DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1999/54

Resources of the sedimentary basins of North and East Greenland

Lars Stemmerik and the TUPOLAR project group

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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Contents

Introduction

The multidisciplinary project "Resources of the sedimentary basins of North and East Greenland" was initiated in 1995 with financial support from the Danish Research Councils through the "POLARFORSKNING" research programme. The aim of the three year project, financially supported from 1995-1997, was twofold: 1) to carry out process-oriented studies in North and East Greenland, including the large, then newly discovered zinc deposit at Citronen Fjord, in order to establish models for the formation of sediment-hosted ores, 2) to provide biostratigraphic, sedimentological, geochemical and structural data to develop models for the petroleum systems in the East Greenland basins and the Wandel Sea Basin (Fig. 1).

The research grant was awarded to Lars Stemmerik (GEUS) on behalf of a group of researchers from the Geological Institute, University of Copenhagen (Finn Surlyk), Geological Institute, University of Aarhus (John Korstgård), Department of Arctic Biology, National Environmental Research Institute (Hanne Petersen), and the departments of Economic Geology and Stratigraphy, Geological Survey of Denmark and Greenland (GEUS) (Hans Kristian Schønwandt, Flemming G. Christiansen and Stefan Piasecki).

The project has resulted in submission of more than 60 manuscripts, 47 of which are published or accepted for publication.

The Tupolar project group:

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Project background

The project "Resources of the sedimentary basins of North and East Greenland" developed from what were originally two applications for research grants from the "POLARFORSKNING" programme: "Petroleum systems of the sedimentary basins of Greenland" and "Sediment-hosted ore mineral occurrences in the High Arctic". The two applications were asking for a total of *c.* 26 million DKK in support, receiving 11 million DKK to the combined project. Accordingly, the research plans have been adjusted considerably compared to the two original applications.

The main focus of the petroleum system studies has been on the sedimentary basins along the east coast of Greenland, including the Wandel Sea Basin in the far north, the East Greenland rift basins in central East Greenland and the Kangerlussuaq Basin in the south-east (Fig. 1). Studies of the Franklinian Basin of North Greenland primarily concentrated on the Cambrian and Silurian successions from where potential hydrocarbon source rocks are well known.

The research on mineral resources and sulphide-related microbiology focussed on the Citronen Fjord deposit in North Greenland, regional studies of mineralizations in the Franklinian Basin, and a detailed study of mineralizations in the Upper Permian sediments in East Greenland.

The project was planned to include 2 full Ph.D. studentships and 3 post. docs. However, the project has been a very efficient platform to generate further funding since it has enabled us to provide a logistic platform for field work in Greenland, and as a consequence 7 Ph.D. students have been involved in the project (2 fully financed) together with 5 post. docs. (3 fully financed). Furthermore, 4 cand. scient. (~M. Sc.) students have undertaken field work for their thesis within the frame of the project. Additional funding of Ph.D. students and post. doc. projects comes from the Danish Natural Science Research Council, University of Copenhagen, University of Aarhus and GEUS (through a grant from Saga Petroleum).

Field work was carried out in East Greenland and in various parts of North Greenland from 1995 to 1997, and additional field studies have been carried out in 1998 and 1999 financed by GEUS and Saga Petroleum.

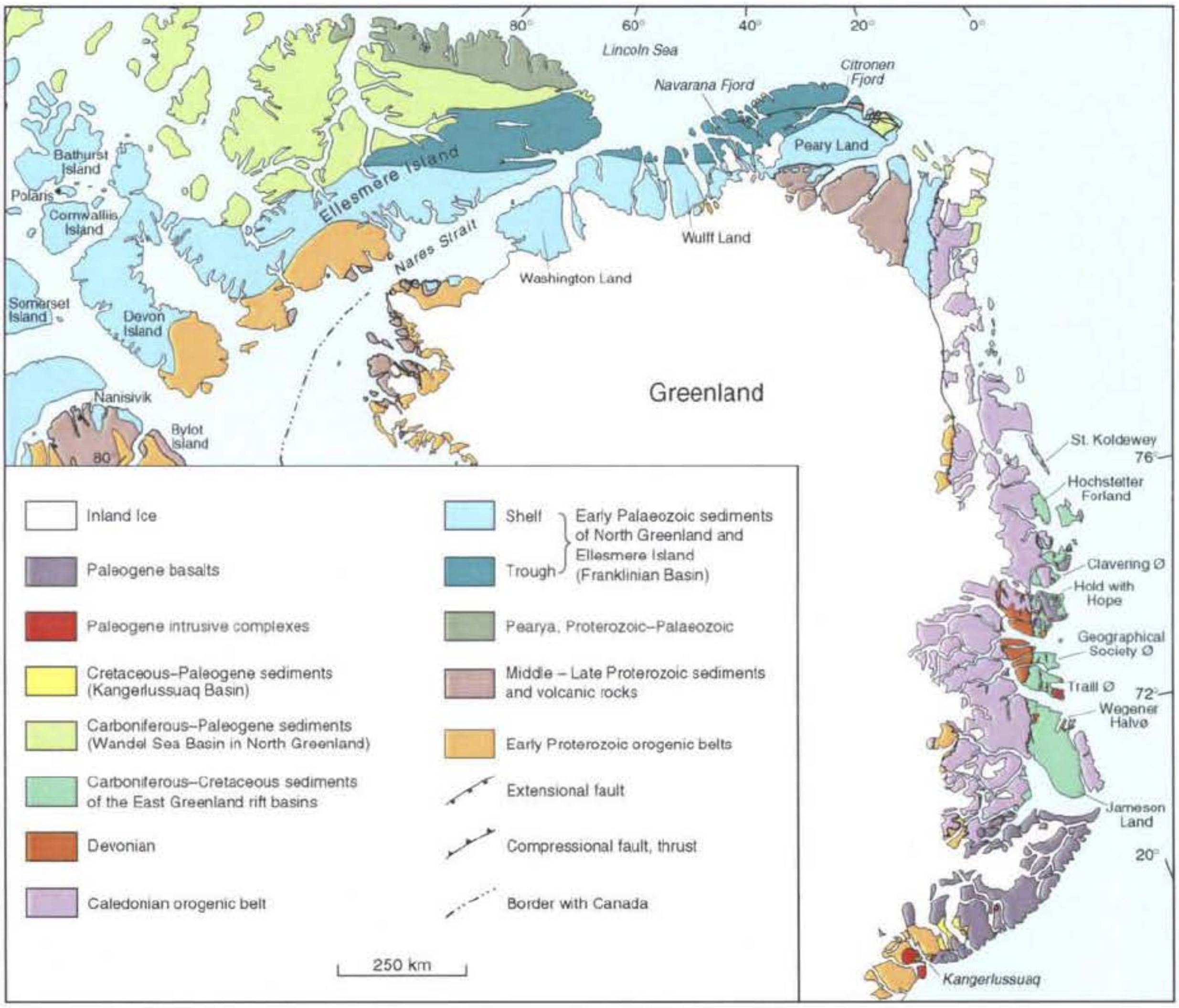

Figure 1. Geological map of northern and eastern Greenland and north-eastern Canada showing outline of investigated basins and localities mentioned in the text.

Mineral resources field studies

The mineral resource studies started with field work by one post.doc. (S.M. Jensen) and 3 Ph.D. students (H. Fougt, K. Kragh, B.R. Langdahl) at Citronen Fjord, North Greenland in 1995. The work included microbiological investigations of the gossans, and detailed petrographical, geochemical and isotope geochemical studies of the mineralization. The studies continued in 1996 and were expanded to include regional geochemical and isotope geochemical investigations of the Franklinian Basin from Citronen Fjord and westwards to Wulff Land (SMJ, HF, KK, BRL, B. Elberling and D.J. Kontak, Nova Scotia Department of Natural Resources) (Fig. 1). In 1997, the regional studies were continued in Washington Land where a new zinc-lead-silver occurrence was discovered in Ordovician platform carbonates (SMJ, H.K. Schønwandt).

The study of the zinc and lead occurrences in the Upper Permian sediments in East Greenland started in 1996 as part of a post. doc. project (M. Pedersen). One team investigated the mineralised black shales of the Ravnefjeld Formation on Wegener Halvø in order to constrain the timing and genesis of the mineralisation. The study of the Ravnefjeld Formation shales continued in 1998 as part of a Ph.D. project focussing on the sulphides (J.K. Nielsen).

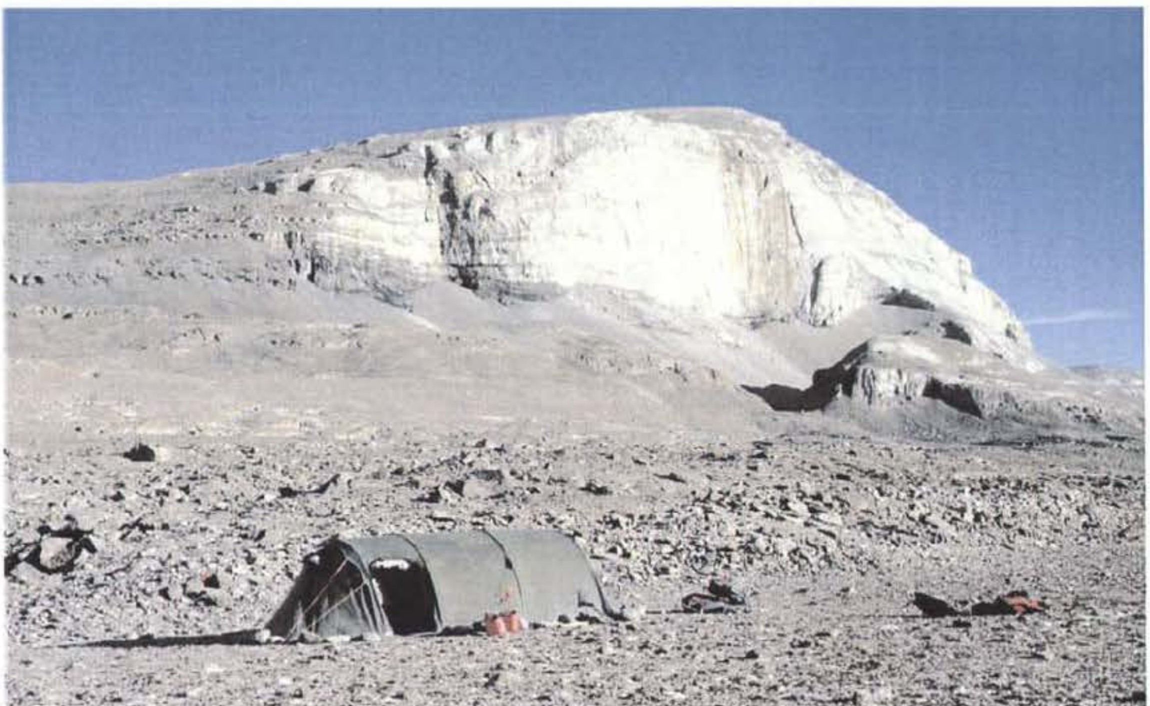

Figure 2. Silurian carbonate buildup sitting in dark, organic-rich shales. Washington Land.

Petroleum-related field studies

The petroleum-related field work in central East Greenland included 2 teams in one month in 1995, 8 teams for a full season in 1996, and 2–3 teams in 1997 and 1998 (partly financed by GEUS and Saga Petroleum). The field work included a post. doc. (O.R. Clausen) working with structural geology of the Mesozoic basin of Traill Ø and Geographical Society Ø (Fig. 1) together with J. Korstgård, a Ph.D. student (J. Therkelsen) studying the diagenesis of Jurassic sandstones, a Ph.D student (L. Seidler) working with the depositional evolution of the marine Lower Triassic sediments, and from 1997, a post. doc. (H. Vosgerau) working with Jurassic sedimentology and a Ph.D. student (T. Preuss) studying the thermal influence of Tertiary intrusions on reservoir properties. Furthermore, the Upper Palaeozoic and Mesozoic sediments in the Traill Ø – Clavering Ø area have been studied from 1995 and onward by F. Surlyk, M. Larsen, L. Stemmerik and N. Noe-Nygaard together with partners from Saga Petroleum (Snorre Olaussen, Bjørn Tørudbakken and Tor Nedkvitne) and a cand. scient. student from University of Copenhagen (M. Kreiner-Møller). Two cand. scient. thesis on Triassic and Jurassic ammonite stratigraphy, respectively, are near completion by students from University of Copenhagen (M. Bjerager, P. Alsen) in close co-operation with palynostratigraphic studies (S. Piasecki). In 1996, a team of biologists from National Environmental research Institute (P. Aastrup, F. Riget) was monitoring the wildlife in the northern part of the East Greenland sedimentary basin, mainly focussing on the distribution, number and herd structure of muskoxen on Traill Ø, Geographical Society Ø, Ymer Ø and Hold with Hope (Aastrup & Riget submitted).

In South-East Greenland field work was carried out by one team (post.doc. project by M. Larsen) in 1995 in the Mesozoic–Paleogene Kangerlussuaq Basin supported by the Danish Lithosphere Centre's expedition to the area. The aim was to establish a basic stratigraphic and depositional model for the basin. Field work was supported by Saga Petroleum and DOPAS, and involved geologists from these companies (Lars Hamberg, DOPAS and Snorre Olaussen, Saga Petroleum).

In North Greenland, petroleum-related field work was carried out in the Wandel Sea Basin in 1995 by L. Stemmerik and S. Piasecki. The work was a continuation of a regional mapping programme initiated in 1993 and focussed on Upper Palaeozoic sedimentology and stratigraphy and involved a cand. scient. project on Carboniferous palynology (C. Thomsen). In 1996 and 1997, combined petroleum and economic geological expeditions visited Wulff Land and Washington Land in western North Greenland. The petroleum-related studies focussed on sedimentological and geochemical aspects of the Cambrian and Silurian successions, and were continued in 1999 as part of GEUS mapping of Washington Land (LS, J. Ineson and M. Sønderholm).

Figure 3. Jurassic sandstone (light) faulted against Triassic sediments at the south coast of Traill Ø. Note numerous sills and dykes cut the section. The study by Therkelsen (submitted) is from this locality.

Results

The project has resulted in submission of 66 manuscripts to international journals and to the reviewed Geology of Greenland Survey Bulletin (GEUS own series) and at present 47 are published or accepted for publication (see bibliography). In addition data have been presented at more than 40 conferences (see list of abstracts). Since the project is a continuation of the petroleum and economical geological work carried out at the involved institutions over the last, more than 20 years, some of the results presented here, rely partly on data obtained as part of other externally financed projects.

In the following, the main results of selected focus areas will be summarised with reference to the work listed in the bibliography and the abstract list. Special emphasis was placed on the educational aspects and these results are summarised in a separate section.

Franklinian Basin mineral occurrences [15, 16] (12–14)

Two large zinc deposits are known from Arctic Canada, the Nanisivik deposit of the Borden basin and the Polaris deposit in the Canadian part of the Franklinian Basin (Fig. 1). Lead isotopes from these two deposits suggest that both occurrences were formed from hydrothermal fluids which have circulated through the oldest sediments in the Borden Basin remobilising zinc and lead. The isotope data thus indicate a common source of the metals in the two deposits despite they formed 1000 Ma and 365 Ma ago, respectively (Jensen 1997). Lead isotope studies of mineralizations in the Greenland part of the Franklinian Basin show that individual lead-zinc occurrences have a relatively homogeneous lead isotope signature, but that large variations exist between the occurrences. The Citronen Fjord deposit has the most radiogenic lead isotope ratios, probably reflecting a lead source in the crystalline basement. The less radiogenic lead isotope ratios of minor occurrences in the basin on the other hand are believed to reflect local remobilisation. On this basis it is suggested that favourable conditions for formation of large zinc-lead deposits exist around deep crustal lineaments within the basin, where there is good fluid communication to the underlying crystalline basement.

The model was tested in Washington Land where the combination of faulting and dolomitised host rocks were expected to be favourable by comparison to the Nanisivik and Polaris deposits in Arctic Canada. It resulted in the discovery of a new promising zinc-lead-silver occurrence hosted in Ordovician carbonates in eastern Washington Land (Jensen 1998a). The occurrence is characterised by radiogenic lead isotope ratios comparable to those seen in the Citronen Fjord deposit, suggesting a deep source for the metals. Most likely the hydrothermal fluids were carried along fault planes to porous, dolomitised zones with available sulphur.

Citronen Fjord zinc-deposit [18, 19, 26, 48] (8, 9, 15, 16)

Studies of the large Citronen Fjord zinc-deposit aim to understand the processes that led to accumulation of metals in Upper Ordovician – Lower Silurian deep-water mudstones.

The deposit consists of at least five major massive sulphide mounds of mainly pyrite, sphalerite and galena. Microscopic studies of the ore texture show that the massive mound contains primary (syndepositional) textures that are overprinted by later recrystallisation textures (Kragh et al. 1997). The most characteristic textural feature is spheres with a radial intergrowth of pyrite, carbonate, sphalerite and galena overgrown by colloform sulphides and finally sub- to euhedral pyrite. Laminated sulphides of framboidal pyrite with interstitial sphalerite, quarts, clay minerals and carbonate occur on the aprons of the massive sulphide mounds. These sulphides also display primary sedimentary and diagenetic textures like graded bedding, ripple cross-lamination and de-watering structures.

Sulphur isotope studies of pyrite in the non-mineralised mudstones indicate that the sulphides were deposited in two different palaeo-environments. The lower succession is characterised by heavy sedimentary pyrite with sulphur isotope values in the range +10‰ to +49‰ (CDT), indicating an anoxic to euxinic, restricted basin and very high bateriogenic sulphate reduction rates and thereby little fraction. The upper succession is characterised by pyrite with sulphur isotope values in the range ÷28‰ to +9‰ (CDT), indicating deposition under anoxic conditions. Sulphur isotope ratios in samples from the sulphide mounds range from +5‰ to +50‰ (CDT) with the lowest values recorded in the synsedimentary formed framboidal pyrite.

Fluid inclusion microthermometry of inclusions in the sphalerite indicates that the mineralising fluids were highly saline with moderate temperatures ranging from 80º C to 160º C (Kragh & Kontak submitted). The same temperature range is recognised on basis of oxygen isotope ratios of the associated dolomite whereas oxygen isotope ratios of the associated calcite indicate a somewhat lower temperature, in the range 50º C to 100º C. The fluid inclusion data are thus in accordance with the oxygen isotope data from the upper succession, indicating precipitation from a dense brine that formed at the sea floor.

Figure 4. Sulphide mound at Citronen Fjord.

Microbiological degradation of sulphides at Citronen Fjord [12, 21–26, 48] (19, 20)

The aim of this part of the project was to investigate the role of bacteria in oxidation of massive sulphides in a high Arctic area. It is based on studies at Citronen Fjord, where oxidation of exposed sulphides has produced impressive, vividly coloured gossans (Langdahl et al. 1998).

The investigations indicate that microbes can be almost omnipresent, even in environments as the Citronen Fjord gossans that is intuitively considered to be devoid of life (Langdahl & Elberling 1998). The diversity and distribution of acidophilic bacteria were determined using MPN-analysis (most probable number), plate counts, enrichments, plate isolations and ISR-region (intertranscribed spacer region) polymorphism analysis (Langdahl et al. submitted b). The number of mineral-oxidising bacteria reaches up to $4x10^4/cm^3$, which is comparable to the numbers found in mining areas at temperate latitudes. Surprisingly, the highest number of bacteria were found just above the permafrost layer at temperatures of 1 to 2º C. The number of bacteria decreases by an order of magnitude at the gossan surface. In small acid streams draining the gossans, the bacterial number of acidophilic iron oxidisers was comparable to that in the gossan material whereas low numbers were detected in streams unaffected by the heavy sulphide oxidation. ISR-region analysis of water and gossan material indicates that the bacterial diversity is very low. The ISR amplification product profiles obtained from either isolated strains of *Thiobacillus ferrooxidans* or from gossan and stream water samples show that *Thiobacillus ferrooxidans* was the most significant species in the area.

The porewater and small streams draining the gossans are characterised by low pH values (1.9-2.5) and high concentrations of dissolved metals and sulphate (Fe: 10.000 mg/l; Zn: 650 mg/l; Pb 16 mg/l and SO_4^{2-} 50.000 mg/l) in agreement with the surprisingly high oxygen consumption rates measured at the gossan surface (Elberling & Langdahl 1998). High rates of sulphide oxidation were observed in gossan material at temperatures around 0ºC due to the activity of an indigenous population of *Thiobacillus ferrooxidans*. Sulphide oxidation also occurs at measurable rates at subzero temperatures. Data obtaine from a pure culture of *Thiobacillus ferrooxidans* from the Citronen Fjord gossans, show that the strains of *Thiobacillus ferrooxidans* are capable of growing exponentially at -1ºC with ferrous iron as electron donor (Langdahl & Ingvorsen submitted). Activity of ferrous iron oxidation at -3ºC was still approximately 40% of the maximum recorded. This is the first study describing significant rates of ferrous oxidation by *Thiobacillus ferrooxidans* at temperatures below 2ºC (Langdahl & Ingvorsen 1997).

Furthermore, a novel acidophilic and psychrophilic yeast strain with optimum pH and temperature of 3-4 and 14ºC ,respectively, has been identified. It was capable of growing on several substrates, including polymeric substrates and tolerated heavy metals in high concentrations. It is described as a novel psychrophilic and acidophilic strain of *Cryptococcus albidus* var. *albidus* (Langdahl et al. submitted a), but genetic sequencing may reveal that it is a new species.

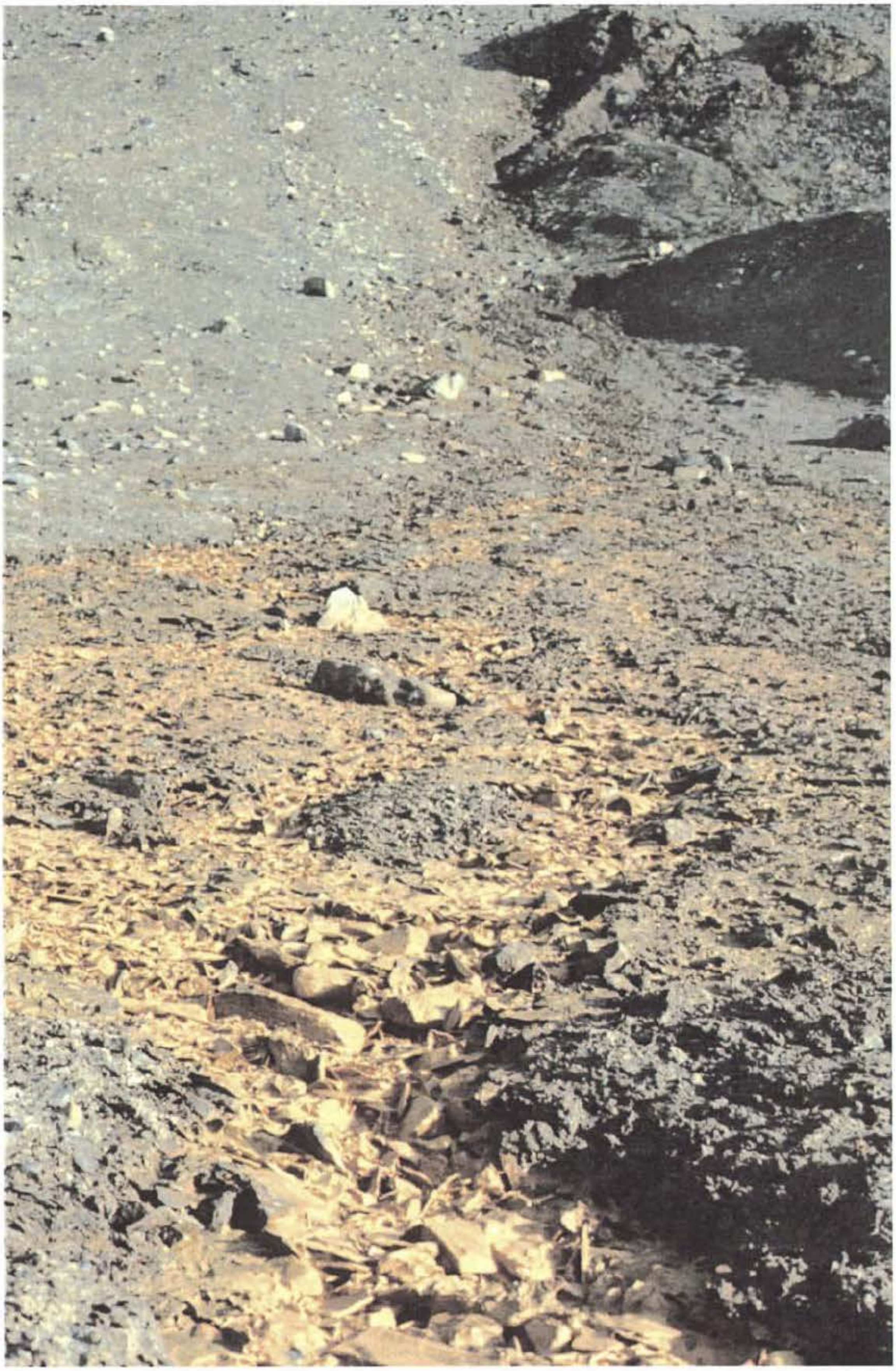

Figure 5. Small stream draining a gossan at Citronen Fjord.

Ravnefjeld Formation zinc- and lead occurrence [36, 37, 49] (26–28)

Kupferschiefer-type base metal mineralisations have been known since the 1960'es from the bituminous shales of the Upper Permian Ravnefjeld Formation at Wegener Halvø (Fig. 1). The aim of this part of the project was to constrain the timing and genesis of the mineralisation and to elucidate the relationships to metal occurrences in the time equivalent carbonate buildups of the Wegener Halvø Formation (Stemmerik et al. 1997a).

The Ravnefjeld Formation shales are mineralised in a c. 50 km² area to the west of the major Vimmelskaftet lineament. The main sulphide minerals are sphalerite and galena with some chalcopyrite present locally. The mineralised zone is confined to the lowermost metres of the formation, except at Lille Ravnefjeld immediately west of the lineament where the ore minerals have a considerable vertical distribution. The occurrence of base metal sulphides in concretions that were lithified prior to compaction suggests an early introduction of base metals (Nielsen & Pedersen 1997), and very homogenous lead isotope signatures of the galena and sphalerite indicate that it took place during one single hydrothermal event (Pedersen submitted). The base metal sulphides show sulphur isotope values between ÷4‰ and ÷13‰ (CDT), suggesting precipitation from sulphide-dominated pore water, enriched in ^{34}S due to preferential removal of ^{32}S by sulphide-reducing bacteria. The combined textural and isotopic evidence thus suggests that mineralisation of the Ravnefjeld Formation took place much earlier than precipitation of base metals in the associated Wegener Halvø Formation carbonate buildups that clearly post-dates hydrocarbon migration (Stemmerik et al. 1997a).

Figure 6. Black laminated shales of the Ravnefjeld Formation overlying karstified carbonates of the Wegener Halvø Formation, Wegener Halvø.

Kangerlussuaq Basin [10, 11, 30–32] (6, 10, 23, 25, 58)

The Cretaceous–Paleogene Kangerlussuaq Basin in southern East Greenland has attained little attention prior to field work in 1995, and the main objective therefore was to establish a depositional model for the basin fill based on modern stratigraphical concepts. The pre-drift position close to new petroleum exploration areas like the Faeroe–Shetland, Vøring and Møre basins makes the Kangerlussuaq Basin an interesting outcrop analogue for these, and other, volcanic-influenced basins (Larsen *et al.* 1996, 1999a, 1999b).

Field work led to the recognition of a more than 1 km thick sedimentary succession, including a Lower Cretaceous sandstone-dominated unit, at least 150 m thick, below the previously recognised oldest sediments of the Upper Cretaceous Sorgenfri Group (Larsen *et al.* 1996). The basin fill is divided into two megasequences related to regional tectonic events and sea level changes. The oldest megasequence was deposited in four different environments: (1) alluvial plain and shallow marine (Late Aptian), (2) fluvio-eustarine (Late Aptian – Early Albian), (3) offshore marine (Late Cretaceous – Early Paleogene), and (4) submarine fan and channel-levee (Early Paleocene) (Larsen *et al.* 1999a). Sea level rise started in the late Aptian with maximum flooding in the Late Albian – Cenomanian, followed by sea level highstand in the Late Cretaceous – Early Paleocene. The lower megasequence is truncated by a basin-wide unconformity related to regional uplift and reorganisation of the basin in the mid-Paleocene. The upper megasequence spans the mid- to Late Paleocene time interval and was formed under fluvial (mid-Paleocene) and volcanic (Late Paleocene) conditions. Deposition took place during early rise in sea level and was terminated by the formation of a thick successions of flood basalts.

The basin fill has been buried to a maximum depth of more than 6 km, and the basin has thus not a potential as a petroleum basin. The study forms the basis for development of conceptual play models that may serve as analogues for similar volcanically influenced offshore basins. Three such models have been developed: (1) An Early Albian stratigraphic trap with estuarine and marine mudstones as source and seal, and fluvio-estuarine sandstones as reservoir, (2) An Early Paleocene stratigraphicl trap with Upper Cretaceous mudstones a s possible source, Paleocene mudstones as seal and Paleocene submarine fan and channel-levee sandstones as reservoir, and (3) A Paleocene structural trap with Upper Cretaceous mudstones as possible source and Cretaceous–Paleocene mudstones as seal. Aptian–Albian sandstones form the reservoir of structural unconformity traps in rotated fault blocks. The traps formed during late Cretaceous–early Paleocene tectonic reorganisation of the Kangerlussuaq Basin (Larsen *et al.* 1999b).

The study of the Kangerlussuaq basinal fill has also added to the understanding of the response of the sedimentary basins along the North Atlantic margin to mantle plumes (Dam et al. 1998, 1999).

Figure 7. Continental flood basalts covering subvolcanic Cretaceous-Paleogene sediments of the Kangerlussuaq Basin (see Larsen et al. 1999a, 1999b).

Wandel Sea Basin [8, 9, 34, 35, 43–45, 47, 54–56] (7, 35–39, 41, 42, 44, 45, 47, 57)

The Wandel Sea Basin in eastern North Greenland is the northernmost of the post-Caledonian onshore basins along the east coast of Greenland. It has a complex structural history compared to the basins in East and South-East Greenland, and is characterised by Late Palaeozoic – Early Triassic extension and deposition in a simple system of grabens and half-grabens followed by Mesozoic strike-slip movements and deposition in isolated pull-apart basins. The Mesozoic events only influenced the northern part of the basin, north of the Trolle Land fault zone. Basin modelling excludes the basin as a potential petroleum basin, but the marine Upper Palaeozoic carbonates serve as analogues for the time-equivalent reservoir targets in the Barents Sea (Stemmerik *et al.* 1999b, 1999c).

The project has resulted in new biostratigraphic, sedimentological and structural data that have improved correlation to Spitsbergen, East Greenland and the Barents Sea (Dalhoff & Stemmerik 1999; Dalhoff *et al.* 1999; Stemmerik *et al.* 1996a; Stemmerik, 1999). The oldest post-Caledonian unit in the Wandel Sea Basin, the Lower Carboniferous Sortebakker Formation has been dated to the Upper Visean based on a poorly preserved but stratigraphically confined microflora in the upper part of the formation (Dalhoff *et al.* 1999). Dating of the overlying marine deposits has been refined using a variety of calcareous microfossils, and it has become apparent that a major early Permian hiatus is present throughout the basin (Stemmerik *et al.* 1996). It separates Upper Carboniferous warm water carbonates with abundant calcareous algae below from mid- to Upper Permian cool-water carbonates dominated by bryozoans and brachiopods above (Stemmerik *et al.* 1996a, 1999c; Stemmerik 1997, 1999; Mamet & Stemmerik 1999).

A structural study of northern Amdrup Land shows that the Sommerterrasserne fault is the south-eastern extension of the Trolle Land fault zone, and that it divides Amdrup Land and the adjacent shelf into two areas with different stratigraphic and structural evolution, and accordingly different thermal histories and hydrocarbon potential (Stemmerik *et al.* 1999a). The upper age limit of the Mesozoic structural event is given by the flat lying, stucturally undeformed Thyra Ø Formation. These sediments form the youngest preserved deposits within the Wandel Sea Basin and new palynological studies have shown a more diversified microflora of spores, pollen and dinoflagellates suggesting a latest Paleocene – early Eocene age of the sediments (Lyck & Stemmerik 1999).

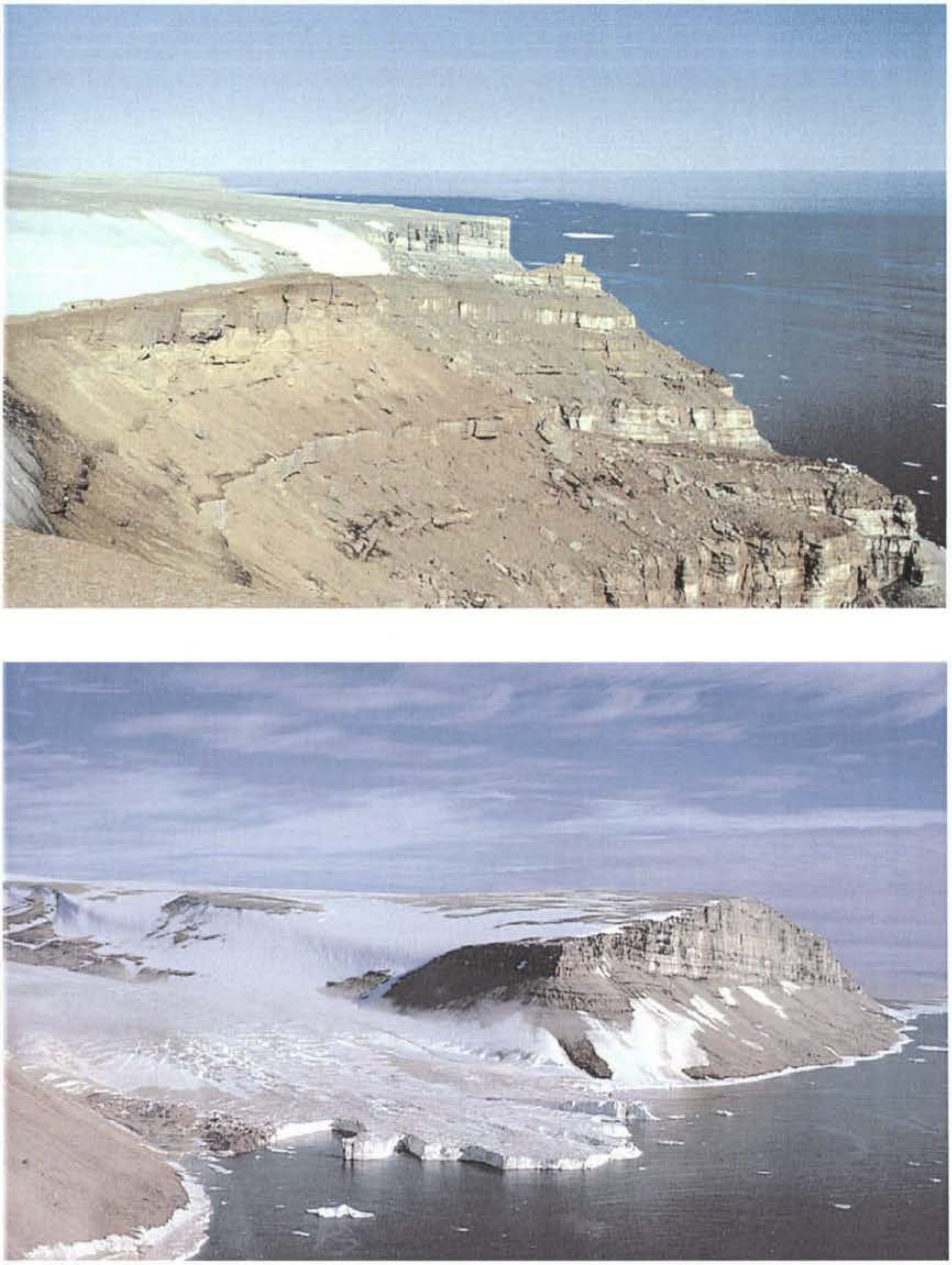

Figure 8. Upper Carboniferous, Moscovian-Gzelian sediments in eastern Holm Land. Above: cyclic interbedded siliciclastics and carbonates. Below: cyclic interbedded shelf carbonates and siliciclastic deposits; the upper part is dominated by shelf carbonates.

East Greenland Basin [2–7, 14, 19, 27–29, 33, 38–42, 46, 48, 49, 51–53, 57–66] (1–5, 17, 18, 22, 24, 29–34, 40, 43, 48–56, 59)

The post-Devonian sedimentary succession onshore central East Greenland was deposited in two basins with different structural and depositional histories. The southern Jameson Land basin between 70º and *c.* 72º N, is the best known of the two basins with a long exploration history for hydrocarbons and minerals, and the basin is a key area for Jurassic biostratigraphy. Studies of the Jurassic succession in this part of East Greenland are based on field data collected prior to and during the project and have particularly focussed on the Jurassic part of the succession (Engkilde & Surlyk 2000; Larsen & Surlyk 2000; Larsen *et al.* 2000; Surlyk 2000; Surlyk & Noe-Nygaard 2000; Surlyk *et al.* 2000; Stemmerik *et al.* 1998b). New data from northernmost Jameson Land indicate that the Upper Permian and Lower Triassic sediments were deposited on antithetic, eastward tilted fault blocks and apparently this part of the Jameson Land basin is more closely associated with the area to the north (Seidler 1999; Kreiner-Møller & Stemmerik submitted).

The project has resulted in a considerable amount of new biostratigraphic, organic geochemical and sedimentological data particularly from the Mesozoic succession in the North-East Greenland basin, north of *c.* 72º N (Stemmerik *et al.* 1996b, 1997c; Larsen *et al.* 1998). The stratigraphy of the oldest, uppermost Devonian – Carboniferous was established based on palynomorphs (Stemmerik *et al.* 1998a; Vigran *et al.* 1999). Palynomorphs have also been used to improve the stratigraphy of the Jurassic deposits at Hochstetter Forland and Store Koldewey in the northernmost part of the basin (Piasecki & Stemmerik submitted; Piasecki *et al.* submitted), and to date a Jurassic succession at northeastern Hold with Hope (Vosgerau *et al.* submitted a). The Jurassic coals in the northernmost part of the basin form a highly oil-prone source rock adding to previously recognised Jurassic and older source rocks (Bojesen-Kofoed *et al.* 1996, 1997; Petersen *et al.* 1998; Petersen & Vosgerau submitted). Ammonites form the basis of dating of the thermally post-mature Jurassic deposits in southeastern Traill Ø (Alsen & Surlyk submitted; Vosgerau *et al.* submitted b). These sediments differ from other Jurassic succession in East Greenland since they were deposited on an antithetic, eastward tilted fault block and show eastward deepening and eastward directed palaeo-currents, in contrast to the usual Jurassic pattern of westward tilted blocks and southward deepening and southward directed palaeo-currents (Vosgerau *et al.* submitted b).

Studies of the Cretaceous succession have focussed on the deltaic and shallow marine sediments in northern Hold with Hope and on gravity flow deposits along faults in Traill Ø, Geographical Society Ø and Hold with Hope (Larsen et al. submitted; Surlyk and Noe-Nygaard submitted). The Lower Cretaceous sandstones in northern Hold with Hope occur on the crests of a Jurassic fault block. The deltaic sandstones reflect at least two episodes of southwards progradation separated by a marine flooding event. and is overlain by tidally influenced shallow marine sandstones grading into offshore mudstones (Larsen et al. submitted).

A major change in basin organisation occurred at the end of the Early Cretaceous; it is reflected by a change from shallow marine into deep marine deposition. The sea-level rise led to submergence of the Jurassic rift topography and mud deposition dominated throughout the Late Cretaceous. Locally sandy turbidites and fault scarp derived conglomerates are present indicating palaeocurrents towards the east. The Upper Cretaceous of East Greenland thus may form an onshore analogue to the gravity flow deposited sandstones in the deeply buried Cretaceous succession of the Vøring Basin.

The studies in East Greenland have resulted in an improved biostratigraphic zonation, better understanding of controls on depositional facies and thereby distribution of reservoir and source rocks within the basin, and the first more detailed diagenetic studies of potential reservoir units. These data are important for developing petroleum system models for the basin and when the detailed stratigraphic, sedimentological and diagenetic studies have been completed the aim is to publish a model for the petroleum systems in the East Greenland basins. Preliminary integration of the data into coherent petroleum system models has been attempted (Larsen et al. 1998; Stemmerik et al. 1999-abstract), and it is evident that several new petroleum systems will be described.

Figure 9. Barremian-Aptian sandstones of the Steensby Bjerg Formation crop out in a prominent coastal cliff in northern Hold with Hope. The sandstones consist of large-scale foreset units, up to 50 m thick, representing southwards prograding deltas.

Education

The project has supported 7 Ph.D. and 4 cand. scient. (~M. Sc.) projects of which two Ph.D. and two cand. scient. projects are completed. Two Ph.D. projects started in 1997 and they are expected finished by the end of year 2000, while the remaining Ph.D. and cand. scient projects are in their final stage of compilation and expected to be completed within the next six months. The Ph. D. and cand. scient. students have so far contributed to 22 of the 66 submitted manuscripts [2, 10, 15–23, 29, 30, 33, 39, 45, 48, 55, 57, 58, 61, 62] and to 22 of the 59 abstracts (1, 2, 4, 8, 9, 15–20, 28, 30–34, 55–57, 59).

The completed Ph.D. projects by Henrik Fougt ("The Citronen Fjord mineralisation, North Greenland – a sulphur isotope and geochemical study of the Lower Palaeozoic sediments hosting the Zn-Pb mineralisation and a detailed sulphur isotope study and textural study of the mineralisation") and Bjarne R. Langdahl ("Acidophilic microorganisms in a High Arctic gossan environment – ecology, physiology and phylogeny of indigenous acidopiles") are both based on field studies in the Citronen Fjord area. The results of these two theses are included in the previous sections on the Citronen Fjord zinc-deposit and the microbiological degradation of the sulphides. Aspects of the Citronen Fjord mineralisation is also the topic of a nearly finished Ph.D. project by Karsten Kragh ("Mineralogical, petrological and chemical characteristics of primary and diagenetic sulphides from the Citronen Fjord lead-zinc deposit, North Greenland"). A fourth economic geological Ph.D. project by Jesper K. Nielsen focuses on the sulphides in the Ravnefjeld Formation of East Greenland ("Integrated morphological and geochemical study of suphides with respect to palaeoenvironment, palaeotemperature and basinal fluids, Ravnefjeld Formationen, Upper Permian, East Greenland") and is expected to be completed in late 2000.

The three sedimentological Ph.D. projects are all based on material from central East Greenland. Jens Therkelsen is undertaking a diagenetic study of Jurassic sandstones in the Traill Ø area, equivalent to the Brent Group in the northern North Sea ("Petrography and diagenesis of the Jurassic sandstones in the Traill Ø area, East Greenland"), expected to be completed early in year 2000. Thomas Preuss is studying the thermal effect of Paleogene intrusives on the diagenesis of Upper Carboniferous – Cretaceous sandstones in order to predict effects on reservoir quality in the volcanic influenced offshore basins. This study ("Thermal maturity of volcanic influenced sedimentary basins, central East Greenland") is planned to be finished by the end of year 2000. The sedimentological study of the Lower Triassic Wordie Creek Formation by Lars Seidler ("A sedimentological and sequence stratigraphic interpretation of the Lower Triassic Wordie Creek Formation in East Greenland") mainly focuses on the interplay between tectonism and development of the depositional systems. The work is in its final stage and will be completed in late 1999.

The completed cand. scient theses deal with Upper Carboniferous palynomorphs in the Wandel Sea Basin (C. Thomsen, 1998: "Upper Carboniferous (Moscovian) miospores from the Kap Jungersen Formation, Amdrup Land, eastern North Greenland (in Danish)") and the sedimentology of the Upper Permian Bredehorn Member in East Greenland (M. Kreiner-Møller, 1999: "Sedimentological and hierarchic element analysis of the Schuchert Dal Formation, Upper Permian, East Greenland (in Danish)"). The projects dealing with Triassic (M. Bjerager: "Ammonite stratigraphy of the Lower Triassic Wordie Creek Formation, East Greenland (in Danish)") and Jurassic ammonites (P. Alsen: "Middle Jurassic ammonite stratigraphy, Traill Ø, central East Greenland (in Danish)") in East Greenland will be finished late in 1999.

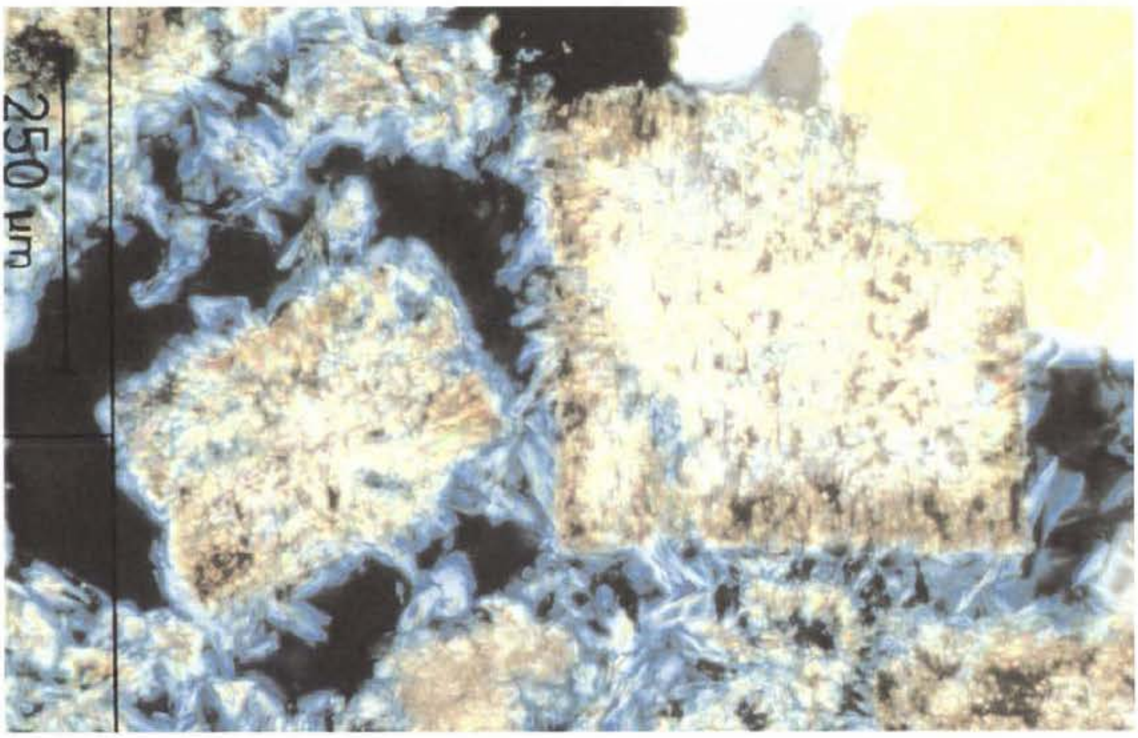

Figure 10. Microphotograph of two euhedral pseudomorphed crystals of coarse-grainesd illite flakes probably representing replacement of andalusite close to a Paleocene sill intruding into Middle Jurassic sandstones. Traill Ø.

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K: Kangerlussuaq Basin
EG: East Greenland basins
NG: North Greenland (Franklinian Basin)
WSB: Wandel Sea Basin
-E: Economic geology
-B: Biological-/Microbiological-related
-P: Petroleum-related

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