North-East Greenland 1997–1998: a new 1:500 000 mapping project in the Caledonian fold belt (72°–75°N)

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The Geological Survey of Denmark and Greenland (GEUS) continued in 1997 the systematic geological mapping programme for the 1:500 000 regional map series, with initiation of field work on sheet no. 11, which covers part of North-East Greenland. Of the 14 planned map sheets at 1:500 000 which will cover all of Greenland, 11 have been published, and one additional sheet for which field work has been completed is under compilation. Only two areas of Greenland are not yet covered by map sheets of this series: part of North-West Greenland (sheet no 6) and the target for the present project in North-East Greenland (sheet no. 11). The field work for the latter sheet is planned for two seasons, with the first season completed in 1997 and the second and final season to follow in 1998.

The map sheet (no. 11) covers the region between Kong Oscar Fjord and the Stauning Alper in the south (72°N) and Kuhn Ø and Grandjean Fjord in the north (75°N, Fig. 1). The western part of this region is dominated by crystalline complexes of the East Greenland Caledonian fold belt. A post-Caledonian sequence of Upper Palaeozoic and Mesozoic sediments and Tertiary plateau basalts and intrusions covers the eastern part of the region. This article focuses on the Caledonian geology, whereas results from the work in the post-Caledonian sediments are described in the article by Stemmerik *et al.* (1998, this volume).

The new Survey work for map sheet 11 represents a reinvestigation of areas extensively studied by geologists of Lauge Koch's expeditions to East Greenland (1926–58), the principal results of which were compiled by John Haller for the 1:250 000 map sheets covering the region 72°–76°N (Koch & Haller 1971) and incorporated into an impressive regional description of the East Greenland Caledonides (Haller 1971).

The Scoresby Sund region to the south of latitude 72°N and the Dove Bugt region to the north of latitude 75°N have already been investigated by the Geological Survey of Greenland (Henriksen 1986, 1997; Higgins 1994) as part of the present ongoing 1:500 000 regional mapping programme. The 1997–1998 mapping project will fill the last remaining gap in the Survey's 1:500 000 coverage of North-East Greenland.

All of North-East Greenland is covered by a set of wide angle black and white vertical aerial photographs taken in the period 1978–87 from an altitude of *c.* 14 km. On the basis of these aerial photographs and ground control points established by Kort- og Matrikelstyrelsen (National Survey and Cadastre – formerly the Geodetic Institute), new topographical maps of the entire region 72°–75°N, at a scale of 1:100 000, with 100 m contours, are being drawn at the Survey and will serve as a basis for the field investigations and the subsequent geological map compilations. Drawing of the topographic maps in the Survey´s photogrammetric laboratory is combined with photogeological interpretation both prior to and following the field investigations.

In addition to establishing a general overview of the regional geology, the project includes activities aimed at supplementing knowledge of the economic potential of the region, in respect to both minerals (Harpøth *et al.*1986) and hydrocarbons (Christiansen *et al.* 1992; Stemmerik *et al.* 1997). The field work co-ordinated by the Survey included co-operation with a geophysicist from the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, who undertook rock magnetic investigations to facilitate interpretation of an AWI aeromagnetic survey, and four Norwegian sedimentologists from Saga Petroleum whose work was integrated with a Survey group working with Mesozoic sediments (Stemmerik *et al.* 1998, this volume). Logistic support was also given to three groups of geologists from the University of Oslo and three geologists from Massachussetts Institute of Technology, with whom agreements on scientific co-operation had been arranged in advance.

Some aspects of the project are based on funding from the Danish National Science Foundation and Carlsberg

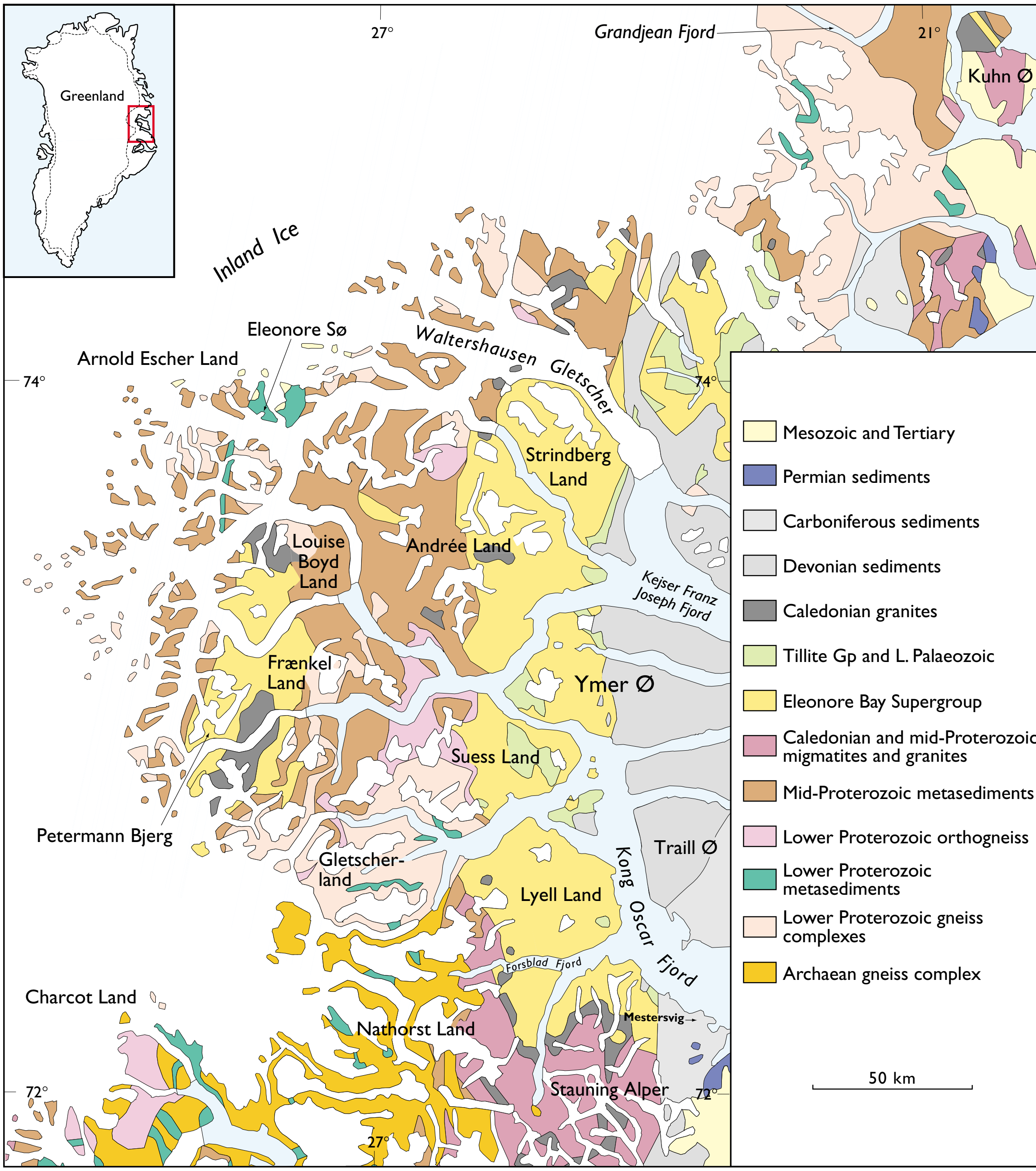


Fig. 1. Simplified geological map of the East Greenland Caledonian fold belt between 72° and 75°N. After Escher & Pulvertaft (1995).

Foundation, with support for special research topics concerning the pre-Caledonian basement terrain, Caledonian metamorphism, and studies of Upper Proterozoic carbonate sediments.

The field investigations in 1997 were carried out during a seven week field season between early July and late August with participation of a total of 38 persons, including 32 geologists (Henriksen 1998). The work was supported by two helicopters and a small, fixed wing, Twin Otter aircraft, which operated from Mestersvig, a former airport which is kept open for limited special operations by the military sledge patrol Sirius. The GEUS

Fig. 2. Stauning Alper with summits reaching almost 3000 m with a relief of 1500 m. View from the north.

group benefitted substantially from base facilities at Mestersvig, organised and manned by the Danish Polar Center (DPC). Transport between Mestersvig and Denmark was carried out by the Royal Danish Air Force (RDAF) using a C-130 Hercules aircraft.

Regional geological studies

The East Greenland Caledonian fold belt from 72° to 75° N comprises late Archaean and Proterozoic crystalline complexes which are tectonically overlain by a thick Upper Proterozoic (Eleonore Bay Supergroup) to Middle Ordovician sedimentary sequence. These units were subjected to large scale orogenic deformation and mountain building processes during the collision of Laurentia and Baltica following closure of the Iapetus Ocean (Harland & Gayer 1972; Henriksen 1985). The Lower Palaeozoic sediments contain 'Pacific-type' faunas indicating that East Greenland comprised part of the North American craton (Laurentia) prior to continental collision. Devonian – Lower Permian, late orogenic, continental sedimentary sequences were deposited in local intramontane basins during the late extensional phases of the Caledonian orogeny.

The classic interpretation of the East Greenland Caledonides erected by John Haller (1971) and coworkers envisaged the fold belt to be composed of two main structural levels (stockwerke); an upper suprastructural level of low grade to non-metamorphic sedimentary rocks with N–S trending, upright, open to gentle folds, and a lower infrastructural level dominated by intensely deformed gneisses, schists and granitoid rocks, generally metamorphosed to amphibolite facies grade. According to John Haller´s interpretation the rock units of both structural levels were correlatives, the infracrustal units being metamorphosed and gneissified equivalents of the overlying sediments. Later work, and notably isotopic age determinations have, however, demonstrated that the infrastructural levels comprise polymetamorphic Precambrian basement complexes which preserve evidence of three orogenic events prior to Caledonian reworking – late Archaean (3000 Ma), lower Proterozoic (1800–2000 Ma) and middle Proterozoic (*c.* 1000 Ma; Steiger *et al.* 1979; Henriksen 1985).

Large scale west-directed thrust nappes have previously been described from both the Scoresby Sund region to the south as well as from the northern part of the East Greenland Caledonides (Hurst *et al.* 1985; Henriksen 1986; Strachan *et al.* 1994), but had not hitherto been proven from the central part of the East Greenland Caledonides. In the summer of 1997, however, evidence was found to demonstrate that this region (72°–75°N) is also built up of major thrust and nappe sequences (see below).

The terrain of this part of North-East Greenland is characterised by a rugged alpine topography with mountain summits reaching almost 3000 m in the Stauning Alper (Fig. 2) and Petermann Bjerg regions. Wide fjord and glacier valley systems with steep walls and general E–W trends, transect the region approximately perpendicular to the main trend of the Caledonian fold belt (Fig. 3). Numerous local ice caps and glaciers are pre-

Fig. 3. Nordenskiöld Gletscher occupies a deep trough eroded into crystalline basement complexes. The steep walls and exposures are typical for the inner fjord zone. Summits reach 2300 m in altitude and about 1200 m above the glacier.

sent, and towards the west merge with the Inland Ice; a broad border zone of the Inland Ice is characterised by the occurrence of numerous nunataks. Except for some valley areas, vegetation is sparse and exposure is therefore generally very good.

Field work in 1997 covered, in addition to general mapping, most aspects of the regional geology in the Caledonian fold belt. The main projects included:

1. Pre-Caledonian basement in the crystalline complexes – a study using radiometric age determination methods;
2. Structure and lithostratigraphy of the crystalline complexes;
3. Metamorphic studies of Caledonian infracrustal and supracrustal units;
4. Granites in the fold belt – their relative and absolute age, geochemistry and plate tectonic setting;
5. Migmatisation processes and mechanisms, with studies of partial melting and emplacement patterns;
6. Sedimentology and basin analytical studies of the carbonate sediments in the Upper Proterozoic Andrée Land Group (Eleonore Bay Supergroup);
7. Mineral resource investigations in the basement crystalline complexes associated with major tectonic lineaments;
8. Magnetic susceptibility in the crystalline complexes of the southern part of the investigated region (72°–73°N); an AWI project.

Preliminary results of the field work have been summarised by the participating geoscientists in a volume of the Survey's Rapport series (Higgins & Frederiksen 1998), which forms the basis for the following presentation.

Crystalline complexes

The crystalline basement complexes within the East Greenland Caledonides are segments of the Precambrian Greenland shield (part of the North American Laurentian shield), which have been reactivated during the Caledonian orogeny. These complexes are dominated by polyphase orthogneisses, foliated granites and migmatites interbanded or overlain by sequences of paragneisses, amphibolites and metasediments (psammitic, pelitic and calcareous). The oldest complexes, which have yielded Archaean isotopic ages, are found in the southern part of the region and are most likely to be a northerly extension of the *c.* 3000 million year old Flyverfjord infracrustal complex of the Scoresby Sund region south of 72°N (Rex & Gledhill 1974). The gneisses of these complexes are characterised by abundant, cross-cutting, basic dykes and sills, which when deformed by later events occur as pods, lenses, layers and bodies of amphibolite (Fig. 4). Middle Proterozoic complexes are found in the Charcot Land tectonic window in the south-western part of the region, where a thick sequence of metasedimentary and metavolcanic rocks (Steck 1971) overlying an older gneissic basement is intruded by Middle Proterozoic granites (*c.* 1850 Ma old).

Quartzofeldspathic intrusive bodies of similar age are also represented in the crystalline basement complexes elsewhere in the region between 72° and 75° N; a number of granites and gneisses have given isotopic ages of *c.* 1700–2000 million years (Rex & Gledhill 1981). Throughout the region the infracrustal parts of the basement complexes are interleaved or overlain by a several kilometres thick sequence of metasedimentary rocks (psammitic and pelitic) now occurring as amphibolite facies schists and paragneisses, in places invaded by granitic sheets and bodies. Rb-Sr errorchron ages of *c.* 1000 Ma (Rex & Gledhill 1981), suggest a correlation with the Krummedal supracrustal sequence of the Scoresby Sund region farther south (Higgins 1988). However, the results of the 1997 field investigations indicate that there may be several different Proterozoic sedimentary sequences, although the dominant structures developed in these supracrustal rocks seem to be Caledonian (Leslie & Higgins 1998; Escher & Jones 1998). The unravelment of the geological development and composition of the crystalline basement complexes is an important goal for the present project, and four teams are involved with regional studies of structural, metamorphic, lithological and isotopic aspects of the problem (Elvevold & Gilotti 1998; Escher & Jones 1998; Friderichsen & Thrane 1998; Leslie & Higgins 1998). The contribution of K. Thrane is undertaken as a Ph.D. research topic.

Studies of the metamorphic evolution have focused on east–west transects across the fold belt. The boundary between the non-metamorphic or very low grade Upper Proterozoic Eleonore Bay Supergroup and the structurally underlying crystalline complexes is marked by a prominent east-dipping extensional detachment zone; it is possible that parts of this zone had an early compressional history. Metasedimentary sequences in the footwall of the detachment are amphibolite facies kyanite or sillimanite bearing schists and paragneisses; these may or may not be correlatives to the non-metamorphic to greenschist facies quartzites and banded pelites and sempelites which occur in the hanging wall of the detachment zone. Similar studies in the nunatak region to the west of a transition between the Upper Proterozoic Petermann Bjerg Group (Eleonore Bay Supergroup) and underlying high grade crystalline complexes have been interpreted as reflecting two phases of Caledonian metamorphism; an early phase of kyanite grade metamorphism associated with migmatisation was succeeded by a later phase associated with formation of extensional detachment zones which now separate high level and deeper seated parts of the fold belt (Escher & Jones 1998). Metamorphic pressure-temperature-time data will be integrated with a structural analysis in order to understand the tectonic evolution, and will involve studies of phase equilibrium, mineral zoning and geothermometry in the rocks.

Fig. 4. The oldest parts of the crystalline basement complexes within the East Greenland Caledonides have yielded Archaean radiometric ages of *c.* 3000 Ma. Veined orthogneisses are injected by later cross-cutting basic dykes which have been metamorphosed and recrystallised under amphibolite facies conditions. Tærskeldal, south-west of Forsblad Fjord. Person as scale.

Granites are abundant throughout the region, as components of the crystalline complexes and as discrete or diffuse intrusive bodies emplaced into Middle and Late Proterozoic metasediments. It is only when the granites invade the Upper Proterozoic Eleonore Bay Supergroup that they can clearly be identified as Caledonian. Geochronological and (isotope-) geochemical investigations of the granites have been undertaken by H.F. Jepsen and F. Kalsbeek. Field interpretations enable distinction of various deformed and undeformed granites of Caledonian age emplaced into Eleonore Bay Supergroup sediments (Fig. 5), as well as lithologically similar granites emplaced in other metasediments which

Fig. 5. Leucocratic Caledonian granite cutting recumbent fold in Upper Proterozoic Eleonore Bay Supergroup sediments. Grejsdalen, Andrée Land. The profile is approximately 700 m high.
Photo: Feiko Kalsbeek.

may be older. Jepsen & Kalsbeek (1998) suggest that granite formation may have taken place by partial melting of the metasedimentary sequences. The close spatial relationship between granites and metasediments, and the absence of lithologically similar granites in the gneissic basement complexes, is taken as strong evidence that all Caledonian granites were formed by anatexis and that they were not derived from melts at depth.

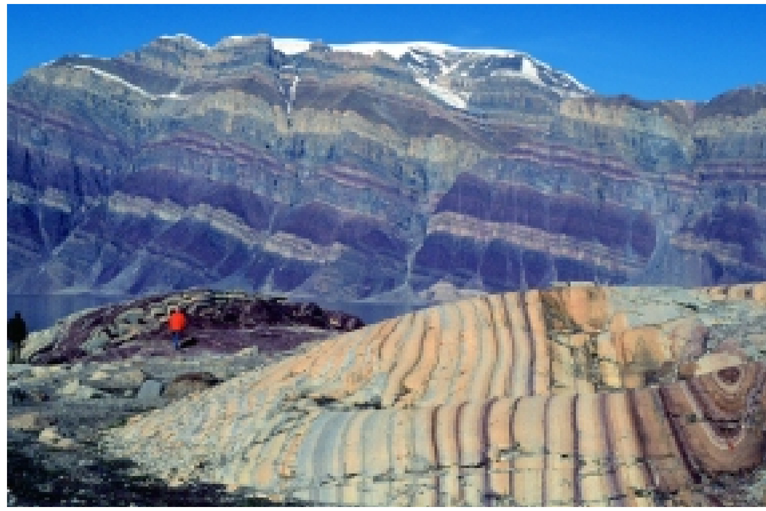
Migmatisation processes, due to partial melting of existing rock units during Caledonian or older orogenic events, are a prominent feature in the study region, and a special research project focused on this problem was organised in collaboration with Gordon R. Watt (Watt & Kinny 1998) with support from the Australian Research Council. The field aspect of the project involves mapping and logging of migmatites in an attempt to trace the introduced granite (neosome phase) from their site of formation to emplacement levels. This will be supplemented by geochemical and geochronological studies to determine the influence of melt-extraction mechanisms on melt chemistry and granite segregation processes. The migmatisation studies were mainly carried out in Nathorst Land and in the Stauning Alper, where distinction may be possible between migmatites of Caledonian age and possibly older but comparable migmatites. SHRIMP analysis on zircon concentrates will illuminate those questions which could not be solved on field criteria alone. It is expected to obtain a fuller appreciation of how granites are formed, how they migrate from their melting sites and ascend through the crust, and the factors which control their emplacement and final geometry.

Caledonian thrusts and foreland windows

The field studies in the nunatak region between 73° and 74°N have provided convincing evidence for the existence of large scale westwards directed Caledonian thrust sheets and nappes (Escher & Jones 1998; Leslie & Higgins 1998). This evidence, together with data from other regions, implies that major compressional tectonic events led to a thickening of the crust during the early phase of the Caledonian orogeny. Subsequent later phases encompass various transverse structures (Escher & Jones 1998) and the formation of the post-Caledonian basins (Hartz & Andresen 1995), and were related to extensional collapse and thinning of the crust.

The volcano-sedimentary complex of the Eleonore Sø region, Arnold Escher Land, was first described by Katz (1952) who presumed a correlation with the Eleonore Bay Supergroup. The 'Slottet Quartzite', which overlies the Eleonore Sø volcano-sedimentary complex, was in 1997 (Leslie & Higgins 1998) found to have a basal unconformable contact (not a thrust contact as originally described) and to preserve *in situ Scolithus* trace fossils indicating correlation with similar quartzites elsewhere in northern East Greenland and an uppermost Proterozoic to lowest Cambrian age (Sønderholm & Jepsen 1991; Strachan *et al.* 1994). The succession in Arnold Escher Land outcrops beneath a broad arched roof thrust transporting granite-veined and sheeted

Fig. 6. Exposures of part of the Ymer Ø Group and Andrée Land Group (Eleonore Bay Supergroup) in Forsblad Fjord. Berzelius Bjerg on the north side of the fjord is about 1900 m high.



metasediments to the north-west. There is a pronounced metamorphic contrast between hanging and footwalls of the thrust, which must be Caledonian in age. However, the footwall Eleonore Sø sequence carries the full sequence of Caledonian fold phases, and is thus provisionally interpreted as parautochthonous rather than autochthonous Caledonian foreland.

Other research topics

A sedimentological and stratigraphic basin analysis of the Upper Proterozoic Andrée Land Group (the former 'Limestone–Dolomite Series') of the Eleonore Bay Supergroup (Fig. 6) was undertaken as a Ph.D. research topic. Six profiles through the Andrée Land Group between Strindberg Land in the north and Scoresby Land in the south, were studied in detail (Frederiksen & Craig 1998). At each locality the succession was logged in detail to establish sedimentary facies divisions. The Andrée Land Group was found to be up to 1300 m in thickness and comprises a range of limestones and dolomites which can be divided into seven formations. The field work shows that they were deposited in a carbonate ramp system setting, with a steepened ramp towards the deep sea to the east and with a sheltered inner lagoon behind an inner, shallow barrier or shoal. The vertical sedimentary development of all sections shows a large-scale deepening upwards trend. The sedimentary, tectonic and climatic development will be analysed in terms of the sequence stratigraphic concept.

The nunatak zone north-west of inner Kejser Franz Joseph Fjord was known to preserve outcrops of Tertiary alkaline mafic lavas (Katz 1952; Brooks *et al.* 1979). In 1997 several new examples of Tertiary volcanic necks or plugs were discovered in the same region, some of which contain small mantle nodules (Leslie & Higgins 1998).

Mineral resource investigations were carried out in 1997 in the crystalline complexes between Andrée Land (73°30′N) and Lyell Land (72°30′N). Attention was focused on major tectonic lineaments, and in particular along the detachment zone between the Eleonore Bay Supergroup to the east and the underlying crystalline metamorphic complexes to the west (Stendal & Wendorff 1998). The detachment zone is a semi-brittle N–S trending, late Caledonian extensional fault zone, and can be traced for more than 100 km. Other geological settings investigated included various vein-related mineralisations in granite, aplite and pegmatite veins in the metamorphosed supracrustal sequences, and associated with Caledonian intrusives. More than 250 samples were collected (stream sediments, heavy mineral concentrates, grab and chip samples), and the results of the analyses will provide an evaluation of the mineral potential in the investigated area.

Since 1990 the Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven has undertaken extensive airborne and shipborne magnetic and seismic investigations in order to investigate the crustal structure of East Greenland. As a follow-up of this extensive programme a geophysicist from AWI joined the

GEUS group in 1997 to carry out *in situ* measurements of magnetic susceptibilities in the crystalline complexes between *c.* 72° and 73°N (Schlindwein 1998a). The magnetic properties of the rocks will be used as an aid to interpretation of the aeromagnetic data. Basement rocks generally have low susceptibilities, apart from three relatively late magnetite-bearing granites; the latter cut early structures, but were themselves partly deformed. Metasedimentary sequences interleaved with the crystalline basement rocks also have low susceptibilities, but highly magnetic units were encountered in some associations of amphibolites, schists and marbles. Although less than one kilometre across, the magnetite-bearing granites are revealed on the aeromagnetic data as pronounced positive magnetic anomalies (Schlindwein 1998b). In general the aeromagnetic patterns and the ground susceptibility measurements help to distinguish crystalline complexes with different petro-magmatic evolution, and in this way contribute to understanding of the general geological development of the region.

Co-operation with other institutions

As noted above, the long term close co-operation between the Survey and AWI was continued in 1997 with a programme of ground magnetic susceptibility measurements. Scientific and logistical co-operation was also established with a group of geologists from the University of Oslo, Norway who have worked for several years in the Caledonian fold belt in the region north of Mestersvig. Their project has focused on the formation of late- to post-Caledonian extensional structures both in the crystalline complexes and in relation to the formation of the Devonian sedimentary basins. This group included a party from Massachussetts Institute of Technology (MIT), Cambridge, USA, studying the structural and metamorphic evolution of a late Caledonian detachment zone in the Forsblad Fjord area. Another group from the University of Oslo was given limited logistic support in their studies of the structures and emplacement of Tertiary sills in the Mesozoic sediments around Kong Oscar Fjord.

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