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FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF GEOLOGY

Permian depositional and environmental development in Svalbard

Anna M. Dustira

A dissertation for the degree of Philosophiae Doctor
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Preface

This doctoral thesis is the result of research carried out from 2009–2013. The doctoral studies were funded for a four-year period by the University of Tromsø; three years of funding for research, and a fourth year for teaching and other duties at the Department of Geology. The majority of work was carried out at the University of Tromsø and the Norwegian Polar Institute. The Norwegian Polar Institute funded fieldwork on Svalbard during summer 2009, and provided additional materials, samples and data integral to the doctoral research.

First and foremost, I´d like to thank my supervisors Dierk Blomeier and Kåre Kullerud for all they have done. Dierk has been a pillar of support, a source of both motivation and inspiration, and a major driving factor in making the completion of this thesis possible. I would also like to express my gratitude to my coauthors: Paul Wignall, David Bond, Michael Joachimski, Christoph Hartkopf-Fröder, Christian Scheibner, Holger Forke, Dierk Blomeier, Michael Greenacre, Mikko Vihtakari, Daniel Collins, Ralph Groen and Thomas Goode. Especially Paul, Dierk, Mikko, Michael Joachimski, and Michael Greenacre provided invaluable contributions to the scientific quality of the work. Additional thanks go to Jürgen Mienert for his help with logistical matters of the PhD studies, Winfried Dallmann and Synnøve Elvevold for the translation of the thesis summary into Norwegian, and to all the students, PhD students, post docs and staff at both the Department of Geology and the Norwegian Polar Institute who have made the work more bearable. Last but not least, most heartfelt thanks go to my friends, family, and especially to Mikko, who now knows more about geology than he probably ever wanted to.

List of papers

Five papers are included in this thesis:

Paper 1: Blomeier, D., Dustira, A.M., Forke, H., Scheibner, C., 2011. Environmental change in the Early Permian of NE Svalbard: from a warm-water carbonate platform (Gipshuken Formation) to a temperate, mixed siliciclastic-carbonate ramp (Kapp Starostin Formation). *Facies* 57, 493–523.

Paper 2: Blomeier, D., Dustira, A.M., Forke, H., Scheibner, C., 2013. Facies analysis and depositional environments of a storm-dominated, temperate to cold, mixed siliceous–carbonate ramp: the Permian Kapp Starostin Formation in NE Svalbard. Accepted in *Norwegian Journal of Geology*.

Paper 3: Dustira, A.M., Blomeier, D., Collins, D., Goode, T., Groen, R.D., 2013. Sequence stratigraphic arrangement and sea-level curve for the Early to Late Permian Kapp Starostin Formation of Svalbard, Norway. Unpublished manuscript (To be submitted to *Geological Magazine*)

Paper 4: Dustira, A.M., Vihtakari, M., Greenacre, M., Blomeier, D., 2013. Distinguishing Permian chert facies from Svalbard, Norway on the basis of geochemical criteria. Unpublished manuscript (To be submitted to *Chemical Geology*)

Paper 5: Dustira, A.M., Wignall, P.B., Joachimski, M., Blomeier, D., Hartkopf-Froder, C., Bond, D.P.G., 2013. Gradual onset of anoxia across the Permian-Triassic Boundary in Svalbard, Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology* 374, 303–313.

Summary (English)

The main objective of this thesis was to improve the knowledge on the depositional and environmental development of Svalbard during the Permian (299–252 Ma), with a primary focus on the Early to Late Permian Kapp Starostin Formation (Tempelfjorden Group). Thirteen localities of Permian sedimentary strata were investigated with respect to their sedimentological and geochemical properties. Sediments from this period reflect mostly marine deposition on a broad epicontinental shelf at the northern margin of the supercontinent Pangea. Sedimentary facies reveal distinct changes in depositional environment, from marginal/restricted marine settings in a warm and dry climate, to a temperate to cold-water, open-marine shelf. The latter is characterized by cool-water biota including brachiopods, echinoderms, bryozoans and siliceous sponges. These sedimentological shifts are related to a number of controlling factors including changes in palaeolatitude, ocean circulation and upwelling, global climate, and sea level changes. A sequence stratigraphic analysis revealed several orders of relative sea level fluctuations that could be traced within the sediments across the basin, which were likely controlled by a combination of eustasy and local shelf subsidence. By the latest Permian (at the top of the Kapp Starostin Formation), an abrupt loss of biota reflects the End-Permian mass extinction. Geochemical pyrite and stable carbon isotope analyses revealed a gradual onset of marine bottom water oxygen restriction that coincided with the stepwise decrease in biodiversity in the latest Permian.

Summary (Norwegian)

Hovedmålet med denne avhandlingen var å øke kunnskapen om avsetningsmiljøet og dets utvikling på Svalbard under permtiden (299-252 Ma), med hovedfokus på den tidlig- til senpermiske Kapp Starostin-formasjonen (Tempelfjordgruppen). Permiske sedimentære lag ved tretten lokaliteter ble undersøkt med hensyn til sedimentologiske og geokjemiske egenskaper til sedimentene. Sedimenter fra denne perioden gjenspeiler hovedsakelig marin avsetning på en bred kontinentalsokkel på den nordlige randen av superkontinentet Pangea. De sedimentære facies gjenspeiler distinkte endringer i avsetningsmiljøet, fra marginale og avgrensede marine områder i et varmt og tørt klima, til en temperert til kaldtvanns, åpen marin sokkel. Sistnevnte er preget av kaldtvanns biota som omfatter armfotinger, pigghuder, mosdyr og kiselsvamper. Disse sedimentologiske endringene kontrolleres av en rekke faktorer som endringer i breddegrad, havsirkulasjon og 'upwelling', globalt klima og havnivåendringer. En sekvensstratigrafisk analyse avslører flere nivåer av relative havnivåsvingninger som kan spores i sedimentene over hele bassenget, og som trolig ble styrt av en kombinasjon av eustasi og lokal sokkelinnsynkning. I øverste perm (på toppen av Kapp Starostin-formasjonen), gjenspeiler en brå nedgang av livsformer den senpermiske masseutryddelsen. Geokjemiske analyser av svovelkis og stabile karbonisotoper viser et gradvis minkende oksygeninnhold i det marine bunnvannet som sammenfaller med en trinnvis reduksjon av det biologiske mangfoldet i seneste perm.

1. Introduction and objectives

The Permian period (Fig. 1) was a time of extensive and dramatic environmental changes. Global climate underwent a fundamental transformation during this period. While the Early Permian was characterized by an ice-age with extensive continental glaciation on Gondwana (Fielding et al., 2008; Isbell et al., 2003), by the latest Permian the earth had transformed to a “hothouse”. The onset of abrupt global warming and corresponding sea level rise, believed to be caused by the unparalleled eruption of the Siberian Traps flood basalts, brought about the end-Permian extinction, widely considered as the greatest mass extinction of all time (Beerling et al., 2007; Renne et al., 1995; Wignall, 2001). During the same time period, major paleogeographical rearrangements were ongoing, with the consolidation of the supercontinent Pangea resulting from the collision of Siberia with Euramerica that caused constriction and closing off of the Uralian Seaway, and the formation of the Ural Mountains by the end of the Permian (Scotese, 2001). This consequently broke the connection between the warm-water Tethys and cool-water Panthalassa oceans, and may have been one of the factors in changing ocean circulation patterns, considered to be possible contributory factors in the end-Permian environmental crisis (Beauchamp and Baud, 2002).

Permian marine sedimentary strata worldwide reflect the effects of these dramatic environmental and climatic changes, especially with regard to the end-Permian mass extinction, and have been a longstanding focus of research. However, less information is available for relatively remote regions, such as the Svalbard archipelago. The main objective of this thesis is to improve the knowledge on the depositional and environmental development of Svalbard during the Permian, with a primary focus on the Early to Late Permian Kapp Starostin Formation (Tempelfjorden Group). In order to understand large-scale and long-term processes such as basin development, paleoenvironmental or paleoecological changes, a detailed comprehension of the sedimentary facies, sedimentological and geochemical processes and depositional conditions responsible for them is necessary.

2. Study Area

The Svalbard archipelago (Fig. 2) was situated at the northeastern margin of Pangaea during the Permian, forming part of a broad epicontinental shelf consisting of a number of platforms and basins (Fig. 3). In the time-period from Carboniferous to Permian, the region experienced a steady northwards drift from approximately 20°N to 45°N (Steel and Worsley, 1984; Stemmerik and Worsley, 2005). Marine sedimentary deposits from adjacent basins within this expansive shelf area are located around the circum-Artic today, including parts of eastern North Greenland (Wandel Sea Basin), the Barents Sea (offshore: Finnmark Platform, Stappen High; onshore: Svalbard), Arctic Canada (Sverdrup Basin) and Russia (Timan–Pechora Basin) (Beauchamp and Baud, 2002; Ehrenberg et al., 1998; Reid et al., 2007; Stemmerik, 1997; Stemmerik and Worsley, 1995; Stemmerik and Worsley, 2005).

Numerous outcrops of Permian sedimentary rocks can be found across the Svalbard archipelago, including Spitsbergen, where the majority of exposures are located, as well as Nordaustlandet, Edgeøya, Barentsøya and Bjørnøya (Fig. 2; (Dallmann, 1999)). Outcrop distribution across Svalbard can be ascribed to the Tertiary orogeny, related to opening of the Norwegian-Greenland Sea. Eastwards-directed compression resulted in the formation of a fold belt concentrated along the western margin of Spitsbergen while leaving the central to eastern regions generally unaffected. As a result, strata in the central to northeastern regions of Svalbard are near-horizontal or show only a very low dip and are primarily undeformed, whereas strata in western Spitsbergen within the Tertiary deformation zone are steeply dipping to near-vertical (Steel and Worsley, 1984). Thirteen localities of Permian strata were studied within the scope of this thesis, including sections in western, central and eastern Spitsbergen and from Nordaustlandet (Fig. 2).

The main structural controls affecting Permian sedimentation across Svalbard can be related to a number of NNW–SSE-oriented lineaments. These were previously active in the Carboniferous, forming a series of graben or half-graben structures (St. Jonsfjorden Trough, Inner Hornsund Trough, Billefjorden Trough and Lomfjorden Trough) and topographic highs (Sørkapp-Hornsund High, Nordfjorden High, Ny Friesland High), which continued to influence facies distribution and sedimentation patterns throughout the Permian (Dallmann, 1999; Steel and Worsley, 1984). As a result, the thickness of the Tempelfjorden Group widely varies, from a maximum of 460 m in western Svalbard (e.g. >400 m on Akseløya, 380 m at the Kapp Starostin

Formation type section in Festningen, outer Isfjorden) at what are interpreted as the deepest points in the depositional basin, to only a few meters thick in the Hornsund area, and wedging out completely against the margins of the Sørkapp-Hornsund High (Dallmann, 1999).

The current lithostratigraphic scheme for most of Svalbard arranges Permian sedimentary strata into two groups: the upper part of the Gipsdalen Group and the Tempelfjorden Group ((Dallmann, 1999), Fig. 1), which reflect sedimentation in one cohesive depositional basin. A major hiatus (Artinskian) and disconformity marks the boundary between the Gipsdalen Group (Gipshuken Formation) and Tempelfjorden Group (Kapp Starostin Formation), resulting from subaerial exposure of extended platform areas and related erosion of the uppermost Gipshuken Formation sediments (Dallmann, 1999; Ehrenberg et al., 2001). The Bjørnøya–Sørkapp–Hornsund region, not addressed within this thesis, comprised a distinctively separate depositional basin, the Permian strata of which are arranged into an underlying Bjarmeland Group, and unique formations within the Tempelfjorden Group (Tokrossøya Formation (Hornsund) and Miseryfjellet Formation (Bjørnøya)).

The oldest sediments studied within this thesis (Paper 1) are from the NE-Svalbard Templet and Sørfonna members in the Gipshuken Formation (Gipsdalen Group, Fig. 1). Age determinations based on brachiopods, bryozoans, conodonts, foraminifers and palynomorphs indicate a late ?Sakmarian to early Artinskian depositional time frame (Buggisch et al., 2001; Mangerud and Konieczny, 1991; Nakrem, 1994a, b; Nakrem et al., 1992; Sosipatrova, 1967).

The Kapp Starostin Formation, the focus of this thesis (Papers 1-5), is the most extensive formation within the Tempelfjorden Group, extending across the greater part of Svalbard (Fig. 2). Biostratigraphic studies provide varying age estimates for the Kapp Starostin Formation with a depositional time frame of approximately late Artinskian to ?Kungurian for the Vøringen Member, and ?Kungurian until latest Permian (?Changhsingian) for the overlying strata of the formation (Biernat and Birkenmajer, 1981; Buggisch et al., 2001; Chwieduk, 2007; Mangerud and Konieczny, 1993; Nakamura et al., 1987; Nakrem, 1988, 1991; Nakrem et al., 1992; Stemmerik, 1988; Szaniawski and Malkowski, 1979). The basal Vøringen Member is rich in diagnostic fossils, however the lack of fossils within the uppermost part of the Tempelfjorden Group makes a biostratigraphic age constraint for the top of the group and for the Permian–Triassic Boundary less certain (Nakrem et al., 1992; Wignall et al., 1998). Chemostratigraphic methods provide an alternative method for the closer approximation of the Permian–Triassic Boundary, and are addressed in paper 5.

3. Summary of papers (1-5)

3.1. Depositional interpretation and depositional models: Papers 1 and 2

Blomeier, D., Dustira, A.M., Forke, H., Scheibner, C., 2011. Environmental change in the Early Permian of NE Svalbard: from a warm-water carbonate platform (Gipshuken Formation) to a temperate, mixed siliciclastic-carbonate ramp (Kapp Starostin Formation). *Facies* 57, 493–523.

Blomeier, D., Dustira, A.M., Forke, H., Scheibner, C., 2013. Facies analysis and depositional environments of a storm-dominated, temperate to cold, mixed siliceous–carbonate ramp: the Permian Kapp Starostin Formation in NE Svalbard. Accepted in Norwegian Journal of Geology.

Detailed facies analyses of the Early to Late Permian Templet and Sørfonna members of the Gipsdalen Group (Gipshuken Formation) and the overlying Tempelfjorden Group (Kapp Starostin Formation) in NE Svalbard (sections H, G, J and K, Fig. 2) allow the reconstruction of depositional models of a warm-water carbonate platform to a temperate to cold-water, mixed siliceous-carbonate ramp and show the spatial and temporal development from the Artinskian into the Lopingian (?Changhsingian).

The transition from the Gipshuken to Kapp Starostin Formation represents major paleoenvironmental, paleoecological and paleoclimatic changes, and is key to understanding the evolution of the basin within a greater context. The main lithologies of the Gipshuken Formation include carbonates (dolostones, limestones) and evaporites (gypsum and anhydrite), which were deposited under a warm and dry climate within fully- to marginal-marine settings (Lauritzen, 1981). The upper five meters of the formation contain microbial (algal) limestones (Hüneke et al., 2001), mudstones, bioclastic/peloidal wacke- to packstones (Bensing, 2007; Reid et al., 2007), *Microcodium* facies (Kabanov et al., 2008) and carbonate breccias. Low-diversity fossil assemblages are classified as heterozoan/reduced photozoan and suggest restricted-marine to hypersaline warm-water conditions within the inner platform areas. Extensive weathering (meteoric alteration, dolomitization, micritization, recrystallization, fragmentation, dissolution), karstification, erosion, reworking and pedogenesis reflect the subaerial emergence of marine limestone strata in a supratidal sabkha depositional setting (Kendall and Harwood, 1996).

The transition from the Gipshuken Formation to the Kapp Starostin Formation is abrupt in all locations, due to a well-documented unconformity and hiatus (Dallmann, 1999) related to the subaerial exposure of extended parts of the platform during the Artinskian. The extent of erosion appears to vary greatly from location to location, suggesting local variations in the duration of the sedimentary gap, with shorter durations in the offshore Barents Sea basins and more extensive exposure on paleohighs (Stemmerik, 1997). The duration of the hiatus on Svalbard has been suggested to be 1 to up to 15 Ma (Ehrenberg et al., 2001), although with closer assessment of depositional periods for the Gipshuken Formation (Sakmarian–early ?Artinskian) and the Vøringen Member (late Artinskian–early Kungurian), the time frame is more likely restricted to the Artinskian with a maximum duration of 9 Ma or less.

The overlying Vøringen Member of the Kapp Starostin Formation, in contrast, reflects a markedly different depositional setting on a temperate to cold-water, open-marine shelf, which was populated by a diverse, fully heterozoan biotic assemblage, mainly consisting of brachiopods, echinoderms, bryozoans and siliceous sponges. In the lower part of the member, allochthonous coarse-grained, mixed-bioclastic, sandy limestones, imply high-energy, storm-related depositional conditions, probably at water depths between the storm weather wave base (SWWB) and fair weather wave base (FWWB) on the inner to mid ramp zones. These sediments are overlain by coarse-grained brachiopod-dominated sandy allochem limestones and allochemic sandstones interbedding with fine-grained sandy allochem limestones and calcareous standsones which form "stacked sediment couplets" interpreted to be the result of repeated storm events. In general, the Vøringen Member in northeast Svalbard is observed to transition upwards from mixed-bioclastic (bryozoan, echinoderm, brachiopod) limestone, to brachiopod-dominated limestone, and calcareous limestone facies towards the top of the member, implying a shallowing-upwards from approximate mid-shelf to inner shelf nearshore environments.

The basin-wide deposition of marine shales at the boundary of the Vøringen Member to the overlying Kapp Starostin Formation signifies the drowning of the shelf and a shift to mainly deeper-marine, outer to mid-shelf depositional environments. The main facies types found within the upper Kapp Starostin Formation include black shale, dark and light chert, siltstone to silty mudstone, sandstone, and brachiopod-, echinoderm-, bryozoan-dominated or mixed-bioclastic limestones. These are arranged into three facies associations, reflecting inner-, mid- and outer-ramp environments. The inner shelf section is characterized by generally well-sorted, glauconitic sandstones and various limestones types (coarse-grained, sandy brachiopodal rudstones, finer-grained, sandy, peloidal-bioclastic packstones and grainstones), reflecting nearshore sand flats, sandy shoals and coarser, bioclastic shell banks (brachiopod coquinas), intensively reworked by tides, waves and occasional storms.

With the transition into the mid-shelf, roughly between the FWWB and SWWB, light-colored, nodular to massive, spiculitic cherts prevail, reflecting spacious offshore plains populated by abundant siliceous sponges, which constitute the dominant silica factory. Minor carbonate-producing biota, mainly consisting of brachiopods, crinoids, bryozoans and solitary corals are present in local, in-situ bryozoan build-ups or accumulate in allochthonous bryozoan, crinoidal or mixed-bioclastic limestone (floatstones, wackstones) bed-sets interbedding with cherts and minor shales. Bryozoans and echinoderms are thought to occur mainly at the margin between the mid and outer ramp, forming local build-ups on slightly elevated areas, though on Svalbard they do not appear as major reef/mound-builders, compared to the more distal settings in the offshore Barents Sea region (Samuelsberg et al., 2003).

The outer shelf includes the deepest depositional zone from the SWWB to far below. Its facies association mainly includes dark, bedded to massive spiculitic cherts, silicified mudstones and black shales formed due to the accumulation of enormous quantities of sponge spicules and fine-grained suspended matter under quiet-water conditions. Occasionally interbedded limestones formed due to the accumulation of fragile, fenestrate bryozoans, as well as bioclasts and lime mud imported via distal tempestites from the inner- and mid-shelf areas. Changing sea-floor oxygen levels controlled bioturbation and the preservation of primary lamination or massive fabrics of the sediments. The depositional model shows a distally deepening, homoclinal ramp, gently sloping towards the S or SW.

3.2. Sequence stratigraphy and basin development: Paper 3

Dustira, A.M., Blomeier, D., Collins, D., Goode, T., Groen, R.D., 2013. Sequence stratigraphic arrangement and sea-level curve for the Early to Late Permian Kapp Starostin Formation of Svalbard, Norway. Unpublished manuscript (To be submitted to Geological Magazine)

The aims of this paper are to improve understanding of the spatial and temporal relationships of facies and stratigraphic units, and to use this information as the basis for a sea level curve for the study area and time period. Field data and facies analysis of the Kapp Starostin Formation from seven vertical sections situated across Svalbard (sections, A, D, G, H, J, L and N, Fig. 2) are included in this study. The depositional environments of the sedimentary strata are interpreted according to the depositional model presented in Paper 2, and grouped into three facies associations for the inner, mid- and outer shelf zones.

Sequences are defined as regressive facies-set successions bounded by maximum marine flooding surfaces (MMFS), in the absence of subaerial unconformities, after the genetic stratigraphic sequence definition of Galloway (1989). Sediment stacking patterns reveal three different orders of depositional sequences, loosely termed 4th, 3rd, and 2nd order, in reference to their relative magnitude to each other, and in conforming to previously used terminology (Ehrenberg et al., 2001; Stemmerik, 1997). 4th order sequences are not prominent, and are only identified sporadically within the upper Kapp Starostin Formation. Up to five 3rd order regressive, shallowing upward sequences are defined in the Kapp Starostin Formation. These may typically include black shale and dark spiculitic chert at the base (outer shelf), overlain by light spiculitic chert, bryozoan- and crinoid-dominated limestone (mid-shelf) with brachiopod-dominated limestone at the top (inner shelf), and bounded by MMFS. These are superimposed on a long-term, 2nd order sea level curve that is subdivided into systems tracts corresponding to respective transgressive, normal regressive, or forced regressive stages (Catuneanu, 2006).

The upper part of the Gipshuken Formation represents the late part of a falling stage systems tract, characterized by decreasing accommodation space (as seen by low sedimentation rates and very thin depositional sequences) and an increasing restriction of the depositional area (paper 1). The subsequent lowstand systems tract is represented by the subaerial unconformity surface separating the Gipshuken Formation from the overlying Vøringen Member.

The Vøringen Member, the lowermost 3rd order sequence (S1) in the Kapp Starostin Formation, is interpreted as a transgressive systems tract, representing flooding of the depositional area in the Artinskian and sedimentation within mainly inner to mid shelf zones during the Kungurian. Deposition of black shale above the Vøringen Member indicates the termination of shallow-marine sedimentation and reflects sediment starved, outer shelf deposition with water depths far below the SWWB. This marks the MMFS and the transition from a transgressive to highstand systems tract. Cycle stacking patterns for 3rd order sequences S2-S5, deposited from Kungurian to Lopingian (?Changhsingian), reflect the succeeding highstand to late highstand systems tracts. Successively thinner packages and sedimentary facies reflecting shallower depositional environments show evidence for decreasing accommodation space and the beginning of sea level fall. Continual infilling of the depositional basin, with higher sedimentation rates within the basin depocenter (western to central Spitsbergen), results in an increasingly gentle and shallow basin profile by the end of the Permian.

Cyclicity appears to reflect eustatic sea level fluctuations (Rygel et al., 2008; Stemmerik, 1997), however direct comparison with a global seal level curve (Haq and Schutter, 2008) reveals discrepancies in the Kungurian transgression seen on Svalbard but not seen in the global curve. Regional shelf subsidence across the northern Pangean shelf region may provide an alternative explanation. Evidence for variable rates of subsidence within the Svalbard basin, as interpreted from a cross-section of the seven vertical sections, may be linked to some extent of local downwarping throughout the Permian near previous graben structures (Steel and Worsley, 1984; Stemmerik and Worsley, 1989).

3.3. Chemical criteria to enhance interpretation of chert facies: Paper 4

Dustira, A.M., Vihtakari, M., Greenacre, M., Blomeier, D., 2013. Distinguishing Permian chert facies from Svalbard, Norway on the basis of geochemical criteria. Unpublished manuscript (To be submitted to Chemical Geology)

Biogenic cherts, such as the spiculitic chert successions of the Kapp Starostin Formation, are strongly affected by diagenetic silicification processes, which obscure original sedimentary structures, fabrics and other features, making the interpretation of the primary depositional environments more challenging. This study tests the use of a multivariate statistical approach (logratio analysis) as a potential method to systematically compare geochemical, facies, and color-related factors differentiating light and dark chert facies. The aims are to establish whether the color-based classification of cherts is a reliable reflection of their respective depositional conditions, and whether chemical criteria might be useful in the interpretation of depositional environments. Thus far, the majority of interpretations of chert facies, from Svalbard and from corresponding strata in adjacent depositional basins, are based on field data, microfacies analysis, and facies associations (Beauchamp and Baud, 2002; Beauchamp et al., 2009; Ehrenberg et al., 2001; Gates et al., 2004; Hüneke et al., 2001; Stemmerik, 1997). The categorization into dark and light chert facies types, based primarily on coloration in the outcrop sections, is often used as an indicator for depositional environment (Paper 2; (Ehrenberg et al., 2001).

Dark and light chert samples used in the study come from 10 locations across Svalbard (sections A, B, C, D, E, F, G, H, J, K, Fig. 2). Three different methods for the analysis of geochemical components are used: a Leco analysis for whole-rock total organic carbon (TOC), total inorganic carbon (TIC) and total sulfur (TS), and two separate x-ray fluorescence (XRF) methods for the analysis of whole-rock major/minor and trace elements. Because individual datasets obtained with different methods cannot be directly compared with one another quantitatively, the logratio method is used to normalize and give equal variance to each dataset, which allows for more accurate comparison (Greenacre and Lewi, 2009). This method is a variation of a principal component analysis (PCA), and is connected to correspondence analysis (Greenacre, 2010a; Greenacre, 2010b).

Results from logratio analysis of the geochemical datasets indicate that the dark and light chert sample pools have distinct but overlapping compositional ranges, meaning that many light chert samples have chemical compositions recognizably different to dark cherts, but a portion of samples from each group have "transitional" compositions somewhere in between. Light chert facies seems to be best characterized by a carbonatic geochemical association comprised of CaO, TIC, MgO, Sr, related mainly to higher ratios of primary calcareous material within most samples, caused by bioclastic input from cool-water carbonate factories on the inner to mid-shelf regions. Dark chert facies is best characterized by higher SiO_2 content, and a redox-organic matter association of TOC, TS, and Fe_2O_3 that is attributed to increased supply and/or increased preservation of organic matter in restricted basin depositional environments with periodic reduced-oxygen conditions (Montero-Serrano et al., 2010). Although logratio analysis did not determine clay minerals/detrital content to be a major factor differentiating chert facies composition, results show a clear correlation between the darkness of chert facies and clay mineral element concentration, and that the clay mineral component within the rock matrix is possibly an additional controlling factor in chert facies coloration.

3.4. The End-Permian environmental crisis: Paper 5

Dustira, A.M., Wignall, P.B., Joachimski, M., Blomeier, D., Hartkopf-Froder, C., Bond, D.P.G., 2013. Gradual onset of anoxia across the Permian-Triassic Boundary in Svalbard, Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology* 374, 303–313.

The Permian–Triassic extinction event is considered to be the most devastating environmental crisis of the Phanerozoic, eliminating approximately 90% of all marine species globally. Amongst the many coinciding contributory processes involved, oceanic anoxia is believed to be a key factor, although the exact role it played during the extinction is still poorly understood. In this study, a Permian–Triassic Boundary (PTB) section (Kapp Starostin and Vikinghøgda formations) from central Svalbard (Section M, Fig. 2) has been investigated with the aim to improve the understanding of the timing and nature of local marine anoxia and their role and connection with the global extinction event across the PTB.

In studying the Permian–Triassic extinction event, it is imperative to establish the stratigraphic position of the PTB. We use a $\delta^{13}C_{org}$ record, analyzed from samples across the transition, which can be compared to more well-constrained sections from Norway and globally. The carbon isotope record across the PTB is commonly characterized by a major negative excursion reaching -31.3‰, usually showing two negative peaks interrupted by short-term positive events (Algeo et al., 2012; Algeo et al., 2008; Algeo et al., 2007; Hermann et al., 2010; Korte and Kozur, 2010). In contrast, only one negative shift is evident in the study section, probably related to the very condensed sediments of the top of the Kapp Starostin Formation. Correlating both the lithology and $\delta^{13}C_{org}$ record to the Festningen section (Wignall et al., 1998), it appears most likely that it is the first negative shift which is missing, and that the second one is preserved. On the basis of this, the PTB is estimated to be just above the base of the Vikinghøgda Formation above the Kapp Starostin Formation.

Alongside sedimentary facies and fossil assemblages, the timing and development of environmental changes across the PTB are established using pyrite framboids and complementary geochemical data and palynological assemblages. Pyrite framboids are microscopic, raspberry-shaped microcrysts usually from approximately 1 to 20 µm in diameter, and are easily distinguishable from later diagenetic pyrite crystals (Wilkin et al., 1996). They are a product resulting from the production of hydrogen sulphide (H_2S) by anaerobic sulfur-reducing bacteria, in a redox-dependent process entailing weakly oxidizing steps that can only happen at the redox boundary (Sweeney and Kaplan, 1973; Wilkin et al., 1996). Framboids forming within the water column (under anoxic to euxinic bottom water conditions) have a limited size range compared to those growing within the sediment (oxygenated bottom water), making their size distributions a useful and reliable proxy for bottom water conditions at the PTB (Bond and Wignall, 2010; Liao et al., 2010; Shen et al., 2007; Wignall et al., 2005).

Results from pyrite framboid analysis (and supported by TOC data) at Tschermakfjellet a gradual transition from oxic to dysoxic bottom water conditions within the upper two meters of the Kapp Starostin Formation. The onset of anoxic conditions occurs at the base of the Vikinghøgda Formation, coinciding with the loss of marine benthos as seen by the disappearance of sponge spicules and bioturbation marking the formation boundary at this level. As with the onset of anoxia, the marine ecosystem crisis occurred not at once but over an extended period of time, as indicated by changes in biotic assemblages at the top of the Kapp Starostin Formation. The scenario on Svalbard, with biotic changes coinciding with several small pulses in anoxia before the final, long-term onset of anoxic to euxinic conditions is identical to other Boreal sections, for example in NW Canada and the Canadian Arctic (Algeo et al., 2012; Grasby and Beauchamp, 2009; Wignall and Newton, 2003).

4. Synthesis

Within this thesis, a combination of sedimentological and geochemical approaches is used to expand on the current knowledge of the depositional and environmental development of Svalbard during deposition of the upper Gipshuken Formation (Gipsdalen Group) and the Kapp Starostin Formation (Tempelfjorden Group). Detailed outcrop investigations and facies analysis provide the basis for updated and improved depositional models of the Gipshuken and Kapp Starostin formations with a focus on the previously less-studied northeastern Svalbard strata. A new approach to the interpretation of the chert facies involves the analysis of chemical criteria using a multivariate statistical method (logratio analysis). This proves to be an effective tool to classify sedimentary rocks into meaningful geochemical associations and assess the most important compositional differences, and improves the established chert facies classifications. Results from these studies reveal several fundamental transitions in the paleoecology and depositional environment of the sedimentary basin, which are inferred to reflect changes in paleolatitude (northwards drift of Pangea), paleogeography (local uplift, closure of the Uralian seaway), paleoclimate (cooling, increased precipitation), and paleoceanographic variables (temperature, upwelling and nutrient flux).

Interpretations of the Kapp Starostin Formation within a sequence stratigraphic context reveal depositional sequences reflecting several orders of relative sea level fluctuations that can be correlated across the basin. A sequence stratigraphic model and relative sea level curve for Svalbard suggest a switch from high-amplitude, high-frequency fluctuations in the Gipsdalen Group to low-amplitude, low-frequency in the Kapp Starostin Formation. This is believed to partly reflect the transition from glacio-eustatic to eustatic sea level fluctuations during the deglaciation phase of Gondwana. On the other hand, the sea level curve for Svalbard poorly reflects the established global eustatic sea level curve, and suggests the importance of local or regional controls in relative sea level changes, such as regional subsidence of the epicontinental shelf. The 2nd order sea level cycle comprises four clear systems tracts: regressive and lowstand systems tracts during deposition of the Gipshuken Formation and the overlying subaerial exposure; a transgressive systems tract represented by the Vøringen Member; and a highstand to late highstand systems tract visible within the upper Kapp Starostin Formation. The sea level stage represented by the strata at the top of the Kapp Starostin Formation is unclear due to thorough condensation of the sediments. Results from the study on the End-Permian environmental crisis reveal evidence for a renewed marine transgression in the upper boundary of the Kapp Starostin Formation shortly before the extinction event, and imply that marine ecological changes coincided with sea level rise. The timing of changes in biotic assemblages and redox conditions suggests the beginning of a marine ecosystem crisis already before the onset of long-term anoxia.

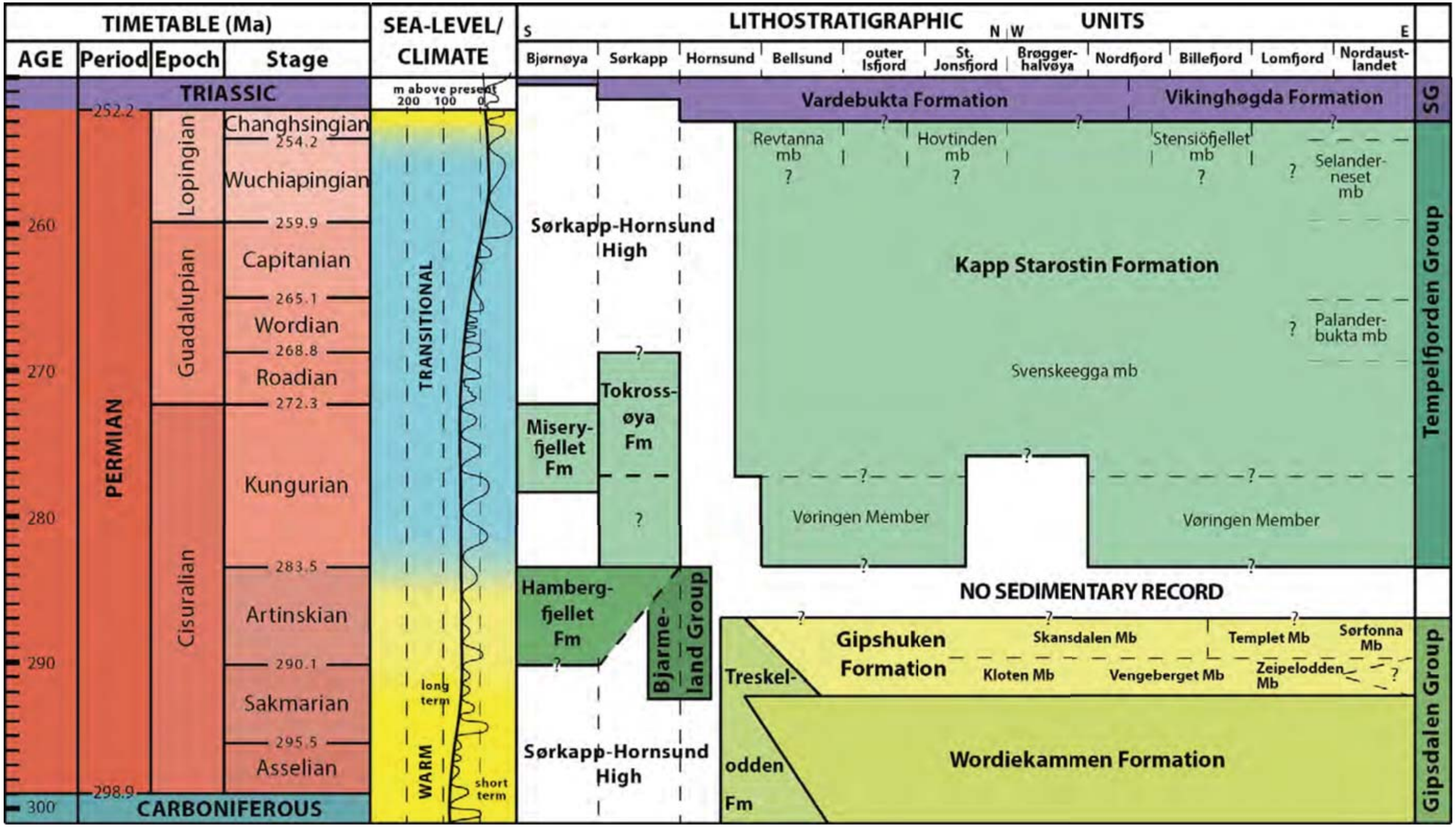

Figure 1. Permian timetable (International Stratigraphic Chart, 2012), global sea-level curves and climate (modified from Haq and Schutter, 2008) and lithostratigraphic system of Svalbard (modified from Dallmann et al., 1999). SG: Sassendalen Group

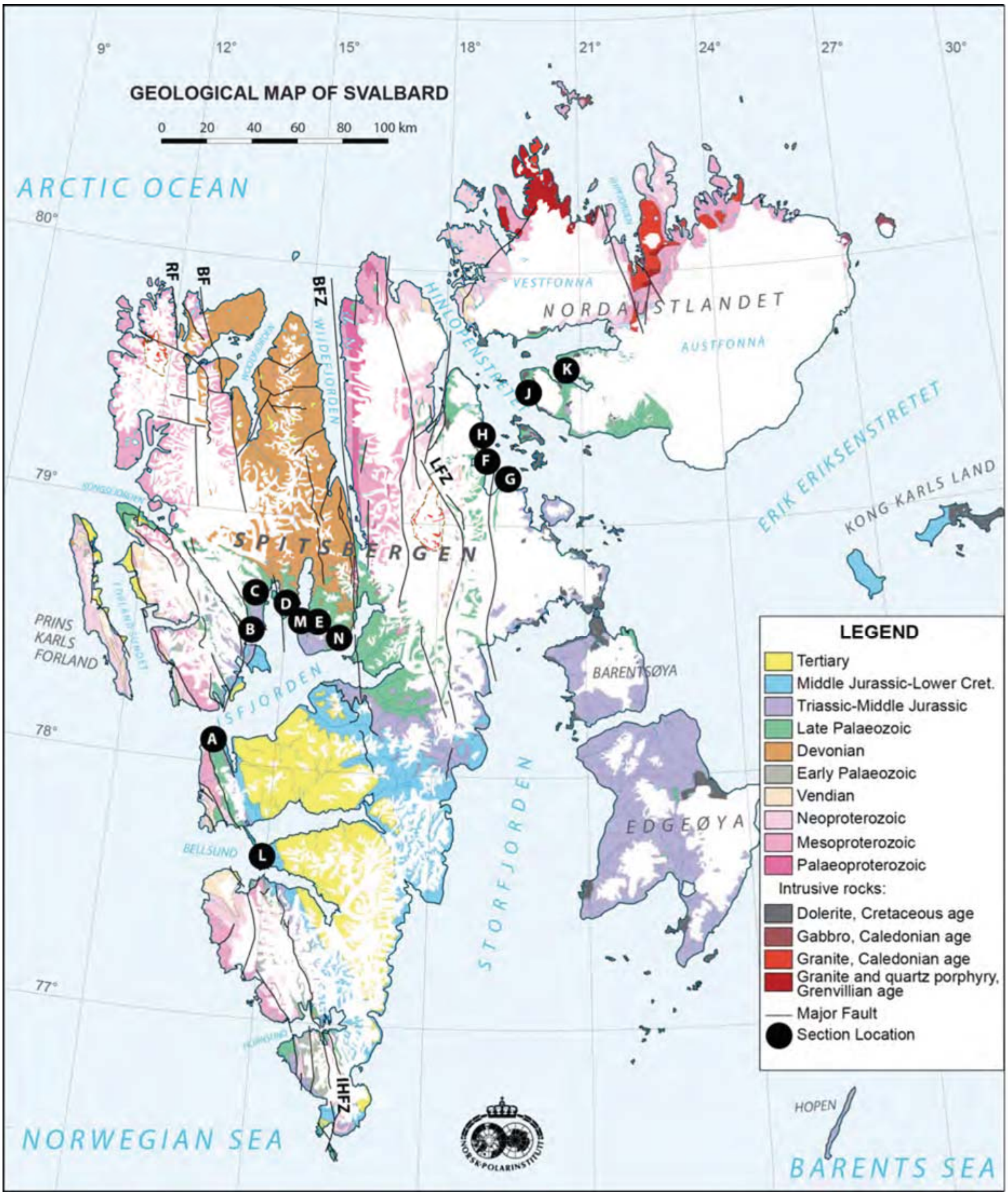

Figure 2. Geological map of Svalbard (excluding Bjørnøya) showing collective study locations (black circles, with letters defining location name) for all of the papers included in this thesis. Location A: Festningen; B: Mediumfjellet; C: Bertilryggen (Ekmanfjorden coastal outcrop); D: Tålmodryggen; E: Idodalen; F: Emblafjellet (Vaigattbogen); G: Eremitten; H: Hódbreen; J: Selanderneset; K: Zeipelodden; L: Forkastningsdalen; M: Tschermakfjellet; N: Kapp Fleur de Lys. Major faults are labelled as follows: RF: Raudfjorden Fault; BF: Breibogen Fault; BFZ: Billefjorden Fault Zone; IHFZ: Inner Hornsund Fault Zone; LAFZ: Lomfjorden-Agardhbukta Fault Zone.

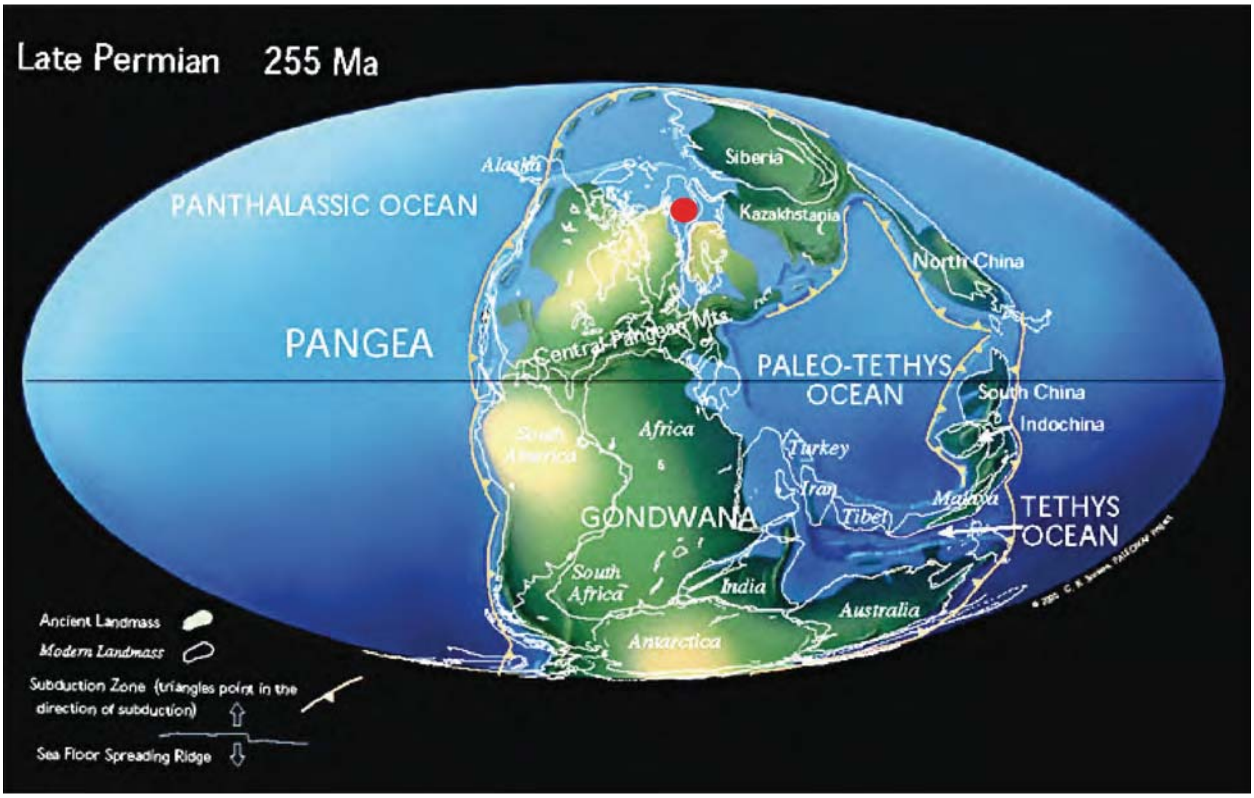

Figure 3. Global paleogeographic map for the Late Permian with the location of Svalbard (red dot) off the northern margin of Pangea. Modified from Scotese (2001).

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Paper 1

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