Kane Basin 1999: mapping, stratigraphic studies and economic assessment of Precambrian and Lower Palaeozoic provinces in north-western Greenland

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The geological map coverage of Greenland at scale 1:500 000 is nearing completion, with the Kane Basin sheet of north-western Greenland the last to be compiled (sheet 6 between 78°–81°N; Fig. 1). Sporadic work by the Survey since the 1970s identified the main geological provinces and structure of the region but the lithologies of the Precambrian shield were not sufficiently mapped inland to warrant final compilation. Project *Kane Basin 1999* was designed to provide this knowledge; the optimal use of logistics enabled a range of geological activities to be undertaken, as well as other scientific disciplines.

Study region, field party and logistics

The study region is divided into two land areas by the Humboldt Gletscher: the *southern area* comprises Inglefield Land and part of northern Prudhoe Land, and the *northern area* Daugaard-Jensen Land, Washington Land, Petermann Halvø and part of south-western Hall Land (Fig. 1).

The field party of 30 persons comprised the authors, forming the main group from the Geological Survey of Denmark and Greenland (GEUS) dealing with bedrock investigations, eight persons dealing with surficial geology, archaeology and botany sponsored by the Danish Polar Center (DPC) and research foundations, as well as base-camp and aircraft personnel.

The logistics of this one season activity in July and August were organised by DPC and GEUS. The mobilising stations for C-130 Hercules and Twin Otter aircraft were Thule Air Base (TAB) at Pituffik and the Canadian Forces Base at Alert on the northern coast of Ellesmere Island (Fig. 1). Base camps at Hiawatha Gletscher in Inglefield Land and at Cass Fjord in Daugaard-Jensen Land, supported two-man teams working by helicopter (Ecureuil AS 350), on ground traverses and from fly camps.

Previous work

The appreciable geoscientific work undertaken by early expeditions, the Survey and industry was reviewed prior to the field season (Dawes 1999). Maps for the northern and southern areas at 1:250 000 by Jepsen *et al.* (1983) and Bengaard (1995), respectively, were based heavily on photogeological interpretation. In the southern area, airborne geophysics in 1994 revealed many anomalies in the Precambrian shield (Stemp & Thorning 1995) and this triggered field work by the Survey and industry, i.e. Nunaoil A/S, Platinova A/S and RTZ Mining and Exploration Ltd. The Survey work, directed towards assessment of the anomalies and revision of the geological map, included bedrock, surficial and mineralisation studies and a geochemical stream-sediment survey (Steenfelt & Dam 1996; Thomassen & Dawes 1996). These data, as well as the geophysics from 1994, were collected in a set of thematic maps (Schjøth *et al.* 1996) and released in GIS format by Schjøth & Thorning (1998). In the northern area, resource assessment in 1997 by the Survey resulted in the discovery of lead-zinc-silver mineralisation in Ordovician rocks (Jensen & Schønwandt 1998). This led to geological, geochemical and geophysical work by Platinova A/S in 1998 and an airborne electromagnetic and magnetic survey (Rasmussen 1999). Platinova's prospecting continued with drilling in 1999 in a joint venture with Rio Tinto Mining and Exploration Ltd.

General geology and scope of this report

The bedrock comprises three geological provinces, all of which continue into Canada: the Palaeoproterozoic Inglefield mobile belt (Precambrian shield), the Mesoproterozoic Thule Basin and the Palaeozoic Franklinian Basin. The contacts between these provinces are pre-
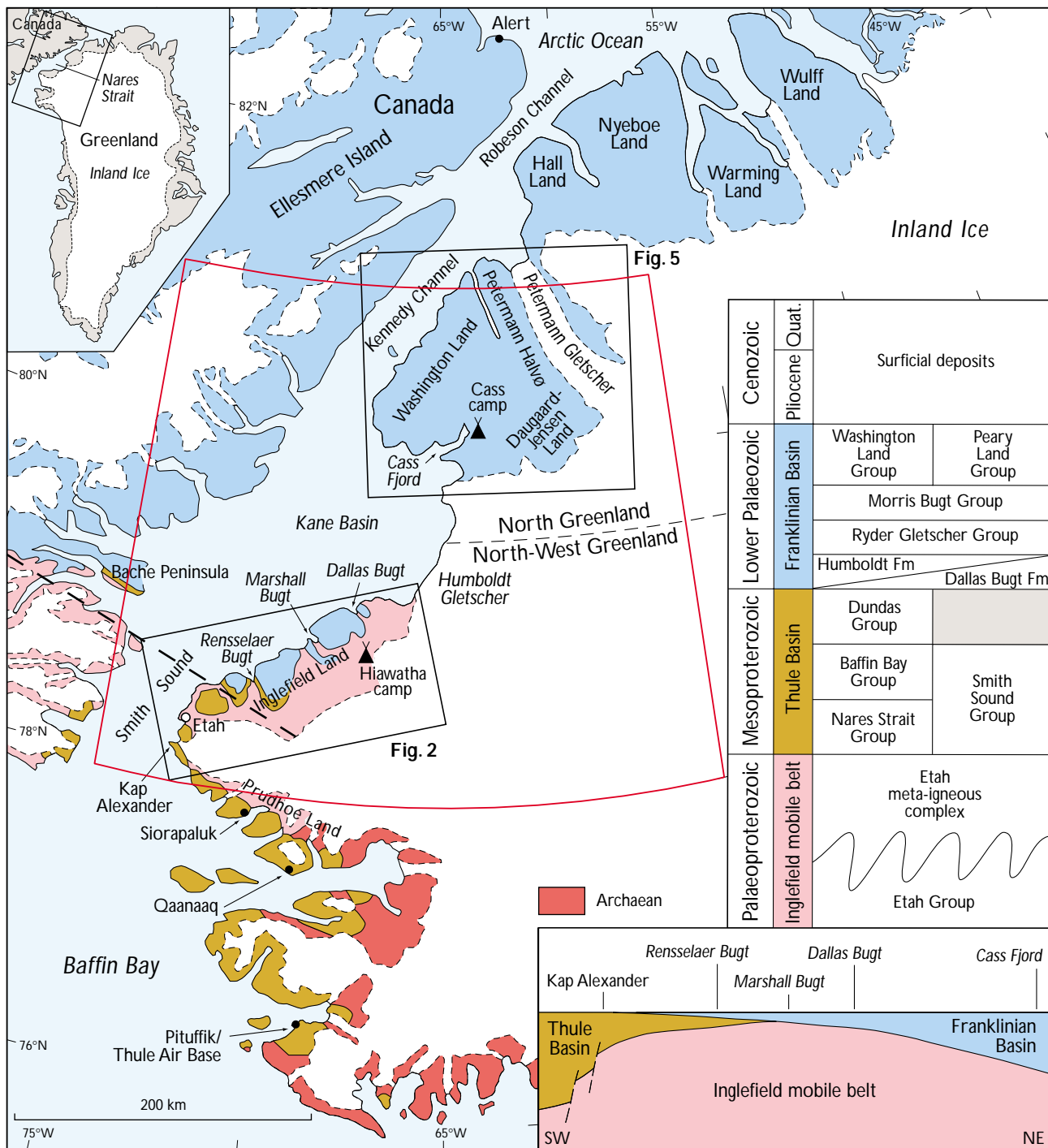
Fig. 1. Geological and location map showing the main Precambrian and Palaeozoic provinces, the outline of the Kane Basin 1:500 000 scale map sheet (**red frame**), and the southern and northern areas of the study region (Figs 2 and 5, respectively). A schematic cross-section from Kap Alexander to Cass Fjord shows the relationships between the three bedrock provinces (modified from Peel *et al.* 1982) and a stratigraphic chart shows the principal lithostratigraphic divisions of the study region. The Nares Strait, Baffin Bay and Dundas Groups of the Thule Basin crop out in northern Prudhoe Land just off the region shown in Fig. 2. The Smith Sound Group is the northern platform and basin margin equivalent of the Nares Strait and Baffin Bay Groups and the **grey shading** in the stratigraphic chart emphasizes the hiatus with the Franklinian Basin succession. The implied contact between the basinal Dundas Group and the Franklinian Basin is fictitious since the strata crop out in essentially different regions (see cross-section). Outcrops of Carboniferous–Tertiary strata in Ellesmere Island (Sverdrup Basin) are not shown. The **dashed line** across Smith Sound locates the rock sampling traverse referred to in the text. **Dots** indicate some present-day settlements; Etah (**open circle**) is abandoned. **Nares Strait** is the seaway between Baffin Bay and the Arctic Ocean including Smith Sound, Kane Basin, Kennedy Channel and Robeson Channel.

12

served in Inglefield Land (Figs 1, 2); the northern area preserves only Lower Palaeozoic strata of the Franklinian Basin. Cenozoic deposits are represented by small outliers of pre-glacial (?Pliocene) fluvial strata in the northern area and widespread Quaternary and Recent deposits.

The 1999 work focused on the Inglefield mobile belt and Franklinian Basin and new observations form the basis of this report. Thule Basin strata are only briefly mentioned while results on Cenozoic geology are found elsewhere in this volume (Bennike 2000; Dawes *et al.* 2000).

Inglefield mobile belt

The main aims of the work in northern Prudhoe Land and Inglefield Land were:

1. To delimit the lithologies of inland areas, particularly the distribution of orthogneisses and paragneisses and the various plutonic rocks.
2. To reconstruct the geological evolution of the almost exclusively Palaeoproterozoic lithologies.
3. To determine the relationships between the contrasting structural styles that characterise the shield and to assess whether more than one terrane might be present.

The study region constitutes the eastern part of the Palaeoproterozoic Ellesmere–Inglefield mobile belt (Frisch & Dawes 1982; Dawes 1988). The polydeformed and polymetamorphic rocks can be divided into two main groups (Fig. 2): supracrustal rocks and associated gneisses (Etah Group) that are intruded on all scales by a polyphase igneous suite (Etah meta-igneous complex). The metamorphic grade reached granulite facies and both rock groups show evidence of intense deformation and partial melting.

The two 'Etah' terms (Etah is an abandoned settlement in Foulke Fjord; Figs 1, 2), introduced in the early 1970s, were based on the Foulke Fjord – Sunrise Pynt area where key relationships between supracrustal rocks and younger intrusions are particularly well exposed (e.g. Dawes 1976, fig. 228). The paragneisses of Hatherton Bugt to the north and the orthogneisses of Hartstene Bugt to the south were initially placed in a third rock division of 'variable gneisses' (Dawes 1972, 1976). The distinction between these gneiss types is difficult to make in many areas since intrusion has led to intricate associations on all scales and there has been repeated partial melting of paragneiss. At the mapping scale, both the paragneiss and orthogneiss map units contain intermixed packages of both lithologies (see Fig. 3A).

The 1999 mapping confirmed the broad bipartite division of the shield throughout Inglefield Land and thus the 'Etah' units are retained here. The relationships of lithological units to aeromagnetic signatures have been discussed by Schjøth *et al.* (1996); notes on each unit shown on the map (Fig. 2) are given below.

Etah Group

This group comprises the oldest rocks recognised: mainly metasediments and paragneiss, with smaller units of mafic and ultramafic rocks assumed to be parts of the supracrustal package. Mafic rocks also form a minor part of the Etah meta-igneous complex.

Marble and calc-silicate rocks. These rocks are intercalated in units from under a metre to 2 km thick as in the Sunrise Pynt belt (Fig. 3). They may be the site of high-strain zones several hundred metres wide, and boudins and isoclinal folds are common. The marble and calc-silicate units commonly contain disrupted inclusions of wall rock and some exposures represent isolated enclaves in granite. The rocks contain calcite, dolomite, diopside, forsterite, spinel and wollastonite; locally wollastonite-rich and diopside-rich layers occur (see Frontispiece of this volume, p. 3). In some areas, for example south of Kap Agassiz, large tracts of diopside gneiss are common.

Paragneiss sensu lato. This unit, making up over half of the exposed shield (Fig. 2), comprises a variety of pelitic, semi-pelitic and quartzo-feldspathic gneissic rocks with varying amounts of garnet, sillimanite, biotite with or without cordierite, together with garnet-biotite (-sillimanite) schists. Garnet is common as porphyroblasts and as mm-size seams; sillimanite may occur in coarse sheaves. Many paragneisses are essentially migmatites containing several generations and varying amounts of anatectic melt fraction. Gneiss bands with disseminated sulphides (largely oxidised) associated with graphite stand out because of their brown to reddish brown colours (see Fig. 9 and p. 24). Most paragneisses are banded with a distinct foliation but homogeneous types occur, such as the large areas of leucocratic rocks in central and eastern Inglefield Land, i.e. the garnet granulites of Sharp (1991).

Amphibolite and pyribolite. This unit comprises foliated melanocratic rocks containing plagioclase + amphibole ± pyroxene. Locally, some units contain disseminated to semi-massive sulphides and others are magnetite-rich (see *Mineral occurrences* p. 24). A prominent unit strik-
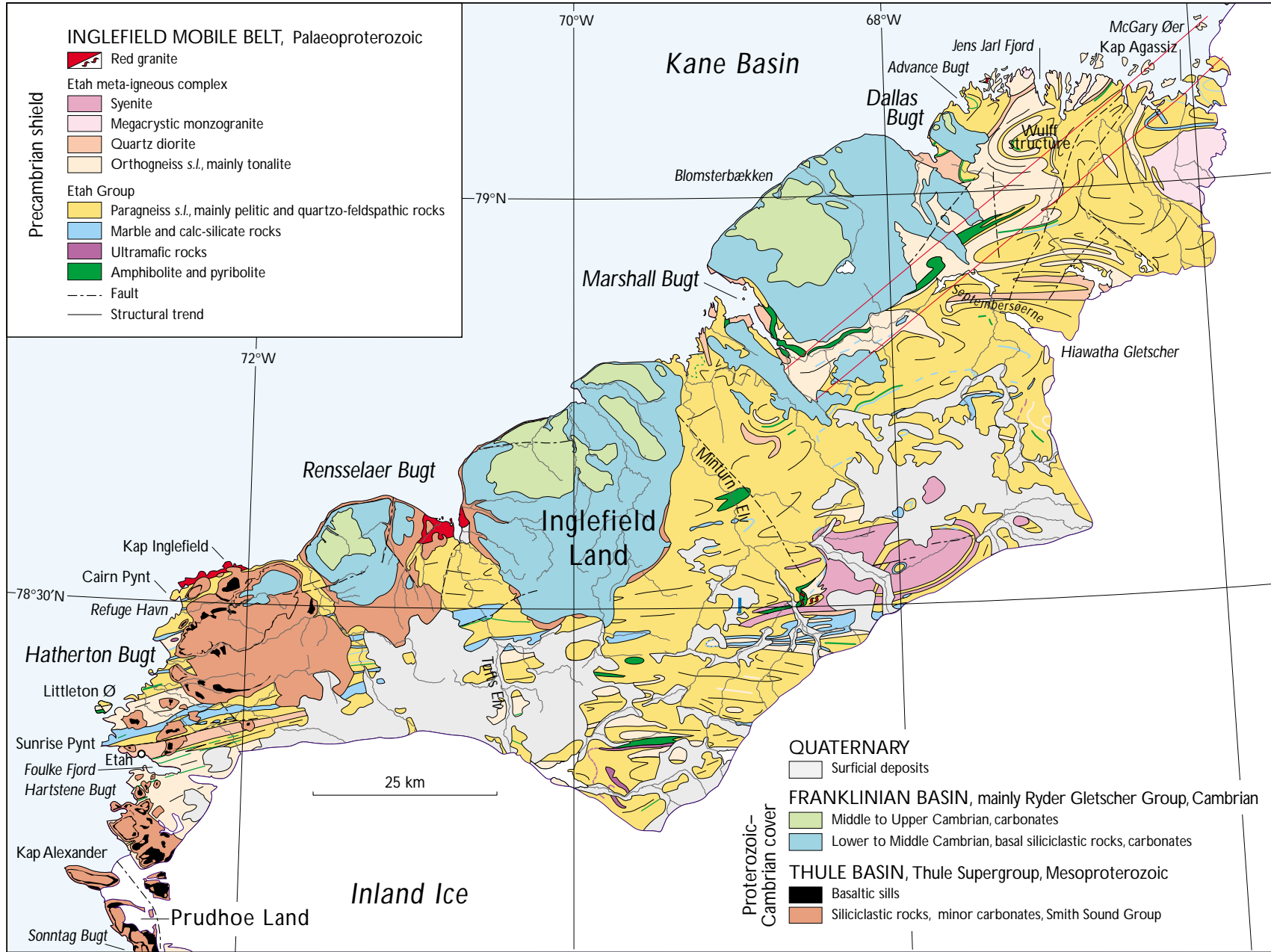
Precambrian shield

INGLEFIELD MOBILE BELT, Palaeoproterozoic

- Red granite

Etah meta-igneous complex
- Syenite
- Megacrystic monzogranite
- Quartz diorite
- Orthogneiss *s.l.*, mainly tonalite

Etah Group
- Paragneiss *s.l.*, mainly pelitic and quartzo-feldspathic rocks
- Marble and calc-silicate rocks
- Ultramafic rocks
- Amphibolite and pyribolite
- — · — Fault
- —— Structural trend

Proterozoic–Cambrian cover

QUATERNARY
- Surficial deposits

FRANKLINIAN BASIN, mainly Ryder Gletscher Group, Cambrian
- Middle to Upper Cambrian, carbonates
- Lower to Middle Cambrian, basal siliciclastic rocks, carbonates

THULE BASIN, Thule Supergroup, Mesoproterozoic
- Basaltic sills
- Siliciclastic rocks, minor carbonates, Smith Sound Group

Kane Basin

70°W 68°W *McGary Øer* *Kap Agassiz*
Jens Jarl Fjord
Advance Bugt
Dallas Bugt
Wulff structure
Blomsterbækken
79°N
Septembersøerne
Marshall Bugt
Hiawatha Gletscher
72°W
Rensselaer Bugt
Minturn Elv
Inglefield Land
Kap Inglefield
Cairn Pynt
78°30′N
Refuge Havn
Hatherton Bugt
Tufts Elv
Littleton Ø
Sunrise Pynt Etah
Foulke Fjord
Hartstene Bugt
25 km
Kap Alexander
Inland Ice
Prudhoe Land
Sonntag Bugt

Fig. 2. Preliminary geological map of Inglefield Land and northern Prudhoe Land (southern area). Geology of the Thule Basin and Franklinian Basin is slightly modified from Thomassen & Dawes (1996). The two **red lines** delimit the 'North Inglefield Land gold belt' described by Thomassen *et al.* (2000); the **blue bar** at 78°30′N, 69°00′W marks the magnetometer ground traverse referred to in the text (p. 24). For regional location, see Fig. 1.

Fig. 3. The Sunrise Pynt marble belt, western Inglefield Land.

A: Aerial view to the south-east about 17 km east of Sunrise Pynt where the flanking rocks are a mixed package of para- and orthogneisses (on Fig. 2 shown as 'paragneiss *s.l.*'). At the fault displacement in the centre of the view, the belt is about 2 km wide. Inland Ice is in the background. **X** and **Y** define the view in Fig. 3B.

B: View of the southern margin of the belt looking east from position **X** on Fig. 3A. Note the intense deformation. Pale granite sheets (**Pg**) invade the marble/calc-silicate rocks (**M**) and mainly dark orthogneisses (**O**); red granite (**Rg**) occurs as veins and inclusions in the marble. The marble outcrop in the distance is marked **Y** on Fig. 3A. Top of the cliff in the foreground is *c.* 100 m above the river that flows in a fault zone.
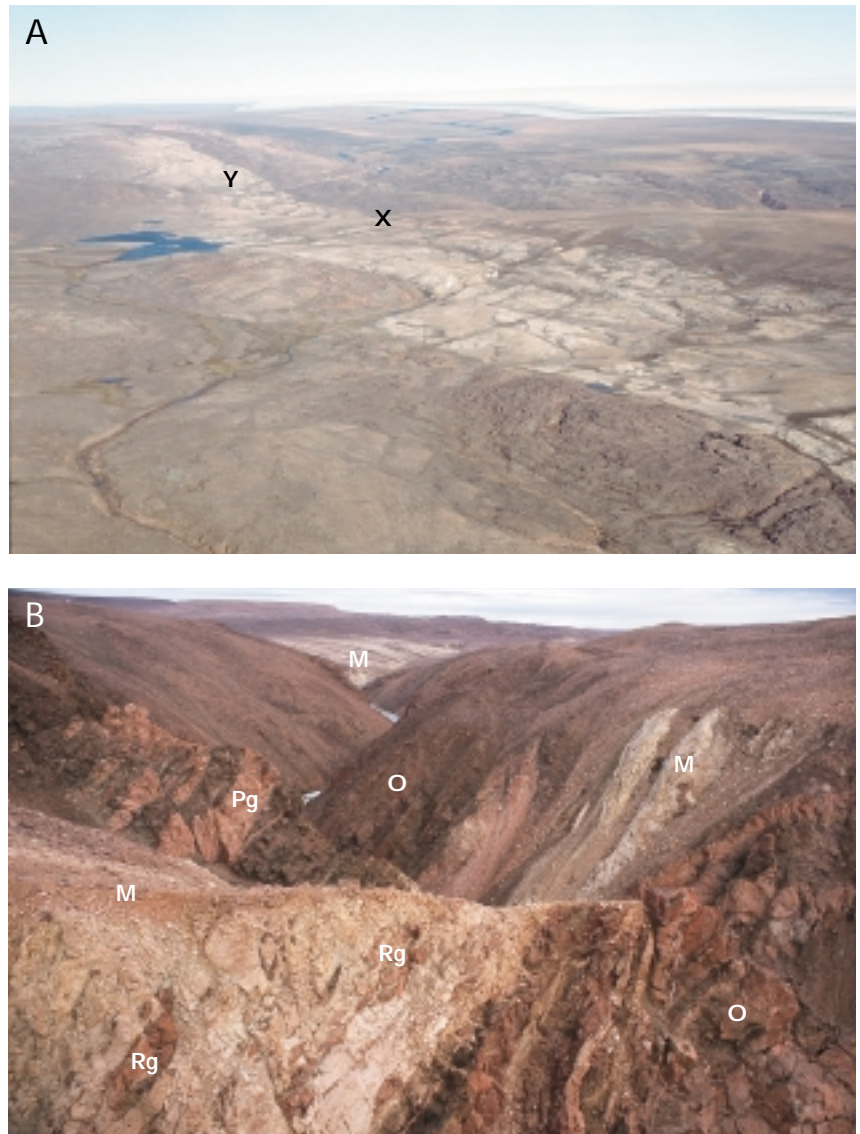
ing north-east from the head of Marshall Bugt is up to 300 m thick and traceable for 70 km; like many others, it is interlayered with other rocks including orthogneisses and ultramafic rocks. Relict layering, interpreted as a primary magmatic feature, has been observed in parts of the belt. South-west of Kap Agassiz, a shallow-dipping succession of calc-silicate rocks and pyribolite is interpreted as a mineralised, layered mafic–ultramafic intrusion emplaced into carbonate sediments (Pirajno *et al.* 2000).

Ultramafic rocks. These include massive to crudely layered metamorphic rocks of harzburgite, pyroxenite and hornblendite compositions with some serpentinites. Typically they form units up to a few metres thick, either independently or associated with amphibolite and pyribolite in relationships that suggest an origin as

layered intrusive complexes. Larger units occur in southernmost central Inglefield Land (Fig. 2).

Etah meta-igneous complex

This complex is composed of intermediate to felsic meta-igneous rocks and subordinate metagabbros and magnetite-rich rocks. All gradations are seen in outcrop from homogeneous rock to foliated and severely deformed layered gneiss (Fig. 4A, B). Pervasive foliation and gneissic fabric are commonly developed near and along intrusion margins. Orthogneiss *sensu lato* and quartz diorite crop out in two main areas: in the south and south-west including Prudhoe Land, and in north-eastern Inglefield Land (Fig. 2); because of gradational relationships, choice of map units is often arbi-
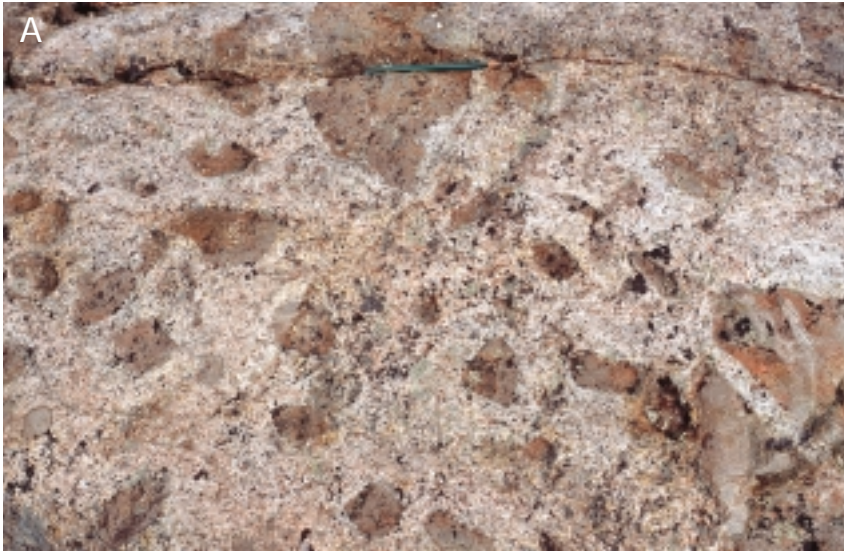
Fig. 4. Variably deformed rocks of the Etah meta-igneous complex in Inglefield Land.
A: Homogeneous tonalite with angular inclusions of paragneiss. North side of inner Marshall Bugt. Pencil as scale.
B: Veined, isoclinally folded melanocratic orthogneiss, north coast of Littleton Ø. Hammer is 50 cm long.

trary and orthogneiss *s.l.* contains rocks elsewhere distinguished as quartz diorite. Despite intense deformation, both the orthogneiss and quartz diorite have locally well-preserved intrusive contacts and xenoliths (Fig. 4A).

Orthogneiss sensu lato. The homogeneous to gneissic rocks (see above and Fig. 4) are mainly of dioritic, quartz dioritic, granodioritic and tonalitic composition with varying amounts of orthopyroxene, hornblende and biotite. Locally present are K-feldspar, garnet and magnetite; some varieties lack orthopyroxene. Exposures range from isoclinally folded bodies several kilometres thick to sheets a few centimetres thick.

Quartz diorite. This unit comprises the homogeneous dark-weathering, greenish grey rocks originally described by Bugge (1910) as 'hypersthene-quartz diorite'; also found on the Canadian side of Smith Sound

(see Frisch 1981). The rocks are composed chiefly of oligoclase, K-feldspar, quartz, othopyroxene, hornblende and biotite; magnetite and garnet are locally present. The two largest occurrences of quartz diorite, in the originally described area at Foulke Fjord ('Bugge-type rock' is also common in the orthogneiss belt to the south) and north of Hiawatha Gletscher, include bodies up to 2 km thick.

Megacrystic monzogranite. Two bodies in north-eastern Inglefield Land are shown on the map (Fig. 2). The largest, partly covered on the east by the Inland Ice, is a quartz-poor, K-feldsparphyric granite, with biotite and subordinate orthopyroxene. This pluton is foliated and interleaved with gneiss at its margins; the foliation is generally concordant with the regional structure. Crude alignment of feldspar megacrysts in unde-

formed matrix in the central part suggests that some deformation occurred during crystallisation. The coastal body to the north-west at Jens Jarl Fjord, similarly megacrystic but with orthopyroxene as the main mafic mineral, contains an impressive assortment of inclusions, up to 50 m across, of orthogneiss, paragneiss and pink granite.

Syenite. The large syenite body at the headwaters of Minturn Elv (Fig. 2) has attracted attention due to its high magnetic susceptibility and conspicuous black-lichen cover (Schjøth *et al.* 1996). The syenite, typically homogeneous and weathering purplish, has biotite as the main mafic mineral, accompanied in places by magnetite and orthopyroxene. The outcrops represent sheet-like bodies up to several kilometres thick, interleaved with paragneisses; the margins are commonly intensely foliated. The overall structure is thought to be a dome-shaped doubly plunging antiform.

Red granite

The coastal exposures of red granite shown on Fig. 2 and smaller outcrops between Advance Bugt and McGary Øer, were noted by early explorers. Red granite is also conspicuous as intrusions in Etah Group rocks and as inclusions in remobilised marble throughout the region (Fig. 3B). Cross-cutting relationships indicate several granite generations, viz. some grade into gneisses, some red granites cut migmatitic pink gneisses and some appear to be post-tectonic (see *Late intrusions* below).

The red granite of the map unit was probably derived by *in situ* partial melting of paragneisses. It is leucocratic, homogeneous or porphyritic and locally contains garnet. Much of the red granite in coastal areas appears to be associated with garnetiferous melt segregations, migmatitic veining and granite sheets in adjacent gneisses. Transitions from pink pelitic (biotite-garnet) gneiss with few leucosome veins to veined gneiss with abundant pink granite layers to homogeneous red leucogranite have been observed. Our interpretation is that these gradations represent progressive stages of partial melting.

Late intrusions

Minor felsic and mafic intrusions post-date the latest folding event (see Table 1).

Felsic rocks are of two main types: (1) pale or white alaskite and pegmatite sheets and dykes seen throughout Inglefield Land, and (2) younger brick-red, fine- to medium-grained syenitic cross-cutting dykes up to a few metres thick, noted only east of 68°W. One SE–NW-trending dyke, cutting paragneiss and alaskite south of Hiawatha Gletscher, has yielded a Sm–Nd model age of *c.* 3000 Ma and must be derived by melting or reworking of Archaean crust (M.A. Hamilton, in Dawes 1999).

Basic dykes, less than 15 m thick and of at least two ages, occur sparsely (see Table 1).

Crustal history

The crustal history – involving polyphase metamorphism and deformation and several episodes of melting – is undoubtedly complex. Isotopic ages from both Greenland and Ellesmere Island (Canada) suggest that the Etah Group and the Etah meta-igneous complex were metamorphosed about 1.9 Ga ago under low- to medium-pressure granulite facies conditions, as shown by widespread cordierite in addition to sillimanite and orthopyroxene (Frisch & Hunt 1988 and references in Dawes 1988). Retrograde metamorphism appears to be related to shear zones and faults.

The earliest fabric recognised is the gneissic or migmatitic layering in the paragneiss which is accompanied by metamorphic differentiation into leucocratic and melanocratic layers. This is overprinted and commonly transposed by a strong penetrative fabric that also affects rocks of the Etah meta-igneous complex and that subsequently was folded into map-scale interference structures.

At least three (but possibly several more) phases of deformation produced folds on all scales and the varying map-scale structural style: persistent linear belts with isoclinal folds, and areas of open folds with large interference fold patterns, such as the Wulff structure, east of Advance Bugt in north-eastern Inglefield Land (Dawes 1988). Detailed study of selected exposures documented at least three episodes of partial melting in repeatedly folded paragneisses. The Sunrise Pynt linear belt striking E–W from the coast to the Inland Ice, is characterised by steeply dipping gneissic fabrics and thick marble/calc-silicate units (Fig. 3). Folds are dominantly isoclinal, upright or overturned moderately to the south or north; no intense lineation was recognised. The E–W-striking linear belt appears to represent a zone of increased strain with early structures being transposed into steep to moderate inclinations. The origin of some dips as low as 20–30° in some areas is uncertain.

The lithological similarity noted by Thomassen & Dawes (1996) between south-western and north-eastern Inglefield Land, for example, marble/calc-silicate rocks with red granite dykes and sheets, as well as mar-

ble enclaves in orthogneiss, was confirmed in 1999 throughout the region, leading to the conclusion that only one lithotectonic terrane is represented. The similar range of sediment precursors corresponds to that in nearby parts of Ellesmere Island suggesting the presence of a single tectonic unit. Finds in 1999 of quartzite units in southernmost central Inglefield Land, together with those previously reported there, and from Sonntag Bugt (Dawes 1972), are noteworthy because these rocks are characteristic of supracrustal sequences to the southwest in Prudhoe Land, which are regarded as cover to the Archaean basement of the Thule district (Fig. 1; Dawes 1991). A preliminary chronological sequence of events is given in Table 1.

Thule Basin

The northernmost exposures of the Thule Basin are in Inglefield Land, and in Bache Peninsula, Canada, where clastic strata of the Smith Sound Group overlie the peneplaned crystalline shield (Fig. 1; Dawes 1997). These strata contain basaltic sills of Mesoproterozoic age and the unconformity at the base of the Thule Basin represents a time gap of at least 500 Ma (Table 1). The feather-edge of the Smith Sound Group in Greenland occurs somewhere in the poorly exposed region between Rensselaer Bugt and Marshall Bugt. Sporadic observations in 1999 suggest that the Thule strata wedge

out farther east than previously thought (Fig. 2, cf. Thomassen & Dawes 1996, fig. 2). At Bache Peninsula, a section through the Smith Sound Group was studied during the *Greenland – Ellesmere Island traverse* mentioned later (page 26).

Franklinian Basin

The base of the Franklinian Basin succession is exposed in Inglefield Land where Lower Cambrian rocks overlie Thule Basin strata and overstep north-eastwards onto the shield (Fig. 1). The youngest Franklinian strata in Greenland are lowermost Devonian beds in Hall Land (Blom 1999); Upper Silurian (Ludlow) shales are the youngest strata preserved in the study region (Fig. 5; Hurst 1980).

Lower Cambrian – Ordovician

Field work in the Cambro-Ordovician succession in 1999 was mainly in Daugaard-Jensen Land and Washington Land, with short visits to Inglefield Land and Hall Land (Fig. 5). The main aims were:

1. To measure sections to delineate lateral and vertical facies and thickness changes and to correlate with known logs, including the unpublished work of H.F. Jepsen in 1976–77.

Table 1. Principal Proterozoic events of the Kane Basin region

Event	Age in Ma
15. Basic dykes, pre-Franklinian Basin.	*c.* 700
14. Faulting, including block faulting in northern Prudhoe Land.	
13. Smith Sound Group: sediments and basaltic magmatism.	*c.* 1250
12. Uplift and erosion with development of mature peneplain.	
11. Faulting and fracturing.	
10. Basic dykes, faulted but pre-peneplanation.	
9. Brick-red syenite dykes.	
8. Local high-strain shear zones, mylonites, retrograde metamorphism.	*c.* 1750
7. Alaskite and pegmatite.	
6. Deformation and metamorphism: large-scale, upright to overturned, west-plunging folds, with overall N–S compression as seen in the Sunrise Pynt belt.	
5. Metabasic dykes: cut penetrative fabrics and migmatites and are deformed.	
4. Deformation and granulite-facies metamorphism: isoclinal folds with development of a new penetrative fabric, some migmatisation.	*c.* 1910–1950
3. Etah meta-igneous complex: a mixed suite of calc-alkaline affinity (?island-arc setting), timing of different intrusion phases is imprecise but cross-cutting and xenolith relationships suggest the general sequence (a) quartz diorite and tonalite, (b) red granites, and (c) syenite and monzogranite.	
2. Repeated deformation and metamorphism up to granulite-facies grade leading to partial melting.	
1. Etah Group: deposition of mixed sediments with important carbonate sequences, associated with mafic–ultramafic rocks.	

Ages are from the sources quoted in Dawes (1988, table 1).

2. To improve correlation with successions farther east in western and central North Greenland and, for the Cambrian section, between Daugaard-Jensen Land and Inglefield Land.

3. To check the 1:250 000 map of Jepsen *et al.* (1983) for faults and formation boundaries, particularly in the previously unstudied parts of Daugaard-Jensen Land, Petermann Halvø and Hall Land.

4. To collect bulk samples throughout the succession for conodont studies.

Lower–Middle Cambrian

Lower to lower Middle Cambrian strata, studied in the Romer Søer area of Daugaard-Jensen Land and at Dallas Bugt and Marshall Bugt in Inglefield Land (Figs 2, 5), record the subsidence and transgression of the Protero-zoic basement followed by creation of a carbonate plat-form that dominated the Franklinian shelf for much of the early Palaeozoic (Higgins *et al.* 1991). Three genetic packets, or preliminary sequences, each recording a
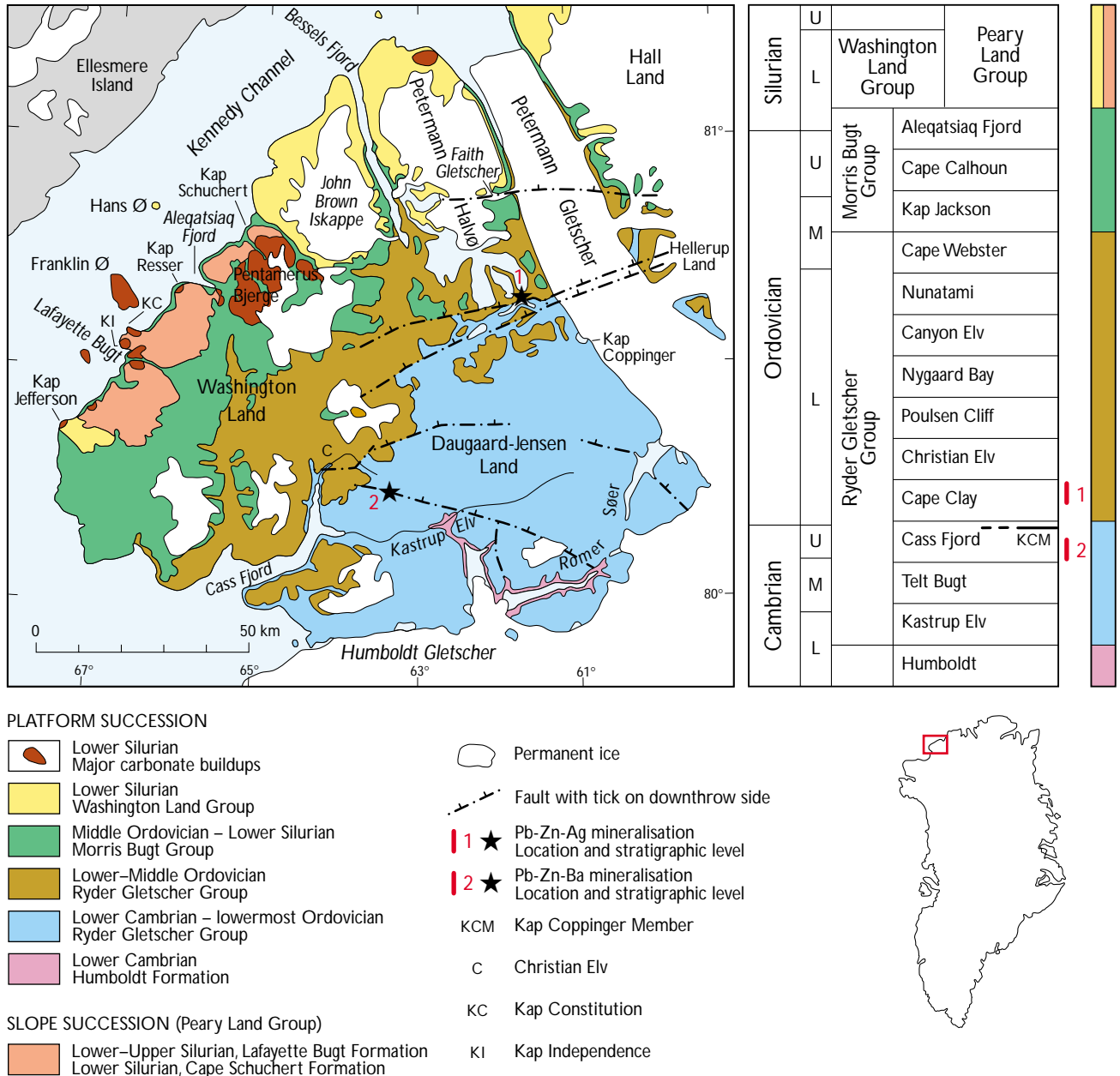
Fig. 5. Geological map of Daugaard-Jensen Land, Washington Land, Petermann Halvø and south-western Hall Land (northern area), and general stratigraphic column showing main levels of lead-zinc mineralisation. Modified from Jensen (1998); for regional location, see Fig. 1.
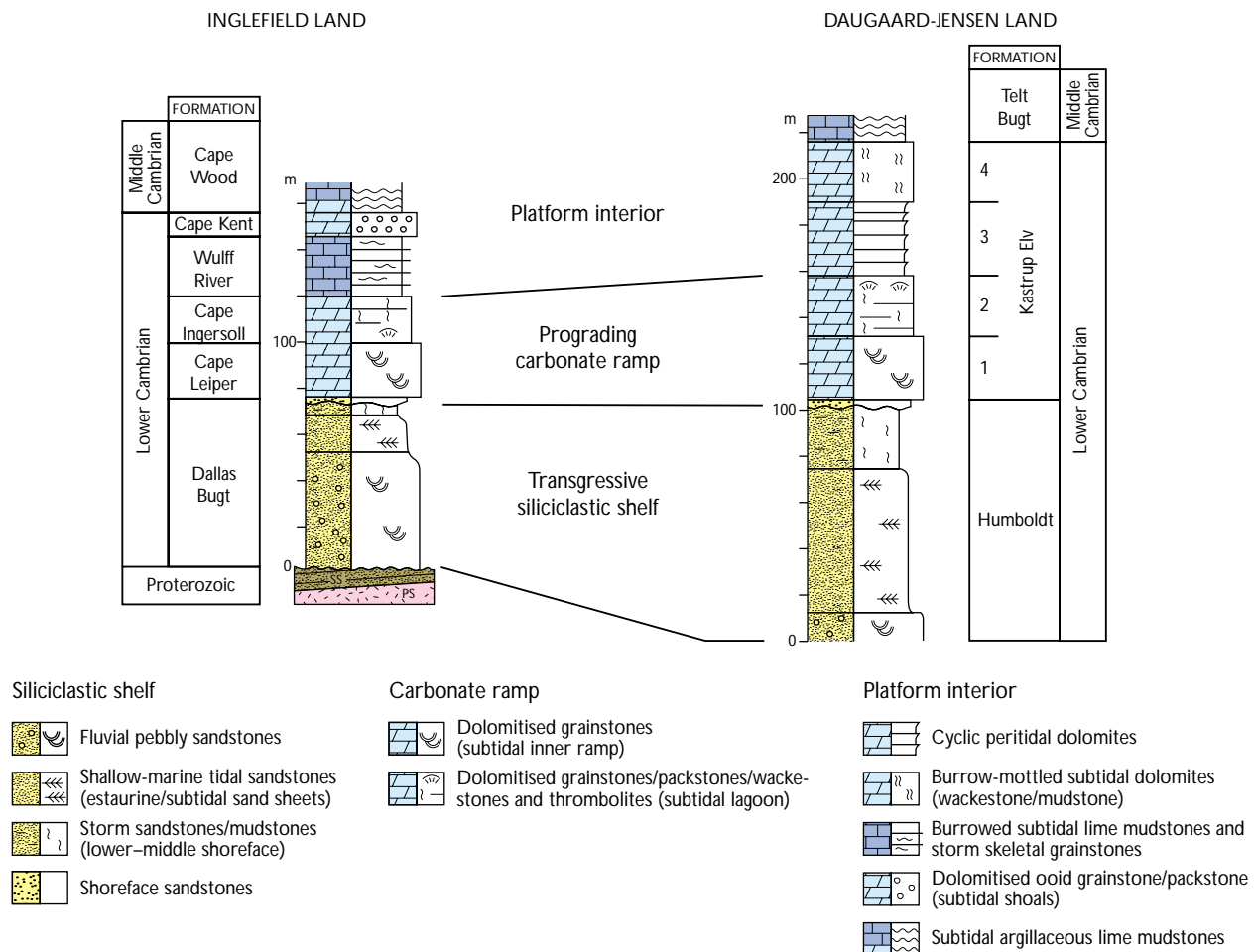
19

INGLEFIELD LAND   DAUGAARD-JENSEN LAND

Fig. 6. Schematic logs through the Lower – lower Middle Cambrian of Inglefield Land and Daugaard-Jensen Land showing the proposed correlation and the main evolutionary phases discussed in the text. The Kastrup Elv Formation is subdivided into four informal units, **1**–**4**. **SS**: Mesoproterozoic Smith Sound Group; **PS**: Palaeoproterozoic shield.

discrete phase of shelf evolution, are recognised and described below.

Transgressive siliciclastic shelf. This is represented by the Dallas Bugt and Humboldt Formations of Inglefield Land and Daugaard-Jensen Land, respectively (Fig. 6). Basal fluvial pebbly sandstones are succeeded by a uniform sand-dominated succession deposited in a shallow-marine or estuarine tide-dominated setting. The upper levels are more mud-rich, representing a middle–lower shoreface environment. This tripartite division, formalised at member level in Inglefield Land (Peel *et al.* 1982), is also applicable to Daugaard-Jensen Land and it is recommended that the Dallas Bugt Formation be extended to this area.

Prograding carbonate ramp. A marked erosional surface and facies change near the top of the siliciclastic succession heralds a shift to carbonate sedimentation. Hummocky cross-stratified sandstones typically overlie this surface and grade up into dolomitised cross-strat-

ified grainstones (Kastrup Elv Formation, unit 1 in Daugaard-Jensen Land; Cape Leiper Formation in Inglefield Land) followed by a broadly fining-upward unit of subtidal burrowed wackestones, packstones and grainstones, locally showing decimetre-scale thrombolitic mounds (Fig. 6; Kastrup Elv Formation, unit 2 in Daugaard-Jensen Land; Cape Ingersoll Formation in Inglefield Land). A comparable succession, recording the northward progradation of a proximal ramp, is developed in the uppermost Bistrup Land and lowermost Blåfjeld Formations of southern Wulff Land (Ineson & Peel 1997), thus allowing correlation eastwards to the successions of central North Greenland.

Platform interior. The upper Kastrup Elv Formation (units 3, 4) of Daugaard-Jensen Land and the broadly equivalent Wulff River and Cape Kent Formations of Inglefield Land comprise a heterogeneous suite of shallow-marine, typically low-energy, carbonate facies recording deposition in a protected platform interior set-
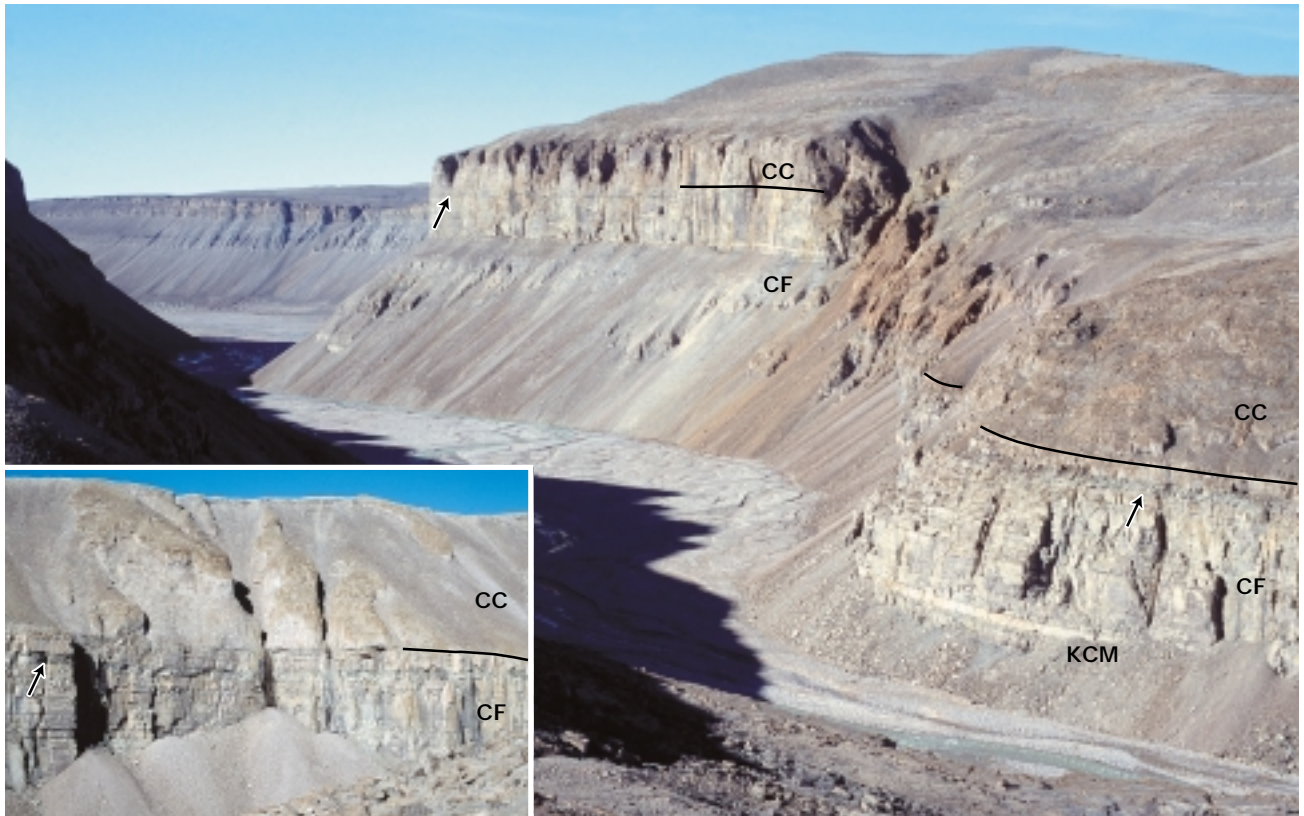
20

Fig. 7. Faulted Cambro-Ordovician strata in western Christian Elv, Daugaard-Jensen Land: the Cass Fjord Formation (**CF**) overlain by the Cape Clay Formation (**CC**). The view is to the south-west with the fault downthrow to the north. The pale, clastic Kap Coppinger Member, marked **KCM** in the downthrow block where it is about 2 m thick, is supposedly of earliest Ordovician age. The fault shows brownish weathering typical of ferroan dolomitisation that can be associated with sulphide mineralisation. The **inset** illustrates the well-defined nature of the formational contact just right of the foreground exposures; the **arrow** marks a dark silty limestone unit about 3 m thick that is also arrowed in the main view.

ting (Fig. 6). Stacked peritidal cycles and subtidal burrowed wackestones/mudstones characterise the succession in Daugaard-Jensen Land whereas the subtidal facies of Inglefield Land includes storm-dominated skeletal grainstones and ooid grainstones/packstones, perhaps reflecting a more exposed position on the platform.

Middle Cambrian – Ordovician

The Telt Bugt and Cass Fjord Formations were mainly studied in the Cass Fjord, Kap Coppinger and Romer Søer areas of Daugaard-Jensen Land. In an attempt to determine the age of the youngest Franklinian strata preserved in Inglefield Land, samples for conodont studies were collected at the top of the section south-west of Blomsterbækken in the Cass Fjord Formation (Fig. 2; see Troelsen 1950, fig. 3).

The boundary between the Kastrup Elv and Telt Bugt Formations in Daugaard-Jensen Land is a dolomite front

(Henriksen & Peel 1976); it is subparallel to bedding locally but is markedly diachronous on a regional scale. Thus, limestones of the Telt Bugt Formation thin westwards from about 100 m at Romer Søer to less than 5 m at Cass Fjord (Peel & Christie 1982; Higgins *et al.* 1991). The Cass Fjord Formation is also dolomitised at certain levels, locally associated with lead-zinc mineralisation (see *Mineral occurrences* page 25). The Cass Fjord Formation was determined to thin westwards from 380 m at Kap Coppinger to 283 m north-east of Cass Fjord; this thinning trend is also exemplified by the prominent clastic marker in the upper part of the formation (Kap Coppinger Member; Figs 5, 7) that thins from 25 m to just 1 m over the same distance. Three units were recognised in the Cass Fjord Formation. The lower and thickest unit comprises cyclic intraformational conglomerates, platy limestones, lime mudstones and stromatolitic mounds, each cycle being capped by sandstones. This is overlain by a unit of dolomites, siltstones and bitu-

minous limestones and a few laterally extensive stromatolite mounds capped by brown-weathering sandstone. The upper unit includes cycles of intraformational conglomerates and platy limestones grading upwards into bioturbated limestones with mounds.

The interval from the Cass Fjord Formation to the Cape Calhoun Formation was studied along the south coast of Washington Land at localities previously reported on by Koch (1929) and Troelsen (1950), east of Cass Fjord, and across central and southern Petermann Halvø (Fig. 5). Systematic collecting for conodont studies was undertaken throughout the interval and into the overlying Aleqatsiaq Fjord Formation. Most formations were found to be reliable map units, but in any lithostratigraphic revision the Nygaard Bay Formation may be best considered as a member of the Canyon Elv Formation as it appears to belong to the same depositional cycle. The Cass Fjord, Cape Clay and Canyon Elv Formations host mineralisation; see under *Mineral occurrences* p. 25.

Silurian

Field work in 1999 was between Kap Jefferson and Aleqatsiaq Fjord and in the southern Pentamerus Bjerge in Washington Land, and on Franklin Ø, Petermann Halvø and Hall Land (Fig. 5). It had the following aims:

1. To better understand the relationships between reef and platform carbonates and the slope siliciclastics and to assess current lithostratigraphic divisions.
2. To determine the distribution of reefs; several noted in the literature are not shown on the 1:250 000 map.
3. To identify possible hydrocarbon palaeoreservoirs within the carbonate succession.

Hurst (1980) divided the Silurian of the study region into 13 formations. The Lower Silurian buildups south of Aleqatsiaq Fjord (Fig. 1), included in the Hauge Bjerge Formation (Hurst 1980; Sønderholm & Harland 1988), occur as isolated mounds encased in the siliciclastic-dominated deposits of the Lafayette Bugt and Cape Schuchert Formations (Fig. 8). Between Aleqatsiaq Fjord and Kap Schuchert, the time-equivalent buildups are included in the Pentamerus Bjerge Formation whereas further north other formations are recognised. Sequence stratigraphic studies in 1999 elucidated the detailed relationships between the buildups of the Hauge Bjerge and Pentamerus Bjerge Formations and their time-equivalent shelf and slope deposits of the Adams Bjerge, Lafayette Bugt and Cape Schuchert Formations.

The Lower Silurian can be divided into three (possibly four) depositional sequences based on the internal geometry of the buildups and the facies stacking-pattern in the slope deposits. In off-platform and off-reef areas, each sequence is upward-coarsening passing gradually from fine-grained siliciclastics, cherts and nodular limestones into interbedded shales and limestone turbidites with increase in thickness and frequency of the turbidites. In the platform and larger buildups, individual sequences are aggradational to slightly progradational packages often with erosional tops, separated by thin transgressive shales. The tops record events of platform and buildup destruction during sea-level lowstand and the buildups are often surrounded by thick haloes of carbonate breccias and conglomerates.

The three largest of the buildups not on the map of Jepsen *et al.* (1983) are at Kap Resser, in southern Lafayette Bugt and about 10 km north-east of Kap Jefferson (Fig. 5). These, like others of the Hauge Bjerge

Fig. 8. Kap Independence (**KI**), Washington Land, about 450 m high, seen from the south-west. A major Silurian build-up of the Hauge Bjerge Formation passes into slope sediments of the Cape Schuchert and Lafayette Bugt Formations (**S**). In the extreme right, the shales contain pale limestone blocks shed from an adjacent reef to the south (out of view). Note the well-developed bedding in the lower part of the build-up and the large blocks in the upper part. Another major build-up forms Kap Constitution (**KC**). This magnificent coastal geology was first described by Lauge Koch; see Dawes & Haller (1979, figs 4–6, 9, 10). For location, see Fig. 5.

Formation, have massive cores of stromatoporoid- and coral-dominated facies surrounded by crinoid-rich flank deposits. The Kap Resser and Kap Jefferson reefs, drowned earlier than most others of the formation, are overlain by slope sediments of the Lafayette Bugt Formation.

The Aleqatsiaq Fjord Formation thins along Faith Gletscher from 370 m in the east to 283 m on the west side of Bessels Fjord. A considerable amount of palaeo-relief, probably related to mound developments, was noted at the upper contact of the AF-3 member beneath the Washington Land Group; previously, palaeorelief has been reported between the upper two members (AF-2 and AF-3; Sønderholm *et al*. 1987).

Faults in the northern area

ENE- and WNW-trending faults are in focus in connection with mineralisation potential (see under *Mineral occurrences* below). In 1999 new faults were mapped in Hall Land and Petermann Halvø that cross Petermann Gletscher; one of these, named herein the Faith Gletscher fault after the glacier it follows, has the largest displacement of any known structure in the northern area (Fig. 5). It has a minimum of 365 m downdrop to the north. Surprisingly, the fault could not be recognised in Bessels Fjord only 30 km to the west, but in Hall Land the structure appears to pass into a monocline suggesting that it is a hinged fault zone. The proximity to the mounds in the Aleqatsiaq Fjord Formation mentioned above may not be coincidental if the fault was initially syn-depositional.

Economic geology

Evaluation of both mineral and petroleum resources was undertaken. Mineral prospecting and sampling for mineral deposits was carried out concurrently with the mapping in both Precambrian shield and Lower Palaeozoic rocks. Petroleum studies were carried out in conjunction with sedimentological work in the northern area.

Mineral occurrences

The main aims of the 1999 field studies were:

1. To investigate and evaluate known mineral occurrences and to collect samples for lead and sulphur isotopic work.

2. To assess and check the mineral potential of fault zones in Lower Palaeozoic areas.
3. To investigate geochemical anomalies detected during the 1995 season in the southern area.
4. To check airborne geophysical anomalies from the 1998 survey in the northern area.

Inglefield mobile belt (southern area)

Newly discovered and previously known mineralisation examined in 1999 allow a preliminary classification with reference to three host rocks, viz. paragneisses, orthogneisses and mafic–ultramafic rocks. These are briefly described below. Investigation in 1999 of geochemical gold anomalies outlined by Gowen & Kelly (1996) and Steenfelt & Dam (1996) did not lead to the location of the mineralisation source; however, stream sediment and soil sampling (Fig. 9) confirmed anomalies in northern Inglefield Land (17–46 ppb Au, 588–1419 ppm Cu and 290–580 ppm Zn in five samples) and in central Inglefield Land (34–150 ppb Au in five samples).

Fig. 9. Geochemical sampling of soliflucted material from a rust zone in paragneisses, 10 km south of Marshall Bugt, central Inglefield Land. Analysis of the soil samples here gave up to 75 ppb Au, 101 ppm As, 172 ppm Cu and 235 ppm Zn.

Paragneiss-hosted mineralisation. Garnet-sillimanite paragneisses in central and northern Inglefield Land host widespread bands containing disseminated iron sulphides associated with graphite, the oxidation of which has resulted in conspicuous rust zones up to 5 km long and 200 m wide (Fig. 9; Sharp 1991). In the rust zones, sulphides concentrated in swarms of bands subparallel to foliation occasionally form strongly deformed lenses and layers of semi-massive to massive pyrrhotite with minor pyrite and traces of chalcopyrite. Massive sulphide bodies are up to 30 m long and 0.5 m wide (Fig. 10). Mineralised grab samples returned up to 1.4 ppm Au, 0.24% Cu, 0.15% Zn, 0.04% Pb and 0.06% Mo.

Orthogneiss-hosted mineralisation. In north-eastern Inglefield Land, gold-copper mineralisation was discovered in three lithologies: in granodioritic gneiss, in a quartzitic layer within the gneiss, and in quartz and pegmatite veins. The mineralisation in the first two types is disseminated bornite-digenite-covellite-chalcocite; the quartz and pegmatite veins contain blebs and disseminations of chalcopyrite, bornite and pyrrhotite. Assays of grab samples returned up to 12.5 ppm Au (the highest value recorded in northern Greenland), 35 ppm Ag and 1.28% Cu (see section below).

Mafic–ultramafic-hosted mineralisation. Two major belts mentioned earlier under the Etah Group are mineralised: the amphibolite belt extending from Marshall Bugt towards the north-east, and the pyribolite/calc-silicate rocks 10 km south-west of Kap Agassiz (Fig. 2). The amphibolite belt, with its ultramafic components, exhibits rusty weathering sulphide mineralisation in conformable layers up to several metres thick. Associated with these rocks are minor sulphides in shear zone-controlled quartz-rich veins. Sulphides are disseminated to semi-massive pyrrhotite, with minor pyrite and chalcopyrite. Analyses indicate that the amphibolite belt contains anomalous abundances of copper, zinc, vanadium, manganese and gold. Near the western end of Septembersøer, a pyroxenite with semi-massive pyrrhotite-chalcopyrite mineralisation yielded up to 0.3 ppm Au, 0.2 ppm Pd and 0.38% Cu, whereas a quartz-vein from the same locality, with stringers of pyrrhotite and chalcopyrite, returned 6.9 ppm Au and 0.24% Cu. The mineralisation south-west of Kap Agassiz hosted in sheared calc-silicate and mafic rocks consists of pyrrhotite, chalcopyrite, bornite, ilmenite and magnetite. Values of up to 0.6 ppm Au and 0.9% Cu were obtained from grab sampling.

Magnetite, as disseminations and massive lenses, is locally common in amphibolite and associated gneissic rocks; one occurrence near the headwaters of Minturn Elv has been described (Appel *et al.* 1995). In 1999, a magnetometer ground traverse of *c.* 2 km across the main magnetic anomaly gave a maximum value of 10 000 nT (for location, see Fig. 2). This is about two-thirds of the peak value obtained by the 1994 airborne survey (Stemp & Thorning 1995).

A new gold-copper exploration target

Analyses of 120 mineralised samples from throughout Inglefield Land show that anomalous gold abundances are associated with copper. Samples with more than 0.2 ppm Au (14 in all), are derived from six localities, five

Fig. 10. Mineralisation in the Precambrian shield of Inglefield Land. Sheared, pinch-and-swell layer of massive sulphides in rusty-weathering garnet-sillimanite paragneisses. South-south-east of Marshall Bugt. Hammer is 50 cm long.

of which fall in a 70 km long, NE–SW-trending belt that coincides with an aeromagnetic lineament. The highest gold values in rock grab samples are 12.5 and 6.9 ppm; soil samples show 11–46 ppb Au and 588–1419 ppm Cu, see pp. 23, 24. Stemp & Thorning (1995) suggested that the lineament represents a major geological structure. This anomalous belt, informally named the 'North Inglefield Land gold belt' (marked on Fig. 2), is considered a promising exploration target (Thomassen *et al.* 2000).

Lower Palaeozoic rocks (northern area)

Mineralisation of possible economic interest was examined in two areas: in southern Petermann Halvø where Rio Tinto – Platinova drilled a lead-zinc-silver mineralisation, and east of the head of Cass Fjord on a lead-zinc-barium showing discovered in 1999 (Fig. 5). Notes on these are given below. Baryte was identified in 1999 in the Canyon Elv Formation along the south coast of Washington Land: it principally occurs along bedding planes and joints and gives the unit a vuggy, white-spotted appearance.

The ground checks in 1999 of four electromagnetic anomalies outlined by Rasmussen (1999) did not reveal any mineralisation. The geophysical anomalies are in areas of surficial deposits and they may be caused by clay and gypsum in outwash. Numerous colour anomalies were also tested but the largest and most intense of these, located in burrow-mottled to dolomitised limestone along ENE-trending faults (such as that shown in Fig. 7), contained no mineralisation.

Lead-zinc-silver mineralisation. The precise stratal level of this mineralisation in the Ordovician carbonates has hitherto been in doubt (Jensen 1998; Jensen & Schønwandt 1998). Our 1999 work shows that it occurs within the middle to upper part of the Cape Clay Formation – stratigraphically much lower than previously surmised – in massive, burrow-mottled micritic to stromatolitic limestones and calcisiltite (Fig. 5). Where mineralised, the carbonates are pervasively dolomitised. The major E- to ENE-trending, steeply dipping fault that appears to control the alteration, has a northern block downdropped 30–40 m, with mineralisation sites along NW- to NNW-trending lineaments. Our observations indicate the strike length of the showings along the main fault to be 19 km, with float in the west returning 13.5% Zn and 184 ppm Ag. The mineralisation is locally impressive, for example one drill hole intersected two massive pyrite intervals totalling 16.8 m thickness (Platinova 2000).

The lead contained in galena is highly radiogenic: $^{206}Pb/^{204}Pb$ ratios range from 20.3 to 20.5, $^{207}Pb/^{204}Pb$ ratios from 15.8 to 15.85 and $^{208}Pb/^{204}Pb$ ratios from 43.3 to 44.3. These isotopic ratios suggest that the most probable source of the lead is the Precambrian shield underlying the Franklinian Basin.

Lead-zinc-barium mineralisation. This mineralisation in Daugaard-Jensen Land was discovered and drilled in 1999 by Rio Tinto – Platinova. Our investigations show that it is hosted in the Cass Fjord Formation (Fig. 5) in three massive 'reactive' limestone levels. The lower level, within the 'Lower massive unit' of Jepsen (1976), appears to be the most pervasively dolomitised and mineralised, and is related to a major WNW-trending fault. The mineralisation consists of fine-grained sphalerite and coarse-grained galena and barite in brown-weathered limestone associated with pervasive ferroan dolomitisation (Fig. 11). Chip sampling returned: 3–9% Zn, 7–11% Pb and 40–95 ppm Ag; one drill hole gave an intersection of 8.4% Zn, 0.04% Pb and 94 ppm Ag over 1.2 m (Platinova 2000).

Fig. 11. Mineralisation in Cambrian carbonates of Daugaard-Jensen Land. Typical sample from the lead-zinc-barium mineralisation in the Cass Fjord Formation: conspicuous galena crystals in a pale dolomitic matrix etched out on the weathered surface. Cut surface shows variety of crystal forms, some showing skeletal growth structures. Sample GGU 448662. Photo: Jakob Lautrup.
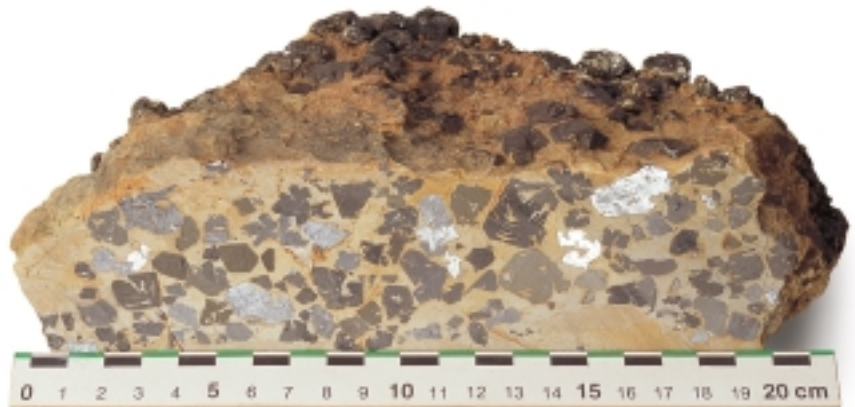
Petroleum geology

Petroleum studies focused on the Silurian where the argillaceous Lafayette Bugt Formation contains organic-rich intervals of potential source rocks (Christiansen & Nøhr-Hansen 1989). The conceptual play model proposed by Christiansen (1989) with shales and reefs as source and reservoir rocks, respectively, was confirmed in 1996 by the discovery of a palaeo-oil field in Wulff Land to the east (Fig. 1; Stemmerik *et al.* 1997).

In 1999 several buildups in southern Pentamerus Bjerge and southward to Kap Jefferson were determined to be small palaeo-oil fields with pore space filled with bitumen. In contrast to Wulff Land, these buildups are in an area where the shales are immature to mature. It is expected that the pending geochemical studies of the bitumen and organic-rich shales will improve understanding of the petroleum system.

Greenland – Ellesmere Island traverse

Most reconstructions of Greenland and North America interpret Nares Strait as a Cenozoic plate boundary of major convergence and strike-slip and the site of subduction and continental collision (e.g. Srivastava & Tapscott 1986). However, these views are not supported by the exposed geology, e.g. the same undeformed Protero-zoic–Palaeozoic succession occurs on both sides of Kane Basin (see Dawes & Kerr 1982; Okulitch *et al.* 1990).

To test the Cenozoic tectonothermal history, crystalline rocks from a traverse at right angles to Nares Strait were collected for thermal dating by fission track analysis (traverse line shown in Fig. 1). Minerals such as sphene reset at less than 100°C, i.e. well below subduction and collision zone temperatures. The traverse was completed in 1999 with sampling at 17 sites in Canada; rocks from the Greenland segment were sampled in 1995.

Air photography

Precipitous cliffs etched from homoclinal strata characterise much of the outer coast of both southern and northern areas. The cliffs between Petermann Gletscher and Cass Fjord, and Advance Bugt and Foulke Fjord (Figs 2, 5), were photographed in late August 1999 from a Twin Otter aircraft. Such photography has proved useful elsewhere in North Greenland for map compilation and stratigraphic studies.

Concluding remarks and future work

The 1999 field work provided the outstanding information for the compilation of the Kane Basin 1:500 000 map sheet. While it has been established that the shield forms a single terrane, the high-grade metamorphism and, by Greenland standards, poor outcrop limits detailed insights into the tectonomagmatic history. Isotopic age determinations of intrusive rocks and a provenance study of detrital zircons now in progress should improve understanding. In the Franklinian Basin, where map revision was limited, detailed sedimentological and sequence stratigraphic work have improved models of the depositional evolution of the basin.

The economic potential of both the Precambrian shield and Franklinian Basin has been confirmed by new discoveries: gold-copper mineralisation in orthogneisses and mafic–ultramafic rocks of the shield, and lead-zinc-barium mineralisation in Cambrian rocks. The lead, sulphur and carbon isotopic studies in progress should help in ore deposit and metallogenic modelling. Of the new finds the distribution of anomalous gold-copper along a 70 km long belt coinciding with a pronounced aeromagnetic feature in north-eastern Inglefield Land is intriguing, particularly since these metals' anomalous abundances were obtained from reconnaissance sampling. The newly identified mineralised belt constitutes an important target for future work.

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