CRUSMID-3D

**Crustal Structure and
Mineral Deposit Systems:
3D-modelling of base
metal mineralization
in Jameson Land
(East Greenland)**

**Nordic Council
of Ministers**

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*Pierpaolo Guarnieri, Anaïs Brethes, Thorkild M. Rasmussen,
Anett Blischke, Ögmundur Erlendsson and Tobias Bauer*

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Introduction

East Greenland offers good opportunity to study the relationship between geodynamic processes and mineral deposits along plate boundaries. Since ore systems are closely linked to processes resulting from plate tectonics and global dynamics, an understanding of the genetic controls on ore deposit formation implies that deposits themselves can be sensitive indicators of geologic process. Mineral deposits often represent extraordinary metal concentrations that form by magmatic, magmatic–hydrothermal or hydrothermal processes in geodynamic environments typified by anomalously high thermal gradient and/or tectonic stress near plate boundaries. Jameson Land experienced rifting episodes leading to the spreading of oceanic crust in the Northeast Atlantic during Tertiary time. The area is covered by detailed geological maps, a good coverage of regional seismic reflection data surveys, regional potential field surveys and newly acquired detailed structural and airborne time-domain electromagnetic (TEM) and magnetic surveys.

The Jameson Land basin is the southernmost basin outcropping along the east coast of Greenland. The basin fill starts with a series of non-marine clastic rift sediments of Late Devonian to Early Permian age. The Upper Permian to Upper Cretaceous post-rift succession is dominated by marine deposits, with the exception of Triassic continental red beds. At the beginning of the Paleocene, in association with the opening of the North Atlantic Ocean, extrusive and intrusive igneous activity took place throughout the region. This resulted in the extrusion of a thick volcanic series, of which more than 2 km thickness is still preserved south of Jameson Land. $^{40}\text{Ar}/^{39}\text{Ar}$ ages demonstrate that the high-Ti dolerite dykes and sills intruded at 53–52 Ma. Subsequently, uplift and erosion took place over the whole area during a regional tectonic episode, which affected most of the North Atlantic margin and related to the separation of the Jan Mayen Micro Continent (Blischke *et al.* 2016).

Summary

Geological investigations in the Jameson Land Basin in central East Greenland started at the end of the 19th century and subsequent exploration work was carried out by hydrocarbon and mineral exploration companies as well as by public organizations such as the Geological Survey of Greenland (GGU).

Recent field investigations and follow-up on mineral findings by mineral exploration companies encouraged the acquisition of licenses in Jameson Land with sedimentary-hosted base-metals as main target. An airborne high resolution gradient magnetic survey conducted by Fugro Airborne Surveys and a combined time-domain electromagnetic and magnetic survey carried out by SkyTEM Aps were commissioned in 2013. Subsequent cooperation took place between the mineral exploration company Avannaa Resources and the Geological Survey of Denmark and Greenland as part of the CRUSMID-3D project financed by Nordmin. GEUS was the project coordinator and provided geological and structural analysis in the field and collaborated together with the Luleå Technical University (LTU) in Sweden on the magnetic and electromagnetic data and with the Iceland Geosurvey (ISOR) for the interpretation of available 2D-seismic lines.

A drilling program was carried out along the eastern margin of the Jameson Land Basin during summer 2014 that revealed no evident mineralization. However the work provided useful information for the understanding of the basin architecture. The exploration activity ended in 2014 but several scientific questions remained. These questions constituted the main part of the Crusmid-3D research project.

In fact, along the eastern margin of the Jameson Land Basin, Pb, Zn and Cu mineralization are observed to occur in several stratigraphic horizons and along structures in the Upper Permian and Triassic sediments. A good understanding of the basin architecture and evolution is therefore essential for future exploration in this area.

3D-photogeology from high resolution aerial and oblique photos along with a structural interpretation of aeromagnetic and electromagnetic data, together with the results from structural mapping and the drilling campaign were integrated into a 3D-geological model. 3D inversion was performed on aeromagnetic data to reduce uncertainty regarding the depth to the crystalline basement and the variation of the sedimentary thickness. This data integration allowed highlighting the presence of a Triassic basin called Carlsberg Fjord basin and modelling its rift architecture. The eastern border of the basin is composed of three down-faulted blocks separated by NE-SW and NNE-

SSW oriented NW-dipping normal faults. The southern part of basin is characterized by shallow-depth crystalline basement unconformably covered by a relatively thin Triassic cover. The northern part of the Basin is characterized by a thick Lower-Middle Triassic syn-rift sedimentary sequence composed of conglomerates and arkosic sandstones. Magnetic data inversion results suggest that the sedimentary sequence could be more than 2000 m-thick in the northern part of the basin with possible presence of pre-Triassic sedimentary package.

Furthermore, Induced Polarization (IP) effects were observed in the airborne Time Domain EM (TEM) data. To characterize and understand the possible causes of these IP effects, IP indicators were extracted from the shape of the transient curves at every measurement location and analysed by using a Self-Organizing Map (SOM) procedure. Six areas with significant IP effects were identified. In the central part of the area, IP effects seem to be correlated with the outcropping geology close to the boundary between Early Triassic and Middle Triassic sediments while, in the north-western part, the IP effects occur along a N-S elongated trend without any correlation with the outcropping geology. Further work is currently performed to invert the airborne TEM data for the Cole-Cole parameters in order to constrain the source of the IP effects. The resistivity, chargeability and time constant parameters obtained from the inversion will help discriminating sulphide sources from permafrost or clay content.

The integration of the results obtained from this multi-disciplinary project into a 3D model is crucial in order to define the crustal architecture of the basin, the distribution of the petrophysical properties and understand their control on the mineralization systems in the area.

1. The project CRUSMID-3D

The project CRUSMID-3D (Crustal Structure and Mineral Deposit Systems: 3D-modelling of base metal mineralization in Jameson Land, East Greenland) is based on a consortium between GEUS (The Geological Survey of Denmark and Greenland), LTU (Luleå University of Technology), ISOR (Icelandic Geosurvey) and Avannaa Resources (Mineral Exploration company). The Project was co-funded by NordMin (A Nordic Network of Expertise for a Sustainable Mining and Mineral Industry) for a period of thirty months. Unfortunately the private company closed down for several reasons at the end of 2014 without continuing the economic support to the project. The economic loss was partially covered by NordMin with an amendment to the contract in 2015.

The project proposal applied to Core Action 2 "Research and Innovation" within the Core Theme 1 "Exploration" focusing on "Mineral systems mapping; 2/3/4D modelling, ore deposit models, spatial data mining". The scientific objective of the project is totally integrated within the suggested challenges of the NordMin Agenda. In fact the basic idea of the project was the understanding of the relationships between intrusions, hydrothermal fluids-bearing mineralization and the tectonic setting to explain how small and large-scale mineralizing systems operate and how this information can be used in exploration targeting. New techniques as 3D-photogeological mapping combined with 3D-geophysical modelling and 2D-seismic reflection data mapping allowed us to work over different scales of detail from a regional one down to a detailed 3D-modeling. The main part of funding was dedicated to a PhD position focusing on the understanding of the relationship between crustal structures and mineral deposits.

The expected outcomes of the project were regional structural models for East Greenland combined with selected and integrated ore exploration areas to compare the regional settings with smaller analogue field study areas. These models include regional and local data and interpretations focused on the structural settings, mapped stratigraphy, igneous processes, and resulting hydrothermal mineralization.

The structure of the Consortium gave the possibility to develop a collaborative platform between research institutes, university and mineral industry. The involvement of PhD in this initiative ensured skill development of a post graduate student. The project is basic research and applied research at the same time. The outcome of the structural analysis and the 3D geophysical modelling is a tool for the industry for targeting and, in this light the project has a potential for post 2016 funding.

1.1 Structure of the Consortium

The Consortium is composed by scientific partners from three Nordic Countries and one partner from the industry. The first partner with coordination and leading of the Consortium was GEUS – the Geological Survey of Denmark and Greenland (DK) represented by Pierpaolo Guarnieri (Senior Structural Geologist), the second partner ISOR – the Icelandic Geosurvey (IS) represented by Anett Blischke (Senior Geologist) and the third partner LTU – Luleå University of Technology (SE) represented by Thorkild Maack Rasmussen (Professor in exploration geophysics at LTU) and Tobias Bauer (associate senior lecturer in geology). The industry partner was the mineral exploration company Avannaa Resources Ltd. The PhD (Anaïs Brethes) is held at LTU for the administrative and academic part while the PhD student is based mainly at GEUS (75 % of time).

The different skills and experience of the four partners guaranteed the high quality of the Consortium. GEUS supported the project with new technology as the 3D-PhotoLab for 3D-Photogeology together with the experience in 3D-Geological modelling and fieldwork in Greenland. ISOR provided the experience in seismic reflection data interpretation especially for those areas off-shore East Greenland. LTU supervised the processing and interpretation of potential field data together with 3D-geophysical and 3D-geological modelling. Finally Avannaa Resources Ltd supplied their field experiences and detailed geological/geophysical data in Greenland.

1.2 Detailed work description

1.2.1 *Work package 1 – Structural Geology*

This WP is based on fieldwork in 2014 in East Greenland for Structural mapping and collection of oblique photos for 3D-Photogeology. The latter constitutes the basic tool for geological mapping in 3D high resolution aerial and oblique photo using the GEUS 3D-photo Lab.

1.2.2 *Work package 2 – Geophysics*

This WP is composed of LTU working with magnetic and electromagnetic field data and ISOR working primarily with 2D multi-channel reflection seismic data. The available magnetic data from GEUS and Avannaa Resources Ltd encompass: 1997 combined TEM and magnetic (GEOTEM; Geoterrex-Dighem) survey; 2013 airborne fixed wing horizontal gradient magnetic (Fugro) survey; 2013 helicopter borne combined TEM and

magnetic (SKYTEM) survey; the TEM data from 1997 GeoTEM and 2013 SKYTEM surveys assist the structural interpretations and the mineral targeting. The seismic reflection line database is composed by ARCO lines, BGR and the National Energy Authority (NEA) of Iceland; the geophysical and the geo-properties modules of Petrel is used interfacing with ArcMap and SMT's Kingdom Suite for seismic interpretation.

1.2.3 *Work package 3 – 3D-modeling*

This WP integrates all the results from fieldwork, drilling campaign, seismic line interpretation, and gravity/magnetic/TEM data analyses. GoCad, ModelVision, Noddy, Amira and Geosoft for 3D-Geological and Geophysical modelling were used.

1.3 Work Plan

First year (April–December 2014): Collection of literature data; compilation of geological and structural data, analysis of magnetic data, TEM survey data and preliminary 3D-Geophysical modelling; fieldwork in Klitdal area of Jameson Land; participating with the drilling campaign; structural mapping and collection of oblique photos; interpretation of available seismic lines onshore and offshore; preliminary 3D-modelling

Second year (January–December 2015): Validation of preliminary 3D-modelling with results from boreholes. Depending on the results from the drilling campaign in East Greenland the first three months of the second year can be dedicated to the completion of the 3D-modeling of the Klitdal area from Jameson Land.

Third year (January–September 2016): Dedicated to the completion and validation of the structural models from East Greenland together with the 3D-models from geophysical and geologic data. This time period was dedicated to write the final report for NordMin and prepare manuscripts to be submitted for peer review in specific journals.

2. Geological Setting

2.1 Introduction

Geological investigations in the Jameson Land Basin in central East Greenland started at the end of the 19th century and subsequent exploration work was carried out by hydrocarbon and mineral exploration companies. Seismic reflection surveys were conducted in the 1980's by Atlantic Richfield Company (ARCO) over the Jameson Land Basin. In 1997, an airborne magnetic and electromagnetic survey was conducted by the Geological Survey of Denmark and Greenland (GEUS) in the northern part of the basin. In 2012 GEUS and NERC (Natural Environment Research Council, UK) led a Lidar, Hyperspectral and aerial photos survey over the eastern part of the basin. This enabled the production of a high resolution Digital Elevation Model and of a photogrammetric model for 3D-Photomapping. Field investigations in 2011 and 2012 in the Klitdal area (eastern part of the Jameson Land basin) encouraged the exploration company Avannaa Resources in 2013 to form a joint venture with Anglo American to drill in the Klitdal area the sedimentary-hosted base-metals sequence.

2.2 Tectonic setting of the Jameson Land area

The Jameson Land basin is the southern part of N-S elongated Palaeozoic – Mesozoic basins extending over 800 km. The basin is 80 km wide and bordered to the West and to the East by mostly crystalline basement composed of Caledonian metamorphic and plutonic rocks, along with sedimentary to low grade metamorphic rocks. The Caledonian orogeny was followed by the collapse of the over-thickened crust. The intramontane basins were filled with 5 to 10 km of continental clastic sediments and affected by post-tectonic granite intrusions and rhyolitic and basaltic volcanism in Devonian time. The sequence was widely deformed by N-S syn-sedimentary open folding, westward thrusting and by uplift. Transtensional pull-apart basins started to form in Middle to Late Devonian with large scale ESE-WNW extensional faulting that displaced the Caledonian thrust units north of Kong Oscar Fjord (Higgins *et al.*, 2004), and N-S directed sinistral wrench faulting (Larsen and Bengaard, 1991). The stress pattern shifted from oblique to a more orthogonal rifting in latest Devonian leading

in late Carboniferous-early Permian to rotational block faulting along the new half graben basin margins (Fig. 7; Larsen and Marcussen, 1992; Surlyk, 1990; Surlyk *et al.*, 1986 and incl. ref.).

Upper Carboniferous to lower Permian continental sedimentation took place within the wide tilted blocks (Larsen and Bengaard, 1991). Upper Permian sediments are observed both along the Post-Devonian Main Fault System on the western margin of Jameson Land and in Wegener Halvø showing that the original basin was more than 80 km wide (Henriksen, 1986). The whole sequence was uplifted and peneplained over the basin while along the basin margins the rift shoulders were deeply eroded. With an angular unconformity the vast and widespread continental sediments of the Huledal Fm were deposited. Up to 20 to 30 m thick on the basin margin, their thickness increases in the central part of the basin. The Upper Permian marks a change in tectonic regime and sedimentation environment, to one controlled by thermal subsidence. The transgression coming from the north-east allowed marine deposition in hypersaline environment with the carbonate build-ups and shale basins of the Foldvik Creek Group. Sedimentation was, however, affected by several events of subaerial erosion in the Upper Permian leading to the karstification of the carbonates. Sedimentation continued through the Permo-Triassic transition and occurred in incised submarine channels during sea-level rise in an anoxic environment. It was controlled by active faulting and rapid subsidence leading to deposition of the thickest known sequences of Griesbachian (Seidler, 2000; Wignall and Twitchett, 2002). In addition to tectonic subsidence and eustatic sea-level changes the mostly continental sedimentation from Triassic to Middle Jurassic was influenced in Middle Triassic by a change from a warm arid to a more temperate humid climate (Surlyk, 1990). This was expressed by a change in sedimentation from continental red-beds, carbonates and evaporites in early Triassic times to playa mudstone, lacustrine carbonates and floodplain deposits from mid to late Triassic. In latest Triassic organic-rich sediments of the Kap Stewart Fm including thin coal beds were deposited. In Early Jurassic a long term sea-level rise led to the full inundation of the basin for the first time since Upper Permian. Terrigenous sandstones and siltstones were deposited almost continuously until Early Cretaceous into N-S elongated basins still tectonically active in the north and dominated by gradual subsidence in the south (Surlyk *et al.*, 1986). The sedimentary pile was intruded by sills and dykes and covered by flood basalts in early Eocene time. The extensive magmatism associated with the

continental break-up of Northeast Atlantic (Hald and Tegner, 2000) has affected the East coast of Greenland over 2400 km. Jameson Land is part of the Palaeogene North Atlantic Igneous Province that is one of the largest igneous provinces in the world (Brooks, 2011). In East Greenland the major extrusive activity ceased after 55 Ma, whereas high-Ti sills and dykes intruded at 53–52 Ma, marking the passage of the proto-Icelandic mantle plume under East Greenland (Tegner *et al.*, 1998b). It resulted in a regional pattern of ESE trending dykes affecting the whole Scoresby Sund region and cutting the tholeiitic flood basalts in the South. Sills were restricted to the Jameson Land basin whereas its northeastern part was poorly affected by all these events. By combining surface mapping with several seismic data and notably through deep reflection seismics, Larsen and Marcussen (1992) constructed a composite image of the entire crustal structure of the basin. The sills are mostly exposed along the basin margins with a thickness of 10–15 m but are up to 300 m thick in the centre of the basin. They were interpreted as mid-crustal magma chambers ascending towards the basin margins and feeding the flood basalts. Five geochemical types of intrusions can be distinguished: from very high-Ti basalts to low-Ti basalts; plagioclase ultraphyric basalts; and alkali basalts.

Later igneous activity occurred in East Greenland from 35 and 25 Ma, related to the reorganization of the North Atlantic (Geissler *et al.* 2016), notably with the plate separation of the Jan Mayen microcontinent (Blischke *et al.* 2016). Plutonic and subvolcanic intrusion affected the northern part of the basin in Oligocene time, drawing a NE-SW trend of plutonic centers over 100 km (Haller 1971; Noe-Nygaard 1976). It is in the continuation of the initial North Atlantic spreading ridge. These intrusions have a distinct alkaline to per-alkaline composition and comprise a variation from gabbro to alkali granite with important nepheline syenite complexes. Renewed basaltic volcanism took place in Miocene, 14 Ma and continues to present at Jan Mayen volcanic complex, as well as in Iceland due to the mantle plume mid-oceanic ridge interactions, accompanied with several ridge jumps across Iceland (Saemundsson 1974 & 1979; Hardarson 1997 & 2008; and Hjartarson 2003), the present location of the Iceland plume is interpreted to be under the Vatnajökull glacier, in south-east Iceland (Brooks, 2011).

Tectonic back-stripping allowed determining the thickness of the magmatic rocks which formed a wedge thicker than 2 km in the south of Jameson Land, and thinning to less than 100 m in the north (Mathiesen *et al.*, 2000). After the onset of rifting and magmatism, sedimentation has probably continued as early Tertiary sediments are preserved in the south-east of Scoresby Sund region. Apatite fission-track constrained the maximum burial of the sediments estimated before 25 Ma in the north and increases to the central part and the south of the basin (Hansen *et al.*, 2001). Subsequent erosion of 2–3 km took place in response to an uplift of a calculated magnitude of 1 km and even more in the northern part of the basin (Mathiesen *et al.*, 2000). The thermal evolution differs from east and west of the basin. In the north-eastern part, a slow cooling would have occurred since 15–20 Ma ago with a mean exhumation rate of ca. 270–200 m/Ma (with a cooling from 125°C). In Cenozoic time the cooling became rapidly below the annealing interval since 5–10 Ma. This evolution coincides with the reorganization of the North Atlantic plate-tectonics setting with the change in the ridge position around 25 Ma, which followed the passage of the proto-Icelandic mantle plume at 63–40 Ma (Hansen *et al.*, 2001).

3. Exploration History and recent activity

Mineral occurrences in Greenland are known to occur in almost all rocks from Paleoproterozoic to Oligocene but the present study only focuses on mineral occurrences in the sediments inside the Jameson Land Basin; i.e. from Devonian to Oligocene rocks (Fig. 1). The next paragraphs follow the inventory of mineral occurrences in East Greenland made by Harpøth *et al.* (1986) and treat them by age of the host rocks they are found to outcrop into.

Mineralization hosted in Lower Palaeozoic rocks is in general believed to be associated with Caledonian orogenic activity. It comprises tungsten skarn occurrences mainly associated with granodiorite intrusions, base-metal and tungsten mineralization associated with late-kinematic probably calcalkaline granite, tin-tungsten- arsenic quartz veins associated with late-kinematic probably mildly alkaline granites, gold-bearing quartz veins associated with late-kinematic granite, uraniferous veins in probably Devonian alkaline granite, tungsten-antimony-gold and silver-bearing base-metal veins in low-grade metamorphic sediments, uranium-fluorite veins in Devonian felsic volcanic rocks and strata-bound uranium occurrences hosted in Devonian clastic rocks.

Figure 1: Geological map of the Jameson land Basin (modified after Kokfelt *et al.*, 2013). The letters refer to localities of Tertiary intrusions (B) Kap Simpson, (C) Kap Syenit, (D) Oksehorn, (E) Werner Bjerger and (F) Malmbjerg. The contours of aeromagnetic surveys are plotted in black

3.1 Pre-Permian hosted mineralization in Wegener Halvø and Canning Land

On Wegener Halvø, sulphide bearing veins are found in Devonian rocks. These veins can be found either abundantly in wide zones as mm to cm enechelon veins, or as massive veins up to 6 m thick. They are filled by quartz, barite, fluorite and calcite with ore minerals as chalcopyrite, bornite, sphalerite, galena, pyrite and hematite with high contents of copper, lead and zinc from 1 to 20 %. Structurally controlled, they were emplaced along NNW-SSE sinistral shear faults probably in Upper Devonian as they cut Middle Devonian but not Carboniferous (Harpøth *et al.*, 1986).

Mineralization hosted in Upper Palaeozoic sediments (Carboniferous- Permian) occurs in veins associated with faults or strata-bound associated with Upper-Permian sediments. These sediments are mostly found outcropping along the western margin of the basin and in the Wegener Halvø area along the eastern margin. Mineralization includes base-metal quartz-baryte veins locally enriched in precious metals, gold-bearing quartz veins, uraniferous veins, carbonate-hosted strata-bound baryte base-metal occurrences, carbonate-hosted strata-bound celestite occurrences, strata-bound base-metal showings of Kupferschiefer type and strata-bound red-bed copper occurrences.

Along the western margin of the basin, mineralization is associated with a more than 400 km long NNE-SSW fault system called the Post-Devonian Main Fault System, initiated in the Early Carboniferous and reactivated during the Mesozoic and Cenozoic (Bütler, 1957).

3.2 Pb-Zn epithermal veins in Mesters Vig

Mesters Vig is located in the northern part of the Jameson Land Basin, just north of the intrusive Werner Bjerre complex (Fig. 1). The Mesters Vig area hosts the only ore deposit mined in East Greenland. The Blyklippen Pb-Zn mine has produced 545,000 t of ore with 9.3 % Pb and 9.9 % Zn between 1956 and 1962. The area is dominated by the Mesters Vig graben where fault-controlled epithermal Pb-Zn sulphide-bearing quartz veins occur over 300 km². This graben is 4 km wide and 15 km long and controlled by N140–160 and No-25 orientated faults. Continental syn-rift Upper Carboniferous – Lower Permian deposits are unconformably overlain by Upper Permian marine sediments and Lower Triassic shales only preserved within the graben. The area was affected in the Tertiary by igneous intrusions:

- Widespread doleritic sills up to 100 m thick and locally intersecting quartz veins. They are cut by N-S, NNE-SSW and NNW-SSE oriented faults.
- Subvertical doleritic dykes oriented N160–180 which intersect the sediments, the quartz veins and the sills.
- Subvertical doleritic dykes oriented N20–30 mapped in the southeastern part of the Mesters vig area. They locally intersect the N170 striking doleritic dykes.

The graben has accommodated more than 1000 m of displacement at different times since the Late Carboniferous as the sills are much less offset than the sediments. Two major veins zones are found on either side of the graben's borders faults. They are mostly oriented N150/80E along the western side of the graben and oriented 150/80W along the eastern side. The veins are made of quartz, barite, galena and sphalerite with minor calcite, pyrite and chalcopyrite. On the western side one of the lenses was estimated to host 200,000 t of ore with 9.3 % Zn, 2.1 % Pb and 0.7 % Cu.

The mineralizing veins are both observed to be cut by and to cross-cut the dykes and are thought to be related to the Tertiary magmatism.

3.3 Strata-bound mineralization in the Upper Permian

Copper, lead and silver mineralization in the Upper Permian carbonates of the Wegener Halvø Fm was first discovered by the Danmarks Expedition from 1930 to 1934 (Noe-Nygaard 1934, Eklund 1944). Subsequently, other studies were led in East Greenland leading in 1968, to the discovery by Nordmine of base-metal mineralization in black shales of the Ravnefjeld Fm. Mineral exploration ceased because of too low grade mineralization but the oil industry became interested in the hydrocarbon source rock potential of the Upper Permian shales. They led different studies on them which now allow a good stratigraphic knowledge of this formation.

In the Wegener Halvø Fm, copper, lead, zinc, barite and silver mineralization is mainly found stratabound in the 150m to 200m thick massive limestone. The main ore minerals are chalcopyrite, galena, sphalerite, tennantite-tetrahedrite and pyrite. Samples indicate an average concentration of 0.5 % Cu, 0.2 % Pb and 0.1 % Zn. They are scattered over the Wegener Halvø where veins of calcite-barite and minor dolomitization occur. The highest base-metal concentrations are however focused in Quensel Bjerg and Devondal areas (Fig. 1) that are affected by intense silicification and quartz veining. At Quensel Bjerg, mineralization occurs in the upper part of the formation, close to the overlying Schuchert Dal Fm. They are concentrated in a 2–4 m thick quartz-

barite zone, along N-S trending faults and joints. Barite and copper mineralization dominates in the southwest whereas quartz and lead-zinc mineralization dominates the northeastern part. Harpøth (1980) has estimated the Quensel Bjerg area to host 10 million tons, with 2–4 % sulphides and 30–40 % barite. On the southern side of Devondal, Cu, Pb, Zn and Ag mineralization is associated with barite and quartz veinlets found in the upper part of the carbonates along the 5 km of outcropping. Scattered and less pervasive than in Quensel Bjerg, their intensity increase from west to east. Barite and copper are mostly found in the west whereas quartz-copper-lead-zinc dominates in the east (Harpøth *et al.*, 1986).

Widespread in the Ravnefjeld Fm, mineralization is found inside an area of almost 50 km² on Wegener Halvø peninsula. It occurs in the lowermost 15 m of the formation, at the contact with the carbonates. They are found in incursions of carbonate debris-flow coming from the surrounding paleotopographic highs of the Wegener Halvø Fm. Lead and zinc are the main mineralization, the occurrence of copper increases toward the north-west and barite is absent (Pedersen *et al.*, 2002). The sulphides are fine grained, stratiform and occur as sphalerite, galena, minor chalcopyrite, pyrite and marcasite. They replace fossils, calcite and cement with colloform textures (Harpøth *et al.*, 1986; Pedersen *et al.*, 2002). Metal content was estimated with an average of 0,13 % Pb, 350 ppm Zn and 200 ppm Cu (Thomassen, 1973) and generally decreases toward the top of the formation.

Although mineralization is stratabound in both the Wegener Halvø and the Ravnefjeld formations, the heaviest mineralized zones are found in the vicinity of a N-S lineament at least 12 km long, the Vimmelskiftet lineament (Pedersen, 1997b, Pedersen *et al.*, 2002). It occurs in the axial plane of a deep and narrow shale basin that has also been intruded by a Tertiary dyke. At this location, a N-S trending fault has been reported on the 1:100,000 scale geological map but no significant displacement has been noticed in the Upper-Permian sequence. However, in its northern continuity, a NE-SW trending normal fault with a 5 m offset is found to radiate out from the N-S lineament (Pedersen, 1997b). This lineament was interpreted to be associated with strike-slip movement, and to have acted as a (probably deep-seated) zone of weakness at least until the Tertiary (Pedersen, 1997b). It would have controlled, as well as other major faults, the incursion of hydrothermal fluids. By analogy to the Kupferschiefer deposits, base-metal mineralization in Upper Permian sediments of Wegener Halvø was first thought to be syngenetic. However, based on fieldwork, lead and sulphur isotopes and fluid inclusion studies (Pedersen and Stendal, 2000; Pedersen, 2000, 1997a, 1997b), Pedersen *et al.* (2002) proposed another model. In an euxinic basin, early diagenetic pyrite would have precipitated from bacteriogenic sulphur, just below the sea floor. The consequently iron depleted sediments and the bacterial sulphate reduction allowed the

creation of a pore water sulphide reservoir in the sediments. The brines would have risen up along the Vimmelskafte lineament by overpressure caused by the subsidence of the Wegener Halvø block into Upper-Permian sediments. Brines would have been redistributed laterally out from this lineament, along permeable layers and radiating faults and fractures into the carbonates of Wegener Halvø Fm. (Fig. 1). Lead would have been introduced in the two formations from the same source but during two separate events. However, homogeneous lead isotope signatures of galena and sphalerite from the shales suggest that all base-metals were introduced during a single hydrothermal event within the Ravnefjeld Fm. They would have precipitated when the base-metal bearing fluids met the sulphide-dominated pore water trapped in the shales. The sulphides post-date the hydrocarbon migration in Cretaceous and is thought to be Tertiary. The colloform textures in the fossil replacements, first interpreted as post-compactional are actually believed to result from recrystallization of early diagenetic sulphides during deep burial from Upper Cretaceous to Tertiary. Fluid inclusions and particularly gas analysis from Permian to Triassic sediments of Wegener Halvø suggest that these sediments were subjected to liquids of 130–150° C, thought to have a sedimentary origin. Furthermore, apatite fission track data show that the pre Permian to Triassic sediment succession cooled below the temperature of 125°C 25 Ma ago. Thus the Pb-Zn vein-type mineralization is due to Tertiary heating to maximum paleotemperature of 100° C, most likely linked to the Tertiary volcanic activity.

From its several studies in the area, Pedersen and Stendal (2000) concluded that the post-Caledonian area of East Greenland has a good potential for mineral deposit formation and that more attention should be paid to the extension faults, wrench faults and zones of dilatation that play an essential role in the mineralization patterns.

3.4 Mineralization hosted in Mesozoic sediments

The mineralization is represented by Triassic stratiform and strata-bound base-metal occurrences of red-bed type and Jurassic placers rich in zirconium and rare-earth elements.

Mineralization is found throughout the whole Triassic sequence and is particularly widespread in Wegener Halvø area (Fig. 1). Sulphides occur in permeable beds where reduced and oxidized beds are interfingered. The ore minerals are chalcocite, galena with minor bornite, chalcopyrite, pyrite, sphalerite, tennantite and betekhtinite. Mineralization varies laterally and vertically with lead-mineralized beds of an average grade of 2–2.5 % Pb with minor zinc and subordinate silver, which are more persistent than the copper-mineralized beds of an average grade of 0.1–1.0 % Cu and 5–80 ppm Ag (Harpøth *et al.* 1986). Due to the presence of ore minerals in sandstone cements, the

mineralization is believed to be diagenetic with later remobilization of sulphides into cross-cutting massive veins and lenses (Harpøth *et al.* 1986).

3.5 Tertiary mineralization

It includes a major porphyry-molybdenum occurrence, granite roof-zone molybdenum mineralization, niobium mineralization associated with alkaline intrusive rocks, lead-zinc skarn occurrences, a minor magnetite-skarn showing, lead-zinc-bearing quartz veins and precious-metal, base-metal, molybdenum and fluorite mineralization associated with fumarolic volcanic activity.

In the northern part of the basin occurs the Malmbjerg deposit which is a molybdenum porphyry of Climax-type. It is among the world's largest molybdenum deposits with measured and indicated resources of 217 Mt at a grade of 0.20 % MoS₂ and additional inferred resources at lower cut-off grade (Thomassen, 2005). This deposit is associated with a 25.7 Ma composite alkali granite stock which intruded in Carboniferous sandstones. The granite is part of the Tertiary Werner Bjerger alkaline intrusive complex, circular in shape and 17 km of diameter. The Werner Bjerger complex can be decomposed into three lithological units (Beauregard, 1959):

- A mafic subcomplex in the SE part.
- A nepheline syenite subcomplex in the SW.
- An alkali syenite-granite complex in the northern part.

The granite stock was dated by K-Ar to 26.0 ± 1.1 Ma to 21.1 ± 0.9 Ma and intruded Carboniferous to Lower Permian sediments from south towards North (Harpøth *et al.*, 1986 and incl. ref).

4. Geophysical data

4.1 2D seismic reflection data – Jameson Land Basin

A 2D seismic reflection database (2D-MCS) was compiled in combination with bathymetry, regional gravity, magnetic and surface geological mapping data along the central East Greenland coast, with the main focus along Jameson Land Basin area, but also included the Blossøville Kyst, Scoresby Sund, and the Liverpool Land High area.

4.1.1 Database compilation

The main seismic surveys concerning the Jameson Land Basin (10,000 km²), were acquired from 1985 to 1989 by ARCO (the Atlantic Richfield Company), acquiring nearly 1800 km of 2D lines over the basin (Table 1 & Figure 2), and central East Greenland offshore surveys were selected as well (Table 1 & Figure 2). The data were extracted from the GEUS geophysical databases. Some problems due to incomplete information were encountered in preparing the data for interpretation.

Additionally are included bathymetry-, magnetic-, gravity- and onshore geology map data sets (Table 2) into the project database using ArcGIS 10.2.1 for Desktop (ESRI) and the Schlumberger's (<http://www.software.slb.com/>) data interpretation tool PETREL 2013.05.

Both systems were used to tie in 2D subsurface observations with regional geophysical grid data, such as bathymetry, gravity and magnetic anomaly data. The 2D-MCS were tied to the bathymetry or topography grids for a vertical adjustment and consistent structural tie of the different surveys together to form this regional database.

Table 1: List of the 2D MCS data surveys made available by GEUS, geological data information, magnetic-, gravity-, and bathymetry grid data

Year	Survey ID	Conducted by	Country	Data repository	Data types
1980	GGU1980	GGU	Denmark	GEUS	Geological Survey of Greenland (GGU), SEGY, offshore
1981	GGU1981	GGU	Denmark	GEUS	Geological Survey of Greenland (GGU), SEGY, offshore
1982	GGU1982	GGU	Denmark	GEUS	Geological Survey of Greenland (GGU), SEGY, offshore
1986	ARC1986V	Geophysical Service Incorporated	Denmark	GEUS	ARCO data owner, SEGY, onshore
1987	ARC1987D	Geophysical Service Incorporated	Denmark	GEUS	ARCO data owner, SEGY, onshore
1988	ARC1988D	Western Geophysical Co.	Denmark	GEUS	ARCO data owner, SEGY, onshore
1989	ARC1988V	Western Geophysical Co.	Denmark	GEUS	ARCO data owner, SEGY, onshore
1989	ARC1989D	Western Geophysical Co.	Denmark	GEUS	ARCO data owner, SEGY, onshore

Figure 2: Location of the prepared and loaded 2D-MCS data surveys along the central East Greenland margin and Scoresby Sund area

Note: The surveys are GGU1980 (Orange), GGU1981 (Pink), and GGU1982 (Green)

This database is used to correlated the main known formation sequences for the Jameson Land Basin area (Figures 3 & 4) from their onshore exposures to the sub-

Table 2: List of the 2D MCS data surveys made available by GEUS, geological data information, magnetic-, gravity-, and bathymetry grid data

Year	Survey ID	Conducted by	Country	Data repository	Data types
2009	ETOPO1	NOAA	U.S.A.	National geophysical data center	ETOPO1 Global Relief Model, Bathymetry (Amante and Eakins, 2009)
2010	DTU 2010	DTU-Space, EAPRS lab., NGA	Denmark	Danish National Space Center	Global Gravity Field Model (Andersen <i>et al.</i> , 2010)
2011	CAMP-GM	CAMP-GM group	Norway	CEED University of Oslo	Magnetic anomaly grid (Gaina <i>et al.</i> , 2011) north of 60N
1984	Scoresby Sund	GEUS	Denmark	GEUS	Geological Map of Greenland, Sheet 12 (Kokfelt <i>et al.</i> , 2013)
1995	ODP 162–987	IODP & Lamont-Doherty Earth Observatory	U.S.A.	ODP-TAMU	Site 987 (East Greenland Margin) coring and wireline logging

A 2D seismic reflection database (2D-MCS) was compiled in combination with bathymetry, regional gravity, magnetic and surface geological mapping data along the central East Greenland coast, with the main focus along Jameson Land Basin area, but also included the Blossville Kyst, Scoresby Sund, and the Liverpool Land High area.

Offshore well ODP Leg 162 987 only gives a very shallow tie in for the youngest strata off the coast of the Liverpool Land High tying into line GGU1982-12, and is the only direct well control for the area (see Table 2).

Before the 2D-MCS data was imported, several data checks had to be performed in regards to the line navigations data, the SEG Y file consistency, static shifts, duplicate data points, and tie to the bathymetry or topography grids.

The entire project database is converted into the WGS84 projection system at UTM Zone 28 North. First the navigation data files were imported into Petrel as a first step, using the navigation data of the shot-points (SP).

During a first SEG Y data review became it clear that a lot of the SEG Y data files had header file information missing, such as SP, X-Coordinate or Y-Coordinate data entries (see Figure 4).

Thus the next step was to assess the alternative 2D-MCS data set in form of the Landmark exported files, which had the coordinate information already included. However, as the Landmark format is a stand-alone format, not supported by Petrel or Kingdom Suite directly, that data set was not of any use to solve the data location and

header errors. As it was clear that a manual adjustment of all SEG-Y lines for the coordinate and header data information would take a lot of time, a second 8 bit Petrel export of the data was request from GEUS. This caused a one month delay, but actually saved project time by not duplicating data preparation work.

Figure 4: Example of missing information in header of the SEG-Y-files

The review of the Petrel exported SEG-Y data files from GEUS for surveys ARC1987 to ARC1989 and GGU1980 to GGU1982, showed that all header information were only in order for surveys ARC1987 to ARC1989, which could be imported correctly into the Petrel database.

4.1.2 Seismic reflection data tie to onshore geology – Jameson Land Basin

The onshore outcrop geology (Figure 5) was tied to seismic reflection data profiles with a detailed seismic reflection correlation scheme (Figure 4, Legend). The main at surface mapped structural trends are provided by GEUS (2015), and are based on a field mapping campaign in 2015. Previously published results on structural trends and their timing were included for comparison as well.

Figure 5: Geological surface map and tie seismic reflection horizons of the northeast-central Jameson Land Basin area. Displayed are the seismic reflection data grid (yellow lines), key tie lines of the northeast area, and the main structural surface trends (black dashed lines) observed by GEUS in 2015. The legend for seismic reflection horizons and interpreted features to the right correlate to the onshore geology maps record Kokfelt *et al.*, 2013

Figure 6: Permian angular unconformity definition for outcrop location at the Mestersvig sub-basin (Seidler *et al.* 2004), north of the Jameson Land Basin and for the northeastern end of seismic reflection data profile E in comparison, see location in Figure 5

Figure 7: Major fault trends along the East Greenland coast displayed with outcrops and sub-basins of the Wordie Creek Formation (Lower Triassic) by Seidler *et al.* 2004. The red dashed line trend indicates the post-Caledonian rift system trend and the yellow the Permo-Triassic rifting trend, with NW-SE basin boundary elements

The work by Seidler *et al.* (2004) has been helpful for calibrating the seismic unconformity boundaries for the post-Caledonian section, specifically the example of the mappable low angle unconformity between the Carboniferous and the Permo-Triassic section (Figure 6). The previously mapped regional trends by Seidler *et al.* (2004) in Figure 7 and GEUS (2015) in Figure 5 were compared with mappable trends of the Jameson Land Basin basement top surface. Similarities and differences are then described in the results section.

4.1.3 Seismic reflection data structural framework and trend comparisons

The base of the Jameson Land Basin grid was mapped along all seismic reflection lines (Figure 8–9, where structural trends can be seen for the entire project area). Three distinct trends can be seen on this basement map, the red – dashed lines correspond to the original Caledonian trend N-S, the yellow dashed lines to the Permo-Triassic rifting stage (NE-SE), and the third and light blue dashed trend (NW-SE) is associated with the mid- to southern area of the Jameson Land Basin only. The underlain magnetic anomaly data grid indicates parallel trends at least for the latter two.

The best area to start tying the seismic reflection data to the surface geology is the north-western and north-easternmost extend of the JMLB area (Figure 6). From that area, several key seismic reflection lines were tied to the onshore geological records (Figures 10 & 11).

Onshore review of the northeast area of the Jameson Land Basin

The general structural interpretation shows a narrow, NNE-SSW post-Caledonian, coast parallel rift basin (Figures 8 & 9) that has been overprinted by a Permo-Triassic rifting event and changed the sub-basin axis trends to NE-SW (yellow trend on Figure 8 & 9) (Seidler *et al.* 2004). Rifting continued during the Jurassic and Cretaceous period (Henriksen 2008; Henriksen *et al.* 2008, 2009). Tertiary intrusive sections, e.g. thick sills (Larsen 1990, Larsen and Marcussen, 1992; Hald and Tegner, 2000) intruded into the Paleozoic- and Mesozoic sediment sections mostly along fault planes during the breakup of the Northeast Atlantic region. Today's topography represents the erosional surface and the result of the Tertiary uplift, and the erosion of approximately >2 km (Mathiesen *et al.* 1994).

Figure 8: Caledonian basement top marker grid surface for the onshore Jameson Land Basin area, regional structural trends that effected the basin its base structure, and the magnetic anomalies map (Gaina *et al.* 2011)

Devonian – Carboniferous

The Devonian and pre-Devonian structures are characteristics by regional steep dipping sequences, anticlines and syncline that can also be seen in the seismic reflection record (Figures 8 & 9). The area started to rift during the Devonian. First initial post-Caledonian deposition initiated the basin during a time of block faulting, and continued rifting during the Early and Late Carboniferous (Surlyk, 1990, 2003; Stemmerik *et al.*, 1993).

Figure 9: Isochron – top structure maps for three major section intervals, and the present day elevation map. The structural trends overlay (Figure 9) is based on the basin basement map, for comparison if these trends are seen consistently throughout the area. Well visible is the NE-SW Permo-Triassic to Mesozoic rifting trend that appears to cross-cut and offset elements of the N-S Paleozoic trend. The NW-SE structural trend appears very distinct for the southern and into the central part of the JMLB, up to the Upper Triassic period. That could be a structural trend that connects with the pre-breakup JMMC structures

Up to 3000 m of fluvial and lacustrine sediments were deposited in active half-grabens (*Henriksen et al., 2009*) onto the Caledonian basement (Figure 11 & 12) forming a distinct unconformity (seismic reflection horizon "Caledonian Basement – Pre-Devonian"; Figures 10–15). A major hiatus marks the time period between the Devonian-Carboniferous early rifting sequences and the earliest Permian, when deposition ceased caused by a regional Early Permian uplift period (*Henriksen et al., 2009*).

Permo-Triassic

During the Permo-Triassic period, the basin alignment direction changed to NE-SW prompting a basin and ranges area of NE-SW striking sub-basins and half graben areas that were in-filled by on-lapping sediments onto basin shoulders accompanied by normal faulting within a complex wrench fault system (Figure 7–15) (*Seidler et al. 2004*). During Late Permian and throughout the Mesozoic, the basin primarily was controlled by thermal subsidence and localized wrench faulting and subsidence (*Henriksen et al., 2009*).

The stratigraphic sequences of the basin primarily consisted of alluvial fan conglomerates to marginal marine carbonates and evaporate formations in the lower part, and carbonate platform to basin shale deposits in the upper part (*Henriksen et al., 2009*). During the Latest Permian and Triassic time periods, marine sandstones and shale deposits dominated the area, regressing to alluvial conglomerates and lacustrine dolomite, gypsum, and shale deposits during the remainder of the Triassic epoch (*Clemensen, 1980a, b*).

Jurassic – Cretaceous

The rifting and block faulting processes continued throughout the Mesozoic, specifically the Late Jurassic and Cretaceous time periods (*Surlyk, 1990, 2003 and Stemmerik et al., 1993*). This can be seen on seismic reflection line data as shallower extension fault systems and basin infill sequences (Figures 10–16).

The latest Triassic to earliest Jurassic formations consist of a major lacustrine basin deposits (*Dam and Surlyk, 1993, 1998*), which also includes the Lower Jurassic oil-prone, lacustrine shale deposits (*Dam and Christiansen, 1990*). In the Middle and Late Jurassic the depositional environment changes to shallow-water sandstone's in the northern half, and deeper water shale deposits in the southern part of the basin, belonging to a large deltaic system during that period.

Figure 10: Key seismic reflection line "A" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences

Figure 11: Key seismic reflection line "F" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences

Figure 12: Northeast JMLB seismic reflection line "B" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences. Shortening and structural reversal of the initial central Devonian – Carboniferous rift basin

Figure 13: Northeast JMLB seismic reflection line "C" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences

Figure 14: Northeast JMLB seismic reflection line "D" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences

Figure 15: Northeast JMLB seismic reflection line "E" that has been tied to onshore outcrops of Carboniferous, Permian and Triassic sequences

Figure 16: Regional reconstruction of the central Northeast Atlantic area (Blischke *et al.* 2016). The overall trend of the Jurassic basin is north-south with a deepening trend due south for the southern JMLB area

Using pre-breakup reconstructions suggest that the JMLB continued south towards the Blosseville Kyst area and probably across the central part of the still attached Jan Mayen micro-continent region, see white dashed line projection polygon on Figure 16. This can be truth-check by compiling a set of isopach maps for the JMLB area that should give clear indications if the basin continued and / or deepened towards the south.

For this purpose a set of isopach thickness maps was generated for true-vertical thickness differences in TWT (ms) for the main sequences to assess the paleo-thickness distribution of sediments in between major hiatus events (Figure 16). The sequences were subdivided into:

- *Jurassic* (topography- Neill Klintner Group – Upper Triassic).
- *Triassic* (Neill Klintner Group – Upper Triassic – Foldvik Creek Group – Upper Permian).
- *Permian* (Foldvik Creek Group – Upper Permian – Traill O Group – Carboniferous).
- *Paleozoic – post-Caledonian* (Traill O Group – Carboniferous – Post-Caledonian Paleozoic).

Figure 17: First path isopach thickness map (true vertical TWT (ms) estimates for the main sequences for the onshore area of the JMLB. Overlays are the structural grain map based on the basin's basement topography, and possible paleo-geographic highs marked as a dashed white line

An overlay of the structural grain map (Figure 8) was used to assess, if the basin sediment lows fit into the structural trend pattern at the time. This appears to correlate well with the NW-SE trend that aligns well with the Permian, Triassic, and Jurassic basin fills for the southern extend of the JMLB. Possible paleo-geographic highs marked were marked as dashed white line, where sediments appear the thinnest.

5.1.4 Seismic reflection data structural model

The northern extend of the Jameson Land Basin was structurally remapped at surface by GEUS, clearly distinguishing between the Caledonian trend (N-S) and the Permo-Triassic to Jurassic rifting trend (NE-SW). These were also compared to previous studies that observed this difference by Seidler *et al.* 2004, who also indicated a NW-SE trend that specifically limits the Permo-Triassic rift basins (Figure 7).

Figure 18: Northeast view of the northern JMLB extend along strike of the Mesozoic basin axis and the top basement (see Figure 5) seismic horizon structural surface and the three dominating fault pattern distribution for the Devonian post-Caledonian fault system (red), the Paleozoic rifting faults (wrench and normal faulting in light green), and the youngest Mesozoic fault trend (white)

The line tie correlation of Jameson Land Basin's regional grid in comparison with the surface geology and fault observations has been concluded. The timing of the rift system with a special focus along the northern- and north-eastern extends of the basin has been subdivided into 3 main systems visible on formation section characteristics and the fault pattern mapped (Figure 18).

These 3 main structural phase observations can be subdivided into (1) Caledonian – Carboniferous with large north-south striking half-grabens and wrench fault structures; (2) the Permo-Triassic period with flower type structures that have been located within the NE area of the basin and a NE-SW basin axis trends and a NW-SE rift basin boundary trend; and (3) the Jurassic-Cenozoic where older Mesozoic structures were re-activating Permo-Triassic structures with moderate subsidence and infill.

Figure 19: 3D structural and sequence model of the Jameson Land Basin along the northeastern extend. Also displaying a horizontal section is displaying the sub-crop map of the Jurassic to Later Triassic basin indicating a shift of depo-center towards the south-southwest along the western main boundary fault system

4.2 Aeromagnetic and Electromagnetic data

4.2.1 Airborne magnetic surveys

Several aeromagnetic surveys were flown over the years covering different parts of the Jameson Land Basin with various resolutions. The survey locations and parameters are respectively shown and summarized in Figure 20 and Table 3.

Figure 20: Magnetic intensity overlaid on its shaded relief from 4 merged surveys. The contours of the aeromagnetic surveys are plotted in yellow: AEM97 survey; blue: Fugro survey; white: SkyTEM survey. Background: CampGM survey

The CAMP GM dataset with a cell-size of 5 km of the interpolated data is based on a compilation of various old airborne surveys covering the entire arctic area. The AEM 97, Fugro and SkyTEM surveys cover smaller parts of the Jameson land basin with a much higher resolution. The AEM97 survey is a combined airborne magnetic and time-domain electromagnetic survey flown in the northern part of Jameson Land along E-W lines with a separation of 400 m. The Fugro and SkyTEM surveys cover the Klitdal area along the eastern margin of the basin for base-metal exploration purposes. The Fugro survey was flown along N-S lines with a line spacing of 200 m with a fixed-wing aircraft flying at a nominal terrain clearance of 120 m. The magnetic data were collected using horizontal gradient magnetometer recordings orthogonal to flight lines. The SkyTEM survey is a combined helicopter-borne magnetic and time-domain electromagnetic survey flown at a nominal terrain clearance of 30m along 300 m spaced and E-W oriented lines.

Table 3: Parameters of the different aeromagnetic surveys used for interpretation

	SkyTEM	Fugro	AEM97	CampGM
Survey area	Klitdal	Klitdal, Wegener Halvø	Northern JL	Arctic region
Survey period	Sept-Oct 2013	May-June 2013	July-Aug 1997	
Acquisition company	SkyTEM Surveys Aps	Fugro Airborne Surveys	Geoterrex-Dighem	
Acquisition System	Helicopter-borne	Fixed-wing horizontal gradient survey	Fixed-wing	Data Compilation
Line km flown	2,275	10,171	14,622	
Flight height	30–40m	120m	120m	
Flight orientation	N-S	Klitdal: N-S Wegener Halvø: NNE-SSW	E-W	
Line spacing	300m	200m / 100m	400m	5km cell size grid
Tie line orientation	E-W	E-W	N-S	
Tie line spacing	4000m	2000m	4000m	
Reference	[1]	[2]	[3]	[4]

Note: [1] SkyTEM Surveys Aps, 2013. Unpublished report. SkyTEM Survey: Klitdal-Wegener, Greenland Data report.
[2] Fugro Airborne Surveys, 2013. Unpublished report. LOGISTICS AND PROCESSING REPORT – Airborne High Resolution Gradient Magnetic Survey – East Greenland Copper Project Klitdal & Wegener-Halvø Blocks
[3] Geoterrex-Dighem, 1997. Unpublished report. Logistics and processing report – project AEM GREENLAND 1994–1998 Airborne Geotem/Magnetic Survey over northern Jameson Land of central East Greenland.
[4] Gaina *et al.*, 2011. Chapter 3 Circum-Arctic mapping project: new magnetic and gravity anomaly maps of the Arctic. Geological Society, London, Memoirs 2011; v. 35; p. 39–48

The aeromagnetic data were reprocessed and the magnetic signal was decomposed to create several maps enhancing specific geological features, in different directions and at different depths (Figs 21 to 25). For this purpose, the gradient tensor elements of the magnetic field and its invariants were calculated (Pedersen and Rasmussen, 1990) along with the tilt-derivative, analytic signal, the directional analytic signal in the East and North directions and their vertical derivative. Additionally, an Edge function (Beiki, 2010) was calculated to emphasize edges between magnetic domains. Several images

were created with the phase preserving dynamic range compression (DRC) technique from Kovesi (2012) for different high pass filters. Maps of the entropy of the magnetic intensity were also generated to emphasize the distribution of the magnetic signal in the area. The analysis of the maps allows extracting most of the information contained in the magnetic signal by delineating and outlining trends and features. Those are correlated afterwards with the geological knowledge of the area (see Section 10).

Figure 21: Shaded relief image of the tilt derivative of the magnetic field from the AEM97survey (location on Figure 20)

Figure 22: Examples of magnetic signal decomposition map: magnetic intensity filtered using a phase preserving dynamic range compression filter at a cut-off wavelength of 7500 m, in nT, from the AEM97survey (location on Figure 20)

Figure 23: Examples of magnetic signal decomposition maps of the Fugro survey. Left: vertical derivative of the analytic signal in the eastern direction upward continued to 75 m (in nT/m²); Right: vertical derivative of the analytic signal in the northern direction upward continued to 150 m (in nT/m²). Note how these two maps enhance trends in different directions

Figur 24: Examples of magnetic signal decomposition maps of the SkyTEM survey. Left: gradient tensor element dy/dy (east [y] magnetic component with differentiation in the east [y] direction) upward continued to 100 m (in nT/m); Right: gradient tensor element dx/dy (north [x] magnetic component with differentiation in the east [y] direction) upward continued to 100 m (in nT/m.)

Figure 25: Examples of magnetic signal decomposition maps of the SkyTEM survey. Left: First invariant of the gradient tensor upward continued to 100 m, in nT²/km (Pedersen and Rasmussen, 1990); Right: Entropy of the magnetic field showing the texture of the magnetic field by measuring the statistical randomness of neighbourhood data values within a square sliding window of 225m and using a bin size of 7nT

4.2.2 Electromagnetic data from the SkyTEM survey

The SkyTEM acquisition system uses a dual moment transmitter; i.e. with a Low Moment (LM) and High Moment (HM) allowing a high-resolution at shallow depth and a great depth of investigation with coarser resolution. LM and HM data were recorded over 20 and 21 time gates from 12 to 1220 μs and from 119 to 14686 μs , respectively. The electromagnetic data were processed and inverted by SkyTEM ApS. They used the software code AarhusInv to perform a 1D laterally constrained inversion (Auken *et al.*, 2014). The result was provided as 2D conductivity maps at various depth intervals and as vertical sections along the flight lines (Figures 26 and 27).

It is clear that crystalline basement is associated with resistive material in the eastern part of the area. However very resistive material also occurs in the central part of the area and is very unlikely to be due to the occurrence of crystalline basement. Negative transient (polarity reversal) are recorded in the response curves and must be associated to Induced Polarization (IP) effects that are not accounted for in the inversion. These IP effects indicate that material in the subsurface acts as a capacitor. This could be due to the presence of metallic particles, to the presence of clays but also to permafrost. This causes the signal to be lower than the noise (but larger numerically) resulting in a high misfit value. High residuals can also be due to the 3D character of the material, which is not resolved with the 1D inversion. White shadings in the sections (Fig. 27) indicate undetermined conductivity, which is calculated almost only with the regularization process of the inversion.

Figure 26: Example of conductivity maps. Left: layer 4 from 16.2 to 22.5 meters below the terrain elevation; right: layer 25 from 323.9 to 354.1 meters below the terrain elevation

Figure 27: Example of model section delivered by SkyTEM. From top to bottom: conductivity section in logarithmic scale, LM and HM data and model plots for each time gate (data: dots; model: line), data residual

5. 3D-photogeology

The Geological Survey of Denmark and Greenland is equipped with a computer-based photogrammetric tool to do accurate mapping from aerial and oblique photos. The photo coverage used in the project comes from a combined airborne hyperspectral and LIDAR survey done in 2012 (Thorning *et al.*, 2014), with a spacing of c. 500 m and the pixel size in the centre of each image is 27×27 cm. The stereoscopic model was then built in the photogrammetry laboratory at GEUS using the method described by Dueholm (1993). The digital photogrammetric workstation is a 3D-stereoplotter with two LCD polarized monitors set one above the other with an angle of 110° separated by a half-mirror (Fig. 28).

Figure 28: The 3D workstation at GEUS

The polarized screens display a left-eye image and a right-eye image which together represent stereo pair images overlapping each other by at least 60 %. The half-mirror is a beam-splitter that transmits 50 % of the light and reflects the others 50 %. Therefore the

left-eye image is transmitted through the half-mirror while the right-eye image is reflected on it. To allow the depth perception, the geologist is wearing 3D polarized glasses with left- and right-eye lenses polarized in different directions. Furthermore, a 3D-mouse allows full navigation in the 3D environment. The workstations are equipped with SOCET-SET and the module SOCET for ArcGIS that creates a dynamic link between SOCET and ArcGIS. Geological features observed in 3D, such as intra-formational beddings, formation boundaries along with faults and fractures can be digitized as 3D polylines, extracted and then edited in the ArcGIS environment (Figs 29 and 30). They can later be imported into other software such as the 3D modelling platform Gocad (Figs 31 and 32).

Figure 29: Example of a high resolution aerial photo used for the 3D-photomapping with 3D polylines digitized and edited interactively in ArcGIS. Note the different colours indicating different geological features

Figure 30: Example of the 3D polylines in ArcGIS map view

Figure 31: 3D view in Gocad of the Digital Elevation Model with 3D polylines from 3D-photomapping plotted

Figure 32: 3D view in Gocad of the digital elevation Model, 3d polylines collected with Photomapping and interpreted geology

6. Drill-core data

Based on prospecting results throughout the summers 2012 and 2013 by Jameson Land Resources (the joint venture between AngloAmerican and Avannaa Resources), a diamond drilling campaign of about 2,500 m was designed and concluded for the Klitdal area along the central eastern margin of the Jameson Land Basin. Initially three key areas – Ice Cave, Copper Creek and Triangle – were targeted to test the economic potential of sediment-hosted copper mineralisation in Permo-Triassic sediments. The Klitdal valley represents the eastern edge of a Phanerozoic sediment package in contact with a Precambrian crystalline basement block of Liverpool Land. In outcrop the oldest formations found resting on top of the basement are arkoses and conglomerates of the Lower-Middle Triassic Klitdal member (Pingo Dal formation) (Fig. 33).

Figure 33: Geological map of the Klitdal area with location and code of boreholes

Prospecting in the Klitdal valley revealed chalcocite-chalcopyrite-minor galena mineralisation within various settings near the basin margin. Most valuable occurrences with an economic potential were discovered in Lower Triassic arkosic beds of the Klitdal member. The sulphide mineralisation was found as fine grained matrix replacement and also in massive veinlets along fractures or fluid pathways. Type-outcrops are found in Ice Cave (also as native Cu and Ag) and Copper Creek east. Another interesting style in the Copper Creek target is the Gipsdalen formation right at the contact to the underlying Pingo Dal formation. Stratiform plant fossil horizons up to 2 cm thickness within the lowermost Kap Seaford arkoses are replaced with massive chalcocite and galena. A third mineralisation type observed along the north to south running main basin – crystalline block contact is hosted by granitic basement within sub-vertical breccia horizons. The semi-massive to massive blebs and veinlets are dominated by chalcocite-chalcopyrite-pyrite and locally galena. Due to the fact that the occurrences (e.g.: Triangle) are very small and patchy over small fracture zones no economic potential is seen.

Table 4: Drill-hole position, depth, dip and azimuth

DH Hole	DH East	DH North	DH RL	DH Bottom	DH Dip	DH Azimuth
14CEGC CC-001	449,225	7,879,850	350	101	-90	90
14CEGC CC-002	449,425	7,880,700	336	62	-90	0
14CEGC IC-001	450,850	7,890,975	370	512.5	-90	180
14CEGC CC-003	447,320	7,881,085	228	179	-90	135
14CEGC IC-002	449,110	7,890,840	326	170	-70	270
14CEGC IF-001	450,800	7,896,000	177.5	89	-60	45
14CEGC IF-002	450,840	7,894,050	216	395	-90	90
14CEGC CK-001	447,600	7,887,000	360	266	-75	90

All drill locations were laid out in UTM zone 27N and distances are expressed in meters (Tab. 4). Altogether 1,807.0 m of diamond drilling was completed over a period of about four weeks. Within four drill targets eight boreholes were drilled: Ice Cave (2 DDHs), Inderfjord (2 DDHs), Copper Creek (3 DDHs), Central Klitdal (1 DDH). Due to a generally shallow dipping sediment package, about 5–7° to the SW, vertical drilling was proposed for the whole programme. However, three drill holes were drilled in an angle due to morphology of the target horizon. All drill cores were geologically logged in detail using the help of portable XRF (NITON) and on-core susceptibility (GDD instrument [mSI]) 1 m interval measurements in addition. Furthermore all drill core boxes have been photographed dry and wet for possible further investigation at a later stage.

The very first drill hole 14CEGC-IC-001 was the deepest drilled throughout the programme and it caused certain difficulties for the drilling due to no previous experience in the area. Horizons of disintegrated and sub-surface weathered arkoses near the top

and continuously changing grain size within the main conglomerate formation challenged the stability of the long drill string. The string snapped twice but was recovered both times. However, during the tripping out process three rods (3 x 3m) had to be cut and left in the hole at a depth of 385 m. Another loss was registered while removing the casing when one casing rod (3 m) plus the welded in casing shoe had to be given up and therefore remain in the hole at shallow depth. Otherwise nothing was left in any of the other completed boreholes, such as casing, rods, etc. and no other difficult rock conditions were met. For the entire drill campaign the underlying crystalline basement was the intended end of hole horizon to close off the stratigraphy of the prospective sediment strata. An approach to plan the depth of each individual borehole was to use the modelled basement surface of the inversion of the aeromagnetic dataset produced by the consulting company Mira Geoscience (Mira Geoscience, 2014). The constrained inversion was based on gridded near surface susceptibility of the Liverpool Land block with its variety of crystalline rocks.

6.1 Ice Cave (IC)

The Ice Cave target was initially selected as the highest priority area after its discovery during the summer prospecting work in 2013. A highly altered outcrop of Klitdal member arkoses with Cu-Ag rich boulders (native metals in samples) in the scree and drainage led to the concept of a strong fluid penetration and therefore a potential of economic mineralisation in the area. The target is located near a significant break in the magnetic pattern, striking NE-SW.

Drilling of the first hole 14CEGC-IC-001 was laid out about 800 m west of the north-south striking sub-cropping basin-basement contact. The results are summarised as follows:

The drill hole collared after 5.5 m of overburden in the Klitdal member arkoses which changed after 85.7 m into a coarse conglomerate to the end of hole, both composed of local basement clasts and pebbles. Oxidised and hematite rich reddish layers are dominant whereas reduced light grey horizons appear as well. It shall be noted that the transition from a sandier top arkoses into conglomeratic beds at about 86.0 m matches the depth of the modelled and expected top surface of the crystalline basement. An explanation might be the coarse texture of the conglomerate consisting of basement pebbles up to 50 cm in diameter. The susceptibility contrast to the basement is less significant than to the overlying sandy arkoses. Hence the constrained inversion model could not differentiate the conglomerate from the basement in the first attempt. Drill core susceptibility measures range from 0 – 3.5 mSI for the conglomerates, whereas the basement in other

boreholes shows values up to 9 mSI. Furthermore the top 50 m show a strong sub-surface weathering, which was observed in proximal outcrops as well. An initial interpretation of the strong disintegrated arkoses beds was to be an alteration overprint. This together with the described trace of native Cu and Ag from float samples underlined the target selection. Neither strong alteration features, nor mineralisation was intersected throughout the whole hole. The borehole was stopped at 512.5 m without having reached the footwall contact into basement (Fig. 34).

Figure 34: Photo of core boxes showing the lithology of the Klitdal member drilled in IC-001

14CEGC-IC-001 43-52m Klitdal Mb: Arkoses: mix of hematite rich redbeds and reduced pink layers and patches

A second drill hole was completed about 2 km west of IC-001 to follow the strata down dip towards the basin. Borehole 14CEGC-IC-002 was also targeting a geophysical IP phenomenon seen in the EM data. An interpreted IP effect (conductivity dropping into negative scale) appears along a NNW-SSE trend over several kilometres. The results are summarised as follows:

After 4.3 m of overburden the drill went into green to grey mud- and clay stones of the Gipsdalen Formation. The unit also consists of frequently occurring gypsum layers up to 10 cm thick that are predominant bedding parallel with minor cross-cutting veinlets of gypsum. At a depth about 90 m dark mudstone layers, several cm-thick, contain very fine grained sulphides. Measurements with a portable XRF (NITON) read values of up 2 % Zn and 1 % Pb, no elevated Cu values though. From about 93.0 m to 104.0 m grey sandy and arkosic layers appear which mark the transition into Klitdal member of the underlying Pingo Dal formation. The top 50 m of the Klitdal member are a fine to medium sandstone which grades from about 157.0 m into a coarse conglomeratic arkoses (Fig. 35). This contact is seen as the strike/down dip continuation of the intersected beds in hole IC-001. Therefore the hole was stopped as no mineralisation was observed.

The gypsum rich mudstone beds of the Gipsdalen formation are interpreted to be possible cause of the IP effects in the AEM data. A follow-up study on the drill core has not been done to date.

It should be noted, that an initial attempt to complete IC-002(A) had to be given up at 32.5 m due to a technical failure. To complete the setup the first 32.5m were simply re-drilled which caused some "half-moon" drill core within the top meters of IC-002(B).

Figure 35: Core logs and magnetic susceptibility (in mSI) of IC-001 and IC-002

6.2 Inderfjord (IF)

The target area of Inderfjord was selected due to its location near a significant break of magnetic domains that are coincident with morphological features. Major NE-SW striking fjord systems appear along the whole Liverpool Land block and also the main river and smaller drainages change direction abruptly near the Inderfjord valley.

Borehole IF-001 was positioned to intersect the lower Klitdal member and the contact into the basement in shallow depth. The interpretation from the electromagnetic section suggested a steep fault contact, which might have acted as a major fluid pathway. Generally, in the area, outcrops of mineralization are only preserved in the basement that shows minor structural controlled chalcocite occurrences. Also structures such as slickensides have been observed that indicate steep dip slip movements.

Diamond drilling collared in the expected Klitdal member conglomerate after 7.7 m of overburden. The beds consist of large basement pebbles in a hematite rich matrix and are similar to the formations at the Ice Cave area. The hole went already into granite after 75.3 m and was stopped at 89.0 m. No indication of faulting or fluid alteration was observed. In fact a paleosurface (weathered top) is interpreted within the first meters of the granite with a normal on-lap of the overlying conglomerates (Fig. 36).

The hole IF-002 within the Inderfjord was drilled to check the structures interpreted from the magnetic data and to test the immediate vicinity to strongly altered conglomerates. This outcrop shows intense disintegration of the formation, minor cross-cutting fluid pathways and trace of malachite staining in floats of the scree slope.

Figure 36: Photo of core boxes showing the lithology of the Klitdal member drilled in IF-002

The borehole collared again in Klitdal member conglomerates of the typical appearance observed in other drill holes. After 4.3 m of overburden the variable conglomerate formations hold on to a depth of 364.55 m where the footwall granite was intersected again. Again, no sign of fluid movements is visible within the contact and no mineralisation has been spotted, neither within the conglomerate, nor in the granitic basement. The hole was stopped at 395.0 m in “fresh” coarse grained orthoclase rich granite (Fig. 37).

A final conclusion was made immediately that there is no further prospectivity in the Inderfjord area, as both drill holes have tested a large portion of the most promising Klitdal member strata and no major structures have been identified in the contact to the crystalline basement.

Figure 37: Core logs and magnetic susceptibility (in mSI) of IF-001 and IF-002

6.3 Copper Creek (CC)

The area of Copper Creek has been defined in 2013 after various local stream sediment anomalies along a major E-W drainage system led to a number of mineralised outcrops. Copper Creek river drains the crystalline basement in east and seeps westwards through the on-lapping Klitdal member arkoses grading into the overlain Kap Seaford member. Another pronounced feature in the area is a sub-vertical Tertiary dyke, striking WNW-ESE, of about 30 m width (field observation) that cross cuts the crystalline basement and the Triassic sediment package over several kilometres. Disseminated chalcocite mineralisation has been found near the main basin margin and next to the dyke within Klitdal member arkoses. Two main out-/sub-crops about 500 m apart of each other host several chalcocite-hematite (specularite) rich matrix replacing samples of the typical poorly cemented arkoses. In addition plant material replacements of massive chalcocite and galena were discovered within the lowermost Kap Seaford member arkoses, right above the contact to the last Klitdal member bed. Those several cm thick organic rich layers can be traced in outcrop along Copper Creek over 10th of meters and were described in float samples already in the 1970's exploration campaigns (Nordisk Mineselskab A/S).

Initial drilling in the target area was laid out south of the mineralised arkoses localities in the highest local elevation level to test the whole prospective Triassic stratigraphy (Pingo Dal and Gipsdalen fm) and the basement contact. The expected lower contact of the Klitdal member arkoses was projected at about 85 m (magnetic inversion model) (Fig. 38).

The CC-001 borehole collared after 4.0 m of overburden in Kap Seaford member mudstones with bedding-parallel gypsum stringers – as also seen in the Ice Cave target area. At 21.1 m the transition into the Klitdal member arkoses was reached which appears as the typical “pink arkoses” described from outcrops of the region. Layers are alternating between hematite rich red beds and more reduced poorly cemented horizons. A fractured and strong hematite-carbonate rich contact into granitic basement was hit at 88.4 m whereas the alteration and fracturing appears in both formations. Besides that no mineralisation occurs in the whole borehole.

Figure 38: Photo of two core boxes showing the lithology of the Klitdal member drilled in CC-003. The arkoses in the upper box are mixed redbeds and reduced pink layers, hematite-carbonate in matrix while the lower box represents the basement gneiss

A follow-up drill hole was positioned, about 0.85 km north of CC-001, next to the WNW-ESE striking Tertiary dyke where the chalcocite mineralised arkoses were found in sub-crops along a ridge over 100 m. The arkoses host flaky hematite (up to 1–2 cm plates specularite) and are in general hardened and bleached due to an interpreted proximal alteration halo (overprint) by the Tertiary dyke intrusion. This explains the morphological ridge caused by more weathering resistive altered arkoses (Fig. 38).

The drilling collared about 15 m north of the outcropping edge of the dyke in Klitdal member arkoses, after intersecting 8.0 m of overburden. No intention was put on drilling the dyke, but instead its immediate vicinity and possibly contact aureole that hosts potential sulphide mineralisation. After 53.8 m drilling the typical pink arkoses of the Klitdal member the granitic footwall was reached. The contact again shows crosscutting fractures and a pronounced hematite-chlorite (glauconite?) alteration over several meters in both directions of a sharp contact. No mineralisation was observed (Fig. 39).

A third drill hole was completed in the Copper Creek area approximately 2 km west of the two initial boreholes. Hole CC-003 was supposed to test the potential of sulphide

mineralisation in the strike-dip continuation of the sediment package and collared about 400 m south of the main local Tertiary dyke feature.

Drilling started with 5.0 m of overburden and went into the expected Kap Seaford member with the typical green-grey gypsum bearing mud- and clay stones that have been observed in earlier boreholes. At about 64.1 m the transition into Klitdal member arkoses was reached which appears as pink arkoses with alternating oxidized and hematite rich red beds. From 139.0 m meters conglomeratic beds arise in the sequence and strong sub-vertical fractured horizons occur near the lower contact into granitic basement at 157.6 m. Very minor euhedral pyrite was observed over 30 cm within a low angle carbonate vein in the Klitdal member arkoses around 154.0 m together with a general strong alteration (hematite-chlorite-carbonate). The alteration and fracturing continues to 170.5 m into the footwall granite. Other than the trace pyrite in the Klitdal member arkoses no sulphide mineralisation has been identified until 179.0 m.

After the completion of the three drill holes showing no sign of economic mineralisation potential whatsoever it was decided to write off the Copper Creek area.

Figure 39: Core logs and magnetic susceptibility (in mSI) of CC-001 and CC-002

6.4 Central Klitdal (CK)

The area of Central Klitdal has been chosen as the last potential target for the 2014 Klitdal drilling programme and also closes off the north to south prospection drilling along the Jameson Land basin eastern margin in the Klitdal valley region.

Aiming to test an interpreted structure (major fault) seen in the magnetic data the drilling was supposed to investigate the main stratigraphy intersecting the Late Triassic Fleming Fjord Fm., the Middle Triassic Gipsdalen Fm., the most prospective Pingo Dal Fm. and eventually the crystalline basement. In context with the distinct magnetic change the working model was that two major magnetic domains – weakly magnetic Triassic sediments and higher magnetic crystalline basement – are located near a potential fault that might have acted as a key fluid pathway with possible deposition of copper sulphides in the sediment package. The expected depth to the basement block was modelled at about 400 m.

Figure 40: Core logs and magnetic susceptibility (in mSI) of CC-003 and CK-001

Drilling collared after 4.8 m of overburden in fine grained red beds of the Fleming Fjord Fm and reached the Gipsdalen formation with the typical gypsum bearing mudstone at 36.5 m (Fig. 40). Top beds of the formation are clearly oxidized with hematite in the matrix, whereas from about 85 m the mud- and clay stone is green to grey and contains bedding-parallel gypsum layers up to 10 cm. The lowermost 6–7 m of the Gipsdalen formation show arkosic beds and therefore marks the transition into the Pingo Dal formation that starts at 154.9 m (Fig. 41). Typical pink arkoses with predominant oxidized and hematite rich layers represents the Klitdal member, while gypsum stringers extend about 50 m from above into the arkoses and gypsum partly replaces the matrix. This shows fluid movements with replacement textures that could potentially host copper mineralisation. However, no sulphides have been identified. At 241.3 m the footwall granite has been hit unexpectedly early in the hole. The sharp contact is accompanied with intense Fe + Mn oxides and hydroxides such as hematite and intense fracturing. Chlorite and carbonate alteration is spotted, besides no visible mineralisation throughout.

This last drill hole of 2014 Klitdal campaign has again shown that there is no economic sulphide mineralisation in the area neither within the most prospective Lower Triassic sediments of Klitdal member, nor in the contact zone to the crystalline basement.

Figure 41: Photo of core boxes showing the lithology of the Klitdal member drilled in CK-001

7. Structural mapping in the Jameson Land Basin

The fieldwork was carried out in an area between 71°–72°N and 22°–25°W in Klitdal and Schuchert Dal along the eastern and western margin of the Jameson Land Basin (JLB) with a short reco with the helicopter in the Canning Land-Devondal area (Fig. 42)

The objectives of the fieldwork were:

- To make general geological observations.
- To gather kinematic data along major fault systems.
- A detailed structural mapping close to the drill sites.
- To collect oblique photos from the helicopter for 3D Photogeology.
- To collect samples for geophysical properties, geochronology and geochemistry.
- Ground control of the Photogeology interpretation.

More than 350 fault slip data were collected on 15 structural sites and used for paleostress analysis. The paleostress analysis of the heterogeneous fault slip data set is performed using integrated software for structural analysis (T-Tecto 3.0 Zolohar 2007). The Gauss Method associated with the visualization of P&T Dihedra (Angelier & Mechler 1977) allowed us to distinguish different superimposed tectonic regimes in this area. In Klitdal area, magnetic susceptibility was measured on the different outcropping lithologies with a Nexus handheld instrument in order to constrain the future 3D magnetic model.

Around 1950 oblique photos were taken along the more than 900 km-long flights with helicopter.

7.1 Rationale for fieldwork in the east side of Jameson Land

The architecture and kinematics of the Early Triassic rift is not well known from literature and in general interpretation is that the N-S trending Liverpool Land with its Caledonian basement is the horst bounding the east side of the Jameson Land Basin. Previous field-work in 2013 showed the presence of NE-SW oriented faults oblique to the Liverpool Land horst. The faults mapped from the aerial photos also recognized on the magnetic maps, seem to be related to the Early Triassic rifting event. Structural analysis along the main trends in the Klitdal area was performed to check the kinematics and to define the relationship between tectonics and sedimentation in the Early Triassic (the Klitdal mb of the Pingodal Fm) that represents the main target of the drilling campaign. The western border of the Jameson Land Basin corresponds to a major tectonic boundary, the so-called "Post-Devonian Main Fault", a north-trending fault separating the Jameson Land Basin to the east from the Caledonian basement of the Stauning Alper to the west (Fig. 42). Structural analysis along this main tectonic feature and in Triaselv was carried out to verify the kinematics of the fault and possible re-activation in Tertiary time.

Figure 42: Location of the fieldwork area in the Jameson Land Basin, central East Greenland. The red rectangles show the location of the maps in Fig. 43, on the western and eastern margins of the basin. The triangle shows the position of the base camp

7.2 Structural mapping

7.2.1 The eastern side of Jameson Land

Along the eastern side of the Jameson Land Basin in the Klitdal area, we walked from the rig site 14CECG-IC-001 in the Triassic sediments towards the basement in the east. The Klitdal member is represented by arkosic layers in the west and conglomerates towards the basement with altered granitic boulders in a greenish clayish matrix. Copper mineralization was found as malachite staining on a boulder in this conglomerate (Fig. 44). The altered sediment was sampled for clay analysis (see Chapter 13).

Figure 43: Geological maps of the western and eastern margins of Jameson Land basin showing the visited localities

Figure 44: Malachite staining in a basement boulder close to the contact between basement (Liverpool Land) and Klitdal sediment in Ice Cave area (WP 003)

At the contact between the lower Triassic conglomerate and the Liverpool Land basement, slickensides on a fault plane dipping N287/46 indicate normal movement and another one dipping N221/70 (Fig. 46). Calcite and alkali feldspar vein running with a dip direction of N287 and a dip of 75 was found and sampled.

Another sample of altered clayish layer from Klitdal member was taken. Magnetic susceptibility was measured on outcrop samples with a Nexus handheld kappa meter. The susceptibility is about zero SI in the sediment layers, as well as on the large altered granitic boulders of the conglomerate. The basement includes marbles patches with magnetic susceptibility around zero SI.

Figure 45: Altered conglomerate in the Klitdal mb

Along the surroundings of the drilling site 14CECG-IF-002 altered granitic pebbles and clayish green matrix were sampled for clay analysis (see chapter 13). Bedding dips N250/18° (Fig. 45). The Klitdal Member sediments between the drill site 14CECG-CC-001 and the dyke dip N314/5. North of this area, close to the Tertiary dyke, baked boulders of basement are found in the moraine deposits with hematite (specularite), sulfides and some malachite.

Figure 46: Structural Map of the Klitdal area with stereo plots of the fault-slip data (red dots are GPS waypoints of the localities)

Two photo flights were taken with the helicopter along the northern and southern sides of Perm Dal and Devondal (Fig. 47). One helistop was done in Devondal in the upper Permian carbonates on the northern side of Devondal. Planar surfaces were checked to find evidences of faulting but no kinematics was found (Fig. 47).

Figure 47: The NE-SW trending Devondal Fault offsetting the Permian carbonates. (North is up)

The next stop was in Canning Land, on the south-western side of Kollen more or less at the suspected contact between the Devonian sediments of the Vimmelskaftet Fm and the Carboniferous sediments that both lay with a dip direction to the SW under the more horizontal Upper Permian sediments made of basal conglomerates and carbonates. Due to scree over the slopes this contact could not be identified as tectonic or stratigraphic. Another try was given landing on the top of Kollen on the Upper Permian carbonates where a conglomerate wedges out towards the north between the Devonian sediments and the Upper Permian carbonates (Fig. 48).

Figure 48: Oblique photo of Kollen. Upper Permian conglomerates of the Huledal Fm unconformably overlie Devonian Old Red Sandstones

7.2.2 *The western side of Jameson Land*

In Schuchert Dal the plan was to visit some localities where N-S trending faults could be seen in order to understand the kinematics on the western margin of the basin. We started with localities west of Schuchert Flod where a N-S trending fault is drawn on the geological map, offsetting a Tertiary sill that intrudes the Carboniferous sandstones and the basement (Fig 49). Some kinematics were found and a sample of the sill was taken and malachite was found as staining on boulders in the southern slope. Further south of this locality (Fig. 50) many fault planes were found with calcite steps and kinematics indicating both dip-slip and strike-slip movement.

Figure 49: Tertiary Sill intruding basement and carboniferous sediments

Figure 50: Geological map of the Schuchert Dal area. Numbers correspond to GPS waypoints
 24°33'40"W 24°25'30"W 24°17'20"W

Even further south (WP 068 and 069, Fig. 50) a fault plane was measured with a dip direction of N86 and a dip angle of 40° as well as a dyke dipping 40° towards N76.

West of Schuchert Flod, we first visited the top of Snekkuppel (WP 085 Fig. 51), where the Carboniferous sediments are juxtaposed west and east of the N-S oriented

faults delimiting a migmatitic band from the Caledonian basement. No kinematics evidence was found up there. However a bit east and down from there, along the N-S oriented fault east of the basement, oblique movement was found along fault planes dipping N250/80 (WP o86 Fig. 51). We later went back east of Schuchert Flod, the outcropping didn't allow to see fault evidences in the river. The sandstone of the Kap Stewart Fm dip N110/30.

Figure 51: The Gurreholm and Triaselv area

In Gurreholm Bjerger area we visited a locality where a tertiary dyke is offset by a NNE-SSW trending fault in the carboniferous and Upper Permian sediments. Fault planes were found on the western side of the river (WP 077 Fig 52) with an average dip direction of N107 and a dip of 72 degrees and showing evidences of normal movement. Further south along the river (WP 078, Fig 52) the sandstone beddings mapped as Upper Permian were dipping 22° to N238 whereas the Upper Permian sediments seen further up in the cliff were much more horizontal. Further south (WP 079, Fig 52) a fault plane was measured dipping 70° to N98, no kinematics could be defined.

About 3 km further to the west of the previous locality we visited the contact between Carboniferous and Upper Permian (WP 080, Fig 52). Large amounts of barite were found associated with the Upper Permian sediments but no kinematics along the fault plane was seen.

We landed 900 m further to the south, looking for fault kinematics along the same fault and another one east of it, cutting through Triassic sediments. One fault plane could be measured with a dip direction of N212 and a dip angle of 82° but kinematic evidences were absent (WP 081, Fig 52).

Figure 52: Geological map of the area north of Triaselv

We first went east of Schuchert Flod close to a N-S trending fault at the contact between Jurassic and Triassic sediments. The Kap Stewart conglomerates (2 mm ϕ) are dipping 20° to N25 (WP 084). In the river (WP 083) a fault plane showing dip slip movement, maybe reverse, was found with a dip direction of N108 and a dip angle of 32° (Fig. 53).

Figure 53: Structural Map of the Schuchert Dal area with stereo plots of the fault-slip data (red dots are GPS waypoints of the localities)

8. 3D-modelling of the Early Triassic base-metal mineralized sequence in the Jameson Land Basin

8.1 Introduction

The Jameson Land Basin in central East Greenland has been explored for base-metals since the 1930'ies, essentially along its western and eastern margins. Two main types of mineralization occur: fault-bounded strata-bound mineralization in Upper Permian and stratabound-stratiform mineralization in several stratigraphic levels of Upper Permian and Triassic sediments (Harpøth *et al.* 1986). It is therefore essential for mineral exploration to understand the structure and the stratigraphic architecture of the basin. This study focuses on the Klitdal area (Fig. 1), along the eastern margin of the basin where the exploration company Avannaa Resources Ltd. had an exploration license. In 2011, 2012 and 2013 Avannaa and later Jameson Land Resources A/S carried out investigations of previously described copper mineralization in Klitdal area. This led to the discovery of native copper and silver within clasts of crystalline rocks in the early Triassic coarse sediments of the Pingo Dal Fm, together with chalcocite and hematite in bleached arkoses (Thomassen *et al.* 2014).

Our initial work consisted in mapping the area using 3D-Photogeology combined with a structural interpretation of aeromagnetic data. Electromagnetic data along with fieldwork and results of the drilling campaign led in 2014 were used to constrain a preliminary 3D-model of the area.

Mineralization is recorded in Upper Permian shales as sphalerite and galena with minor chalcopyrite, pyrite and marcasite. Lead, Zinc and Copper-bearing ore grade is in the hundred's ppm range with 4 ppm silver with local enrichments (Harpøth *et al.* 1986). This reduced-type mineralization has been compared with the Polish Kupferschiefer type system (Harpøth *et al.* 1986). In the Upper Permian carbonates, the mineralization (2–4 % sulphides) is represented by chalcopyrite and barite with minor galena, sphalerite and tennantite-tetrahedrite.

The 1 to 2 km-thick Triassic sequence is dominated by continental sedimentation with red-beds and thin evaporitic layers (Surlyk 1990). The earliest Triassic marine sediments pass upwards to sandstones and a coarse-grained syn-rift sequence known as the Pingo Dal Fm (Surlyk 1990). This formation shows important lateral thickness variation from almost 700 m in Canning Land to 50 m in Wegener Halvø (Fig. 1). Mineralization is stratiform or strata-bound throughout the whole sequence and is particularly widespread in the Wegener Halvø area. Sulphides occur in permeable beds where reduced and oxidized beds are interfingered. The ore minerals are chalcocite, galena with minor bornite, chalcopyrite, pyrite, sphalerite, tennantite and betekhtinite. Mineralization varies laterally and vertically with lead-mineralized beds of an average grade of 2–2.5 % Pb with minor zinc and subordinate silver which are more persistent than the copper-mineralized beds that have an average grade of 0.1–1.0 % Cu and 5–80 ppm Ag (Harpøth *et al.* 1986). Due to the presence of ore minerals in the sandstone cements, the mineralization is believed to be diagenetic with later remobilization of sulphides into cross-cutting massive veins and lenses (Harpøth *et al.* 1986).

The rifting terminated in Middle Triassic with deposition of up to 200 m thick red-beds and gypsiferous shales. In Late Triassic the whole area changed into a lake system, with sedimentation of mudstones deposited in an anoxic environment. No distinct angular and erosional unconformities are seen within the Triassic sediments (Surlyk 1990). The Jurassic was dominated by thermal subsidence and no major tectonic events are recorded until the Early Eocene when the North-East Atlantic break-up was accompanied by extensive magmatism. Basaltic lava flows covered the Jameson Land basin together with sill complexes and an ESE-trending dyke swarm that affected the basin. In Miocene time, a dramatic uplift occurred with a magnitude of more than 1 km responsible for 2 to 3 km of erosion (Mathiesen *et al.* 2000).

8.2 Faults and dykes network

Three major trends of faults are recognized in the area: N-S, NNE-SSW and NE-SW while dykes are oriented E-W, NW-SE and NNW-SSE. The aeromagnetic data show a clear NE-SW trend that corresponds to the Klitdal Fault (Fig. 54) separating two magnetic domains. The northern part is dominated by negative long wavelength anomalies while the southern part shows positive anomalies with short wavelengths. The latter has a similar magnetic signal compared to the outcropping basement rocks of Liverpool Land (Fig. 54). The southern part of the Liverpool Land is a relatively flat surface gently dipping few degrees to the west and is interpreted as the Permian peneplain (Fig. 54). The holes drilled in the southern part (CC1, CC2 and CC3 in Fig 54) revealed a shallow

basement at 50–160 m depth. In the northern part, the drill-hole IC1 (Fig. 54) went through 500 m of Early Triassic coarse-grained rocks without reaching the basement. At this location strongly altered meter-size granitic boulder conglomerates were observed in outcrop. East of the drill-hole IC1, at the contact between basement rocks and the Early Triassic sediments, NE-SW and NNE-SSW oriented lineaments are observed on magnetic maps. They could be correlated with field observations of fault planes both in the basement and in the sediments. Dip-slip kinematics interpreted from slickensides indicating normal movement were found together with inherited reverse faults.

In the electromagnetic data, some resistive parts are well correlated with the outcropping basement. In the eastern part of the Klitdal Fault, on the conductivity sections, the resistive parts associated with the basement abruptly pass into a more conductive domain (Fig. 55). This abrupt change in conductivity is observed on several sections and the normal offset is estimated to be at least 500 m. The Klitdal and Passelv faults are interpreted as part of an Early Triassic rift system outcropping to the east but deep seated to the west. This fault system is associated with the syn-rift sequence of the Pingo Dal Fm and in particular with the coarse-grained member. The Pingo Dal Fm presents great lateral variation thicknesses as it is more than 500 m thick north of the Klitdal Fault at the drill-hole IC1 while only 70 m thick in the southern part at the drill-hole CC1. The rift system is sealed by Middle Triassic and younger sediments.

Figure 54: (left) Geological map of the Klitdal area (draped on the DEM) derived from 3D-Photogeology and from fieldwork; (right) residual magnetic field anomaly (RMF) superimposed on the shading of the second vertical derivative of the RMF, upward continued to 100 m. Continuous lines are mapped faults and dashed lines interpreted deep and buried faults. Red line: location of the conductivity section

8.3 3D-modelling

The described datasets were integrated in the 3D modelling software Gocad developed by Paradigm and the Gocad Mining Suite developed by Mira Geosciences. Faults were modelled using map traces, their magnetic signature, field measurements as well as conductivity sections interpretation. The faults were modelled using the structural interpretation shown in Figure 54 (right). Surfaces were first created vertically from their map traces, adjusted in height and depth to fit the geological observations from field-work, photomapping and drilling results. They were then dip-constrained using the conductivity sections. The good coverage of the electromagnetic survey allows a good control on the faults' geometry in their eastern part. In the southern part, the basement was modelled considering the presence of the Permian peneplain. The top of the basement surface was first built using the morphology of the outcropping basement. It was constrained with four drill-hole basement intersections (CC1, CC2, CC3 and CK in Figure 54). The modelled basement was then cut in several blocks using the fault network previously described. In the northern blocks, the top of the basement was offset vertically to fit the top of the basement reached by the nearby drill-holes (IF1 and IF2 in Figure 54). Regarding the few control points available in the northern part, the top of the basement in the northern blocks was modelled with the same strike and dip than in the southern block (Fig. 55).

In addition to the top of the basement, the base of the Middle Triassic, Upper Triassic and Jurassic were modelled. The major faults in this area are Upper Carboniferous and Early Triassic and are sealed by Middle Triassic sediments. Some late deformations of Tertiary dykes offset by faults were observed with the photomapping. However at the modelling scale, the general geometry of the Triassic horizons does not seem to be affected. Therefore, the Middle and Late Triassic along with the Jurassic horizons were modelled as one surface each over the Klitdal area, without being cut by faults. The geological boundaries in Klitdal were refined with the 3D-Photogeology. Due to layer cake geology with sediments dipping around 5° to the west, each stratigraphic horizon was modelled using a flat starting surface. This surface is the average plane that passes through the corresponding 3D-geological boundaries. The surface was constrained precisely with the stratigraphic boundaries from the map and from the drill cores. The starting surface was then interpolated using a discrete smooth interpolation to obtain the best fit with the previous constraints. The modelled base of the Middle Triassic sequence has four drill-hole constraints (CK, CC1, CC3 and IC2) while the base of the Late Triassic formation has only one drill-hole constraint in central Klitdal (CK, Fig. 54). No drilling was carried out in the Jurassic but its base is well outcropping in the topography

in the western part giving a good 3D constrain on its geological boundaries. Furthermore, the Jurassic base is well correlated with a clear change in the conductivity on the electromagnetic sections. The large and tight coverage of the electromagnetic survey allows here a good constrain on the Jurassic horizon over the Klitdal area.

Figure 55: 3D-view in Gocad of the modelled Early Triassic rift, zoomed on the eastern part of the Klitdal fault. (top) The Digital Elevation Model is displayed with the geology mapped from 3D-Photogeology. Note the abrupt change in conductivity on the N-S oriented section located in Fig. 54. The pink surface representing the top of the basement surface was down-faulted 550 m to the north and to the west by the Klitdal Fault (in dark grey); (bottom) Along the drill paths are shown in pink the Early Triassic sediments of the Pingo Dal Fm and in yellow the Middle Triassic sediments. The surface in yellow represents the top of the Early Triassic Fm

The NE-SW and NNE-SSW oriented Klitdal and Passelv Faults are part of an Early Triassic fault system which cuts the Liverpool Land in several blocks. In the southern part, the Triassic sediments lie on top of the flattened basement and dip together a few degrees to the west (Fig. 55). In contrast, in the northern blocks of Liverpool Land the contact between basement and Triassic sediments is tectonic. The Early Triassic fault system described in this section represents the southern boundaries of a relatively small tectonic depression here called “Klitdal Basin” and filled in by the Pingo Dal Fm. The basin continues to the north up to Wegener Halvø that represents the northern border of the basin (Fig. 1). In this sector the syn-rift sediments lie conformably on top of a thick pre-rift sequence comprising Early Triassic marine deposits, Upper Permian, Carboniferous and Devonian sediments. Base-metal stratabound mineralization occurs within this sequence in Wegener Halvø whereas in Klitdal no mineralization was found in the cores drilled in the vicinity of the syn-sedimentary faults probably because the thick coarse grained syn-rift sequence in Klitdal rests unconformably on top of basement rocks.

Some uncertainties remain regarding the basement depth in the north-western part of Klitdal and further work is required to constrain it. For this reason, inversion of magnetic data will be carried out to estimate the depth to the basement. No correlation could be made so far between the conductivity sections and the Triassic formations.

In conclusion, the 3D-modelling has a crucial role in this study allowing to visualize and integrate different datasets in a structural and stratigraphic interpretation of the eastern margin of the Jameson Land Basin. This revealed the existence of the Klitdal basin highlighting a favourable geological setting for future mineral exploration.

8.4 Magnetic modelling with the VPmg code

In order to better understand the mineralization system along the eastern margin of the Jameson Land Basin we try to constrain the architecture and estimate the thickness of the basin over Klitdal area. For this purpose we will use 3D magnetic data modelling and particularly 3D-geologically constrained inversion. In this study we use VPmg, a 3D potential field forward modelling and inversion algorithm developed by Fullagar Geophysics Pty. Ltd (Fullagar and Pears, 2007). Implemented into the 3D modelling software Gocad, VPmg allows to model magnetic data into a geological framework. VPmg discretizes the earth into vertical prisms, themselves divided into cells by geological surfaces. The top of the prisms are coincident with the topography and the bottom extends into a half-space. VPmg offers the possibility to apply geological constraints to

the modelling. Inversion having non-unique solutions, it is essential to use apriori information to constrain the model in order to reduce uncertainty. Setting “hard” constraints such as drill-holes intersections with the basement or soft constraints obtained from the general understanding of the area and from investigative modelling of the data significantly improves the results. Moreover, in order to avoid edge effects in the modelling, a local fine-mesh VPmg model is incised into a regional model with a coarser mesh, itself incised into a uniform half-space.

The first step in the magnetic modelling consisted in working with synthetic data in order to test the code, understand the control and model files and get a good idea on the effect of the inversion parameters. A simple initial geological model was built in Gocad. The model is made from two surfaces: the top of the basement dipping to the west and cut in two blocks by a SW-NE trending fault down-throwing the northern part about 500 m (Fig 56,a). The top of the sediments represents the present day topography. The sediments are attributed a magnetic susceptibility of 0.000002 SI and the basement a magnetic susceptibility of 0.02 SI (Fig56, b). A grid of points was created 50 m above the topography with a mesh of 500 x 500 m to locate the data points where the magnetic field will be calculated in the modelling. After having set the ambient field, inclination and declination, the forward modelling was run and gave the data as shown on Figures 56c and 56d. An edge effect is present with negative anomalies on the grid borders of the calculated data. This can be avoided by running the forward model using a simple regional model incised by a local model as the one presented here.

The second step was to run a geometric inversion on the synthetic data just generated and compare the results with the initial model. Inversion is the process of retrieving a model that fits observed data. VPmg can invert both for the magnetic susceptibility and for the boundaries of the geological units that are assigned with a magnetic susceptibility. A starting geological and petrophysical model is iteratively adjusted in order to get as close as possible to the “true” model. VPmg performs inversion using the Method of Steepest Descent and the inversion styles available include homogeneous, heterogeneous property inversion, and geometry inversion. Heterogeneous property inversion can be performed either using the default least square method, or a statistical method. The degree of convergence of the model is evaluated using the magnitude of the χ^2 data norm L_2 and the L_1 -data norm. A model is considered acceptable if $L_2 \leq 1$ and/or $L_1 \leq 1$. During the geometric inversion, the magnetic properties are fixed and only the cells bounds are allowed to move vertically. As the inversion is a non-linear problem, several iterations are needed. The number of iterations allowed is set as well as the maximum depth percentage of which cell bounds are allowed to move during each iteration. The error or absolute data uncertainty is defined and will be used to define the model acceptability.

Two inversions are presented here (Fig. 57). For both of them we consider a basement fairly uniform in susceptibility but with an uncertain topography. The susceptibility of the enclosing half-space is allowed to vary. The model prisms are 15000 m². We allow 99 iterations with a maximum change in depth of 10 % per iteration and a data uncertainty of 0.5 nT. The first inversion result is completely out along the borders. The model is not acceptable, with an RMS misfit of 2.30 nT after 99 iterations it doesn't satisfy the magnetic data to the prescribed 0.5 nT accuracy. For the second inversion the starting model was changed with a basement surface closer from the initial model and constrained in the southern part over an area of 5 by 5 km, to fix the basement surface at a given elevation (Fig. 57, d). The inverted basement in grey (Fig. 57, d, e, f) is close to the true initial model represented in yellow. The model is acceptable with an RMS misfit of 0.33 nT after 85 iterations. Few constraint points considerably improve the inversion results.

The second step is to perform the modelling on the real data. For this a comprehensive and reliable starting model of the area was built using all the apriori information available described in the previous sections. This starting model is a crucial parameter in the results of the inversion and care must be taken regarding its construction. Convergence has not been reached yet and additional work is required in order to get an acceptable model. However, preliminary results suggest a sedimentary thickness greater than 2000 m in the northern part of the Klitdal basin. This is also supported by the interpretation of seismic data presented in the Section 12.

Figure 56: Forward modelling to generate synthetic data. a, Two surfaces made in Gocad representing in blue the top of the sediments (and the topography) and in red the top of the basement, b, model showing the magnetic susceptibility properties in space according to the geological domains, c, the synthetic data are generated after running a forward modelling on the model shown in (b), d, view from the top of the synthetic data

Figure 57: Geometric inversions of the synthetic data, the properties are fixed. a, flat starting model #1 with surfaces representing the top of the sediments (topography) and the top of the basement. The space under the surfaces is attributed the same magnetic susceptibility than for the forward model (sediments: 2×10^{-6} SI and basement: 2×10^{-2} SI), b, Result of the inversion with in grey the inverted basement compared to the starting surface, c, starting model #2 with a curved basement top closer from the true initial model and constrained in the southern part so that this part is not allowed to move during the inversion, d, inverted basement compared to the starting surface, e, inverted basement, f, inverted basement compared to the initial model in yellow (used to create the synthetic data)

8.5 Depth to magnetic source estimation – Euler deconvolution

The Euler deconvolution technique is commonly used to estimate the depth to a magnetic source from the measured magnetic anomalies. The Euler equation describes the magnetic field for a point source located at (x_0, y_0, z_0) at a single observation point (x, y, z) :

$$(x - x_0) \frac{dT}{dx} + (y - y_0) \frac{dT}{dy} + (z - z_0) \frac{dT}{dz} = nT$$

where T is the magnetic field amplitude, differentiation is done with respect to spatial coordinates (x, y, z) and n is the structural index (SI). The latter is a constant from 0 to 3

depending on the shape of the magnetic source. It takes the value of 0 for stratigraphic contacts and edges of wide intrusive bodies, 0.5 for thick step-normal fault, horst and graben and basin edge, 1.0 for sills/dykes and thin dipping volcanic/sedimentary and metasedimentary beds, 2.0 for pipes and 3.0 for spheres. Therefore the calculation has to be done for a specific target and several calculations are needed to cover the whole grid. The calculation is applied on a grid data sample using a sliding window. The choice of the window size (WS) is important and the optimum size is the quarter width of the considered anomaly.

The Euler deconvolution method was applied within Gocad on the synthetic data generated by the forward model of the faulted basement. As these are synthetic data, the calculation should fit reasonably well the model when the correct parameters are chosen. Different tests were done changing the window size, the structural index and the error tolerance (Fig. 58). In this case the focus was on the NE-SW fault down-throwing the northern block of the basement. Therefore the appropriate structural index should be 0.5. As the width of the anomaly corresponding to this fault is about 3000 m, the optimum window size should be 750 m. The data grid cell size is 125 m so the optimum window size is 6 cells. The error in the Z direction is set to 15 %. The calculation was run for several window sizes and the results are compared in Figure 58. The calculation made with a structural index of 1 are scattered over the fault wall whereas the calculations made with a structural index of 0.5 are focused on the upper part of the footwall. The calculation with window size of 6 cells show scattered solutions over the fault wall whereas the calculation with a bigger windows size show complex focused solutions (arc shape). Between those parameters, the best to choose would therefore be a SI of 0.5 and a WS of 6 cells.

Figure 58: Euler deconvolution applied on the synthetic data for different parameters, compared to the initial model surface (in yellow) representing the top of the basement. WS: window size in number of cells of 125 m, SI: structural index, E: error percentage in depth

9. Regional analysis of aeromagnetic data

In this section we describe and interpret the magnetic data from the surveys flown over the Jameson Land Basin (Fig. 59) that were detailed in the section 5.2.1. First, the regional magnetic intensity is analysed and is followed by a description of the magnetic structures which are compared with the geological knowledge of the area. A new method to analyse the magnetic data is then proposed and is tested on the Mesters Vig area, the north-westernmost part of the AEM97 survey.

Figure 59: Simplified geological map of the Jameson Land Basin. The contours of the magnetic surveys are plotted in black. The letters refer to localities in the Figure 6o. (B) Kap Simpson, (C) Kap Syenit, (D) Oksehorn, (E) Werner Bjerger and (F) Malmberg

9.1 Regional magnetic intensity

In the northern part of the Jameson Land Basin high magnetic anomalies are associated with Tertiary intrusive complexes lining-up along a NE-SW trend over more than 100 km (Fig. 6o). These felsic intrusions were dated with younging ages from the northeast to the southwest between 41.6 ± 0.5 Ma for the syenite at Kap Parry and 25.5 ± 0.4 Ma for the Malmbjerg granite (Brooks, 2011 and incl. ref.). The Werner Bjerger complex is the most studied intrusive complex of the area as it hosts the Malmbjerg deposit, a molybdenum porphyry of Climax-type among the world's largest molybdenum deposits. Sills and dykes are widespread within the intrusive complexes and in the adjacent sediments with a wide range of compositions (lamprophyres, trachytes, etc) (Brooks, 2011).

Similar high magnetic anomalies occur further south in the Jameson Land Basin, on Liverpool Land and in Scoresby Sund (G, H, I and J in Figure 6o). However these anomalies do not coincide with outcropping Tertiary intrusive plutonic rocks. Indeed the anomalies (G) and (H) occur where sediments are outcropping Upper-Carboniferous to Permian sediments and Jurassic sediments, respectively. The positive anomalies (I) and (J) occur on the eastern margin of the basin where Liverpool Land crystalline basement is outcropping or very shallow. Liverpool Land is made of pre-Caledonian gneiss complexes and Caledonian migmatites and plutonic intrusions. These rock types are expected to have a relatively high magnetic susceptibility but as observed on the western margin of the Jameson Land Basin and in the northern part of Liverpool Land these areas are associated with negative anomalies. This can be explained by the adjacent presence of highly magnetic intrusions which have a limited depth extent; i.e. the magnetic susceptibility contrast at the contacts between the bottom of the intrusive bodies and the host rocks contribute significantly to the observed magnetic field. Remanent magnetization could also be present but is not needed to explain the negative anomalies. The high magnetic anomaly in Liverpool Land is continuous to the southwest towards Scoresby Sund region which was strongly affected by Tertiary magmatism and is covered with thick plateau basalts and intruded with dyke swarms. More recent plutonic intrusions similar to the Tertiary intrusive complexes observed in the northern part of the Basin could be present at shallow depth where high magnetic anomalies occur.

Figure 6o: Regional magnetic intensity map with ages of Tertiary intrusive complexes. (A) syenite at Kap Parry, (B) Kap Simpson, (C) Kap Syenit, (D) Oksehorn, (E) Werner Bjerje alkali granite and (F) Granite at Malmbjerg. (G, H, I and J) mark areas with similar high magnetic anomalies than the Tertiary intrusives but that are not associated with known outcropping Tertiary intrusive plutonic rocks

9.2 Structural Geophysics

Magnetic lineaments were digitized over the entire area and are plotted on the Figures 61, 63 and 66 according to their orientation. They can be compared with the faults and dykes from the geological map in the Figure 59. Figure 61 shows lineaments oriented between N₉₅ and N₁₃₀. Most of the lineaments in area (1) are associated with doleritic dykes observed over the entire Basin. However, the lineaments mapped in the Mesters Vig area (2) are offsetting magnetic lineaments associated with dykes and are therefore interpreted as faults. Area (3) in Figures 61 and 62 exhibits NW-SE to WNW-ESE trending lineaments associated with several generations of doleritic dykes cross-cutting each other. These lineaments are cross-cut by N-S trending lineaments that correlate with mapped normal faults affecting the crystalline basement. Along these faults brecciated granite exhibits chalcocite-bornite-hematite and galena-chalcopyrite respectively, assaying up to 6.2 % Cu, 233 ppm Ag and 12.0 % Pb in grab samples. Scattered pyrite-copper-lead showings are also found around the faults highlighting a potential for granite-hosted copper mineralization (Thomassen and Rink, 2013).

Figure 61: Magnetic lineaments oriented between N95 and N130

Figure 62: Geological map of area (3) from Figure 61 in the northernmost part of Klitdal, with the magnetic lineaments interpretation

In Figure 63 the area (4) shows N-S lineaments associated with Tertiary basaltic dykes. They are detailed in the Section 10.3.2. Area (5) displays N-S oriented magnetic lineaments in the southern prolongation of mapped normal faults to the west of Schuchert flod, that are down faulting Carboniferous – Upper Permian sediments to the contact with crystalline basement (Fig. 64, Figure 65). Slickensides were measured along a fault plane dipping 80° to southwest and indicate oblique movement, most likely from a late reactivation (Fig. 64a and 65). These N-S oriented faults are also observed further north in area (5) where they interplay with NE-SW normal faults that offset a basaltic sill intruded in the basement and in the down-faulted Carboniferous sandstones (Fig. 64b). These faults must have been reactivated after the Tertiary intrusions. At this locality malachite staining was found on floats of sandstone boulders.

Figure 63: Magnetic lineaments oriented between N130 and N170 in green and between N170-N180 and No-N10 in orange

Figure 64: Geological map of the area (5) from Figure 63 showing the N-S faults and magnetic lineaments. The magnetic data are only available south of the survey limit plotted with the blue line

Figure 65: Field photo of the fault offsetting the Upper Carboniferous sediments to the contact with the crystalline basement. (Picture location in Figure 64a)

Some lineaments in area (6) coincide with lamprophyre dykes reported with a strike between N116 and N154, subvertical and intruding the carboniferous-Lower Permian sediments but not the Upper Permian sequence. However, K-Ar ages and the chemistry of the dykes suggest Tertiary ages younger than 55 Ma (Larsen *et al.*, 1990). Larsen *et al.*, (1990) conclude that the dykes never penetrated Upper Permian sediments due to chilling and fracturing at the base of Upper Permian water-rich sediments. Area (7) shows N-S and NNW-SSE oriented magnetic lineaments that are well-correlated with mapped normal faults affecting the entire outcropping stratigraphic pile; i.e. from Upper Permian to Jurassic sediments.

Figure 66: Magnetic lineaments oriented between N10 and N30 in pink and between N30 and N70 in red

In the Figure 66 area (8) exhibits magnetic lineaments (in pink) oriented NNE-SSW some of which are associated with basaltic dykes. These lineaments are offset by NE-SW lineaments interpreted as faults (in red) (detailed in the Section 10.3.2). Area (9) located just south of the Werner Bjerre intrusion shows NNE-SSW oriented lineaments that are well correlated with mapped normal faults affecting the Carboniferous and Upper Permian sediments. In Klitdal area (10) some of the NE-SW to NNE-SSW magnetic lineaments are associated with major normal faults down faulting the northern part of the area with an offset of at least 600 m. The main NE-SW fault is interpreted as a syn-sedimentary fault active during the Early-Triassic rift in central East Greenland (see Section 12). The Early Triassic syn-rift sedimentary sequence comprising coarse conglomerates and arkoses is sealed by Late Triassic sediments and only the NNE-SSW border faults are visible at the outcrop. Area (11) is marked by NNE-SSW magnetic lineaments that are correlated with sub-vertical lamprophyre dykes intruding a Caledonian granite. The dyke swarm is parallel to a number of normal faults in the area and was dated at 245 ± 2 Ma (Kofoed, 1998) making it the only evidence of Triassic volcanism in the area.

9.3 Analysing the magnetic signal decomposition using Self-Organizing Maps

9.3.1 *The Self-Organizing Maps (SOM) approach*

The magnetic signal can be decomposed to create maps enhancing specific geological features, in different directions and at different depths. For this purpose, the gradient tensor elements of the magnetic field and its invariants are calculated (Pedersen and Rasmussen, 1990) along with the tilt-derivative, analytic signal, the directional analytic signal in the East and North directions and their vertical derivative. Additionally, an Edge function (Beiki, 2010) is calculated to emphasize edges between magnetic domains. Several images are created with the phase preserving dynamic range compression (DRC) technique from Kovesi (2012) for different high pass filters. Maps of the entropy of the total field were also generated to emphasize the distribution of the magnetic signal in the area. The analysis of the maps generated allows extracting most of the information contained in the magnetic signal by delineating and outlining trends and features and correlate them with the geological knowledge of the area. In order to synthesize the information that can be extracted from each individual map in an objective way we use Self-Organizing Maps (SOM). The idea is to map areas which have a similar magnetic signal based on images of the magnetic signal decomposition. Patterns are found in the data and are used to perform predictions; i.e. we want to find the

magnetic signal pattern of a certain type of geological feature in a particular dataset based on the magnetic signal decomposition. The patterns can then be used to predict the type of geological features occurring in the dataset.

The Self-Organizing Maps (SOM) introduced by Kohonen (2001) are commonly used in “data-mining” science to extract information and patterns from large datasets. The SOM process allows reducing the high dimensionality of the multivariate input data to visualize the output data in a 2D space, typically a map. It preserves the structure of the input data and reveals hidden relationships between them. The SOM is based on a type of neural network model; i.e. the data are considered as layers of neurons interacting with each other. Input neurons from one layer are sending information via synapsis to neurons from another layer and so on until the layer of output neurons. Mathematically it corresponds to approximating a function which has many input variables (usually unknown) in order to find which variables are involved in the function, what are the hidden links between them and what are their respective contributions to the system. The network is trained iteratively using unsupervised data and competitive learning to find the best function. Considering an input dataset made of n variables values at each sampling points, the SOM process goes through two main steps:

1. The initialization phase in which the input data are introduced into the model: the size and the geometrical shape of the neural network are chosen. Each data point is considered as a vector based on the values of the n variables of the input dataset which define a n -dimensional data space (Fig. 67, left).
2. The training phase during which a neighbouring function is applied to the neural net to reduce the number of vectors to Best Matching Units (BMU) vectors, representing the distribution of all input vectors. These BMUs are then projected in a non-linear manner onto a SOM 2D grid so that BMUs representing similar data are mapped in adjacent cells and dissimilar data are mapped far from each other (Fig. 67, right).

Figure 67: Schematic illustrations of the steps (1) and (2) of the SOM process (from Fraser *et al.*, 2010). Left: example for sample points with 3 variables A, B and C. The sample points (yellow) are plotted in a 3D space according to their variable values. A vector (pink) is defined for each sample point and a BMU vector (black) is determined by training the data to represent them. Right: view of n-variate data points represented as coloured vectors in a nD data space and their BMU vectors in white

A colour coding can be applied to the SOM in order to show the distance relation of the data mapped into adjacent cells. This map is called a U-matrix and is displayed in Figure 68a where cold colours indicate a small distance between the data and warm colours suggest dissimilarity between the data mapped to adjacent grid positions (cells) in the SOM. In order to plot the data back into the geographical space a unique colour code is used to identify the position of the data within the SOM (Fig. 68b). Areas mapped with the same colour in the geographical map therefore suggest similar data. The values (BMU values approximating the actual data) of the input variables can be read on the component maps shown in the Figure 68c by comparing the same locations in the grids.

Figure 68: Example of SOM for 3 variables input data. (a) U-matrix showing with a temperature colour scale the distance relationship in data space between the data plotted in adjacent cells (blue: similar data vs red: dissimilar data), (b) Colour code used to plot the data back into the geographical space, similar data will be plotted with similar colour. The image is in the same SOM space than in a; (c) component maps in the SOM space (same space than in a and b) allowing to compare the values of the variables calculated for each BMU by looking at the same cells in the maps

9.3.2 Case study: SOM analysis of the magnetic signal in the Mesters Vig area

Mesters Vig is located in the northern part of the Jameson Land Basin, just north of the Oligocene intrusive Werner Bjerre complex (Fig. 59). Mesters Vig area hosts the only ore deposit mined in East Greenland. The Blyklippen Pb-Zn mine has produced 545,000 t of ore with 9.3 % Pb and 9.9 % Zn between 1956 and 1962. The area is dominated by the Mesters Vig's graben where fault-controlled epithermal Pb-Zn sulphide-bearing quartz veins occur over 300 km² (Fig. 69). This graben is 4 km wide and 15 km long and controlled by N140-160 and No-25 orientated faults. Continental syn-rift Upper Carboniferous – Lower Permian deposits are unconformably overlaid by Upper Permian marine sediments and Lower Triassic shales only preserved within the graben. The area was affected in Tertiary by igneous intrusions:

- Widespread doleritic sills up to 100 m thick and locally intersecting quartz veins. They are cut by N-S, NNE-SSW and NNW-SSE oriented faults.

- Subvertical doleritic dykes oriented N160–180 which intersect the sediments, the quartz veins and the sills.
- Subvertical doleritic dykes oriented N20–30 mapped in the southeastern part of Mesters Vig area. They locally intersect the N170 striking doleritic dykes.

The graben has accommodated more than 1000 m of displacement at different times since Late Carboniferous as the sills are much less offset than the sediments. Two major vein zones are found on either side of the graben's border faults. They are mostly oriented 150/80E along the western side of the graben and oriented 150/80W along the eastern side. The veins are made of quartz, barite, galena and sphalerite with minor calcite, pyrite and chalcopryrite. On the western side one of the lenses was estimated to host 200,000 t of ore with 9.3 % Zn, 2.1 % Pb and 0.7 % Cu. The mineralizing veins are both observed to be cut by and to cross-cut the dykes and are thought to be related to the Tertiary magmatism.

In order to analyse structures of various directions in the area, several images of the magnetic signal decomposition were used as input in the SOM: the analytic signal, the vertical derivative of the analytic signal in the East and in the North directions, the invariant I_2 of the gradient tensor upward continued to 50 m, the vertical and horizontal derivatives upward continued to 50 m, the Dynamic Range Compression (with a high pass filter of 1200 m, the entropy of the RTP using bins of 3 nT and a square sliding window of 1800 m and the edge function. Each of these images were displayed with an appropriate 8 bit display in a 0 to 255 greyscale before being imported in the SOM. In addition to having the same value range, the SOM input data are normalized with their variance.

Figure 69: Geological map of the Mesters Vig area (located in the Figure 1) from the compilation of maps at the 1:250 000 scale (Haller, 1971), at the 1:25 000 scale (Swiatecki, 1981). Below: geological cross section located by the yellow line on the map

The component maps resulting from the SOM analysis of the signal decomposition maps in Mesters Vig area are shown in Figure 70a. The SOM results are plotted back into the geographical space (Fig. 70 b and c) using the specific colour codes presented in Figure 70a. The map in the Figure 70b enhances lineaments barely visible on commonly used magnetic maps and on magnetic maps specially processed to enhance these trends, such as the tilt-derivative or the horizontal derivative (Fig. 71).

Figure 70: SOM result of the analysis of 9 images of the magnetic signal decomposition in Mesters Vig area. (a) Component maps, U-matrix and colour code maps used in (b) and (c). (b and c) geographical maps showing the same SOM data with 2 distinct colour codes. Similar colours on the map indicate that the data points have similar magnetic signal characteristics. Draped on the hillshading of the terrain model. Black lines are faults from the geological map

Figure 71: Magnetic signal decomposition maps of Mesters Vig area. (a) Shaded relief of the tilt derivative, illumination from the SE, (b) East horizontal derivative of the East component upward continued to 50 m

The dark blue lineaments (Fig. 70b) can be associated with mapped doleritic dykes (Fig. 69). The western part of the area displays trends oriented N-S while the eastern part of the area rather displays trends oriented NNE-SSW. These trends have the same orientation as the doleritic dykes described from the geological map. A third trend oriented N140-160 was delineated and is parallel to the main trends of the border faults of the graben. The map in the Figure 70c shows the same data but using a different colour code where one can notice that the dykes' signal is attenuated in the central part of the graben and to the East of the graben. The magnetic signal of the dykes oriented N170 in the western part of the area quickly attenuates at the western border fault of the graben. These dykes are not mapped in the graben and seem not to occur in the upper formation of the Upper Carboniferous sediments. The signal of the dykes oriented N20-30 is visible in the entire area to the East of the graben but is attenuated in areas where the middle formation of the Upper Carboniferous is outcropping. Only few occurrences of these dykes are mapped on the geological map and are not seen to outcrop in stratigraphic levels above the lower formation of the Upper-Carboniferous sediments. The magnetic data allow to delineate these dykes over the entire area (Fig. 72a) and to point out that they are most likely buried under the upper part of stratigraphic pile. The simplest explanation for this would be that the dykes pre date the middle and upper formations of the Upper Carboniferous sediments. This is unlikely as no sign of magmatic activity was reported from this period and the doleritic dykes with the same

orientation are described to cross cut sills themselves observed in Triassic sediments. Another explanation could be that the Tertiary dykes simply did not intrude the upper formations of the Upper Carboniferous.

The magnetic lineaments associated with the dykes are offset by trends that can be mapped over the entire area and are presented in the Figure 72b. Four trends are visible:

- N140–160, parallel to the main faults of the graben along which are found the mineralized veins.
- N30–70, parallel to the bendings of the graben's faults. One major example is the trend along Mesters Vig associated with a normal fault down-faulting the southeastern part of the area so that the lower formation of the Upper Carboniferous outcrop in the northern part at the same elevation than the uppermost formation of Upper Carboniferous south of Mesters Vig (Fig. 6g).
- N90–N110 and N110–130, mostly observed in the northern part of the area, parallel to the Kong Oscar Fjord which was interpreted as a major transfer zone, parallel to the Eastern Jan Mayen Fracture Zone (Olesen *et al.*, 2007).

Figure 72: Maps showing the magnetic trends interpretation on the hillshading of the terrain model. (a) Interpreted dykes (b) faults interpreted from the dykes' offsets

10. IP analysis of SkyTEM data

10.1 Summary

Induced Polarization (IP) effects were observed in airborne Time Domain EM (TEM) data acquired in central East Greenland in the context of exploration for disseminated sulphides in a sedimentary basin. Some of the IP anomalies were targeted by drilling which revealed the absence of mineralization. In order to understand the possible causes of the IP effects we first identified them in the TEM data. IP indicators were extracted from the shape of the transient curves at every measurement location and were analysed by using a Self-Organizing Map (SOM) procedure. Results from K-mean clustering of the SOM are visualized on a geographical map showing the transient curves' characteristics. Some of the clusters are clearly correlated with the geology whereas others merely reflect recordings below the noise level. In order to interpret the cause of the IP anomalies the airborne TEM data were inverted for the Cole-Cole parameters.

10.2 Introduction

A high-resolution dual moment, i.e. Low Moment (LM) and High Moment (HM) airborne time-domain electromagnetic survey was conducted along the eastern margin of the Jameson Land basin in central East Greenland to explore for base metals. The survey area comprises crystalline basement to the East and layered Early Triassic to Jurassic sediments to the West. The layers are dipping a few degrees towards West. The Triassic sequence is 1 to 2 km thick and mostly of continental origin. The fluviatile Early Triassic arkoses and conglomerates, the lower Middle Triassic grey limestone and black shale beds and overlying gypsiferous sandstones and mudstones are known to host disseminated sulphides (Harpøth *et al.*, 1986). Sulphide mineralization was the target of an airborne TEM survey acquired with a SkyTEM system over an area of 550 km². N-S oriented lines were flown with an average terrain clearance of 30 m and a separation of 300 m while E-W oriented tie-lines were flown with 4 km separation. Additional lines were flown over 3 areas of particular interest with different orientation and a separation of 150 m. The data were processed and inverted by SkyTEM Aps.

The conductivity models showed some conductive layers as well as IP effects in the data. IP effects in TEM data reflect the relaxation of polarized charges in the ground which can be good indicators of the presence of metallic particles. Some of these locations were drilled during the following field season but unfortunately did not reveal the presence of mineralization. The aim of this study is therefore to understand the possible causes of these IP effects. The remote location of the area prevents the data to be affected by cultural noise such as power lines, fences, etc. The electrical charge accumulation in the ground can be related to the presence of sulphides, oxides or graphite or to the presence of clays or fibrous minerals. Permafrost may also cause IP effects and is then expected to be associated with a highly resistive subsurface.

In order to spatially locate the areas where IP effects occur in the TEM data and compare them with the geology, the shape of the transient curves was analysed. IP effects can be indicated in the transients by:

- the presence of negative values
- a very fast or very slow rate of decay of the positive part of the soundings (Smith and Klein, 1996).

Several characteristics of the transient curves (IP indicators) of the SkyTEM survey were extracted and analysed by using the Self-Organizing Map (SOM) technique. This is a type of neural network algorithm developed by Kohonen (2001) for analysis of multi-variate data. The basic idea of SOM is to provide a method for easy visualizing of multi-dimensional data. The SOM may be viewed as a two-dimensional grid onto which multi-dimensional input data are projected or mapped from a multi-dimensional space (the space dimension is equal to the number of input variables) containing all the geographically distributed data characteristics from the transient curves. Input data that are similar or close to each other, irrespectively of geographic location, are mapped to the same or adjacent position in the SOM. A standard K-mean clustering procedure on the SOM grid is used to perform yet another simplification for easy visualization. Data that belongs to a particular cluster in the SOM data space can afterward be mapped into the geographical map. The SiroSOM software (Fraser and Dickson, 2007) was used for the SOM analysis. Once IP were identified and located, Cole-Cole parameters were recovered from the airborne TEM data in specific locations using the program AarhusInv developed by the hydrogeophysics group of Aarhus university (Auken *et al.*, 2014).

10.3 Self-Organizing map and spatial analysis of the IP effects

LM and HM data were respectively recorded over 20 and 21 time gates from 12 to 1220 μs and from 119 to 14686 μs . The transients were analysed at every 10th measurement location along the flight lines for which 15 parameters (IP indicators) were calculated: (1) the sum of all negative values, (2) the sum of negative values in the most early local minimum, (3) the first negative value, (4) the gate number of the first negative value, (5) the minimum value, (6) the gate of the minimum value, (7) the number of gates of consecutive negative values, (8) the maximum descending slope in the negative part, (9) the gate of the maximum descending slope in the negative part, (10) the maximum ascending slope in the negative part, (11) the gate of the maximum ascending slope in the negative part, (12) the maximum descending slope in the entire curve, (13) the gate of the maximum descending slope in the entire curve, (14) the maximum ascending slope in the entire curve, and (15) the gate of the maximum ascending slope in the entire curve.

Two examples of HM response curves are shown in Figure 73, which illustrates some of the characteristics of the survey data. The example from line L303 101 (Fig. 73) has a very well-defined local minimum with nine consecutive negative values in early gates. This is considered a clear indication of IP effects in the data. The example from Line 301 901 (Fig. 73a, b) has three consecutive negative values at the latest gates. A small local minimum with positive values is observed prior to the negative values. The data from the late gates from Line 301 901 are close to or below the noise level. However, inspection of adjacent sample locations show a similar pattern, but it is difficult to exclude that systematic noise is causing the observed pattern.

Figure 73: Examples of response curves from HM data. (a) data from L301 101 with clear indication of IP effects; (b) data from Line L301 901 showing possible but uncertain indications of IP, (c) similar as in (b) but different ordinate values

For this study, HM data and LM data are analysed separately but they could easily also be analysed jointly. Prior to the SOM analysis of the response curve characteristics, the data were smoothed laterally using a running mean filter applied respectively over 345 points and 65 points to the HM and LM data. The running mean filtering was applied for random noise reduction. Each data type is furthermore normalized by their standard deviation for floating point number and by the range for integers. SOM grid cell sizes of 66 x 60 and 64 x 58 were used for the HM and LM data respectively. Figure 74 shows the 14 K-mean clusters of the SOM (grid) obtained from the analysis of the 15 dimensional HM data. SOM component maps corresponding to each of the 15 HM IP indicators are shown in Figure 75, which provides easy visualization of data correlations. The link between individual clusters and IP indicators can be seen by comparing similar grid locations in the maps shown in Figures 74 and 75. The corresponding geographical location of data within each cluster is shown in Figure 76 on the geological map.

Figure 74: The fourteen K-mean clusters in SOM data space (66 x 60 grid cells) based on HM data. The dashed lines separate four clusters' groups based on the response curve pattern they represent and on the geological units they are correlated with

A possible cause to the IP effects in this arctic area is permafrost. In this case, IP indicators would be expected over the whole survey area whereas it seems that they are localised to specific places that are discussed in the following paragraphs.

Inspection of Figures 2 and 3 shows that the clusters numbered 3, 8, 10, 12 and 13 have their first negative value of the transient curve at a very late gate. This may be explained by the signal being below noise level in the late gates as illustrated in Figure 73bc. They show very steep descending slope in the very first gates. Three of these clusters (8, 10 and 12) are located in alluvial fans close to the sea and along river beds where high conductivity is indicated in the surface layers. They are therefore considered not associated with IP. On the contrary, the clusters 2, 4, 5, 9 and 14 represent transient curves with the minimum values of the sum of negatives and their first negative and minimum values appear in the first time gates. They furthermore show negative values for at least 13 gates and may be considered as having strong IP effects.

Some clusters (1 and 11 in HM data and 1, 4, 7, 8 and 13 in LM data [not shown]) are associated almost exclusively with areas where crystalline basement is outcropping (Fig. 76). The transient curves corresponding to the clusters from LM data start with negative values and then quickly become positive with oscillating behaviour within the noise level in the late gates. In the HM data the transient curves do not have significant

negative values. Cluster 11 represent response curves that have the same pattern than in the LM data and cluster number 1 represents transient curves starting with positive but low values which pass below zero about 8 time gates later. We do not discuss these further in this study.

The remaining clusters which present stronger IP indicators appear to be concentrated in several areas. In the north-western part of the survey area (Fig. 76a and b), the IP indicators in the HM data reveal a N-S elongated patch of almost symmetrically distributed clusters (from west to east: clusters 6, 14, 5, 4, 5, 14 and 6). These clusters occur over outcropping Upper Triassic sediments and all describe the same transient curve pattern. However, the most negative sum of negatives, minimum value and first negative value are located in the central part of the patch and increase towards the sides. The minimum and first negative values appear in the earliest time gates and negative values are observed for 12 to 15 consecutive gates. The IP effect in this area is significant and stronger along the N-S elongated central part. This symmetry is less clear in the LM data which show quickly decaying transient curves that pass into the negative values in the late time gates. These elements suggest that the IP source body is elongated in a N-S direction.

Figure 75: Component maps corresponding to each IP indicator in SOM data space. Similar data are associated with a common best matching unit (BMU) vector and the distance relation between BMUs for a particular grid location and the surrounding BMUs are visualized in the U-matrix by using a colour scale. In the present case, the clustering range is small

In the central part of the survey area (Fig. 76a and c), the clusters are clearly correlated with the outcropping geology both in the LM and HM data. The area where the upper part of Middle Triassic sediments is outcropping is correlated with the clusters 6 and 14 in the HM data. They describe a transient curve which reaches negative values in relatively early time gates and stay in the negative part. Clusters 5, 4, 2, 9, 7 and 6 have the same transient curve shape starting in the negative part. However the clusters 4 and 2 which are correlated with the location of the uppermost part of the Early Triassic formation show curves with the steepest ascending slopes and the most negative sum of negative value. The clusters 7 and 6 are correlated with the transition between the outcropping Early Triassic sediments and the basement and show insignificant IP indicators compared to where Middle and Early Triassic sediments are outcropping in this area. In the same area the clusters in the LM data represent transient curves that all have the same pattern where Early and Middle Triassic sediments outcrop. However, the maximum decaying slope and earliest negative values reached are correlated with areas where the upper Lower Triassic and lower Middle Triassic sediments are outcropping. These elements indicate that the IP effects are correlated with lithological units in the upper part of Early Triassic sediments and lower Middle Triassic sediments that have been described to host base-metal sulphides (Harpøth *et al.*, 1986).

Figure 76: IP indicators plotted with their respective cluster's colour defined from the SOM analysis of the HM TEM data (see Figure 74 for the clusters colour symbols). They are plotted over the simplified geology of the study area. The dark line represents the coverage of the SkyTEM survey and the blue and pink rectangles locate the Figures 76b, and c on which only clusters associated with strong IP effects are displayed. The rectangle on Figure 76b locates the data that are inverted in Figure 77

10.4 Inversion for Cole-Cole parameters

To further characterize the possible sources of IP that affect the airborne TEM data we inverted them using AarhusInv to recover their spectral content in terms of resistivity and of Cole-Cole parameters (Pelton *et al.*, 1978). We present results from inversion of a subset of a flight line (see location on Figure 76b) with strong IP effects. The conceptual model used for the inversion presented here contains four layers. The noise ascribed to the data is defined as a linear function with slope -0.5 in a logarithmic presentation of data as function of gate centre time. The noise level at 1 ms is defined as $2.5 \cdot 10^{-12}$ T/s. An error of 3 % is furthermore applied in the noise characterisation. The data entering the inversion are normalised by peak dipole moment and receiver area.

Figure 77: Model obtained from inversion of data from Line 104 801 (data are shown in Figure 78)

Figure 77 shows the model and Figure 78 shows the corresponding measured data and model response. The general trend of the measured data is reproduced by the model responses. The highest chargeability values of 900 mV/V are confined to the first 150 m in the central part of the section. It is correlated with high frequency constant c values (0.4–0.6) and resistivities are relatively low (300 Ω m). As IP effects due to permafrost would influence the entire area and also show high resistivity values, we reject this possibility for this case. However, at this stage of the modelling it is difficult to discriminate other possible sources of IP effects; i.e. discriminate between the presence of clays or disseminated sulphides.

Figure 78: Measured HM data and model responses for the model in Figure 77. Measured data are shown by coloured circles and model responses are shown by corresponding solid lines

10.5 Conclusion

The SOM analysis of the IP indicators extracted from the transient curves of LM and HM data is a very easy way to visualize the spatial distribution of the IP effects characteristics. Several areas affected by IP effects were described in terms of spatial distribution allowing correlations with the geology. We exclude permafrost as source of the IP effect. The inversion of the TEM data for the Cole-Cole parameters for a selected area was not conclusive with respect to the actual cause of the observed strong IP effect. The inversion however allowed to spatially define the IP source bodies. To complete the study, we will model the complex resistivity measurements from the drill-core samples of this area in order to recover the Cole-Cole parameters and compare them to the modelled IP parameters in the airborne TEM data.

11. Geometry and kinematics of the Triassic rift in Jameson Land

The Triassic rift along the East Greenland margin described in this paper is represented by NE-SW trending basin and highs segmented by NW-SE trending transfer zones. Coarse grained sediments along the eastern side of Jameson Land are shown to be hosted in half-graben structures belonging to the Carlsberg Fjord Basin that is bounded by NW-dipping normal faults mapped and described after fieldwork in the Klitdal area in Liverpool Land. New aeromagnetic and electromagnetic data together with new drill cores allowed the re-interpretation of available seismic lines showing the continuation of the Triassic rift basin toward the SW where it is buried under the Upper Triassic post-rift sediments and the Jurassic sequences of the Jameson Land Basin. The N-S trending Liverpool Land, thought to be the boundary block of the Triassic basin, is shown to be a structural high inherited from the Upper Carboniferous tectonics down-faulted during the Triassic rifting. The Carlsberg Fjord Basin and the Klitdal Fault System described in this chapter should be seen as analogue to the Helgeland Basin in the Norwegian off-shore that is bounded by the Ylvingen Fault Zone and to the Papa and West of Shetlands Basins that are bounded by the Spine Fault (Doré *et al.* 1999). The Triassic rift zone on both conjugate margins shows a straightforward correlation with the trend of the main normal faults and fracture zones of the North-East Atlantic rift and the initial spreading line, suggesting a legacy of the Triassic rifting.

11.1 Introduction

The Jameson Land in central East Greenland hosts Palaeozoic to Mesozoic sedimentary sequences bounded by the N-S trending Liverpool Land to the East and the Stauning Alper to the West (Fig. 79). During Triassic time East Greenland was affected by a major phase of basin margin uplift and rapid fault-controlled basin subsidence leading to the sedimentation of coarse-grained red alluvial fan sequences (Clemmensen 1980). The coarse-grained sequence passes laterally into sandy floodplain deposits with longitudinal drainage towards the north. Aeolian dune sands continued to be deposited in the western part while variegated gypsiferous sandstone-mudstone cycles characterized

the eastern part (Surlyk 1990). Fault activity documented during the Early Triassic was associated with incised submarine canyons described in the Wordie Creek Formation at Wegener Halvø (Seidler 2000; Seidler *et al.* 2004) (Fig. 79).

This section presents new geological and structural data that together with new aeromagnetic, electro- magnetic and drill-core data allowed to re-interpret 2D-seismic lines defining the architecture of the Triassic rift zone and the geometry of the NE-SW-trending boundary faults cross-cutting the N-S trending Liverpool Land, a structural feature inherited from the Late Carboniferous tectonics.

Figure 79: Geological map of the East Greenland margin (modified after Escher and Pulvertaft 1995; Guarnieri 2015). The location of two interpreted seismic lines (1988-19D and 1988-04D) and geologic cross-sections are indicated with red lines

11.2 Permo-Triassic evolution of the East Greenland margin

According to Vischer (1943) and Haller (1971) the continental margin of central East Greenland was strongly faulted along N-S trending tectonic lineaments in post-Devonian time. During the Upper Carboniferous coarse clastic sediments were accumulated along N-S trending W-ward tilted half-graben structures (Stemmerik *et al.* 1991). In the Upper Permian, shallow marine conditions were established after a long period of peneplanation. The Foldvik Creek Group reached a maximum thickness of about 200 m and is represented by the Huledal Formation consisting of poorly sorted, immature fluvial conglomerate beds and sandstones, resting unconformably on the Mid-Permian unconformity, followed by carbonate and gypsum deposits of the Karstryggen Fm. (Stemmerik *et al.* 1997). The Ravnefjeld Formation follows upward and is represented by black, bituminous laminated mudstones laterally equivalent and interfingered with reef carbonates of the Wegener Halvø Formation.

The Permian-Triassic boundary in East Greenland is reported to be both, unconformable and conformable. Variable and largely unknown amounts of the Upper Permian succession were eroded prior to the Griesbachian transgression (Stemmerik *et al.*, 1997). Numerous Lower Triassic incised submarine canyons were eroded down into the Upper Permian succession giving rise to the reworked Permian sediments occurring high up in the Triassic succession (Birkenmajer, 1977, Seidler, 2000, Wignall and Twitchett, 2002).

The deeper part of the basins experienced a continuous marine sedimentation, as no hiatus between the Permian and the Triassic is observed (Piasecki, 1984). The thickness of the Wordie Creek Formation varies from c. 270 m in the marginal parts of the basin to 750 m basin ward (Seidler, 2000). The thickness variation depends on location in the sub-basins relative to syn-sedimentary faults (Seidler, 2000). In East Greenland, the boundary between the marine Wordie Creek Formation and the succeeding, 700 m-thick, continental Pingo Dal Formation is marked by a major unconformity (Perch-Nielsen *et al.*, 1974; Clemmensen, 1980b; Seidler, 2000). The new paleontological work by Andrews *et al.* (2014) has significantly improved dating constraints and allowed revision of the stratigraphy. The lithostratigraphic scheme erected by Clemmensen (1980b) is broadly followed here. The Mid- to Late Triassic succession of East Greenland consists of the coarse, predominantly alluvial, clastic deposits of the Pingo Dal Formation, which are overlain by the lacustrine, and subordinate fluvial, mudstones and sandstones of the Gipsdalen and Fleming Fjord formations.

The Pingo Dal Formation with the coarse-grained alluvial fan successions of the Klitdal Member and the Paradigma Bjerg Member was deposited along the marginal fault zones. They pass from both sides of the graben, into the sandy floodplain deposits

(Rodstaken Mb) with longitudinal drainage towards the north (Perch-Nielsen *et al.*, 1974; Clemmensen, 1980b; Surlyk, 1990). The thick Middle Triassic succession indicates high rates of accumulation compared to that of the Upper Permian, supporting the creation of accommodation space by Early Triassic tectonic activity.

The Gipsdalen Formation is characterised by aeolian, fluvial and lacustrine sediments and has a maximum thickness of 350 m (Clemmensen, 1980b), indicating lower accumulation or/and accommodation rates. The marine mudstones of the Gråklint Beds (up to 35 m thick) on the East Greenland (Clemmensen, 1980b) are now dated to the Carnian (Andrews *et al.* 2014). The Kap Seaforth Member is characterised by gypsum-bearing sandstone and mudstone deposited in continental sabkha environment with periodic aeolian influence (Clemmensen, 1978b).

The Fleming Fjord Formation is represented by the lacustrine dolomitic mudstone of the Edderfugledal Members (30 to 70 m) (Clemmensen *et al.*, 1978b) followed by the Malmros Klint Member, composed of cyclically bedded, intra-formational conglomerates, red siltstones and fine-grained sandstones and disrupted dolomitic sediments (palaeosols) (Clemmensen *et al.*, 1978b). The upper part is typified by an upward-increasing dominance of fluvial sediments of the Ørsted Dal Member. The thicknesses of the Malmros Klint and the Ørsted Dal Members vary between 50 to 150 m and 125 to 200 m, respectively (Clemmensen *et al.*, 1978b).

The sedimentary succession continues with the Late Triassic-Early Jurassic Kap Stewart Group through all the Jurassic until the Early Cretaceous (Surlyk 1990).

Figure 8o: a) Geological map of the Klitdal area (see location in Fig. 79); b) Stereoplots showing the kinematics of major faults and the paleostress reconstructed from inversion of fault-slip data (lower hemisphere); c) Geologic cross-section of the Trefjord Bjerg-Klitdal transect

11.3 Triassic rift-related faults in the Klitdal area

The eastern margin of the Jameson Land Basin is represented by the N-S elongated Liverpool Land high that is characterized by Caledonian basement rocks and sporadic Palaeozoic sediments. The Klitdal area is located at the boundary between the basin and the structural high (Fig. 79). In this locality the pink conglomerate- sandstone association of the Klitdal Member (Pingo Dal Fm) lies on a flat peneplain surface on top of basement rocks of the Liverpool Land (Fig. 80a). In this area a prominent NE-SW trending escarpment, more than 600 m high, cuts obliquely Liverpool Land (Figs 80a and 81a) and corresponds to what is here named the Klitdal Fault. Due to erosion of the footwall, the scarp is retreated with respect to the fault contact and the morphological feature represents the fault-line escarpment. Toward the tectonic contact between basement rocks and the conglomerates of the Klitdal member the dip of the bedding increases up to 8–10 degrees, suggesting a gentle SE-ward tilting due to block rotation (Fig. 81b). Other fault escarpments mapped to the south belong to the Regolitplateau Fault (Figs 80a and 81c). In the latter locality kinematic indicators as slickensides, found along the fault planes show dip-slip movement (Fig. 81d). The inversion of fault-slip data collected along major faults allowed to calculate a reduced stress tensor (Zâlohar and Vrabec 2007) showing a NW-SE extension that is associated with the NE-SW trending fault system (Fig. 80a). The boundary faults are offset by orthogonal faults with a strike-slip component as measured in the Inderfjord Faults (Fig. 80a) and along similar faults to the south of the Regolitplateau Fault (Fig. 80a). The NW-SE to WSW-ENE trending fault sets are interpreted as transfer faults accommodating the differential movement associated with NW-SE extension.

The partially preserved and mapped peneplain in Liverpool Land (Figs 80a and 81a) represents a marker horizon that is used to roughly estimate the vertical offset of the faults that, along the Klitdal Fault results in more than 600 m (Fig. 80b). The NW-SE oriented geologic cross-section represented in Figure 80c shows the geometry of the SE-ward tilted Klitdal block and the thick succession of the Pingo Dal Fm filling in the basin structure that is here named the Carlsberg Fjord Basin. The Late Triassic sequence of the Gipsdalen and Fleming Fjord Formations seem not to be affected by faulting.

Figure 81: a) Panoramic view toward SE of the Klitdal Fault escarpment separating the Klitdal area (foreground) from the Liverpool Land (background). The gently SW-ward dipping flat top of Liverpool Land corresponds to the Permian peneplain. The estimated vertical offset across the fault is more than 600 m; b) Pink colored coarse-grained conglomerate and sandstones of the Klitdal member. The dip angle increases toward the tectonic contact with the Klitdal Fault indicating a slightly block tilting due to the fault activity; c) a fault escarpment belonging to the NNE-SSW trending Regolitplateau Fault; d) slickensides along a fault plane of the Regolitplateau Fault showing dip-slip movement

11.4 Airborne magnetic, electromagnetic data and core-drilling

During 2013 a combined airborne magnetic and time-domain electromagnetic survey was performed by SkyTEM Aps along the eastern margin of the Jameson Land Basin in the Klitdal area (Skytem Surveys ApS, 2013). A total of 2,325 line km were flown at a nominal terrain clearance of ca. 30 m with 300 m line spacing and E-W oriented traverse lines.

The magnetic data were reprocessed and the residual magnetic intensity is shown on Figure 82 together with mapped and interpreted geological structures. A clear NE-SW trend separates two main magnetic domains with negative anomalies and low magnetic relief to the North while to the South it shows positive anomalies and important magnetic texture (Brethes *et al.*, 2015). This positive and textured signal is also visible along the foot-wall block of the Klitdal Fault where the crystalline basement outcrops.

The electromagnetic data processed and inverted by SkyTEM Aps, offer a large depth of investigation down to 500 m. Figure 83 presents a geological interpretation of three selected model sections (located on Figure 82) resulting from the inversion and showing the mean conductivity in depth intervals. These N-S and W-E oriented conductivity sections cross the trends separating the distinct magnetic signals. The outcropping crystalline basement of Liverpool Land is clearly associated with the resistive parts to the East and South of these cross-sections. The transition to more conductive material to the West and North is relatively sharp and coincides with the boundary between positive and negative anomalies in the magnetic data. The western part of the section 106701 (Fig. 83) appearing to be resistive should not be considered as it is biased by the presence of induced polarization effects in the data (Brethes *et al.*, 2016).

During the summer 2014, eight holes were drilled in the area in order to investigate for base-metals (Fig. 82). The drill-holes CC-1, CC-2 and CC-3, located south of the NE-SW fault trend (Fig. 82) went through mudstones and arkoses respectively belonging to the Gipsdalen Fm and Klitdal member (Fig. 81), before reaching a relatively shallow crystalline basement at depths between 54 and 158 m. Contrastingly, all the drill-holes located north of this trend revealed the presence of a thick sequence of conglomerates. Indeed, the drill-hole IF-2 reached the basement at a depth of 370 m and the drill-hole IC-1 went through 500 m of conglomerates without reaching the basement.

Likewise the magnetic and electromagnetic data, the occurrence of a thick conglomeratic sequence on top of a relatively deep crystalline basement in the northern part of the area, suggests the presence of NE-SW and NNE-SSW oriented deep-seated normal faults down-faulting the north-western part of the area. The conglomerates found north and west of this faults system represent the syn-tectonic deposits that were sealed by younger sedimentary formations in the central part of the Klitdal area as no evidence of faulting across the Gipsdalen and the Fleming Fjord Formations is visible at the surface.

Figure 82: Shaded relief of the residual magnetic field intensity and the interpreted faults in Klitdal area. Yellow circle-drill-hole collar; white dashed line-conductivity section of Figure 83

Figure 83: Interpreted model sections from the SkyTEM survey showing the conductivity in logarithmic scale (see location in Figure 82). The white shading marks areas where the conductivity is undetermined due to a limited depth of investigation at the soundings location (SkyTEM ApS, 2013). Drill-holes and projected drill-holes are shown in the sections. Note the faults in the eastern part between the basement and the sediments that well correlate with the magnetic interpretation as well as the 512 m deep drill-hole IC-01 confirming the presence of thick sedimentary sequence belonging to the Carlsberg Fjord Basin

11.5 2D Seismic data

A seismic data grid was collected during 1986 and 1989 on Jameson Land by Atlantic Richfield Company (ARCO) resulting in approximately 1800 line km crossing the Jurassic basin in central East Greenland. Some transects were collected using dynamite as a source, while others were gathered based on a vibro-source. The data were analyzed in the early 1990 in the context of understanding the basin development (Marcussen and Larsen, 1991) within the license area. Although the seismic data was generally of good quality the presence of sill intrusions presented a problem in maintaining a good signal response at depths greater than 1–2 s TWT, and consequently weakening the recognition of basin boundary faults, strata configurations and unconformities.

Figure 84: Un-migrated seismic lines 1988-04D and 1988-19D of the ARCO dataset together with the geologic cross-sections of the Carlsberg Fjord Basin compiled from geologic data along the eastern border and the approximate depth-migration of the line drawing of the two seismic lines. The intersection of the two seismic lines allowed to define the strike of the main fault and to correlate it the border fault investigated along the Klitdal outcrops indicated also by magnetic data (Fig. 83). The syn-rift package correspond to the conglomerates and sandstones of Klitdal member. The base of the Fleming Fjord Fm is tied up with outcrop data and the compression at the tip of the boundary fault suggests a slight inversion. Ha-Harelv Fm, Fo-Fossil Bjerg Fm, Pe-Pelion Fm, Sh-Sortehat Fm, Nk-Neill Klinter Group, Ks-Kap Stewart Group, FF-Fleming Fjord Fm, Gi-Gipsdalen Fm, Pi-Pingodal Fm (Klitdal member). The basement in Liverpool Land is composed by Caledonian metamorphic rocks and sporadic Devonian sediments. In yellow colors are indicated possible magmatic sills

Figure 84 shows two unmigrated seismic lines from the ARCO dataset located in Figure 79. Some of the westward dipping discordant/concordant reflectors correspond to magmatic sills that are also present in the outcrop along the eastern side of the basin. The two seismic lines intersect each other allowing to estimate the NE-SW orientation of the border fault. The interpreted faults correspond to the SW-ward continuation of the Klitdal Fault System described previously (Figs 80, 82 and 83) and exhibit a rotated fault- block geometry typical of half-graben structures. A slight inversion of the border fault seems to be responsible for the gentle fold at the tip of the fault. The syn-sedimentary wedge filling the tilted block well visible on both seismic lines, corresponds to the Lower-Middle Triassic Klitdal member of whom conglomerates were drilled during

the field campaign in 2014 (Figs 82 and 83). The same structures were previously interpreted as N-S trending normal faults related to Devonian-Carboniferous rifting by Larsen and Marcussen (1992).

Using the available geological data along the eastern margin of the basin and the approximate depth- converted line-drawing of the previous seismic lines two geologic cross-sections are presented in Figure 84 to show the geometry of the NE-SW trending Triassic Rift separating the Hurry Inlet Block to the East from the Carlsberg Fjord Basin to the West. The outcrop geology and the drill-core data suggest that the Gipsdalen Fm post-dates the rift activity since it is not involved in the faulting.

11.6 The Triassic rift along the East Greenland, Norwegian and West of Shetlands margins

Marine rifting during the Early Triassic was described by Seidler *et al.* (2004) who distinguished two Early Triassic rift events in East Greenland in the Early Griesbachian and the Late Griesbachian, respectively, based on ammonoid data and radiometric dating. The first, Early Griesbachian rift event in East Greenland was confined mainly to reactivation of major Upper Carboniferous basin-margin faults and resulted in deepening of the basins and influx of coarse-grained turbidites. The subsequent Late Griesbachian rift event involved faulting along splays of the basin-margin faults, causing fragmentation of the original wide blocks and intrabasinal fault-block rotation. Marine deposition was followed by alluvial progradation marking the onset of continental deposition, which dominated the rest of the Triassic in the region. The study area corresponds to the eastern margin of the basin where the fluvial conglomerate of the Klitdal member of the Pingodal Fm lies directly on a peneplained surface onto the Caledonian basement rocks. To the North, in Wegener Halvø, the Pingodal Fm unconformably lies on the Wordie Creek Fm (Seidler *et al.* 2004). Considering the geometry of the fault plane and the tilting of the sediments in the Klitdal structure (Figs 80 and 84) the estimated thickness of the syn-rift sediments is at least 800 m. In the seismic lines (Fig. 84) that extend toward the basinal area, the amount of Early Triassic sediments accumulated in the wedge-shaped basin seems to be more than 2000 m. To the North the Triassic Basin in Traill Ø is bounded by the NE-SW trending Rod Bjerg Fault (Seidler *et al.* 2004) and in the Hold With Hope area, similar trends are described like the Kap Stosch and Immakradal Faults (Ofstedal *et al.* 2005). Moreover, the Kong Oscar Fjord and the Godthåb Golf to the north were probably still active during the Triassic rifting phase (Surlyk 1990), as transfer faults, similarly to the strike-slip Inderfjord Faults locally described in the Klitdal area (Fig. 80a).

Along the Norwegian margin, in the internal part of the Trøndelag Platform, after the main tectonic episode took place in the Carboniferous to Late Permian time, major faults were active through much of Triassic time, giving rise to several NE-SW trending basins filled with Triassic and Upper Palaeozoic sediments as the Froan and the Helgeland Basins (Fig. 85) (Brekke, 2000). A 750 m thick, fully marine succession of sandstones, coarse grained turbidites, shales, and reworked sabkha sediments has been cored on the eastern margin of the mid-Norwegian shelf in the Trøndelag Platform (Fig. 85). The succession dated as Upper Permian–Lower Triassic is preserved in the NE-SW trending SE-ward tilted wedge-shaped Helgeland Basin (Bugge *et al.* 2002) showing that in the Norwegian offshore the Triassic rift zone is bounded by NE-SW oriented major faults as the Ylvingen Fault Zone (Brekke 2000).

In the West of Shetlands area very thick sequence, up to 7500 m, of Permo-Triassic sediments is preserved within the Papa and East Solan Basins (Fig. 85). The Triassic basin fill, referred to the Papa Group, has been proven by drilling to be at least 2400 m thick (Swiecicki *et al.* 1995). The oldest part is represented by the Otter Bank Shale Formation (earliest Triassic) deposited in a coastal/alluvial plain setting. This is gradationally succeeded by the coarse-grained Otter Bank Sandstone Formation comprising sediments derived from the interdigitation of sheetflood, braidplain and aeolian environments of deposition. These are interpreted as the initial erosional products derived from the uplifted, rifted basin margin (Swiecicki *et al.* 1995). This major phase of Early Triassic rifting is believed to have taken place during the Scythian. The succeeding Foula Sandstone Formation marks the establishment of predominantly axial braidplain systems, deposited during a period of intermittent but waning tectonic influence during Middle to Late Triassic times. The active margin of this Triassic basin lay along the NE-SW trending West Shetland Spine Fault that is a major fault probably linked with the Møre-Trøndelag Fault System to the north (Fig. 85).

The inheritance of basement structural grain is widely considered to be an important factor in the structural development of the northwest European Atlantic margin that, is somehow considered to follow the old Caledonian suture line (Coward, 1990; Doré *et al.* 1999). The lineament analysis of the Atlantic margin shows a predominance of NE-SW, N-S and NW-SE trends reflecting Mesozoic-Cenozoic extensional faulting (Doré *et al.* 1999). The new data from East Greenland together with recently published data from the mid-Norwegian shelf (Bugge *et al.* 2002) allow the construction of a map showing the structural setting and major trends of the Early Triassic rift basins in the northernmost part of the North Atlantic region on both Greenland and European margins (Fig. 85). The overlay of such structures within a plate tectonic reconstruction at the time of break-up of the North-East Atlantic Ocean highlights how the initial line of spreading and the Early Eocene rift zone together with the orientation of major fault

trends and fracture zones have a straightforward relation with the Triassic faults, suggesting a legacy of the Triassic rifting (Fig. 85).

Figure 85: Plate reconstruction of the North-East Atlantic rift at the break-up time showing major features related to the Tertiary development of the area together with the distribution and trends of the main Triassic rift zone in East Greenland, Norwegian offshore and the West of Shetlands (modified after Mosar *et al.*, 2002). CFB-Carlsberg Fjord Basin, FB-Froan Basin, FI-Faroe Islands, GS-Golf Sund, HB-Helgeland Basin, HI-Hurry Inlet, JMFZ-Jan Mayen Fracture Zone, JMMC-Jan Mayen Micro-Continent, KL-Klittedal, KOF-Kong Oscar Fjord, KS-Kap Stosch, LO-Lofoten, ML-Milne Land, MMH-Møre Marginal High, MTF-Møre-Trøndelag Fault Zone, PB-Papa Basin, SA-Stauning Alper, SH-Shannon, SI-Shetland Islands, SS-Scoresby Sund, TP-Trøndelag Platform, TØ-Traill Ø, VK-Viking Graben, VMH-Vøring Marginal High, WSB-West Shetlands Basin, YØ-Ymer Ø

11.7 Conclusion

The present section describes the geometry and the kinematics of the Triassic rifting and the development of the Carlsberg Fjord Basin representing the main tectonic event during the Mesozoic in central East Greenland, followed by Late Triassic post-rift sequences and the Jurassic-Cretaceous Jameson Land Basin succession. The Triassic extensional event is responsible for the structuring of the Carlsberg Fjord Basin with half-graben structures bounded toward the SE by the NE-SW trending Klitdal Fault System and by similar structures toward the north in Mesters Vig and Traill Ø (Seidler *et al.* 2004) at Kap Stosch-Hold With Hope (Müller *et al.*, 2005). NW-SE trending structures, oblique to the boundary faults and a strike-slip component are interpreted as transfer faults within the rift zone. Moreover, some major fjords with the NW-SE orientation as the Kong Oscar Fjord, Scoresby Sund and to the North in Godthåb Golf could represent fault trends activated as transfer faults during the Triassic rifting and reactivated as fracture zones during the Tertiary opening of the North Atlantic. Finally, the N-S trending Liverpool Land is a basement high inherited from the Late Carboniferous rifting and segmented during the Triassic rifting by the NE-SW trending normal faults separating the Hurry Inlet block from the Carlsberg Fjord Basin.

12. Clay alteration analysis from Early Triassic rock samples

Arkoses, sandstones and conglomerates from the Early-Middle Triassic Klitdal member of the Pingodal Fm in Klitdal area (Fig. 86) were described by geologists from Avannaa to be unusually altered into clays. Clay minerals can originate from the contact of pre-existing rocks with water, air or steam and can therefore form under different geological environments such as erosion and sedimentation, burial diagenesis, weathering, and hydrothermal alteration (Velde, 1995). They occur with different mineral structures defining several clay groups and can evolve from one to another depending on their environmental conditions. The mineral composition and the crystal structure of clay minerals are indicators of the range of temperature, chemistry of fluids, fluid/rock ratio or redox conditions prevailing at the time of their growth (Beaufort *et al.*, 2005). Obtaining such information is very useful regarding mineral exploration as these environmental conditions are key parameters to find favourable environment for mineralization, particularly in the case of hydrothermal alteration.

During the field season 2014, six outcrop samples of the altered arkoses, sandstones and conglomerates from the Klitdal member were collected in the northern part of Klitdal area (Figs 86 and 87) to define their clay content in order to discriminate whether they are from diagenetic, weathering or hydrothermal origin. The six bulk samples were analysed using powder X-Ray Diffraction (XRD) at the Geocenter of Copenhagen. Furthermore, freshly fractured rock fragments of the samples were studied with the Scanning Electron Microscope (SEM) at GEUS, with complementary Energy-Dispersive X-ray spectroscopy (EDX) measurements to investigate the shape and the chemistry of the minerals.

X-Ray Diffraction measurements indicate the presence of clay minerals in all the samples (Fig. 88). They all contain a combination of chlorite, illite and smectite except the sample 539907 which lacks chlorite. This sample was taken in the uppermost part of the Klitdal member made of arkoses and gypsum. The XRD shows that it is dominated by gypsum and contains a bit of mixed-layers of illite/smectite. Samples 539901 and 539904 were taken in an area where quartzitic boulders containing chalcocite were found along with malachite staining in reduced layers and native Cu and Ag within granitic pebbles of the conglomerates. They were taken one kilometre apart respectively

in reddish oxidized and whitish bleached non-cohesive arkosic sandstones (Fig. 87). They present a similar clay composition with illite, chlorite and a bit of smectite.

Figure 86: Geological map of the Jameson Land Basin (modified after Kokfelt *et al.* 2013). Yellow dots indicate the position of drill holes from the 2014 campaign

Figure 87: Map locating with black dots the six outcrop samples collected during the field season 2014 in the northern part of Klitdal area: 539901, 539903, 539904, 539905, 539906 and 539907. The yellow dots locate the collars of drillholes. The two pictures on the right show typical altered outcrops of arkosic sandstones from Klitdal member in a non-cohesive red oxidized and white bleached matrix

Sample 539903 was collected from a strongly altered conglomerate composed of softened and crumbling granitic pebbles within a greenish matrix. It is the only sample that possibly contains kaolinite but X-Ray diffraction measurements should be performed on the clay fraction of the sample in order to confirm the presence of kaolinite. This sample also contains chlorite in quite substantial amounts, as well as illite and more smectite than the other samples (Fig. 88).

Samples 539905 and 539906 were collected a hundred of meters apart, in proximity of to the crystalline basement. They have a similar clay composition with a very likely presence of mixed-layers of illite-smectite as the smectite peak is broader than usual (Fig. 88). It also contains normal illite (not mixed) and chlorite.

Vermiculite might be present in the samples 539901, 539903 and 539904, but there is no clear suggestion for it from the XRD analyses. The maximum of vermiculite would overlap the first maximum to the left of the chlorite maximum and give it a shoulder on

the left side. This is not seen in the diagram (Fig. 88) but cannot be fully excluded. An XRD analysis of the sample after a specific clay separation and treatment is needed in order to determine the presence of vermiculite with certitude.

Figure 88: Powder X-ray diffraction measurements showing only the clay range from the bulk analysis of the 6 outcrop samples. Instrument: Bruker-AXS diffractometer D8 Advance with Cu source (wavelength =1.54059 Å), primary beam Ge111 monochromator and LynxEye linear PS detector. The measurement was made in reflection Bragg-Brentano geometry, fixed divergence of 0.450, step 0.020 2θ, time per step 4 sec

Figures 89 and 90 show SEM pictures and EDX analyses from samples 539906 and 539903. Analyses of the sample 539906 suggest the presence of chlorite, smectite and K-feldspar. Analyses of sample 539903 also indicate the presence of K-feldspar and smectite but also illite.

Figure 8g: SEM photos of the sample 539906 locating the EDX measurements shown to the right. On the top figures: (2) chlorite, (8, 19, 24) smectite, (7, 19) K-feldspar. On the bottom figure: (1, 7) smectite, (8) K-feldspar. Note the trace of disappeared cubic crystal at the measurement (1) probably corresponding to pyrite

Figure 90: SEM photos of the sample 539906 locating the EDX measurements shown to the right. On the top figure: (6, 15, 19) K-feldspar, (16, 22) smectite, (12,20) illite. On the bottom figure: (3, 16) smectite, (11) K-feldspar

The mineralogy of clays of Upper Permian-Lower Cretaceous mudstones from East Greenland were investigated by Lindgreen and Surlyk (2000) in order to evaluate their provenance, paleoclimate and detect possible volcanic events. Their results are presented in the Figure 91. Clays from Upper-Permian to Lower Triassic mudstones (corresponding to the formation from Karstryggen to Wordie Creek in the Figure 91) are dominated by illite, chlorite, vermiculite, kaolinite and illite-smectite (I-S), whereas the Middle Triassic to Lower Cretaceous mudstones are mostly dominated by kaolinite. Lindgreen and Surlyk conclude that these clays are largely detrital and that the main

source sediment during the time of deposition was Precambrian and Caledonian crystalline basement. Therefore they suggest that the change in the clay mineralogy between Upper-Permian and Middle Triassic is due to a climate-change with an increase in precipitation. Only the mudstones were analysed and therefore no data are presented for the continental formations between Lower and Middle Triassic.

The clay minerals identified in the present study in Lower Triassic arkoses and conglomerates are in accordance with the clay minerals analysed in Upper Permian mudstones from East Greenland by Lindgreen and Surlyk (2000) with the presence of chlorite, illite and smectite. However, the XRD and SEM results presented here do not allow to conclude on the environmental conditions under which the clays were formed. From the bulk samples analyses only, there is no evidence of the presence of clay minerals which could only form under hydrothermal conditions. An analysis of the clay fraction of the samples, with special pre-treatment would be required to study the mineralogy and crystallinity of the clays with more precision. This might help to discriminate whether the clays formed under hydrothermal or weathering conditions.

An interesting work to do in the future would be to study the clay content in the arkoses and conglomerates from the Klitdal member in the drillcores. This would give information on the variation of clay minerals along a stratigraphic profile as well as across faults and may help understanding the weathering or alteration processes affecting the area.

Figure 91: Stratigraphic scheme, tectonic phases and clay mineralogy of the Upper Permian-Lower Cretaceous formations sampled and analysed by Lindgreen and Surlyk (2000). From Lindgreen and Surlyk (2000)

13. Conclusion

The Crusmid-3D project conducted during the last two and a half years treated several thematics using cross-disciplinary methods in order to investigate the crustal structures and mineralization systems in the Jameson Land Basin in central East Greenland. The scientific questions addressed and results obtained are summarized in the following paragraphs.

(1) One study aimed at reprocessing and interpreting all available magnetic data in the Jameson Land area to extract geological features at the surface or at depth in order to outline the regional structures of the basin and delineate the local structures in areas where mineralization is structurally controlled. Some highly positive magnetic anomalies are associated with Tertiary plutonic intrusive complexes, one of which is the Malm Bjerg molybdenum deposit. Several other high magnetic anomalies were identified and could also be associated with shallow plutonic Tertiary intrusions. Many magnetic lineaments were delineated and classified into 4 main orientation trends: N-S, NE-SW, E-W and NW-SE trends. Some of them were correlated with Triassic lamprophyres, tertiary lamprophyres and Tertiary doleritic dykes and sills. Others could be correlated with different fault systems. This allowed to get a better overview of the regional structures of the northern part of the basin but also to find trends that are associated with mineralization such as N-S trending faults in the northernmost part of the Klitdal area.

(2) The second study aimed at developing a new procedure to analyse and synthesize geological information from the magnetic signal decomposition. Various maps enhancing specific geological features, in different directions and at different depths were analysed using a Self-Organizing Maps approach. Magnetic signal patterns were defined by correlating the geological knowledge of the area with a characteristic magnetic signal. This method firstly allows enhancing subtle magnetic features, barely visible on commonly used magnetic signal maps. Discontinuities within magnetic signal patterns within adjacent locations are identified using averaging errors inherent to the data reduction procedure and allowing the identification of faults. Secondly, this approach enables interpreting magnetic data in a more systematic and objective way.

This method was tested in the Mesters Vig area, in the northern part of the Jameson Land Basin, where Pb-Zn vein type mineralization occurs. Dykes were identified and mapped over the entire area and the intensity of their signal compared to the geology allowed defining areas where they are blind and therefore define which part of

the stratigraphic pile is intruded. Faults were mapped and four fault orientation families were characterized, one of which is known to control the vein mineralization.

(3) The third study aimed at constraining the architecture and estimating the thickness of the basin along the eastern margin of the Basin. For this 3D photomapping, field imagery of magnetic and electromagnetic data and structural measurements along with drilling results were integrated to build a 3D-geological and petrophysical model of the area. Investigative 2D-magnetic modelling was performed to constrain the architecture of the basin, and the surface of the magnetic basement was modelled using a 3D geologically constrained inversion of the magnetic data.

The Klitdal area is divided in two main blocks by a NE-SW fault called the Klitdal fault. The southern block has a shallow crystalline basement, peneplained and tilted few degrees to the West and is overlapped by Triassic sediments. The northern block is down-faulted and inversion results suggest that a sedimentary package of more than 2000m is lying on top of the crystalline basement. A very thick sequence of syn-rift coarse Early Triassic sediments might be present offering a good permeability and source of base-metals but the lack of Upper Permian black shales in this area as reducing agent could possibly be the reason for the absence of obvious mineralization in Klitdal area, as opposed to areas further north such as in the Wegener Halvø area.

(4) The fourth study aimed at mapping and understanding the cause of induced polarization (IP) effects that occur in airborne Time Domain EM (TEM) data acquired along the eastern margin of the basin. IP indicators were extracted from the shape of the transient curves at every measurement location and were analysed using a Self-Organizing Map (SOM) procedure. Transient curves patterns were clustered, plotted on a geographical map and correlated with the geology. We identified five areas affected by strong IP effects. Two of them present IP effects at a stratigraphic level known to host copper sulphides at the boundary between the Early Triassic Pingodal formation and the Late Triassic Gipsdalen formation. Magmatic activity is observed in the area and could be an important parameter regarding the presence of IP. Two other areas affected by IP effects occur where the Upper Triassic Fleming fjord formation is outcropping. One of the areas is N-S elongated and the transient curves present symmetric characteristics across the N-S axis. This could be associated with a small graben or intra-basin depression filled with polarizable material, possibly clays. At these localities TEM sections were inverted for the Cole-Cole parameters as the analysis of the resistivity, chargeability, time constant and frequency dependence would help discriminating between possible sources of IP effects such as the presence of sulphides, clays or permafrost. The stage of the inversion procedure does not allow to be conclusive yet but provides a spatial definition of the IP source bodies.

(5) The Triassic rift along the East Greenland margin described in this report is represented by NE-SW trending basin and highs segmented by NW-SE trending transfer zones. Coarse grained sediments along the eastern side of Jameson Land are shown to be hosted in half-graben structures belonging to the Carlsberg Fjord Basin that is bounded by NW-dipping normal faults mapped and described after fieldwork in the Klitdal area in Liverpool Land. New aeromagnetic and electromagnetic data together with new drill cores allowed the re-interpretation of available seismic lines showing the continuation of the Triassic rift basin toward the SW where it is buried under the Upper Triassic post-rift sediments and the Jurassic sequences of the Jameson Land Basin. The N-S trending Liverpool Land, thought to be the boundary block of the Triassic basin, is shown to be a structural high inherited from the Upper Carboniferous tectonics down-faulted during the Triassic rifting. The Carlsberg Fjord Basin and the Klitdal Fault System described in this report should be seen as analogue to the Helgeland Basin in the Norwegian offshore that is bounded by the Ylvingen Fault Zone and to the Papa and West of Shetlands Basins that are bounded by the Spine Fault. The Triassic rift zone on both conjugate margins shows a straightforward correlation with the trend of the main normal faults and fracture zones of the North-East Atlantic rift and the initial spreading line, suggesting a legacy of the Triassic rifting.

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List of publications, abstracts and conference talks

Publications

- Guarnieri, P., Brethes. A., Rasmussen, T.M., Geometry and kinematics of the Triassic Rift in Jameson Land (East Greenland), submitted in November 2016 to Tectonics.
- Brethes, A., PhD thesis "Crustal structure and mineralization systems in Jameson Land, central East Greenland: an integrated analysis of geological, aeromagnetic and electromagnetic data". To submit in April 2016.
- Brethes. A., Guarnieri, P., Rasmussen, T.M., Bauer, T. Analysis of aeromagnetic data in Jameson Land, central East Greenland: crustal structures and mineralization systems. To submit in Geophysical prospecting or Geophysics.
- Brethes. A., Rasmussen, T.M., Guarnieri, P., Bauer, T. Architecture and thickness estimation of the Klitdal Basin using 3D geologically- constrained inversion of aeromagnetic data in Jameson Land, central East Greenland – to submit in Tectonophysics.
- Brethes. A., Rasmussen, T.M., Guarnieri, P., Bauer, T. Mapping Induced Polarization effects in TEM data using Self-Organizing Maps and inversion for their Cole-Cole parameters, Central East Greenland – to submit in Geophysical prospecting or Geophysical interpretation.
- Brethes. A., Rasmussen, T.M., Guarnieri, P., Bauer, T. Synthetizing magnetic signal decomposition images using Self-Organizing Maps for geological interpretation – Case study over the Pb-Zn Blyklippen mine, Mesters Vig, central East Greenland – to submit in Interpretation.

Abstracts

- Brethes, A., Rasmussen, T.M., Guarnieri, P., Bauer, T. (2015, August). 3D modelling of the base-metal mineralized Jameson Land Basin (central East Greenland) using geologically constrained inversion of magnetic data. Paper presented at the international conference Saying goodbye to a 2D Earth, Margaret River, Western Australia.
- Brethes, A., Rasmussen, T.M., Guarnieri, P., Bauer, T., (2016, June). Mapping and characterization of Induced Polarization in airborne TEM data from central East Greenland – application of a Self-Organizing Map procedure. IP2016 – 4th International Conference on Induced Polarization, Aarhus, Denmark.
- Brethes, A., Guarnieri, P., Rasmussen, T.M., Bauer, T. (2016, September). Geological Analysis of Aeromagnetic Data over the Blyklippen lead-zinc mine at Mesters Vig, central East Greenland. EAGE Near surface Geoscience 2016, First conference on Geophysics for Mineral Exploration and Mining, Barcelona, Spain.
- Guarnieri, P., Brethes, A., Rasmussen, T. M., Bauer, T., Blischke, A., Erlendsson, Ö. (2016, November). Crustal Structure and Mineral Deposit Systems in central East Greenland (NordMin CRUSMID-3D). Presented at the Nordmin Nordic 3D geological modelling workshop – Trondheim, Norway.

NordMin workshops

- Guarnieri, P., Brethes, A., Rasmussen, T. M., Bauer, T., Blischke, A., Erlendsson, Ö. (2016). CRUSMID-3D. NordMin Workshop “How to go further in Nordic collaboration in the mining research and education” October 19, 2016 Helsinki, Finland.
- Guarnieri, P. and Brethes, A. (2015) From 3D-Photomapping to 3D-modelling. Nordmin workshop, March 21-25, 2015 Reykjavik, Iceland.

Sammenfatning

Geologiske undersøgelser i Jameson Land bassinet i det centrale Østgrønland begyndte sent i det nittende århundrede. Efterfølgende er prospektering gennemført af olie- og mineselskaber samt af offentlige myndigheder, f.eks. Grønlands Geologiske Undersøgelse (GGU).

Relativt nye undersøgelser samt opfølgning foretaget af mineralefterforskningsselskaber førte til en ansøgning om efterforskningslicens i Jameson Land med basismetaller i sedimenter som det primære mål. Detaljerede magnetiske gradientmålinger foretaget fra fly af det geofysiske konsulentfirma Fugro Airborne Surveys samt en kombineret tidsdomæne- og magnetisk undersøgelse foretaget af SkyTEM ApS blev gennemført i 2013. Samarbejde mellem efterforskningsselskabet Avannaa Resources og De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS) har indgået som end del af CRUSMID-3D projektet, som er finansieret af Nordmin-programmet. GEUS har været koordinator for projektet og har bidraget med strukturgeologisk feltarbejde, og i samarbejde med Luleå Tekniske Universitet i Sverige foretaget tolkning af magnetiske og elektromagnetiske data. GEUS har desuden i samarbejde med Iceland GeoSurvey (ISOR) foretaget tolkning af 2D-seismiske linjer.

Et boreprogram blev gennemført ved den østre afgrænsning af Jameson Land bassinet i sommeren 2014. Boringerne gav værdifuld information om bassinets opbygning, dog uden påvisning af mineralisering. Efterforskningsaktiviteterne afsluttedes i 2014, men en række uafklarede videnskabelige problemstillinger har efterfølgende været genstand for forskningsarbejdet i Crusmid-3D projektet. Længs med den østlige margin af Jameson Land bassinet er bly, zink og kobbermineraliseringer observeret i flere stratigrafiske horisonter i sedimenter fra Øvre Perm og Trias. En forståelse af bassinopbygningen og dannelsen af bassinet er derfor meget værdifuld for fremtidig efterforskning i området.

Tredimensional (3D) fotogrammetisk analyse af detaljerede flybilleder og skråfoto sammenholdt med strukturgeologiske tolkninger og information fra borer har indgået i en 3D-geologisk model. En 3D datainversion af flybårne magnetiske data er gennemført med henblik på at forbedre bestemmelsen af dybder til den krystalline undergrund. Den integrerede tolkning af data resulterede i en model af det triasiske Carlsberg Fjord bassin og dets forkastningsrelaterede strukturer. Den østlige del af

bassinet er opbygget af tre nedforkastede blokke, som er separeret af nordøst-sydvest samt nordnordøst-sydsydvest orienterede normalforkastninger. Den sydlige del af bassinet er karakteriseret af krystalin undergrund nær overfladen, som er pålejret af relativt tynde lag fra Trias. Den nordlige del af bassinet er karakteriseret af tykke nedre og mellem triasiske sedimentære lag bestående af konklomerat og arkose dannet i forbindelse med opsprækningen af området. Inversion af magnetiske data indikerer, at den sedimentære sekvens kan være mere end 2000 m tyk i den nordlige del af bassinet og med en mulig tilstedeværelse af sedimenter dannet før Trias.

Induceret polarisations (IP) fænomener er observeret i de flybårne tids-domæne-målinger. For at karakterisere og forstå de mulige årsager til disse fænomener, er der foretaget databearbejdning hvor IP-indikatorer er fremkommet ved analyse af de transiente henfaldskurver fra hver måling. Disse IP-indikatorer er derefter analyseret ved hjælp af en neural netværksalgoritme, som omtales som en "Self-Organizing Map" procedure. Seks områder med veldefinerede IP-effekter blev identificeret. I den centrale del af området kan IP korreleres med blotninger tæt ved grænsen mellem tidlig og mellem triasiske sedimenter. I den nordvestlige del findes IP-effekter langs med nord-sydgående strækninger, men her uden korrelation til blotninger. Forskning pågår stadig omkring inversion af de flybårne tiddomæne-målinger for at bestemme Cole-Cole-parametre og dermed tolke kilden til de observerede IP-effekter. Resistiviteter og kapacitive egenskaber fremkommet ved inversion vil bidrage til at skelne mulige sulfidkilder fra kilder knyttet til permafrost og lerindhold.

Integration samt præsentation af resultaterne fra dette multi-disciplinære projekt i en fælles 3D-model er afgørende for at definere bassinets arkitektur, variationen af petrofysiske egenskaber og dermed forståelsen af, hvordan disse forhold er bestemmende for mineraliseringssystemerne i området.

Appendix

Societal implications of the project CRUSMID-3D

Assessment of the societal implications of the CRUSMID-3D project must be based on a long term evaluation of the specific results published during the project as well as publications expected shortly as a result of the project. A more direct result will be the completion of the PhD by Anaïs Brethes that is expected 2017, but again the societal impact of this must be viewed in a longer time perspective.

Importance of the project results to the Nordic region

The project has initiated important cooperation between the involved partners in the project, which is expected to be continued after the completion of the project. Results and experiences obtained during the project can be utilized in future projects. In particular, we recognize the importance of building and consolidating a Nordic research infrastructure.

Importance of the project for the sustainable raw materials sector

We emphasize the education component involved in this particular project. The necessity of providing education at a high international level is a prerequisite for the raw material sector to develop competitive and cost effective exploration methods. During this project, new exploration tools have been developed that are expected to be useful in planning and executing future exploration campaigns in similar but also other geological environments.

The importance of this projects in terms of building a sustainable raw material sector can be summarized with reference to Duke (2010) who states that "Mineral exploration and development differ from most other economic activities in three important respects: the location is constrained by geology; the long duration means that the time cost of exploration greatly exceeds the nominal cost; and the high risk means that com-

panies must spend several times the average discovery cost to have a reasonable probability of success. Government geoscience mitigates each of these challenges. First, it attracts exploration investment by allowing industry to identify areas of favourable mineral potential. Second, public geoscience increases exploration efficiency by making it unnecessary for individual companies to duplicate common information or to spend money on non-prospective ground. Third, it increases exploration effectiveness by providing key information inputs to risk-based decision-making. By reducing exploration costs and risk, public geoscience not only improves returns on private investment but also increases revenues accruing to governments as royalties and taxes.”

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CRUSMID-3D

Providing research and education at a high international level is a prerequisite for the raw material sector to develop competitive and cost effective exploration methods. The NordMin project CRUSDMID-3D is a consortium between research institutes, academia and SME supporting a PhD project to study some of the geological processes in Greenland that are related to ore deposits, to understand the relationships between structures and mineralization. The new geological and structural data together with aeromagnetic/electromagnetic surveys and the drill-core data added new values to the regional knowledge of East Greenland. The exploration tools developed within the PhD-project are expected to be useful in planning and executing future exploration campaigns in similar but also other geological environments.

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