Metamorphic study of metasediment from the Kangilinaaq Peninsula, West Greenland

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Abstract

The Nagssugtoqidian Orogen is represented by an approximately 300 km wide Palaeoproterozoic deformation and metamorphic belt that stretch through the southern and middle parts of west Greenland. The Orogen is characterized and dominated by metamorphosed Archaean orthogneisses with minor supracrustal sequences. Despite its small extent the supracrustal sequences are an important factor in the interpretation of the tectonic evolution of the orogen because these rocks develop a wide range of distinctive mineral assemblages that characterise specific metamorphic zones, and can tell us about the rocks P-T history.

On the Kangilinaaq Peninsula southeast of Christianshaab/Qasigianquit in the northern part of the Nagssugtoqidian Orogen, West Greenland a relatively small belt of supracrustal rocks is situated. The geology of the area is known from earlier mapping but no detailed mapping or micro structural work is documented. Through the area a marble layer stretches with metasedimentary sequences on either side. The behaviour of the marble during deformation and the composition, deformation and metamorphic history of the metasediments were of specific interest in this study. A clear difference in metamorphic history of the metasediments on either side of the marble could indicate that the marble acted as a tectonic boundary (thrust) between two metasedimentary sequences of different origin.

The study showed that the rocks are of pelitic composition and have been metamorphosed in the upper amphibolite facies. No evidence was found indicating that the rocks have been at higher metamorphic grad. The metapelitic rocks sampled for this study showed similar mineral assemblages and metamorphic structures on either side of the marble. Therefore no evidence was found that show the marble was the site of a thrust.

Since the supracrustal rocks are important for the understanding of the tectonic evolution of West Greenland, are the correlations between these areas are of great interest. Metasediments from the Kangilinaaq Peninsula show lithological and mineralogical similarities to the metasediments described from the Naterraq and Ikamiut areas and a continuation of the sediments between these areas can therefore not be excluded. Four deformation phases (D1-D4), large scale structures, are known from the Nagssugtoqidian Orogen. At least three deformation phases, with F2 as the dominating structure, have been identified in the metapelites from the studied area. If the sediments from the Kangilinaaq Peninsula can be correlated with other sediment belts in the NNO, the dominating local foliation (F2) probably were formed during regional D3.

Keywords: West Greenland, Nagssugtoqidian Orogen, supracrustal rocks, Kangilinaaq Peninsula, metasedimentary rocks, pelites, correlation

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Metamorf studie på metasediment från Kangilinaaq halvön, Västra Grönland

Sammanfattning
Den Nagssugtoqidiska orogenen är ett cirka 300 km brett Paleoproterozoiskt deformatert och metamorfosert bält som sträcker sig över de södra och mellersta delarna av västra Grönland. Bergarterna karaktäriseras och domineras av metamorf arkeisk ortognejs och en mindre del supkrustala sekvenser, där metasediment finns representerade. Trots sin ringa omfattning utgör de supkrustala sekvenserna en viktig faktor i tolkningen av orogenesens storskaliga tektoniska utveckling, då det i dessa bergarter utvecklas mineralparageneser som karaktäriserar de tryck och temperaturer bergarterna utsätts för under deformationen.

På yttersta spetsen av Kangilinaaq halvön sydöst om Christianshaab/Qasigiannguit i de norra delarna av den Nagssugtoqidiska orogenen på västra Grönland sträcker sig ett mindre bält av supkrustala bergarter. Områdets geologi är sedan tidigare känt men inga detaljkarteringer eller mikrostrukturella studier av bergarterna finns dokumenterade.

Genom den västra delen av området sträcker sig ett marmorlag som är över- och underlagrat av andra metasedimentära sekvenser. Marmorns roll under områdets deformationshistoria och metasedimentens sammansättning, deformations- och metamorfa historia utgör huvuduppgifter för detta arbete. En fråga som diskuterades var huruvida marmorn var en del i en likåldrig sedimentsekvens eller om detta lager hade agerat som ett glidplan mellan två sedimentsekvenser av olika ålder och ursprung, vilket har observerats i andra orogeneser.

Studien visade att de provtagna bergarterna var metasediment av politisk sammansättning som metamorfoserats i övre amfibolitfacies. Inga indikationer på att bergarterna tidigare varit utsatta för högre metamorf grad har hittats. I denna studie kunde inte marmorns eventuella funktion som överskjutningszon påvisas, då de provtagna metapeliterna över och under marmorhorizonten visade stor likhet i mineralsammansättning och metamorfa mikrostruktur.

Då de supkrustala bergarterna utgör en viktig faktor för förståelsen av den storskaliga tektoniska utvecklingen av västra Grönland, är korrelationen mellan de olika sedimentområdena av stor vikt. De metasedimentära bergarterna på Kangilinaaq Peninsula visar att det finns en stor litologisk och mineralogisk likhet med sedimentsekvenser beskrivna från Naternaq och Ikamiut områdena och en möjlig korrelation mellan dessa områden bör därför inte uteslutas. Den Nagssugtoqidiska orogenesen tros ha utsatts för fyra deformationsfaser (D1-D4), vilka är tolkade från storskaliga strukturer. Minst tre deformationsfaser, med F2 som den dominerande strukturen, har kunnat tolkas utifrån mikrostrukturer i bergartsproverna. Om det supkrustala bältet på Kangilinaaq halvön kan korreleras med andra supkrustala bälten i de norra delarna av den Nagssugtoqidiska orogenen och om dessa bälten veckats i storskaliga veckstrukturen kan den dominerande lokala foliationen (F2) i metapeliterna anses ha utbildats under den storskalig deformationsfasen D3.

Nyckelord: Västra Grönland, Nagssugtoqidiska orogenesen, supkrustala bergarter, Kangilinaaq Peninsula, metasedimentära bergarter, peliter, korrelation

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1 Introduction 5
2 General overview of field work 2002 6
3 Outline of thesis and main aim 7
4 Geological Setting and current Interpretation of the Nagssugtoqidian Orogen 8
   4.1 Southern foreland 8
   4.2 The Southern Nagssugtoqidian Orogen 8
   4.3 The Central Nagssugtoqidian Orogen 8
   4.4 The Northern Nagssugtoqidian Orogen 8
5 Tectonic evolution of West Greenland 9
6 Interpretation of lithotectonic elements (van Gool et al., 2002) 9
   6.1 Archaean precursors to paleoproterozoic orogenesis 9
   6.2 Kangâmiut Dyke swarm (2040 Ma) prior to the Nagssugtoqidian Orogeny 10
   6.3 Drift phase (1950-1920 Ma) 10
   6.4 Convergence – calc-alkaline magmatism (1920-1870 Ma) 10
   6.5 Collision (1860-1840 Ma) 10
   6.6 Metamorphism 10
7 The metasedimentary belts of NNO 11
   7.1 Naternaq (Lersletten) 11
   7.2 Ikamiut 11
   7.3 Isfjord and Akugdlinguaq sequences 12
   7.4 Continuation of Naternaq area, to the East (Areas 28 and 29) 12
   7.5 The Kangilinaaq Peninsula 12
8 Methods 13
   8.1 Field observations 13
      8.1.1 South of the Marble 13
      8.1.2 Marble 14
      8.1.3 North of the Marble 14
   8.2 Structures (Kangilinaaq peninsula) 15
   8.3 Optical microscopy, SEM and EDS-analyses 15
9 Petrography and Mineralogy 16
   9.1 South of the marble (sample nr 489648, 489649, 489650, 489652, 489653, 489654, 489657, 489658) 16
      9.1.1 Sample nr 498654 17
      9.1.2 Sample nr 498652 18
      9.1.3 Sample nr 498658a and b 18
      9.2 Marble (sample nr 498651) 18
      9.3 North of the marble (sample nr 489655, 489656) 19
10 Discussion 20
   10.1 Metamorphism and Deformation History 20
   10.2 Comparison of lithologies and assemblages south and north of the Marble 24
   10.3 Comparison of lithologies and mineral assemblages with Naternaq and Ikamiut 24
   10.4 Regional geology 25
11 Conclusions 25
12 Acknowledgments 25
13 References 26
Appendix A  
Appendix B  
Appendix C  
Appendix D
1 Introduction

The field area is situated in the northern part of the Nagssugtoqidian Orogen in West Greenland. In 1949, Ramberg made the original definition of the Nagssugtoqidian Orogen as the region located approximately between Sendre Strømfjord and Disco Bugt in West Greenland (van Gool et al., 2002a, Fig. 1). The Nagssugtoqidian Orogen is represented by an ENE-trending, 300 km wide Palaeoproterozoic deformation and metamorphic belt. This deeply eroded mountain chain is situated between the North Atlantic Craton of south Greenland and a northern continental segment, including the Rinkian Belt. The Nagssugtoqidian Orogen is thought to be part of an extensive group of Palaeoproterozoic orogenic belts that extend from Canada through Greenland and Scotland over to the Baltic Shield (van Gool et al., 2002a). The Nagssugtoqidian Orogen is subdivided into three segments; the southern (SNO), central (CNO) and northern (NNO) Nagssugtoqidian Orogen. The orogen is characterized and dominated by reworked Archaean orthogneisses with minor supracrustal sequences. Studies of the supracrustal rocks are an important factor in the interpretation of the tectonic evolution of the orogen. In the NNO there are several sedimentary belts (Fig. 2, area 1-5), which show strong similarities in terms of lithologies and mineral assemblages. The depositional ages of these supracrustal belts are, at present, thought to be enigmatic (van Gool et al., 2002a, Hollis et al., 2004).

Fig. 1. Geological map of the Nagssugtoqidian Orogen, modified from Garde et al. 2004
GEUS’s (Geological Survey of Denmark and Greenland) recent mapping project in the Nagssugtoqidian Orogen area shows that evidence of Archaean and Palaeoproterozoic metamorphism and deformation are not uniformly represented in the belt. Part of GEUS work is concentrated on trying to locate and establish the age of the larger metasedimentary belts in the Northern Nagssugtoqidian region, to correlate the supracrustal rocks and to understand why different Archaean metamorphic mineral assemblages are preserved in different regions. Preliminary dating results show both Archaean and Proterozoic ages for metasediments from the Nagssugtoqidian Orogen (Thrane & Connelly, 2002). Keiding’s study (Keiding, 2004), based on Lu-Hf and U-Pb isotope data for zircons from samples taken from the Kangilinaaq Peninsula (Fig. 2, area 1), show metasediments containing zircons of Archaean age as old as 3.6 Ga.

Parallel with the main mapping project in the NNO, other projects have recently been carried out to investigate and compare the tectonic evolution of the Nagssugtoqidian Orogen with the Rinkian Belt situated to the north. Results from mapping in the northern part of the Nagssugtoqidian Orogen and field studies in the central and northern parts of the Rinkian Belt have confirmed the strong link between the developments of the two belts (van Gool, 2004a).

2 General overview of field work 2002

The fieldwork in the summer 2002 was part of a three-year long mapping project, 2001-2003, in West Greenland. The expedition was a cooperation between the department of geological mapping and the department of economical geology at GEUS (Geological Survey of Denmark and Greenland). In 2002, the fieldwork was carried out mainly in the northern segment of the orogen (NNO), producing a 1:100 000 scale geological map of the Kangersuneq map sheet, situated between 68°30’-69°N and 49°45’-51°45’W.

The Kangersuneq area is situated in the northern part of the Nagssugtoqidian Orogen at the transition to the Rinkian belt (Fig. 1, area A and Fig 2, area A). The area is known from coastal reconnaissance mapping in the late 1960: s, spot visits by geologists from the Danish Lithosphere Center in 1994-1997 and local mapping along the coast by GEUS in 2001. Before the start of this fieldwork most of the inland in this area had only been studied from aerial photographs. The area is dominated by Archaean orthogneisses, with large (up to km-scale) enclaves of supracrustal rocks. During Palaeoproterozoic time, they were exposed to mainly amphibolite facies conditions (van Gool, 2001, unpublished). The last days of the fieldwork in 2002 were carried out on the Kangilinaaq peninsula (Fig. 2, area 1 and Fig. 3, sample map) in order to collect data and material for this thesis work.
3 Outline of thesis and main aim

This thesis work is built on a very limited field study on the Kangilinaaq Peninsula, Northern Nangssugtoqidian Orogen, West Greenland in 2002. Metasediments from the tip of the peninsula, southeast of Christianshavb/ Qasigiannguit (Fig. 2, area 1 and Fig. 3, sample map), were sampled for metamorphic studies. The area was known from spot visits during earlier field work by the GEUS field crew, but no detailed studies have been documented from the area. Through the peninsula, a metamorphosed marble stretches, with metasediment packages both to the south and to the north. Marble is a soft rock type and appear weaker and more ductile in nature than for example quartz rich rocks under deformation (Brodie & Rutter, 2000) and can therefore easily work as a sliding horizon. Examples of this can be seen in the Alps where the nappes have slid on thin layers of marbles. Also in Greenland, shear zones associated with marble are found both in the CNO where often Palaeoproterozoic marble in thin lenses lie along thrust zones and in the Rinkian Belt, where Palaeoproterozoic marble is found in thin layers between Archaean orthogneisses (Henderson & Pulvertaft, 1987; van Gool et al., 2002a, Garde et al., 2002 & Garde 2003, pers. comm).

Investigations of the marble with surrounding metasediments were of interest and the main purpose of this thesis study is to:

- determine the petrography and mineralogy of the sampled metasediments from the Kangilinaaq Peninsula
- establish the sequence of metamorphic and deformation events recorded by the metasediments
- compare the metamorphic textures and mineral assemblages in the metasediments on either side of the marble. A clear difference in metamorphic history could indicate that the marble acted as a tectonic boundary (location of thrust)
- make a comparison, based on literature, between metasediments from the Kangilinaaq peninsula and metasediments from the Nateraq and Ikamiut areas to track a possible continuation between the belts

Fig. 3. Sample and detail map, area 1 on Figure 2, scale 1:16000, showing map units and sample locations on the tip of the Kangilinaaq Peninsula
4 Geological setting and current interpretation of the Nagssugtoqidian Orogen

4.1 Southern foreland
The southern foreland represents a complex assembly of early to late Archaean granulite facies gneisses with several sets of intrusive mafic dykes. The steeply dipping, Palaeoproterozoic, NNE-trending Kangâmiut dyke swarm is not only the most voluminous of the dyke swarms but also of great importance in the definition of the southern limit of the Nagssugtoqidian Orogen (van Gool et al., 2002a).

4.2 The Southern Nagssugtoqidian Orogen
The southern boundary of the orogen, the southern Nagssugtoqidian front (SNF, Fig. 1) was defined by Ramberg (1949) on the basis of the reworked Palaeoproterozoic Kangâmiut dyke swarm. Within the orogen, the dykes are deformed and metamorphosed together with the country rock. In the southern foreland, the dykes are undeformed and discordant in respect to the structures in the surrounding gneiss. Amphibolite facies gneisses dominate the SNO but the metamorphic grade increases from amphibolite facies to granulite facies towards the contact between SNO and CNO (van Gool et al., 2002a).

4.3 The Central Nagssugtoqidian Orogen
The CNO is divided into three ENE-trending belts. The Palaeoproterozoic Sisimiut Charnockite dominates the western part of the southern belt and homogenous high-grade Archaean granitoid gneisses are found in the eastern part of the southern belt. The Nordre Isortoq steep belt forms a central belt with Archaean orthogneisses interleaved with Archaean and Palaeoproterozoic paragneisses (Fig. 1). The largest volumes of continuously exposed Paleoproterozoic supracrustal rocks in the orogen can be found in this belt. The steep belt grades into the northern CNO flat belt. This northern belt is a large antiform structure with open, upright folds and contains mainly Archaean orthogneisses but also some Palaeoproterozoic supracrustal sequences. The Palaeoproterozoic rocks are named the Ussuit unit and are intruded by Palaeoproterozoic calc-alkaline quartz-dioritic to tonalitic rocks. The southern and the central CNO are dominated by Palaeoproterozoic granulite-facies assemblages, whereas the northern CNO varies from granulite facies in the west to amphibolite facies towards the east. An ENE-trending linear gneiss belt, the Nordre Strømfjord Shear Zone, separates the CNO from the NNO and is one of the main structures that give the Orogen its dominant ENE grain (Fig. 1, van Gool et al., 2002a).

4.4 The Northern Nagssugtoqidian Orogen
This northern part of the orogen is the least known segment and has a significant different character than the centre of the orogen (van Gool et al., 2002b). It contains Archaean gneisses through which several thin supracrustal belts extend of which some are deformed in large-scale fold structures. The Palaeoproterozoic deformation and metamorphism are quite variable in intensity showing metamorphism of amphibolite facies grade with pockets of upper greenschist grade and at places areas, where partial melting occur (van Gool, 2004a, b). Metasediments from different supracrustal belts have been shown to contain zircons of Archaean and Palaeoproterozoic age. According to Thrane & Connely (2002) it is at this stage not possible to say whether the sediments have an Archaean or a Palaeoproterozoic depositional age. In the NNO, both steep and shallow-dipping shear zones occur. The Palaeoproterozoic deformation in the Archaean gneisses of the NNO decreases gradually to the north and persists northwards into the Rinkian Belt. No definite northern limit of the orogen has been defined. In most of the rocks in NNO, the metamorphic grade is amphibolite facies with no obvious signs of ever having been at higher grade. Only in the southwestern section, granulite facies rocks can be found (van Gool et al., 2002a). Both Archaean and Palaeoproterozoic metamorphism and structural imprints are variable in the NNO (van Gool, 2004b), which indicates a heterogeneous development during the Palaeoproterozoic (van Gool, 2004a).
5 Tectonic evolution of West Greenland
The tectonic evolution of West Greenland is interpreted as a Wilsonian cycle, which involves separation, convergence and eventual collision of two continental masses (van Gool et al., 2002a, Fig. 4). One published interpretation of the geological evolution in this area is the model presented by Van Gool et al. (2002a). In this model, the colliding plates were the North Atlantic Craton to the south and an Archaean plate, called the Ilulissat Craton in Fig. 4, which includes the Rinkian Belt to the north. The most convincing evidence for Palaeoproterozoic inter-continental collision would be the presence of two crustal blocks with distinct pre-collisional tectonic histories either side of the suture. At present, field observations and available Archaean ages for the gneisses across the Nagssugtoqidian Orogen cannot differentiate two distinct blocks (van Gool et al., 2002a).

6 Interpretation of lithotectonic elements (van Gool et al., 2002a)
The constructed model primarily reflects lithotectonic relationships from the CNO but is consistent with observations and data from the rest of the orogen.

6.1 Archaean precursors to palaeoproterozoic orogenesis
Reworked Archaean gneisses dominate all segments of the Nagssugtoqidian Orogen and a complex pre-Nagssugtoqidian history can be seen in areas of low Palaeoproterozoic strain. Field relations show a general age progression from dioritic to granodioritic, tonalitic, and granitic plutonism and the youngest phases intrude sequences of supracrustal rocks. Approximately 300 m wide sequences of metavolcanics with minor siliciclastic rocks dominate the Archaean supracrustal sequences. Granodioritic to granitic gneisses have been dated and give late Archaean ages between 2870 and 2700 Ma. In the northern CNO, older crustal components from orthogneisses have given mid-Archaean ages (3147 ± 6 Ma ion microprobe (SHRIMP) zircon age). Detrital zircons from the CNO and SNO have been dated to mid-Archaean and Pb and Nd-isotope data from CNO and NNO show 3.1 – 3.2 Ga components.

![Fig. 4. Schematic model for the tectonic evolution of the Nagssugtoqidian Orogen. p.e.s., present erosion surface; AIS, Arfersiorfik intrusive suite; SCS, Siaimiut charnockite suite; ITZ, Ikertöq thrust zone; NSSZ, Nordre Strømfjord shear zone; NISB, Nordre Isotoq steep belt. Modified from van Gool et al., 2002.](image-url)
6.2 Kangâmiut Dyke swarm (2040 Ma)-prior to the Nagssugtoqidian Orogen

The formation of the Kangâmiut dyke swarm is one of the oldest Palaeoproterozoic events in the orogen (Fig. 4). The dykes in the main swarm have intrusive ages of ca. 2040-2050 Ma. Field relationships of well-preserved dykes show that most of them intruded into brittle fractures. There is a debate whether the dykes intruded in a strike-slip or an extensional tectonic setting. Van Gool et al., (2002a) prefer the second model of an extensional tectonic setting related to continental break-up prior to the formation of the Nagssugtoqidian Ocean.

6.3 Drift phase (~2000-1920 Ma)

The continent break-up and the formation of the Kangâmiut dyke swarm were transitional to a phase of separation of continental plates and the creation of depositional basins both on the margin of and distal to the North Atlantic Craton (Fig. 4). A number of supracrustal sequences have been recognised within the orogen. They are partially melted and highly tectonized and form at many places 50-200 m wide panels interleaved with Archaean gneisses. Some are clearly intruded by Archaean granite and must therefore be of Archaean age. Others are of Palaeoproterozoic age, based on detrital zircon populations and on isotopic signature.

6.4 Convergence – calc-alkaline magmatism (1920-1870 Ma)

The best evidence for continental convergence with consumption of oceanic crust is Palaeoproterozoic calc-alkaline magmatic rocks found in the CNO (Fig. 4). These rocks occur as one charnockite suite, interpreted to reflect a continental arc, in the southern CNO and two igneous complexes interpreted to represent an oceanic arc setting, in the northern CNO. It is likely that these suites represent a single arc that varied along strike from oceanic to continental. The direction of the subduction is at present not established.

6.5 Collision (1860-1840 Ma)

West – to NW-directed thrusting is the earliest deformation (D1) and marks the onset of the continent collision. The crustal thickening by thrust stacking and following isoclinal folding (D2) led to peak metamorphism at ca. 1860-1840 Ma (Fig. 4). During this period sequences of Palaeoproterozoic supracrustals and intruded arc rocks in the CNO were interleaved with Archaean gneisses. The orientation of the F2 folds are not consistent and field observations indicates folds with several generations of structures. Post-collisional deformation (D3) is defined by large-scale folding, with an east-west trend, which became the dominant response to crustal shortening and the initial WNW-ESE directed thrusting changed to approximately north-south (Fig. 4). Contemporaneous with F3 folding low-angle, high-strain shear zones are developed, seen both cutting and folded by F3 folds. The youngest major structural event is deformation (D4) concentrated to strike-slip shear zones in the Nordre Størmfjord shear zone at ca. 1775 Ma (Fig. 4). Several granite intrusions, with ages in the range of 1780-1770 Ma are interpreted to be related to the strike-slip shearing.

6.6 Metamorphism

Archaean orthogneisses reworked up to granulite facies grade metamorphism dominates the Nagssugtoqidian orogen. The CNO is predominantly in granulite facies, except for the north-eastern corner, which is retrogressed to amphibolite facies, whereas the rocks in the SNO reflect amphibolite facies conditions. Recent work in the NNO has shown that the predominant amphibolite facies metamorphism alternates with areas of lower metamorphic grade. Both Archaean and Palaeoproterozoic metamorphism and structural imprints are variable in the NNO which indicates a heterogeneous development during the Palaeoproterozoic (van Gool, 2004a). Estimates of the peak metamorphic conditions are few, but in the CNO geothermobarometric studies yield temperatures of 800°C at pressures of 7-9 kbar. The peak metamorphism in the CNO occurred at ca. 1860-1840 Ma. A thermal peak is dated to ca. 1785-1780 Ma in the SNO and at ca. 1780-1740 Ma in the NNO and southern foreland. According to van Gool (2004a) was the metamorphic zonation was until recently assumed to be gradually decreasing away...
from the core of the orogen which is in accord with a collisional deformation starting in the CNO and subsequently spreading laterally (north and southwards) into the hinterland and foreland, expanding the width of the orogen. The orogen is now rather considered as a asymmetric orogenic belt and not representing a simple model of an orogenic belt expanding outwards from a single core in the south. Recent field observations strengthen the thoughts of the parallel evolution of the Rinkian Belt and the Nagssugtogidjan Orogen which would mean an orogenic region extending over 1000 km in West Greenland (van Gool, 2004a).

7 The metasedimentary belts of the NNO
In the NNO several large metasedimentary belts occur (Fig. 2, area 1-5), the rocks show strong similarities in lithologies and mineral assemblages. Work is concentrated on the correlation between the belts in the search for understanding the large scale geological history of this part of West Greenland. In the Ikamiut and Naternaq areas relatively large, well known and well studied sedimentary belts occur. Previsously unknown smaller sediment sequences also exist and recent minor field studies indicate similarities with the larger belts. During the initial stage of the fieldwork in 2002 the GEUS field crew shortly visited the supracrystal rocks in the Qasigiannguit/Christianshåb area. The studied area for this thesis, the Kangilinaq Peninsula is in the vicinity of the Qasigiannguit/Christianshåb area. According to the present opinion, the supracrystal rocks near Qasigiannguit/Christianshåb may once have been contiguous with the Naternaq supracrystal belt and the rocks in the Ikamiut area (Østergaard et al. 2002, Fig. 2, area 1-5).

7.1 Naternaq (Lersletten)
In central West Greenland Naternaq, or Lersletten constitute an extensive Quaternary outwash plain. The Naternaq supracrystal belt occurs along the north-western margin of Lersletten, bordered on both sides by Archaean orthogneisses and granitic rocks (Fig. 2, area 2). The three main rock types that dominate this supracrystal sequence are amphibolite, fine-grained siliceous quartzo-feldspathic rocks and garnet-mica schist (Østergaard et al., 2002). The belt is known for its disseminated and massive iron sulphide mineralization, with minor copper and zink. The interior part of the supracrystal belt at Naternaq is a 200-300 m thick succession of mainly siliceous, muscovite schist together with minor biotite-garnet schist and amphibolite (Østergaard et al., 2002).

High-grade metamorphic assemblages are rare in the sediments from this area and most of the rocks are retrogressed to lower amphibolite to greenschist facies (Piazolo, 2002). When it exists the high-grade assemblage in marble is Fo-Cc. In the mafic rocks, the assemblage Grt-Amph-Plag represents amphibolite facies conditions. In pelitic rocks Sill and Grt are present and in most calcisilicate rocks the highest-grade assemblage observed is Di - Cal - Phlog ± Dol, which probably were stable at temperatures of approximately 620 ± 50 °C at 4,5 ± 0,5 kbar (Piazolo, 2002). Assemblages containing staurolite have been reported from these metasediments by Mengel et al. (1998). The garnet-mica schist is fine- to medium grained, commonly sillimanite-bearing and with a strong penetrative S fabric. The unit is intercalated with siliceous schist and fine-grained amphibolite in layers from a few centimetres to tens of meters in thickness. In some areas the schist’s contain irregular to strong planar quartzo-feldspsatic melt veins on a centimetre-scale, which give them a migmatitic appearance (Østergaard et al., 2002).

According to Thrane & Connelly (2002) both Archaean and Palaeoproterozoic zircon ages (206Pb/207Pb-ages) have been obtained in the metasedimentary rocks from the area around Naternaq.

7.2 Ikamiut
South and west of Ikamiut, a settlement between the bays Nivaap Paa and Sydostbugten in the southeast corner of Disko Bugt (Fig 2, area 3) can supracrystal rocks be found. The dominating supracrystal lithologies are psammites to micaceous psammites and schistose to gneissose pelites and semipelites, with subordinate but important amphibolite horizons (Thomas, 2002).

The semipelitic and pelitic lithologies are coarse, schistose to gneissose migmatitic rocks with ubiquitous thin, quartz-feldspar leucosome veins,
commonly with biotite-rich selvages. Garnet is abundant and is wrapped by the penetrative schistose to gneissose fabric. Sillimanite is present locally and, in one or two places, appears to be pseudomorphs after kyanite. Sillimanite is also seen replacing biotite (Ostergaard et al., 2002, Thomas, 2002).

Within the micaceous psammite rocks coarse grained quartz-plagioclase pegmatite is locally abundant. The presence of sillimanite, muscovite and garnet in the pegmatites indicates derivation from the host rock (Thomas, 2002). Most of the siliceous rocks are thought to be of sedimentary origin but where amphibolites occur, the psammitic rocks at places contain amphibole, suggesting a volcanic input (Thomas, 2002).

The subordinate amphibolite units are massive to layered and heterogeneous with thin, marginal calc-silicate bearing units, most likely of metavolcanic origin. They often contain large garnet porphyroblasts with very fine quartz-plagioclase pressure shadows (Thomas, 2002).

Kalsbeek & Taylor (1999) obtained a Palaeoproterozoic Rb-Sr whole-rock age in metasediments from the Ikamiut area. The inferred initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was however so high that the rocks were interpreted to be Archaean rocks reworked during the Proterozoic metamorphic event.

7.3 Isfjord and Akugdlinguaq sequences

Piazolo & Knudsen (2004) and Piazolo & Åberg (2002) described the Isfjord sequence (Fig. 2, area 4) as dominated by a laminated compositionally banded amphibolite. In addition, a mafic unit made up of different subunits was observed. A light grey, massive, homogeneous rock and a very fine grained, massive, dark rock with a greenish appearance make up part of this unit. A subunit of fine to medium grained, felsic amphibolite made up of cyclic bands with a marked gradation and cast features are also represented in this sequence. The mafic sequence is associated with bands of dark-grey massive Bt ± Grt gneiss with variable amounts of quartzofeldspathic or schistose horizons of Bt-Grt semipelitic gneisses. Felsic, quartz – feldsparic streaks, both parallel and perpendicular to the foliation, is seen in the amphibolites and are interpreted as local melts (Piazolo & Knudsen, 2004).

The Akugdlinguaq sequence (Fig. 2, area 4) is described as dominated by a banded, laminated to layered unit associated with a massive, light-green fine-grained sequence. In this mafic unit, intercalated Bt-Grt metasediments with felsic material are also seen. A unit that may resemble pillow lavas and an amphibolite interpreted as metamorphosed gabbro are also observed in this sequence (Piazolo & Knudsen, 2004).

Piazolo and Knudsen concluded that both the Isfjord and the Akugdlinguaq sequences are of Archaean age and are volcano-sedimentary basin fills with partly igneous intrusive gabbro and extrusive materials such as pillow lavas. During the Archaean, the mafic sequence was intruded by granodiorites and they were then deformed together.

7.4 Continuation of Naternaq area, to the East

Three main sedimentary sequences were observed during fieldwork July/August 2002 in the eastern continuation of the Naternaq area (Fig. 2, area 5). All sedimentary units are clearly banded with bands between 10 cm to 0.5–1 m. Due to weathering of muscovite the most northern belt has a brown appearance in field. A "sandy" appearing, muscovite and biotite bearing, homogeneous metasediment dominates the sequence. Some layers are garnet bearing and felsic streaks, probably local melts are at places observed in the metasediment. The second sediment sequence shows similar features as the first one but is markedly thinner and is interlayered with the surrounding orthogneiss. The third, southernmost sequence appears to be more felsic. The metasediment itself contains more felsic material and is interlayered with orthogneiss. In all three sedimentary sequences, amphibolites are observed. The amphibolites are at places layered but are also seen as more massive and homogeneous. Some amphibolite layers are garnet bearing and up to 3 cm sized garnets are observed (Piazolo & Åberg, 2002).

7.5 The Kangilinaaq Peninsula

The Kangilinaaq Peninsula, located south-east of Christianshaab, was one of several target areas during GEUS field work in 2001 in the search for mineralization. It turned out that most of the mine-
ral occurrences in the region are small and therefore of limited economic importance. According to Stendal et al., (2001), spectacular rust horizons associated with a coarse-grained, hornblende-garnet-rich mafic unit containing magnetite and hematite occur on the Kangilinaaq Peninsula.

The Kangilinaaq Peninsula was mapped in 1:100 000 scale during field work in 2002. It was visited by GEUS field crew in order to collect samples for interpretations of the origin of the rocks and their deformation history. Material for two Ms thesis projects was collected. Keidings study (Keiding, 2004), based on Lu-Hf and U-Pb isotope data for zircons from samples taken from the Kangilinaaq Peninsula (Fig. 2, area 1), show meta-sediments containing zircons of an Archaean age as old as 3.6 Ga. Sampled orthogneiss from the same area contains a population of magmatic zircons with a weighted mean $^{206}\text{Pb}^{207}\text{Pb}$-age of 2818 ± 1 Ma and a metamorphic population of zircons with a weighted mean $^{207}\text{Pb}^{206}\text{Pb}$-age of 1835 ± 1 Ma. Around 2.70-2.85 Ga ago a large magmatic event occurred in the area. The Palaeoproterozoic continent collision is dated to around 1.85 Ga, which means that Keidings results correspond well with the overall orogenic ages in the area (Keiding, 2004).

8 Methods

8.1 Field observations

A general mapping was made in the Kangeruneq map area for about five weeks (Fig. 1 area A and Fig 2, area A). The fieldwork included mapping of the Isfjord sequence and the Eastern continuation of the Naternaq supracrustal belt and detailed mapping related to this thesis work. The last camp was in the vicinity of the Kangilinaaq Peninsula (Fig. 2, area 1 and Fig. 3) where I spent a total of four days. Mapping took place in a 1:16 000 scale and the main mapping units were defined. The marble with surrounding metasediment was sampled at one and at nine localities, respectively.

Outcrops along the shores in this area are excellent but the inland ones vary from very overgrown with lichen to very clean, glacier-polished. The metasediments and the gneisses strike in an east-west direction through the area. Due to shortening of the time for the fieldwork, mapping only took place along the coast and samples were only collected on the very tip of the peninsula (Fig. 2 area 1, Fig. 3 sample map and Appendix A). Field investigations show that a very weathered, light brown, "sandy" looking, mica rich schist is the most common rock type in the studied area. The rock is felsic and is mostly garnet bearing and has quartz-feldspatic melt veins as a frequent feature.

8.1.1 South of the Marble

In the very south of the peninsula there is a high strain zone in a medium to coarse grained orthogneiss. The unit (Fig. 3, unit A) is light grey (qz, fsp, bio), strongly banded and have elongated mafic minerals. In contact with the orthogneiss to the north, there is together with light brown schist a dark brown coloured unit (Fig. 3, unit B and Fig. 5).

This sequence is banded with layers in cm, dm and m scale. The whole sequence is garnet rich; some layers contain up to 80-90% garnet. Layers, from 1-2 cm up to metre scale, which are massive, dark grey and are made up of large amphibole crystals, are also observed in this unit. Unit B is interlayered with a 2-3 m thick light brown schist layer marked unit C (Fig. 3, unit C). Unit C is in field described as a small scaled banded, "sandy" looking metapelite. The sequence is weathered and has a light brown colour.

Further to the north another, 400-500 m thick, unit takes over (Fig. 3, unit D and Fig. 6). This is a large-scale banded unit with bands, layers between 1 and 1.5 m in thickness. Two different types of lithologies make up this sequence, one felsic (~60-70%) and one mafic (~30-40%). The felsic, almost
white, medium to coarse grained unit is made up of approximately ~90% fsp with 2-3 mm size garnet crystals, some muscovite and small amounts of biotite. The rock is interlayered with mafic, light brown mica rich schist layers. The unit has a wavy appearance and the contacts between the two

lithologies are not straight (Fig. 6).

North of this sequence there is a ~1 km thick, fine grained, felsic (qz and fsp-rich), light grey, banded, planar, garnet bearing unit (Fig. 3, unit E). Some researchers have interpreted the unit as orthogneiss but the appearance of small garnet crystals indicates that the unit could represent a paragneiss.

More to the north, by a small beach called "the garnet beach", between two dark fine-grained banded amphibolites a ~ 10 m thick schist occur(Fig. 3, unit F and sample nr 489648, 489649). The unit is very schistose with a strong S-fabric, garnet rich and sillimanite bearing.

The next unit is a sequence of bt-schist (Fig. 3, unit G and sample nr. 489650, 489652, 489653, 489654, 489657). It is fine to medium grained, banded, at most places garnet bearing. The rock has an S-fabric, a large amount of biotite and muscovite. Some layers are sillimanite bearing and the whole unit has a more or less brown colour due to weathering. The rock has centimetre-scale quartzo-feldspatic melt veins. Within this bt-schist unit there are banded amphibolite bodies, lenses and schlieren.

At one place, in the bt-schist south of the marble there is sequence with subunits (Fig. 3, unit J). The whole sequence is very garnet rich and has a dark brown colour and is clearly weathered. It contains layers with up to 80-90% garnet, some light brown bt-schist layers, some very massive, dark grey layers, which according to field interpretations have large amphibole crystals (sample nr 489658a) and also some very banded, garnet bearing amphibolite layers (sample nr 489658b). This sequence is very similar to the one in the very south of the peninsula but it has more subunits.

8.1.2 Marble (sample nr 489651)

On the Kangilinaaq Peninsula there is a 2-5 meter thick marble layer (Fig. 3, unit H) between metapelitic sequences both to the north and to the south. The marble is fine grained, banded at and has clusters of coarser grained calcisilicates (Fig. 7). The colour of the marble is light blue-grey and it can easily be traced from distant and from air (Fig. 8) as a light horizon in the otherwise dark brown sediments. On the very tip of the peninsula the marble is intensively folded (Fig. 8). In contact with the marble to the south, there is a fine to even grained, light brown metasediment unit. It has "blobs" of sillimanite possibly after andalusite and is ~1-2 m thick.

8.1.3 North of the Marble

To the north of the marble, there is a thick unit of bt-schist (Fig. 3, unit I and sample nr 489655, 489656). The sequence is sandy- looking and light brown in colour. The sequence is weathered and probably has a relatively high content of felsic minerals. Unit I seems to be more homogeneous than the metasediments/pelites to the south of the marble.
No amphibolite lenses/schlieren and no sediment that have equally strongly schistose as in the south of the marble have been observed.

At places the metapelites have a spotted appearance (Fig. 9). The spots are felsic, less eroded 2-3cm large lenses, some with garnet cores.

8.2 Structures (Kangilinaaq peninsula)

In the very south of the area, a high strain zone in a light grey orthogneiss occurs. No asymmetry is seen, thus no indications of the shear sense can be observed. At the tip of the peninsula the grey marble horizon (Fig. 8) and the metasediments are intense folded (Fig. 10).

Foliation and lineation trends do not change much in the mapped area (Appendix B and Fig. 11). Measured foliations correspond with the overall lineament having a clear WSW-ENE trend (Fig. 11). The aerial photograph shows traces of faults marked as broken lines in Fig. 11.

8.3 Optical microscopy, SEM and EDS-analyses

This study is largely based on optical microscopy work, where minerals, mineral assemblages and deformation related features have been identified. SEM was used for mineral identification and texture documentation. The used SEM in this work was a JSM-6400 with a Link eXL system. A Ge-detector and 18 kV acceleration voltage were used during
the first EDS-analyses. The time for these analyses was 100 seconds and a Co-metal standard was used for calibrating the instrument. During the feldspar analyses 16 kV acceleration voltage were used for 60 seconds.

9 Petrography and Mineralogy

Samples were collected north and south of the marble (Fig. 3, sample and detail map) and the petrography of the rocks will therefore be described as two separate groups.

9.1 South of the marble (sample nr 489648, 489649, 489650, 489652, 489653, 489654, 489657, 489658)

Matrix in these metapelitic rocks is fine-grained, equigranular and consists mostly of quartz and feldspar. The feldspars are plagioclase made up of approximately 68% albite and 32% anorthite (appendix C). The rocks are strongly foliated due to moderate to intense deformation and metamorphism (Fig. 12, sample nr 489650). Biotite is present as platy, elongated; mostly subhedral grains that show a preferred orientation parallel or sub parallel to the foliation. Sillimanite occurs as fibrolitic needles in aggregates defining the main fabric (Fig. 13). Sillimanite can also be seen replacing biotite or growing on biotite grains (Fig. 14). In the sillimanite
aggregates streaks of ilmenite are present (Fig. 13). At some places chlorite is observed. In these metapelitic rocks, 0.3-1 cm-sized garnet crystals are present as porphyroblasts with a large amount of inclusions, poikiloblasts (Fig. 15). The garnets are Fe-rich with between 86% and 74% almandine (appendix C). In some of the garnets, the inclusions are concentrated to the center (Fig. 16) of the grains but in other grains they are evenly distributed (Fig. 15). The garnets are subhedral, strongly fractured and rounded. The sillimanite-defined foliation sweeps around the garnet grains. Garnet inclusions show at one place a star like pattern and in some thin sections biotite is seen growing on the edge of the garnet grains (Fig. 16). In some of the garnet grains the inclusions form an internal foliation which sometime are folded (Fig. 15 and Fig. 17). Staurolite is present in small amounts both as anhedral, rounded, slightly fractured crystals in the matrix associated with feldspars but also as inclusions in garnet (Fig. 18). Ilmenite occurs in small amount as inclusions in garnet. Most rocks contain muscovite in relatively small proportions and tourmaline occurs as an accessory mineral. Radioactive minerals, e.g. zircon and monazite are abundant and recognized by the characteristic haloes especially in biotite (Fig. 19). Plagioclase is sub to euhedral with weak sericitization at some places. Rutile occurs as small, dark brown rounded grains.
9.1.1 Sample nr 498654

This locality, sample 489654, the rock is different from the rest of the rocks south of the marble. It has no garnet, which is prominent in most of the rocks. The rock is fine grained and equigranular with feldspar and mica as major phases and with small amounts of quartz. The rock shows a clear foliation with the fabric defined by aligned plates of mica (Fig. 20). Both biotite and muscovite are present as platy, elongated sub- to euhedral grains. At places the micas are overgrown by fibrolitic sillimanite. Rutile, tourmaline, zircon and monazite occur but no garnets have been found.

9.1.2 Sample nr 498652

The rock is fine grained and equigranular. In the fine-grained matrix cm-sized aggregates of fibrolitic sillimanite are present (Figs. 21, 22). The rock is clearly altered.

9.1.3 Sample nr 489658a and b

Sample 489658b was taken from a banded amphibolite. Amphibole is the dominating mineral and garnet occurs as porphyroblasts (Fig. 23). Sample 489658a is taken from a massive, dark and homogeneous rock with pyroxene as the dominating mineral. In this massive rock small garnet crystals and amphiboles are also present (Fig. 24).
The whole sequence is very weathered and difficult to sample.

9.2 Marble (sample nr 498651)

The marble is fine to medium grained and equigranular. The main minerals in this rock are calcite and dolomite. The rock is foliated with aligned plates of muscovite (Fig. 25). The muscovite grains are fractured and at places altered.

9.3 North of the marble (sample nr 498655, 498656)

The sampled metapelitic rocks are at locality 498655 and 498656 rather fine to medium-grained and equigranular. They have been exposed to moderate to intense deformation and metamorphism and are therefore foliated (Fig. 26). Quartz is the dominant matrix phase with minor feldspar as plagioclase with approximately 69% albite and 31% anorthite (Appendix D). Biotite is abundant with a preferred orientation sub-parallel to parallel to the foliation.

A prominent feature is the porphyroblastic anhedral garnet crystals. The garnets are 1-2 mm in size and are often rich in inclusions (Fig. 27). The garnets in these rocks are strongly fractured, iron rich with between 67% and 71% almandine component (Appendix D). In some thin sections, biotite is seen as rims along garnet (Fig. 27). Matrix-biotite and garnet always occur together. Staurolite as subhedral to anhedral crystals is present in small amounts as inclusions in garnet as well as small, rounded grains in the matrix, where some are altered. Tourmaline
crystals (Fig 26). Sillimanite is also replacing or nucleating on biotite grains (Fig. 28). Similar to the metasediments occurring south of the marble, ilmenite is found in close vicinity to sillimanite and biotite. Radioactive minerals are present and can be traced in thin section by distinctive haloes. Rutile occurs in limited amounts as small, well-rounded dark brown crystals.

10 Discussion

10.1 Metamorphism and deformation history

In the Kangersuneq mapping area metasedimentary sequences only form a minor part of the rocks. Nonetheless these rocks are important for the reconstruction of the Palaeoproterozoic history of the area. The deformation history and metamorphic events of the studied area are constrained by the mineral assemblages observed in the metasediments.

Pelitic rocks, derived from weathering and erosion of continental crust are particularly important in studies of metamorphism because they develop a wide range of distinctive mineral assemblages that characterise specific metamorphic zones. Pelites are mineralogically largely made up of fine-grained Al-K-rich phyllosilicates, such as clays, white micas and chlorite. Commonly high contents of Al₂O₃ and K₂O, and low contents of CaO distinguish pelites from other rocks. The term "true pelites" is used for Al-rich, Ca-poor pelitic rocks and the appearance of staurolite can make a distinction between "true pelites" and other mica schist. Staurolite grows in a range of Al-rich, Ca-poor pelitic rocks but only rarely in other lithologies (Yardley, 1989). The sampled metasediments from the Kangilinaaq Peninsula are considered to be "true pelites".

In the metapelites from the studied area, two foliations and a third late fracture system are observed, which indicates deformation during at least three phases. Foliation F1 is seen inside garnet grains and a second foliation F2 is seen outside them. The first deformation phase, D1 formed the first foliation, F1. F1 occur inside garnet grains as inclusions trails which at places are showing spiral texture (Fig. 29). F1 can be distinguished from later foliation F2, caused by D2, representing the prominent foliation in the metasediments outside the garnet
grains (Fig. 15, 17, 29, 31). The metapelites contain staurolite that occur as inclusions in garnet and only rarely as matrix grains. When occurring in the matrix the staurolite grains are small, rounded and at places altered. Quartz and biotite together with small amounts of opaque minerals also occur as inclusions in garnet. The following minerals, Bt – St – Qtz – Grt, are thought to form the first stable metamorphic mineral assemblage. The approximate stability field of staurolite (Fig. 30, red field, Spear and Cheney, 1989) is showing that staurolite does not occur at all below pressure ~0.2 Gpa. It is also shown that staurolite provides a good indicator of metamorphic temperatures since it is stable only over a narrow temperature range, which does not change much with pressure (Fig. 30). As seen in Fig. 30 staurolite could occur in rocks at temperatures as low as around 525°C but only very Al-rich metapelites will be staurolite-bearing at this grade. Staurolite is usually first occurring in most common pelites at approximately 610 °C (Winter, 2001).

The metapelites contain garnets as large, fractured porphyroblasts where some grains have internal structures showing an early foliation. The growth of these prominent porphyroblasts is interpreted to be syn- or post-tectonic to the development of F1. The interpretation of the garnet growth is based on internal structures showing traces of an early foliation. The garnet growth probably continued during late D1 resulting in rotational patterns of the garnet inclusions (Fig. 29).

The porphyroblastic garnets probably grew rapidly because they all show a polikiloblastic texture, which is a high-energy texture, representing a high surface area situation (Winter, 2001). No chemical zonation in the garnet grains has been detected with the SEM, which could mean that the whole grain has equilibrated with the other minerals in the rock (Yardley, 1989).

Analyses show iron rich garnets with a variation in endmembers between Alm$_{96}$Py$_{3}$Gro$_{3}$Sp$_{1}$ and Alm$_{66}$Py$_{25}$Gro$_{5}$Sp$_{2}$ (Appendix C and D). The garnet compositions within one and the same sample are uniform. Differences in bulk composition between the different sediment layers can explain the compositional variations of the garnets.

The occurrence of staurolite as inclusions in garnet indicates that this mineral probably crystallised in the pelites during an early deformation stage. The reaction shown in eq. 1 could be responsible for breakdown of staurolite (Winter, 2001) at metamorphic conditions corresponding to the sillimanite zone in the Barrovian zonal pattern at temperatures between 600-690°C and pressures between 0,3-0,5 Gpa (Spear and Cheney, 1989).

Staurolite + muscovite + quartz = garnet + biotite + sillimanite + H$_2$O  (eq. 1)

In the metapelites, altered staurolite grains have been observed in the matrix. At sillimanite zone conditions it is not uncommon to encounter pelites
that lack muscovite, because muscovite has appeared as a reactant in most reactions from the biotite isograd and may have been entirely consumed at lower grades. In these muscovite-free pelites, staurolite may still persist, which could explain the observed altered staurolite matrix relics in the metapelites. In the absence of muscovite in the rock, the above reaction (eq. 1) cannot take place. Instead, breakdown of staurolite will commence at higher temperature due to the continuous reaction shown in eq. 2 (Yardley, Leake and Farrow 1980):

$$\text{Staurolite} + \text{quartz} = \text{garnet} + \text{sillimanite} + \text{H}_2\text{O}$$  \hspace{1cm} (eq. 2)

A second deformation phase (D2) caused the formation of the second foliation F2 represented in the studied metapelitic rocks by the prominent penetrative fabric. The F2 foliation is defined by fibrolitic sillimanite needles matted together in broom shaped aggregates. The F2 are seen sweeping around older garnet grains (Fig. 29, 31). The first incoming of sillimanite in the metapelites are thought to be shown by the reactions in eq. 1 (or possibly 2). Sillimanite commonly nucleates as tiny fibrolite needles on micas in certain orientations minimising the surface energy at the interface (Fig. 14, 28). This type of crystallographically controlled preferential nucleation gives rise to epitaxial growth, i.e. in a particular orientation on a particular substrate (Chinner, 1961). Chinner (1961) concluded that biotite can be considered as a nucleating agent and that no permanent breakdown of biotite is taking place. According to Winter, 2001 may the reaction occur as series of interregulated reactions involving limited mass transfer. If the reaction imply breakdown of biotite this would mean element release and possible growth of other minerals. Ilmenite as the only identified oxide could have existed, already, as clastic grains in the original sediment. Iron oxides are according to Winter (2001) common constituents in pelitic sediments. The observed close relation between biotite/sillimanite intergrowth and ilmenite streaks (Fig. 13) could imply that ilmenite were formed at breakdown of biotite.

Sillimanite occur as fibrolite and no prismatic grains has been observed. No indications of sillimanite pseudomorphing kyanite have been noticed in the metapelites. Prismatic sillimanite growth is typical for granulite facies conditions (Yardley, 1989).

Further growth of sillimanite is believed to have occurred at conditions near the reaction known, by some workers as the second sillimanite isograd (eq. 3, Evans & Guidotti, 1966). The reaction indicates high metamorphic temperature, and moderate metamorphic pressure.

$$\text{Muscovite} + \text{quartz} = \text{Al}_2\text{SiO}_5 + \text{K-feldspar} + \text{H}_2\text{O}$$  \hspace{1cm} (eq. 3)

In some of the sampled metapelites sillimanite is visible in hand specimen and the reaction shown in eq. 3 is commonly responsible for the main increase in sillimanite and often make it possible to see sillimanite in hand specimen (Winter, 2001).

At moderate pressures of Barrovian metamorphism in most natural rocks, the reaction in eq. 3 may be replaced by the reaction shown in eq. 4 (Thompson, 1982):

$$\text{Muscovite} + \text{biotite} + \text{quartz} + \text{H}_2\text{O} = \text{sillimanite} + \text{melt}$$  \hspace{1cm} (eq. 4)

In sample number 489652, south of the marble sillimanite appears as fibrolite in large clusters (Fig. 21, 22). The clusters have no crystal shape and show
no signs of being pseudomorphs after another aluminium silicate.

One prominent field feature observed in the studied metasediments on the Kangilinaaq area is the felsic streaks and veins that could be local melts. Partial melting can occur in pelitic rocks by dehydration reactions at temperatures in the range between 650°C and 750°C (Thompson, 1982 & Spear and Cheney 1989).

The metapelites contain biotite as inclusions in garnet, as matrix grains often in close association with sillimanite and as large relatively unaffected grains around garnet. The later could indicate late retrograde metamorphism and breakdown of garnet but are most likely biotite protected against deformation in the pressure shadow around garnet (Fig. 31). Small bands of fibrolite needles in the contact between garnet and the unaffected biotite support this interpretation.

A third deformation phase (D3) caused a third local structure, which is observed in the metapelites as late brittle fractures cutting earlier formed minerals and textures (Fig. 29, 31). The fractures are most prominent in garnets but can be followed throughout the matrix (Fig. 29, 31).

Analyses show that titanium minerals occur both as ilmenite (FeTiO₃) and rutile (TiO₂) in the studied metasediments. These minerals are accessory and are not clearly participating in the main metamorphic reactions. The transition reaction between the titanium minerals can however be a good pressure indicator. High-pressure schist containing rutile is separated from lower pressure schists with ilmenite. One of the best-known geobarometric reactions applicable to metapelites from the amphibolite and granulite facies is the reaction showed in eq. 5, involving ilmenite and rutile (El-Shazly, 2001):

\[
\text{Ilmenite} + \text{Al}_2\text{SiO}_5 + \text{Qz} = \text{Almandine} + \text{Rutile} \\
(\text{eq. 5})
\]

The reaction is called the GRAIL barometer and has been tightly reversed in the temperature range 750-1100 °C by Bohlen et al. (1983). The reaction is an example of a net-transfer reaction in which one or more of the phases have appreciable solid solution.

Provided that samples where these minerals attained equilibrium, can be found, the GRAIL and other Ti-mineral barometers may give clues to the metamorphic pressures.

With the above presented data a tentative P-T-path is drawn in figure 30. Accordingly, the metapelites from the Kangilinaaq peninsula are interpreted to have reached high metamorphic temperatures but moderate metamorphic pressures that indicate amphibolite facies conditions but not as high as granulite facies conditions.

The spectacular rust horizons associated with a mafic, coarse-grained hornblende-garnet-rich unit described by Stendal et al. (2001) corresponds well with unit B and J observed during the field work associated with this thesis work. According to an index map referred to by Stendal et al. (2001), the described locality on the Kangilinaaq Peninsula could even be the same locality described in this work as unit B.
10.2 Comparison of lithologies and assemblages south and north of the Marble

In the studied area a number of different lithologies were observed during the field work in the summer of 2002. A larger area was covered south of the marble horizon compared to the area covered north of the marble horizon. This means that more observation of the lithologies were made south of the marble horizon than north of it. This limits the possibility to make a good comparison of the lithologies on either side of this horizon. The field work showed, in any case that the metasediments north of the marble horizon appear to be more homogeneous in comparison to the metasediments south of the marble horizon. The metasediments in the north is missing the large number of amphibolite bodies, lenses and schlieren observed in the south. The sequence to the south was very variable in field appearance with a large number of small sediment units. The metapelites from the two study areas show strong similarities in mineral assemblages and in the recorded sequence of metamorphic and deformation events. The prominent feature in all of the sampled sediments is the garnet porphyroblasts wrapped by a penetrative fabric defined by sillimanite. The observed sillimanite appears as clusters of fibrolite needles defining the fabric. The sillimanites are not interpreted to be pseudomorph after kyanite or andalusite and no prismatic sillimanite are seen. More or less all the metapelitic rocks contain staurolite as inclusions in garnet or as relics in the matrix.

No structural or mineralogical evidence is found in the metapelites north and south of the marble horizon suggesting that this acted as a tectonic boundary between two metasediment packages of different origin, age and at least in part different metamorphic and deformation history. The metasediments have all been overprinted by the last deformation phase and exposed to similar metamorphic conditions. It is, therefore, difficult to see the original structures.

The metapelites and the marble could be considered as a continuous rock sequence. The possibility that the sediments on either side of the marble are a repetition of the other side can not be excluded. A repetition could be a result of tight folding or a thrust fault within the marble although no evidence for that was found.

10.3 Comparison of lithologies and assemblages with Naternaq and Ikamiut

The metapelitic rocks from the Kangilinaaq Peninsula show strong similarities in lithologies and mineral assemblages with the metasediments from Naternaq and Ikamiut. The metasediments on the Kangilinaaq Peninsula are seen interlayered with surrounding orthogneiss (Fig. 3, unit D). In the very south of the Kangilinaaq Peninsula a high strain zone between the supracrustal rocks and the orthogneiss is observed. These features have also been reported from the Ikamiut area. Lithologies like psammites and schistose to gneissose pelitic rocks and amphibolites with minor marble are present in the Kangilinaaq area. Sequences with garnet-rich massive units interlayered with amphibolite layers are observed in the Kangilinaaq area. Similar lithologies are observed in the Naternaq area. In the Ikamiut area the rocks are, in general, similar to the ones described in the Naternaq area although no marble or banded iron formation have been recorded. The mineral assemblages in the metapelites from the three areas are similar. Commonly fibrolitic sillimanite is present in all metapelites, replacing biotite at some places. In rocks from Ikamiut, sillimanite appears to be pseudomorph after kyanite, which has not been seen in metapelites from the Kangilinaaq Peninsula. Staurolite has been observed in the metapelites from the Kangilinaaq area and Mengel (1998) has reported staurolite from the Naternaq metasediments. A penetrative S-fabric and the quartzo-feldspatic melt veins are common features for metasedimentary rocks from all three areas. They are also all garnet rich and the description of the garnets wrapped by penetrative fabric in metapelites from Ikamiut corresponds similar observations in rocks from the Kangilinaaq Peninsula.

No detailed microstructural work has so far been documented, and published, on metasediments from the Naternaq and Ikamiut areas, so although the mineral assemblages are similar, further microstructural work is needed to verify the sim-
ilarity in terms of deformation history and metamorphic events of the different sequences.

GEUS first preliminary dating results show both Archaean and Proterozoic depositional ages for metasediments from the NNO and, at present, the depositional age of the supracrustal belts are thought to be enigmatic. Recent Lu-Hf and U-Pb isotope data on zircons from metasediments taken from the Kangilinaaq Peninsula show metasediments containing zircons of Archaean age. Rb-Sr data for rock from the Ilkamiut area points at metasediments of Archaean age reworked during Proterozoic metamorphism. Metasediments from the Naternaq area contain zircons of both Archaean and Palaeoproterozoic age. More information is needed and further investigations have to be done to resolve the question about the depositional and metamorphic age of the sediments in the NNO and the possible correlation of the sediments between the different areas. Additional geochronology is underway to address the age relationships of the metasedimentary belts.

10.4 Regional geology
In the Nagsugtoqidian Orogen four different deformation phases can be traced on the basis of the large scale structures. In the metasediments sampled for this study traces of three local deformation phases were observed. Which of the regional large scale deformation phases that is responsible for the observed microstructures, is uncertain and can not be established until the continuation of the belt is clarified. If the folds in the metasediments can be correlated with regional large-scale fold structures, the dominating local foliation (F2) most likely has formed during the third orogenic deformation phase (D3) characterized by kilometre-scale upright folds with a east-west trend. The local foliation F1 would then be a feature of regional D1 or D2 and the local brittle structure F3 a feature of the latest regional deformation phase D4.

11 Conclusions
• Metasediments of true pelitic composition exposed to amphibolite facies metamorphic conditions occur in a sediment belt on the Kangilinaaq Peninsula.
• Three local deformation phases (D1-D3), with F2 as the dominating structure, are traced in the metapelites from the Kangilinaaq Peninsula.
• No structural or mineralogical evidence is found in the metapelites north and south of the marble horizon suggesting that the marble horizon acted as a tectonic boundary between two sedimentary packages of different origin, age and at least in part different metamorphic and deformation history.
• Based on the lithological and mineralogical similarities the best candidates for a continuation of the sedimentary belt on the Kangilinaaq Peninsula are the sediments from the Naternaq and Ilkamiut areas.

12 Acknowledgments
First I would like to thank Christian Knudsen and Jeroen van Gool at GEUS, for giving me the opportunity to experience a summer of fieldwork in Greenland. Sandra, thank you for your help and support during the initial fieldwork and during the following work with this thesis. Thanks to Marie and Jane for helping me during the last days in field and for many laughter. I would like to thank my supervisor Leif Johansson for your valuable opinions and for your time. Thank you Anders Lindh, for your help with the SEM. A special thanks to Henrik Bengtsson, for your patience with all my Illustrator and Pagemaker questions. Thanks to family and friends for support and encouragement. Last but not least I would like to send a big hug to Ann-Sofie, I am hoping our rewarding geological discussions will continue some place else....
13 References


El-Shazly, A.K., 2001, Geothermometry and Geobarometry. Principles of Geochemistry, Geol 481

Evans, B.W. & Guidotti, C.V., 1966. The sillimanite-potash feldspar isograd in western Maine, USA. Contribution to Mineralogy and Petrology 12, 25-62


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Appendix C

Composition of minerals in the metapelites south of the marble

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Garnet endmember composition

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## Appendix D

### Composition of minerals in the metapelites north of the marble

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<th>Al\textsubscript{2}O\textsubscript{3}</th>
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<th>MgO</th>
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<th>CaO</th>
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### Garnet endmember composition

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