Scientific Report MSM52

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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1. General Information

- Cruise No.: MSM52
- GPF identification of the cruise proposal: MerMet15-100
- Chief Scientist: Prof. Dr. Christian Hübscher
- Institution: Institute of Geophysics, University of Hamburg
- Salt- and ice load induced tectonics in the North German Basin and the Baltica-Avalonia Suture Zone (Baltic Sea)
- BalTec
- Kiel (Germany) – Kiel (Germany), Port of Arrival (Country), March 1, 2016 – March 28, 2016
- Four papers under review after one year of DFG funding

Please provide a publication list and keep the following structure:

The following papers are currently under review:


2. Summary

The Baltic sector of the North German Basin and Tornquist Fan area comprises the dominant tectonic Trans-European Suture Zone. The major aims of RV MARIA S. MERIAN expedition MSM52 was to test two major working hypotheses. These were: 1) Advances and retreats of ice-sheets during the glacially initiated and reactivated faulting of the Post-Permian succession, thereby generating several kilometers long near-vertical faults and small scale anticlines. 2) In contrast to generally accepted textbook models deformation of the Zechstein salt started already during salt deposition as the consequence of the intra-cratonic basin subsidence and resulting salt creep. We took advantage of the fact that, for the first time, the seismic equipment allowed for a gapless imaging of the upper crust from the Zechstein base to the sea floor in water depth of less than 20 meters. The seismic equipment comprised a 2700 m long streamer and eight GI-Guns as the seismic source.

The few 10 meters high and some 100 meters wide anticlines comprise Permian to Quaternary strata, and underlie tunnel valleys. Previous studies indicated a geological nature with an origin during ice advantages, while other publications documented the presence of high-velocity infill in tunnel valleys and resulting velocity pull-ups in seismic sections at various locations. The significant move-out of the reflections and the presence of refracted waves in the MSM52-data allowed the application of different quantitative methods to identify the anticlines as velocity pull-ups. First, the generation of partial-offset sections reveals an offset-dependence in the imaging of the anticlines caused by a local, near surface high-velocity zone. This also explains the observed smoothing of the anticlines with depth in the seismic image. Second, a velocity model gained by a traveltime tomography shows positive velocity anomalies in the upper strata correlating with tunnel valleys resolved in the reflection seismics. High-frequency reflection seismic data confirms the result by a crisp image of a tunnel valley with a phase-reversed bottom reflection, caused by the velocity inversion at the base of the high-velocity valley fill deposits. Third, a prestack depth migration performed with a velocity model including a high-velocity zone results in a seismic image free of the anticline structure. This study shows on the one hand that the anticlines are no sign of recent salt tectonics in the Baltic Sea but imaging artefacts due to high-velocity infill of tunnel valleys and on the other hand that small velocity variations in the near-surface strata can lead to imaging artefacts and misinterpretation.

The investigation of salt tectonics is not accomplished yet. So far, we discuss the evolution of salt pillows in the Bay of Mecklenburg in the light of thin- and thick-skinned tectonics and differential loading. Stratigraphic interpretation of a 170 km long multichannel seismic line, extending from the Bay of Mecklenburg to northeast of Rügen Island, includes well information of nearby onshore wells. Our analysis reveals that subsidence during Late Triassic to Early Cretaceous at the northeastern basin margin is associated with transtensional dextral strike slip movements at the Tornquist Zone. We reinterpret the Werre and Prerow Fault Zones west of Rügen Island as an inverted, thin-skinned normal fault system. Salt movement in the Bay of Mecklenburg was initiated in the Late Triassic lasting until the Jurassic. A second phase of salt pillow growth occurred during the Coniacian until Tertiary and correlates with uplift of the basin margin. We associate the initiation of the uplift with Late Cretaceous compressional tectonics. Thin-skinned deformation explains salt pillow evolution in the Bay of Mecklenburg. Additionally, we discuss an impact of gravity gliding induced by basin margin tilt on salt pillow evolution. We propose a slow downdip salt flow alongside homogenous updip salt depletion during the Late Cretaceous to Tertiary phase of salt remobilization.

The data set will be further explored in a DFG-funded project which strives for unraveling to Cretaceous to recent geological processes like plate tectonics, salt tectonics, and fluid migration in the Baltic Sea segment of the Tornquist Zone between Skagerrak and Polish coast.
3. Scientific Results

- Objectives of the project

The Baltic sector of the North German Basin and Tornquist Fan area comprises the dominant tectonic Trans-European Suture Zone. The major aims of RV MARIA S. MERIAN expedition MSM52 was to test two major working hypotheses. These were:

1) Advances and retreats of ice-sheets during the glacially initiated and reactivated faulting of the Post-Permian succession, thereby generating several kilometers long near-vertical faults and small scale anticlines.

2) In contrast to generally accepted textbook models deformation of the Zechstein salt started already during salt deposition as the consequence of the intra-cratonic basin subsidence and resulting salt creep.

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

The BalTec expedition MSM52 ended 28 March 2016. In contrast to the initial cruise proposal, the seismic equipment of the Alfred-Wegener-Institute was not available, because the cruise was scheduled simultaneously to an AWI expedition. We managed to team-up with the BGR colleagues, who kindly provided equipment and manpower. Even more, the BGR invested in new lead-in cables for the seismic streamer, which allowed for gapless imaging even in shallow water depths of less than 20 meters. Both University of Hamburg and BGR provided each four GI-Guns as the seismic source, yielding in a seismic signal with peak frequencies around 80 Hz. Due to technical effort it was not necessary to shoot the seismic two times with different equipment, as it was outlined in the cruise proposal. For that reason, the amount of profile kilometers was almost doubled.

No funding for preliminary data analysis had been granted, so the initial data analysis, a prerequisite for a successful proposal to DFG, had to be carried out in the course of BSc- and MSc-theses. In the course of these theses the scientific objective were adapted to the actual MSM52 data based findings and a DFG proposal was developed. The proposal was submitted summer 2017. We were officially notified early 2018 that the proposal was approved. Position advertising and candidate search was done in mid of 2018. One PostDoc and one PhD position was filled in fall 2018. Consequently, the here documented scientific results are based on a 1-year lasting in-depth analyses of the MSM52 data.

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

The few 10 meters high and some 100 meters wide anticlines comprise Permian to Quaternary strata, and underlie tunnel valleys (Fig. 1). Previous studies indicated a geological nature with an origin during ice advantages, while other publications documented the presence of high-velocity infill in tunnel valleys and resulting velocity pull-ups in seismic sections at various locations. The significant move-out of the reflections and the presence of refracted waves in the MSM52-data allowed the application of different quantitative methods to identify the

![Figure 1: Seismic time section from central Bay of Kiel showing anticlines in Post-Permian strata (Frahm et al., submitted).](image)
anticlines as velocity pull-ups. First, the generation of partial-offset sections reveals an offset-dependence in the imaging of the anticlines caused by a local, near surface high-velocity zone (Fig. 2). This also explains the observed smoothing of the anticlines with depth in the seismic image.

Second, a velocity model gained by a traveltime tomography shows positive velocity anomalies in the upper strata correlating with tunnel valleys resolved in the reflection seismics (Fig. 3). High-frequency reflection seismic data confirms the result by a crisp image of a tunnel valley with a phase-reversed bottom reflection, caused by the velocity inversion at the base of the high-velocity valley fill deposits. Third, a prestack depth migration performed with a velocity model including a high-velocity zone results in a seismic image free of the anticline structure (Fig. 4).

This study shows on the one hand that the anticlines are no sign of recent salt tectonics in the Baltic Sea but imaging artefacts due to high-velocity infill of tunnel valleys and on the other hand that small velocity variations in the near-surface strata can lead to imaging artefacts and misinterpretation.
The investigation of salt tectonics is not accomplished yet. So far, we discuss the evolution of salt pillows in the Bay of Mecklenburg in the light of thin- and thick-skinned tectonics and differential loading. Stratigraphic interpretation of a 170 km long multichannel seismic line, extending from the Bay of Mecklenburg to northeast of Rügen Island, includes well information of nearby onshore wells (Fig. 5). For the first time, we present a complete image from the base of the Zechstein to the seafloor ranging from the Bay of Mecklenburg to the northeast of Rügen Island. The seismic image illuminates Late Permian to recent Cenozoic deposits. The basin margin faults of the Agricola Fault System and associated antithetic Werre Fault Zone initiated during E-W extension in the Late Triassic. In between, subsidence in the Prerow Depression formed a marginal subbasin. The main phase of subsidence attributes to the Rhaetian-Norian until Jurassic times where transtensional strike slip movements at the TESZ dominated.

Major plate reorganization related to the Africa-Iberia-Europe collision led to basin scale inversion and uplift of the Grimmen High. Uplift of the northeastern North German Basin margin started in the Santonian-Coniacian with increased activity during the Maastrichtian-Campanian. Corresponding uplift of the Grimmen High amounts to 430 m to 530 m, which eroded much of the Cretaceous succession of the Grimmen High and within the Werre Fault Zone. The northbound Prerow Depression possibly facilitated uplift of the Grimmen High as it outlined a marginal sub-basin prior to compression.

The Werre Fault Zone is reinterpreted as an inverted thin-skinned normal fault zone forming a rollover structure detached close to the base Zechstein. Antithetic normal faults are associated with the Prerow Fault Zone and suggest thin-skinned deformation related to faulting in the Werre Fault Zone. Faulting began in the Late Triassic and is associated with the formation of the Western Pomeranian Fault System.

Salt pillow growth in the Bay of Mecklenburg initiated in the Late Triassic. Continuous growth until the Jurassic preserved thicker Late Triassic and Jurassic deposits in the rim-synclines while thinning and partly erosion occurred above the pillow crests. A second phase of salt pillow growth was in the Late Cretaceous to Tertiary correlating with the onset of basin margin uplift and reverse faulting in the Werre Fault Zone.

We discussed salt pillow evolution in the Bay of Mecklenburg and invoked two possible driving mechanisms. In the first scenario, a thin-skinned extensional initialization in the Late Triassic and Jurassic was followed by Late Cretaceous-Tertiary shortening which led to further salt pillow growth. The second scenario discusses an effect of gravity gliding induced by basin margin tilt during the Late Cretaceous to Tertiary. This led to updip salt depletion and slow downdip creeping resulting in salt accumulation and pillow formation.
Since November 2018 the German Science Foundation funds one PostDoc and one PhD position for three years (DFG grant HU698/25). Under the umbrella of this “BalTec” project, the MSM52 and other seismic reflection data (Fig. 6) are analyzed regarding the general geological evolution of the southern Baltic regrading inversion tectonics, salt tectonics and fluid migration along the Tornquist Zone from Skagerrak to the Polish coast.
The data MSM52 data further image the exhumed Sorgenfrei–Tornquist Zone (STZ), with pre-Mesozoic basement crust exposed at the surface, considered to have been caused by Late Cretaceous-Cenozoic inversion events, and the surrounding sedimentary basins (Figure 7). According to Pan et al. (submitted), the Sub-Hercynian event led to significant reverse faulting and formation of pop-up. The combination of seismic reflection and streamer traveltime tomography provides an opportunity to constrain the subsurface spatial configuration and the timing of inversion-related tectonics. The uplift of the STZ has been interpreted to have been driven by discrete thrust structures at crustal scale. It occurred along a pre-existing basin depocentre, creating marginal troughs at both flanks of the STZ. Our results reveal the internal architecture of the sedimentary troughs. The SW flank is marked by a remarkably eroded thrust-related fold, and a high-angle major thrust fault with multiple strands. The
folding appears tight and is accompanied by breaching of the forelimb whilst the backlimb is highly fractured and partially preserved in the Vomb Trough. Continuous sedimentary sequences indicate a relatively steady deposition likely pre-dating the primary thrust-fold tectonics. This feature highlights a compression-induced thrusting exerted on the STZ in a late stage of the Sub-Hercynian event, and the Vomb Trough might also records further subsequent shortening. In contrast, the formation of the NE marginal trough in the Hanö Bay Basin appears more likely to be the result of localized subsidence controlled by normal faulting in a complex fault zone with strike-slip movement, where progressively tilted progradational wedges are evident. Tentative interpretation of the stratigraphy of the growth strata across the WSW-ENE Gat Fault allows dating of a primary inversion as late and post-Maastrichtian, consistent with the interpretation of late Sub-Hercynian inversion. This fault also shows strike-slip behavior with a strong overprint by inversion-related reverse faulting, suggesting conjugate faulting with respect to the major NW-SE strike-slip faults in a transpressional regime. Therefore, regionally, the strike-slip and reverse faulting in the vicinity of the Bornholm Gat SW Baltic Sea can be related to a NNW-SSE transpressional relay zone in order to accommodate the oblique convergence of the Late Cretaceous-Cenozoic inversion.

Outlook: Wide-angle reflection/refraction data collected during MSM52 are currently investigated by Polish partners at Univ. Warsaw. The PhD (Niklas Ahlrichs, Yaocen Pan) and PostDoc (Dr. Elisabeth Seidel) projects are in full swing.

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

National partners:
Prof. Dr. Christian Hübscher (Univ. Hamburg)
Prof. Dr. Charlotte Krawczyk (GFZ-Potsdam)
Dr. Vera Noack, BGR
Dr. Volkmar Damm, BGR

Figure 7. Main reflection markers used for stratigraphy interpretation of the Skurup Basin, the VT, the CST and the Hanö Bay Basin in this paper. Superimposed is velocity model derived from refraction tomography. BCU: base Cretaceous unconformity; BCG: base Chalk Group; BCA: base Campanian; BLM: base lower Maastrichtian; ILM: internal lower Maastrichtian; BPU: base Pliocene unconformity; BLC: base lower Cretaceous; TPC: top Pre-Cambrian; ILS: internal lower Silurian; BJ: base Jurassic; BT: base Turonian; BS: base Santonian. From Pan et al., submitted.
International partners:
Prof. Dr. Michal Malinowski (Polish Academy of Science, Warsaw, Poland)
Prof. Dr. Piotr Krzywiec (Polish Academy of Science, Warsaw, Poland)
Prof. Dr. Chris Juhlin (Univ. Uppsala)

- 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: none
  - Number of master theses: 3

Henrik Huster: Revaluation of Cenozoic salt tectonics in the southwestern Baltic Sea by joint interpretation of multichannel seismic and parametric echosounder data (2019).

Laura Frahm: Impact of salt tectonics on the near-surface strata of the outer Glückstadt Graben - insights from seismic depth sections (2019)

Niklas Ahlrichs: Seismic imaging of thin- and thick-skinned tectonics in the Baltic sector of the North German Basin margin: From initial Triassic salt tectonics to Late Cretaceous basin inversion (2019)

- Number of PhD theses: 3 - all in preparation

Niklas Ahlrichs mainly deals with sub-salt and salt imaging and salt tectonics.

Yaocen Pan studies the tectonic evolution of the southern-most Sorgenfrei-Teseyre-Zone and Bornholm Gat. Beside the MSM52 data, he uses BABLE vintage data and new high-resolution seismic data, acquired by University of Hamburg in 2019.

Quang Nguyen uses the MSM52 data for expanding the FWI method.

Dr. Elisabeth Seidel fills a PostDoc position, she mainly studies inversion tectonics in the Tornquist Zone by means of structural restauration.

- Status of the data and sample availability: Please state in form of a table the exact links and dates of the data and sample availability, as well as contact persons.

Publications (4, all under review)


### Data availability

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Data have been collected by BGR. Access might therefore be conditioned.