more site survey data is available. Porewater profiles at lateral distance from ridge axis could tell something about magnitude of changes, in this type of system.

The possibility of preparing for future observatories in a serpentinizing system was discussed. This could be done both in the rift valley and in the faulting on the western flank. It was decided that without extensive survey data such operation is too risky. However, installing casing when drilling should be prioritized which allow post installation of CORKs in the future. Would be interesting to compare data with Middle Valley, as the settings are quite different, with the presence of sediment and relatively high organic carbon content.

Theme 4. Earth in Motion

Challenge 13: *What properties and processes govern the flow and storage and carbon in the subseafloor?*

The location offers an excellent opportunity to investigate calcite precipitation during low temperature serpentinization processes, both in terms of the timing and amount, as well as the potential influence of high temperature and CO_2 formation from organic breakdown and to evaluate the differences between ultramafic versus mafic basement. In addition, could be relevant to investigate how high/low temperatures effect turn-over rates. However, for this more site survey data in the form of heat flux data is needed to evaluate the feasibility.

Challenge 14: *how do fluids link subseafloor tectonic, thermal and biogeochemical processes?*

If the right site locations are targeted it would allow investigating ultramafic serpentinization processes and to what extent that fuel biochemical processes. Data can be compared and contrasted to what is known from the Iberian margin.

3b. Site selection

The general setting and deep and stable sediments at, and in, the SKR spreading system allows for JR-style drilling. This along with the assumed absence of gas-hydrates significantly reduces risk related to hole establishment and drilling initiation, down-hole stability, and elevated formation temperature compromising drilling tools. The consequence is that target sites can be selected based exclusively on scientific impact, and avoid compromising scientific value due to technical limitations.

It was agreed that the most relevant drill sites were to be found on, or in close proximity to, an approximate 75 km long transect crossing the SKR approximately 5 km north of the active hydrothermal field Loki's Castle at the end of the AVR.

A number of potential target sites were selected:

- Sediment pond directly on-top likely ultramafic crust on the W ridge flank.
- Sediment pond closer to the ridge (unit 3 seismic line P21)
- Rift valley on seismic line P21.
- Sediments on Eastern flank.

Critical for final selection is to validate the presence of active faulting and core complexes and to pinpoint exact location. Further, we need to constrain heat flux across the ridge in greater details.
This will require a number of additional site survey data and analyses before final decision on target sites can be made. The following analyses was deemed valuable in this context:
1) Model the likelihood of gas hydrates and re-evaluate seismic lines. 2) Analyze and compare available sediment cores for differences in lithology and organic carbon content, from the E and W flanks as well as in the rift valley. 3) Re-evaluate any existing refractive seismic data. 4) Organize and describe available hard rock samples dredged in the relevant area.

For additional site survey data required see 3d

The following list the potential target sites:
- Sediment pond directly on apparent ultramafic system west of ridge.
- Sediment pond closer to ridge, west of ridge.
- Rift valley – with potential for zero age.
- Sediments on eastern ridge.

3c. Implementation/technology
The potential target sites and main and secondary research objectives render a conventional JR-style drilling platform suitable. A number of piston cores and gravity cores has been taken in the area and suggest that firm and stable sediments are present throughout the target area, which will be suitable for APC coring of the sediments, shifting to RCB when upper crust is reached.
It was agreed that initial implementation of CORKs would not add extra value at this stage, However, drill holes should be prepared for potential post-installation, giving the scientific community the possibility to revisit and implement observatories at a later time point.
The science objectives do not aim at getting exceptionally deep into the crust but rather a high recovery from the sediment sections and a reasonable depth into the upper crust.
Concerning risk assessment then the presumed absence of gas-hydrates and relatively low temperature regime greatly reduces risk, lead and operational time and money consumption. However, site survey data of heat flux will be needed to constrain the temperature regime likely to be encountered during drilling and a modeled gas hydrate occurrence prediction would be beneficial to evaluate the operational risk in greater details.

3d. Site survey data

In the area of interest high-resolution bathymetry, along with a number of high-quality seismic lines exist. In addition, data from dredged rock samples and gravity and piston cores have been taken over the last 10 years. We aim to drill along an already existing seismic line (line 21, Bruvol et al., 2009), thereby avoiding the need for further seismic data. However, a number of site survey data will be important to obtain before a full proposal is submitted. This includes:

1) Heat flow data along seismic line 21 to constrain temperature regimes likely to be encountered during drilling. Such data will be collected during cruise with RV G.O. Sars July/August 2018.

2) Deployment of Ocean-Bottom Seismographs (OBS) to pinpoint active faulting Deployment of a network of a total of 9 OBS is planned during cruise with RV G.O. Sars July/August 2018. They will be retrieved during summer cruise in 2019 after having collected data for 1 year (6 OBS) and 4 months (3 OBS).

3) ROV and AUV surveys along fault lines to obtain high-resolution images and broaden our hard rock sample collection material to pinpoint ultramafic systems. This campaign is planned for scientific cruise with RV G.O. Sars during July/August 2018.

5. References

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6. Program for the workshop

Day 1 – Symposium: Carbon and life in deep sediments in the Arctic

09:15 Welcome and Introduction by Steffen L Jørgensen

10:00 Rolf Birger Pedersen
"*Southern Knipovich Ridge and geological history of the Norwegian-Greenland Sea"*

10:45 Coffee/Tea

11:00 Vera Schlindwein
"Seismicity and lithosphere structure at slow/ultraslow ridges"

12:00 Lunch break

13:30 Wolfgang Bach
"*The role of water-rock reactions for cycling of buried carbon"*

14:15 Hans Røy
"*Carbon cycling by subseafloor microbial life"*

15:00 Coffee/Tea

15:30 Florian Schmid
"*Implications of deep-reaching serpentinization for the deformation mode at ultraslow opening mid-ocean ridges"*

16:15 Andreia Faverola
"*Gas sources in the Norwegian-Greenland sea*"

17:00 Mitch Malone
"Challenges of drilling the SKR"

19:00 Dinner

Day 2 – Overarching Research Questions and Site Selection

09:15 Javier Escartin
"*Structural evolution of ultra-slow spreading ridges*"

09:45 Beth Orcutt
"Ups and downs on CORKs"

11:15 Group discussions related to:

- Key questions about deep carbon cycling can be tackled by drilling the SKR?
- First-order sub-seafloor microbial life questions we attempt to solve?
- Other critical knowledge gaps (tectonics, climate, geochemical fluxes, etc.) can be addressed?
- Best drill sites for accomplishing these science goals?
- Additional site survey data for the potential drilling sites are required for an IODP proposal?

12:15 Lunch break

13:30 Continued group discussions

16:00 presentation by the different groups

19:00 Dinner

Day 3 – Strategies and Implementation

09:30 Final discussion, proposal outline and delegations of tasks

12:00 Lunch/departure

7. List of participants

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