The East Greenland continental margin, the Prinsen af Wales Bjerge and new Skaergaard intrusion initiatives

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The rifted volcanic margin of East Greenland has remained a major area for field studies and the development of models for the dynamics of plume-related continental break-up since the start of the Danish Lithosphere Centre (DLC) in 1994. The studies cover a range of disciplines and geological processes from the early development of pre-break-up basin formation and sedimentation over the main phase of basaltic magmatism to the late stages of alkaline magmatism and structural re-equilibration.

The East Greenland field activities in the summer of 2000, collectively referred to as *EG 2000*, were facilitated by a logistic platform provided by support from Statens Naturvidenskabelige Forskningsråd (SNF, the Danish Natural Science Research Council) and the Bureau of Minerals and Petroleum (BMP) in Nuuk, Greenland for the retrieval of 6 km of drillcore from the Skaergaard intrusion. During 1989 and 1990 mineral exploration had resulted in drilling of more than 15 km of core through the classic layered gabbros. The logistic platform also provided support for DLC and Geological Survey of Denmark and Greenland (GEUS) field work and projects throughout the Kangerlussuaq region and on the Blosseville Kyst (Fig. 1), as well as mineral exploration and petroleum company activities.

Study region, field parties and logistics

EG 2000 operated from 19 July to 28 August 2000 out of a base in Sødalen (Fig. 1), where a 600 m long STOL air strip and base facilities, including two huts, had been established between 1982 and 1990. During the first week of the operation a four-man team packed and air-freighted Skaergaard drillcore to Iceland. Return flights to Greenland were used for the transport of equipment, and from 25 July and onwards for field parties. The field operations were supported by an Aerospatial AS350 B2 helicopter and additional transport was provided by a wooden boat and a rubber dinghy.

The personnel involved in *EG 2000* and their affiliations are listed in Table 1. The main areas of activity (Fig. 1) included:

1. Studies of plateau basalt successions (C.E.L., C.T., L.H., J.S., see Table 1), the Borgtinderne syenite intrusions (P.K., S.B.), the newly discovered ultramafic Ejnar Mikkelsen intrusion (P.K., S.B.), and a regional swarm of lamprophyre dykes with mantle nodules in the area between Savary Fjord and Wiedemann Fjord on the central part of Blosseville Kyst and inland as far as Borgtinderne (P.K., S.B.).
2. Studies of inland plateau basalt successions in Prinsen af Wales Bjerge (H.H., A.K.), and at Tjældebjerget (H.H., A.K., L.H., C.E.L.).
3. Studies of the pre-basaltic sedimentary basin between Sødalen, inland and along Christian IV Gletscher (M.L., M.B., S.O., T.N.; see also Larsen *et al.* 2001, this volume).
4. Correlation of plateau basalt formations across Nansen Fjord and towards Kangerlussuaq in the coastal area between Nansen Fjord and Miki Fjord (M.G., L.H., C.E.L.).
5. Systematic sampling of profiles and field investigations in the Skaergaard intrusion on the eastern shore of Kangerlussuaq (C.E.L., P.T., C.T., A.F., J.J., J.S.) and a reconnaissance gravimetry programme over the intrusion (C.K.B., M.K.).
6. Regional sampling of the Kangerdlugssuaq alkaline intrusion and the Astrophyllite Bay complex on the western side of Kangerlussuaq (C.K.B., D.W.P., M.S.R.).
7. Investigation and sampling of disseminated and vein-related Au-Ag mineralisations in the Amdrup Fjord – Søndre Syenite Gletscher area on the west side of Kangerlussuaq (B.T., J.D.K.; see also Thomassen & Krebs 2001, this volume).

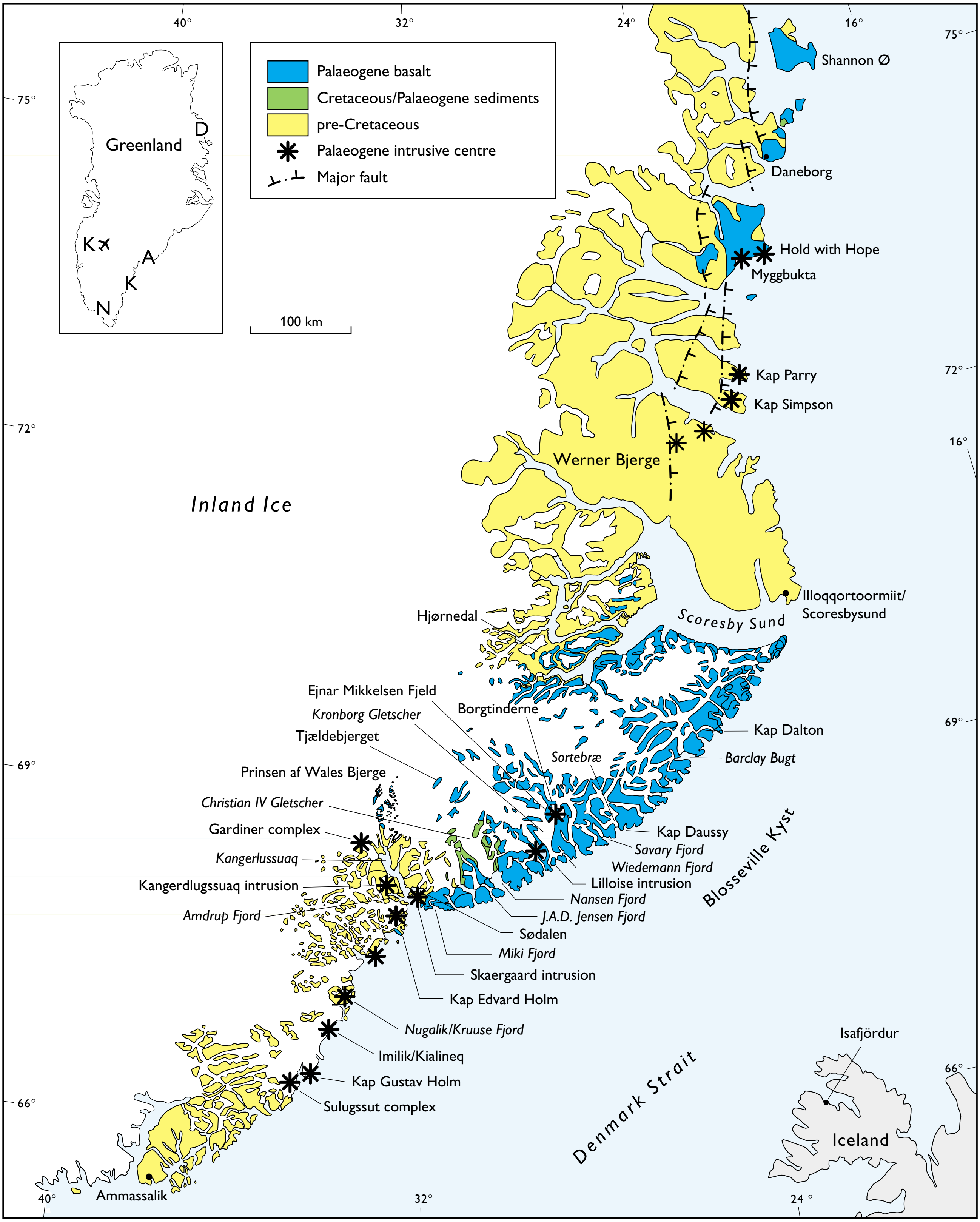


Fig. 1. Map of the Palaeogene East Greenland igneous province. 'Astrophyllite Bay' is located on the north shore of outer Amdrup Fjord. Insert map abbreviations – **A**: Ammassalik; **D**: Danmarkshavn; **K**: Kassortoq; **N**: Narsarsuaq and **K**✈: Kangerlussuaq / Søndre Strømfjord. Modified after Brooks & field parties (1996).

8. Establishment of seismic stations in Sødalen, Hjørnedal in the inner Scoresby Sund fjord system (70°N) and in Singertat intrusion in Kassortoq fjord *c.* 300 km south of Ammassalik (O.G.).
9. Selection, packing and transport of 16 tons of research core and 4 tons of exploration core from the Skaergaard intrusion to the Geological Museum in Copenhagen and to the BMP core library in Kangerlussuaq / Søndre Strømfjord, West Greenland (T.F.D.N., J.G., C.E.L., J.S.).

Pre-basaltic basin development and sedimentation

Since the early description of the 'Kangerdlugssuaq Sedimentary Series' (now Kangerdlugssuaq Basin) by Wager & Deer (1939) and Wager (1947), the pre-basaltic sediments have received periodic attention by a number of research groups (e.g. Soper *et al.* 1976a, b; Nielsen *et al.* 1981; Larsen, M. *et al.* 1996, 1999). Taking the view that the development of the sedimentary basin and its structural evolution is an integrated part of the continental break-up process, the sedimentary studies in the Kangerlussuaq region may provide important constraints for the models of plume impingement and the dynamics of the break-up process.

The summer 2000 field work (see Larsen *et al.* 2001, this volume) focused on sedimentology, biostratigraphy and diagenesis. Special attention was paid to: (1) sedimentology and ammonite biostratigraphy in a coarse-grained Lower Cretaceous succession forming the lowermost sedimentary unit in the area; (2) sampling of a mudstone succession of presumed Upper Cretaceous age in order to improve the existing biostratigraphy; and (3) detailed studies of the transition between sediments and the earliest volcanic succession. In addition a number of sections were sampled in order to illustrate the influence of intrusions on sandstone diagenesis.

In connection with GEUS field work, a group of sedimentologists and geophysicists from the oil industry visited Sødalen. The group focused on the possibility of using the sediments of the Kangerlussuaq Group (Larsen *et al.* 1996) as an outcrop analogue for basin evolution in the offshore areas around the Faeroe Islands. A number of key sections were visited and the sedimentological and sequence stratigraphic models discussed with Survey personnel. The excursion was led by L. Hamberg, Dansk Olie og Naturgas (DONG).

Table 1. List of participants and institutions with abbreviations

Institutions

AU	Aarhus Universitet (Aarhus University), Århus, Denmark.
BMP	Bureau of Minerals and Petroleum, Nuuk, Greenland.
DLC	Danish Lithosphere Centre, Copenhagen, Denmark.
GEUS	Danmarks og Grønlands Geologiske Undersøgelse (Geological Survey of Denmark and Greenland), Copenhagen, Denmark.
KMS	Kort & Matrikelstyrelsen (National Survey and Cadastre, Denmark), Copenhagen, Denmark.
KU	Københavns Universitet (University of Copenhagen), Copenhagen, Denmark.
NGU	Norges Geologiske Undersøgelse (Geological Survey of Norway), Trondheim, Norway.
SNF	Statens Naturvidenskabelige Forskningsråd (Danish Natural Science Research Council), Copenhagen, Denmark.
UCD	University of California Davis, Davis, USA.

Participants and contributors

A.F.	Anja K.M. Fonseca	KU/DLC
A.K.	Adam J.R. Kent	DLC
B.T.	Bjørn Thomassen	GEUS
C.E.L.	Charles E. Lesher	UCD
C.K.B.	C. Kent Brooks	KU/DLC
C.T.	Christian Tegner	NGU/DLC
D.W.P.	David W. Peate	DLC
H.B.	Haukur Brynjólfsson	University of Iceland, Iceland
H.H.	Henriette Hansen	DLC/GEUS
J.D.K.	Johan Ditlev Krebs	GEUS
J.G.	Jens Gregersen	GEUS
J.J.	Jakob K. Jakobsen	KU/DLC
J.S.	Joel A. Simpson	UCD
L.H.	Lara Heister	Stanford University, USA
M.B.	Morten Bjerager	KU
M.G.	Michelle Gras	UCD
M.K.	Mette Kristensen	AU
M.L.	Michael Larsen	GEUS
M.S.R.	Morten S. Rishuus	AU
O.G.	Olafur Gudmundsson	DLC
P.B.	Palle Bay	GEUS
P.K.	Peter Kelemen	Woods Hole Oceanographic Inst. USA
P.T.	Peter Thy	UCD
S.B.	Stefan Bernstein	DLC
S.O.	Snorre Olaussen	Norsk Hydro, Bergen, Norway
T.F.D.N.	Troels F.D. Nielsen	GEUS/DLC
T.N.	Thor Nedkvitne	Norsk Hydro, Oslo, Norway

Palaeogene flood basalts

A dominant field of DLC research is the temporal and spatial chemical variations of East Greenland flood basalts (Fig. 1). These studies provide the chemical basis for the modelling of melting regimes, mantle dynamics and plume involvement in the process of continental break-up in the North Atlantic *c.* 60 million years ago. The volcanic activity lasted from 61 Ma to

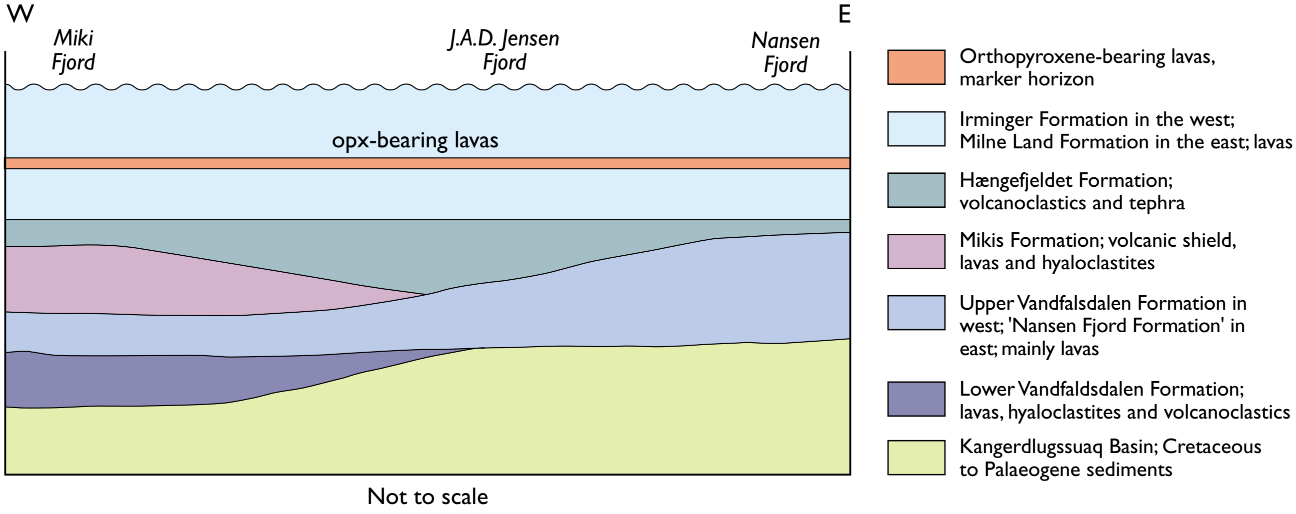


Fig. 2. Schematic correlation from Miki Fjord over J.A.D. Jensen Fjord to the east shore of Nansen Fjord, based on *EG 2000* results and previous observations.

13 Ma, but was episodic and most intense from *c.* 56 to 54 Ma (Storey *et al.* 1996a, b). The total volume of extruded magma places East Greenland amongst the largest onshore volcanic provinces on Earth (e.g. Coffin & Eldholm 1994; Eldholm & Grue 1994; Mahoney & Coffin 1997). Due to Oligocene uplift, the Coast Parallel Flexure of East Greenland (Nielsen & Brooks 1981) and post break-up tilting of the successions, a more than 8 km thick succession of lavas can be studied in great detail.

Stratigraphic and geochemical studies in the northern part of the province had identified a number of basaltic formations (e.g. Larsen *et al.* 1989). A combination of photogrammetric and geochemical methods have made it possible to trace these formations throughout the entire province, which testifies to the uniformity of the magmatism along the East Greenland continental margin (Brooks & field parties 1996; Pedersen *et al.* 1997; Tegner *et al.* 1998a; Larsen, L.M. *et al.* 1999). The tight stratigraphic and radiometric age control allows studies of the lateral geochemical variation within individual formations, and the inland chemical variation which supposedly reflects the effects of an increasingly thick continental lid (Fram & Lesher 1997; Tegner *et al.* 1998b). The *EG 2000* field operations – like those of 1995 (Brooks & field parties 1996) – focused on the sampling and study of strategically located profiles in the > 8 km thick flood basalt succession along the Blosseville Kyst; the regional field programme was completed during the summer of 2000.

The Lower Basalts in the Kangerlussuaq region (C.E.L., L.H., M.G.)

The Lower Basalts of the Kangerlussuaq region were established as a separate part of the volcanic province by L.R. Wager and coworkers (e.g. Wager 1947). Complex stratigraphy and a wide geochemical range (Brooks & Nielsen 1982a) have made it difficult to correlate the Lower Basalts with the prevalent and more uniform tholeiitic plateau basalts to the north and east. Over the years, several correlation schemes have been proposed (e.g. Nielsen *et al.* 1981; Larsen *et al.* 1989), but without the necessary stratigraphic control. The general stratigraphy and structure of the Lower Basalts have been described by Nielsen *et al.* (1981), Hansen & Nielsen (1999) and Ukstins (2000), but the correlation with the regional plateau basalt formations originally identified in the Scoresby Sund region (Larsen *et al.* 1989) has remained unresolved.

The identification of a suite of orthopyroxene-bearing marker flows in the Milne Land Formation on the eastern shores of Nansen Fjord (Fig. 1), and correlation with similar flows on the peninsula between J.A.D. Jensen Fjord and Nansen Fjord, suggests the possibility of a lithological correlation to the type area of the Lower Basalts in the Miki Fjord area. The orthopyroxene-bearing lavas have now also been sampled in the lower part of the plateau basalts (the Irminger Formation of Nielsen *et al.* 1981) overlying the Lower Basalts on the south shore of inner Miki Fjord and these studies show that the Irminger Formation is identical with the Milne Land Formation (see also Larsen, L.M. *et al.* 1999).

The eastward correlation of the formations of the Lower Basalts in the Miki Fjord area (Fig. 1) suggests that the Lower Vandfaldsdalen Formation and Mikis Formation are only locally developed volcanics (Fig. 2). These two formations include the characteristic TiO_2-rich picrite lavas of the Lower Basalts (Nielsen *et al.* 1981; Brooks & Nielsen 1982a, b; Fram & Lesher 1997; Hansen & Nielsen 1999). No equivalents to the wide variety of the Lower Vandfaldsdalen Formation volcanics have been observed towards the east in the Ryberg Fjord and J.A.D. Jensen Fjord area (Fig. 1), whereas the Upper Vandfaldsdalen Formation can be followed eastwards to the shores of Nansen Fjord. The Mikis Formation seems to represent a volcanic structure, probably a shield volcano (Ukstins 2000), between the Upper Vandfaldsdalen Formation and the overlying tuffs and volcanoclastic sediments of the Hængefjeldet Formation.

The variably sorted tephra deposits between the Milne Land Formation and the informal 'Nansen Fjord Formation' on the east shores of Nansen Fjord (Larsen, L.M. *et al.* 1999), like the equivalent deposits in J.A.D. Jensen Fjord, show no signs of reworking and provide a correlation across the fjord, and there is no compelling evidence at this location for a major hiatus between the eruption of the Lower Basalts and the overlying plateau basalts as proposed by Larsen, L.M. *et al.* (1999). The correlation of the tephra deposits indicates that lavas assigned to the 'Nansen Fjord Formation' on the east side of Nansen Fjord (Larsen, L.M. *et al.* 1999) are equivalent to lavas of the Vandfaldsdalen Formation on the west side of Nansen Fjord (Fig. 2), and this suggests that no new formation needs to be formalised.

Spatial distribution of magma types in the plateau basalts (C.E.L., C.T., J.S., L.H.)

Tegner *et al.* (1998b) identified three main geochemical groups of lavas in the 'Master Profile' through the plateau basalts of the Blosseville Kyst: (1) depleted MORB type lavas, (2) the common Fe-Ti tholeiites and (3) high-Ti tholeiites. All of these occur in the Rømer Fjord Formation of the 'Master Profile', but the coexistence of three types of lava formed under very different conditions of melt generation is not easily understood (Tegner *et al.* 1998b).

At the stratigraphic level of the Rømer Fjord Formation the 'Master Profile' is compiled from inland and coastal profiles, and the coexistence of all three geochemical types could be an artefact of the compilation strategy. Resampling and new profiles in the Savary Fjord area (Fig. 1) in summer 2000 suggest that coexistence of the three magma types reflects a lateral variability with MORB types and Fe-Ti basalts in coastal profiles, and Fe-Ti basalts and high-Ti basalts in inland profiles. This would be in better conformity with models of rifting and thinning of the continental crust along the coast of East Greenland.

The Prinsen af Wales Bjerge and Tjældebjerget (H.H., A.K.)

The Prinsen af Wales Bjerge (Fig. 1) consist of a series of inland nunataks, where only few investigations have hitherto been made. The stratigraphical relationship between the Prinsen af Wales Bjerge volcanics and the main exposures of East Greenland flood basalts is poorly known. The present account, based on summer 2000 field work, represents the first detailed description of the volcanic successions in the northern part of the area.

Tholeiitic compositions dominate the entire East Greenland province (e.g. Brooks & Nielsen 1982a, b; Larsen *et al.* 1989), but in the Prinsen af Wales Bjerge (Fig. 1) tholeiitic volcanism was succeeded by eruption of alkaline lavas (Wager 1947; Anwar 1955; Hogg *et al.* 1988, 1989; Brooks & field parties 1996; Brown *et al.* 1996). The main purpose of the summer 2000 field work in the Prinsen af Wales Bjerge area was to determine stratigraphical relationships in the nunatak suite, and to stratigraphically connect the area with the areas investigated during the 1995 DLC field campaign (Brooks & field parties 1996).

The oldest volcanics of the Prinsen af Wales Bjerge (Fig. 3) are located furthest south at Urbjerget (Wager 1947). They are tholeiitic and are intercalated with epiclastic and volcanogenic sediments overlying the Archaean tonalitic gneiss basement. The lowermost *c.* 61 Ma old flows and sediments are part of the new, not yet formalised 'Urbjerget Formation', whereas the overlying 57 to 55 Ma tholeiitic flows are part of the regionally widespread Milne Land Formation. The flows of the 'Urbjerget Formation' and Milne Land Formation dip at 1–2° NNW. The southernmost exposures of alkaline lava flows at '1982 Nunatak' have highly variable dips, probably reflecting proximity to palaeo-eruption sites, but further north the alkaline lavas regain regional dips of 1–2° NNW. This suggests that progressively younger lavas are exposed northwards in the Prinsen af Wales Bjerge. An alkaline extrusive in a volcanic cone structure enclosed in the succession has been dated to 52.5 ± 0.3 Ma (Peate *et al.* 2000), but the age span of the

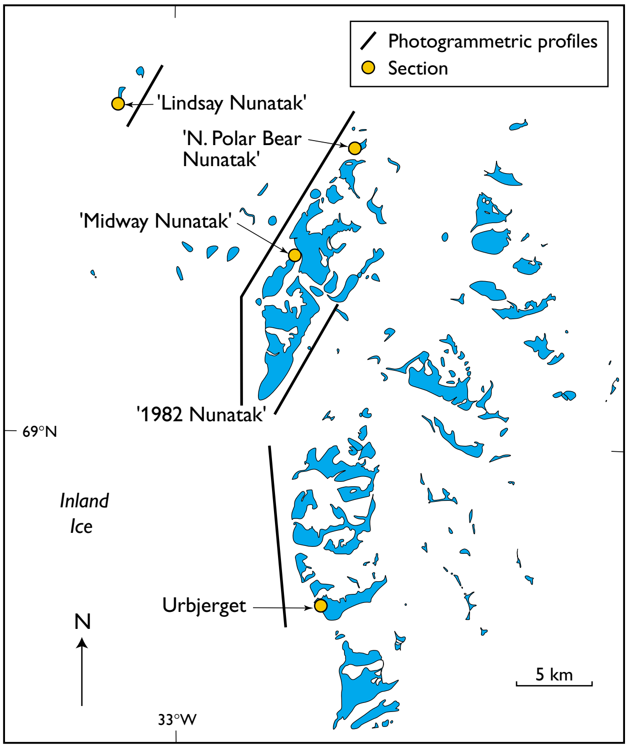


Fig. 3. Prinsen af Wales Bjerge with place names used in text, photogrammetric lines and profile/sampling sections. For regional location of Prinsen af Wales Bjerge, see Fig. 1.

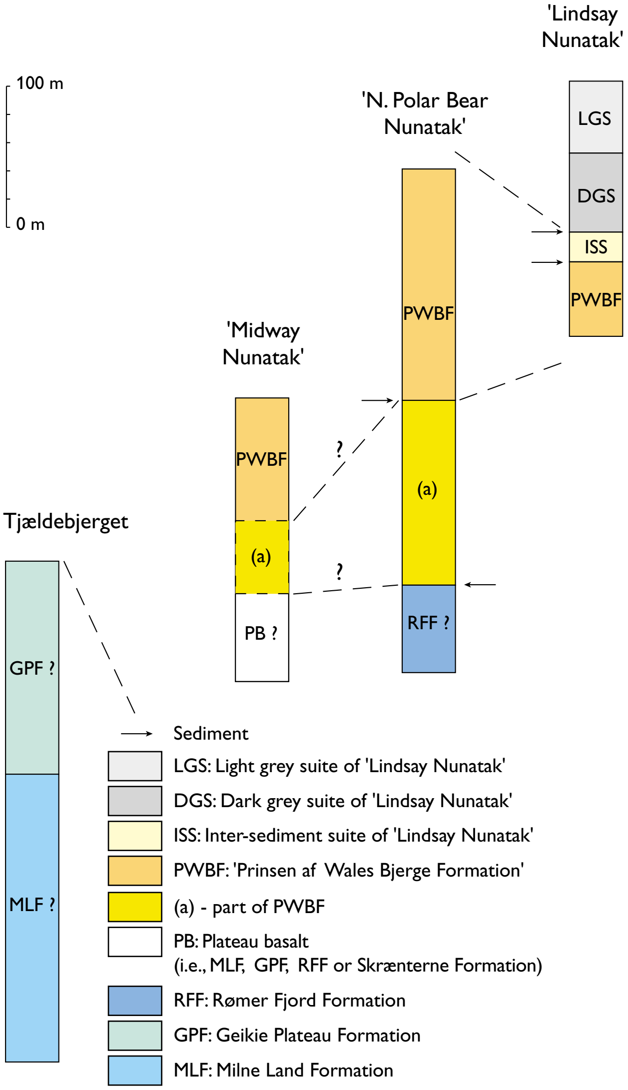


Fig. 4. Correlation of profiles measured in Prinsen af Wales Bjerge, and comparisons with Tjældebjerget profile. The correlation is mainly based on photogrammetry and field observations, with support from geochemical whole-rock analyses and ^{40}Ar/^{39}Ar ages of some 'Lindsay Nunatak' flows.

alkaline volcanism has not yet been established in detail. Photogrammetry was used for identification of four locations, Tjældebjerget, 'Lindsay Nunatak', 'N. Polar Bear Nunatak' and 'Midway Nunatak', where studies of sections through the volcanic succession would provide critical new stratigraphical information and samples suited for geochemical investigations (Figs 3, 4). In addition, Urbjerget was briefly visited to examine the border zone between the 'Urbjerget Formation' and Milne Land Formation.

Tjældebjerget. This nunatak is in a key position between the stratigraphically well-known flood basalt successions of the north-eastern Blosseville Kyst and the Prinsen af Wales Bjerge (Fig. 1). The lowermost *c.* 100 m of the profile (Fig. 5) consists of less than 5 m thick aphyric and olivine-phyric pahoehoe flows and thicker (up to 19 m), massive, highly plagioclase-phyric flows (probably suitable for ^{40}Ar-^{39}Ar dating). The overlying 110 m of the sequence is dominated by up to 10 m thick aphyric and sparsely olivine-plagioclase-pyroxene-phyric flows. Red tuffaceous beds up to 50 cm thick occur commonly. The uppermost 180 m is formed by a succession of aphyric to sparsely phyric, 10 to 30 m thick flows with massive, columnar-jointed lower parts and rubbly flow tops. Red volcanoclastic sediments with thicknesses of 10 to 20 cm are found on top of all thick and massive flows. The top of the nunatak consists of *c.* 15 m of olivine-phyric, vesicular, 0.5 to 1.0 m thick pahoehoe type flows. Based on the petrographic characteristics and photogrammetric observations, the lowermost part of the succession may correlate with the regionally distributed Milne Land Formation, and the upper 180 m with the Geikie Plateau Formation (Fig.

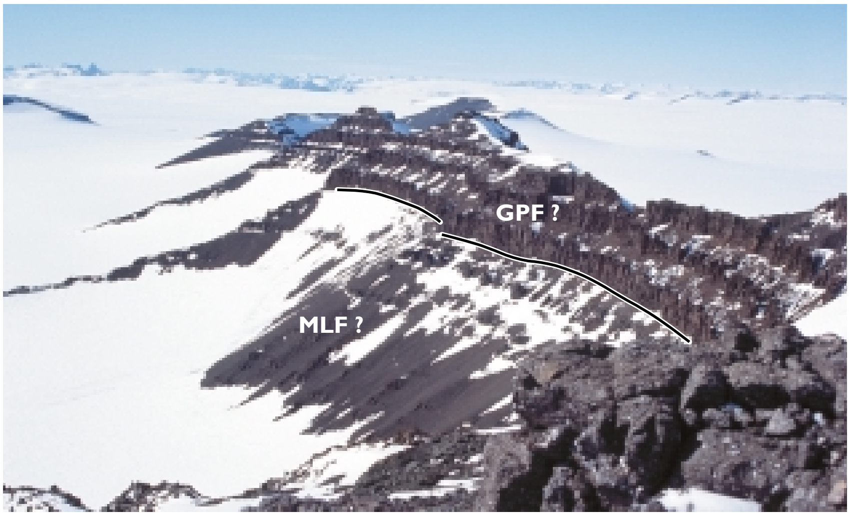


Fig. 5. Tjældebjerget profile locality looking west. The height of the profile is *c.* 300 m, with top of the profile at 2650 m altitude. The suggested Milne Land Formation – Geikie Plateau Formation contact is shown by the **black line**.

4). However, these suggested correlations await confirmation by geochemistry and age determinations.

'Lindsay Nunatak'. The most north-westerly exposures in the Prinsen af Wales Bjerge are found on 'Lindsay Nunatak' and a smaller exposure north of 'Lindsay Nunatak' proper (Fig. 3). These exposures are believed to show the youngest volcanics of the region. 'Lindsay Nunatak' was briefly visited in 1995, and found to comprise alkaline flows of the 'Prinsen af Wales Bjerge Formation' overlain by conglomerates and sediments, and followed in turn by olivine-rich tholeiitic lavas. Further detailed stratigraphical and geochemical sampling was carried out in summer 2000.

A > 5 m thick, sparsely pyroxene-phyric alkaline basalt flow (Table 2) forms the base of 'Lindsay Nunatak'. Gravel slopes above the flow expose abundant fragments of silicified wood, and tuffaceous rock fragments containing silicified wood. The lowest outcrop above the lowermost flow is a polymict, matrix-supported conglomerate with well-rounded, but poorly sorted clasts ranging in size from *c.* 1 to 30 cm. The clasts are mainly porphyritic extrusives, together with a wide variety of intrusive rock types including highly alkaline eudialyte-bearing syenite and alkaline pyroxenites reminiscent of the lithologies at the Gardiner complex (see also Brooks & field parties 1996). The conglomerate con-

Table 2. Selected major element analyses of lava flows from 'Lindsay Nunatak', Prinsen af Wales Bjerge

Sample*	458931	458932	458933	458941	458948
Suite**	PWBF	ISS	ISS	DGS	LGS
	mela-nephelinite	mela-nephelinite	basanite	tholeiite	olivine tholeiite
SiO_2	37.45	42.35	46.03	47.97	49.76
TiO_2	7.82	4.28	3.31	2.88	1.61
Al_2O_3	7.40	6.34	8.53	10.55	11.34
Fe_2O_3	11.02	5.70	4.43	6.92	3.13
FeO	5.57	9.48	9.67	6.44	8.02
MnO	0.26	0.20	0.20	0.19	0.17
MgO	6.67	15.91	13.18	8.78	12.73
CaO	15.53	10.17	10.08	10.06	9.54
Na_2O	2.53	1.59	1.99	2.50	2.05
K_2O	1.35	1.02	0.68	0.77	0.55
P_2O_5	1.17	0.44	0.36	0.34	0.16
Vol.	2.55	1.67	1.07	2.05	0.88
Sum	99.32	99.15	99.52	99.44	99.95

* GGU sample number.
** See Fig. 4 for identification of suite.

XRF analyses on glass discs by GEUS.

tains 30 × 200 cm cross-bedded sandy lenses, elongated parallel to the base of the conglomerate, and is probably a river deposit. Two 10 to 20 m thick olivine and olivine-pyroxene-phyric columnar-jointed flows with massive flow bases and rubbly flow tops (ISS in Fig. 4) separate the lower sediments from a second polymict conglomerate. The latter contains 10 to 30 cm rounded clasts at its base overlain by a yellow volcaniclastic, redeposited (?), sediment with black and red scoria, light grey coloured pumice, and fresh euhedral crystals of feldspar and pyroxene up to 15 mm across. The upper polymict conglomerate is overlain by a 50 m thick succession of dark grey olivine-phyric pahoehoe flows (DGS in Fig. 4) with an average unit thickness of about 50 cm, followed by *c.* 65 m of light grey, olivine-phyric pahoehoe flows (LGS in Fig. 4) that extend to the top of the nunatak.

'N. Polar Bear Nunatak'. This nunatak is located east of 'Lindsay Nunatak' in the northernmost part of the Prinsen af Wales Bjerge (Fig. 3). Photogrammetric studies and the geochemistry of lavas in a parallel section to the south (Peate *et al.* 2000) suggest that the exposed flows belong to the not yet formalised 'Prinsen af Wales Bjerge Formation'. The nunatak was targeted for sampling because pre-field work photogrammetry identified a distinct succession of thin (< 20 m) flows bounded by tuffaceous or soil horizons ('a' in Fig. 4). Succession 'a' may be used for the subdivision of the 'Prinsen af Wales Bjerge Formation' and could prove useful for constraining the timing of volcanism.

Below succession 'a' is exposed a *c.* 50 m thick aphyric basalt, which may belong to the Rømer Fjord Formation (Fig. 4; D.W. Peate, personal communication 2000); a 20 cm thick red volcanoclastic sediment above the aphyric basalts forms the lower boundary of 'a'. The lower part of succession 'a' consists of sparsely olivine-clinopyroxene-phyric 0.5–6 m thick flows, some of which are highly vesicular, red-weathering pahoehoe types. These very thin flows are replaced by thicker, 10–20 m, compound flows with massive bases and associated vesicle-filled pipes up to 10 cm in diameter and from *c.* 20–100 cm in vertical length. In the upper *c.* 30 m of succession 'a', flows are again thinner (2–4 m). Succession 'a' is overlain by dark coloured, brecciated volcanics intermixed with red volcanoclastic sediments, which may have formed near eruption centre(s) or as a result of hydraulic fragmentation of hot flows. The brecciated unit is followed by a *c.* 80 m thick succession of *c.* 5 m thick, compound olivine-clinopyroxene-phyric flows. A red tuff marks the base of a succession of thick massive flows that continues for a further 80 m to the top of the nunatak.

'Midway Nunatak'. South of 'N. Polar Bear Nunatak', a nunatak designated 'Midway Nunatak' was selected for sampling in order to determine the regional extent of succession 'a'. Here, the lower part of the succession consists of three massive 20–30 m thick flows that most likely belong to one of the regional plateau basalt formations, i.e. Milne Land, Geikie Plateau, Rømer Fjord or Skrænterne formations. These flows are interlayered with < 0.5 m thick red volcanoclastic sediments. The two lowermost flows are aphyric, whereas the third is olivine-pyroxene-phyric. Most of the remaining flows in the profile are relatively thin (less than 10 m), highly olivine-phyric, pyroxene-phyric or olivine-pyroxene-phyric flows, forming part of the 'Prinsen af Wales Bjerge Formation'. One exception is a rather thick (*c.* 30 m) massive flow at the top of the profile. Field observations cannot clearly identify the presence of succession 'a' at 'Midway Nunatak' which is tentatively indicated in Fig. 4. Chemical analyses are needed for a more thorough evaluation of the section.

Urbjerget. At Urbjerget (Fig. 3) a mudstone containing sparse, 3–7 cm rounded clasts was observed between the flow successions dated at 61 Ma and 57–55 Ma, respectively. The presence of these sediments supports the existence of a hiatus in the earliest stages of Palaeogene volcanism in this inland region, as has been suggested by Storey *et al.* (1996a) amongst others.

New Skaergaard intrusion initiatives

The 55 Ma old Skaergaard intrusion is associated with and emplaced into the base of the Palaeogene flood basalt succession of the East Greenland volcanic rifted margin. In this classic intrusion layered cumulates provide a complete record of extreme igneous fractionation of basaltic magma (Wager & Deer 1939). The excellent exposures (Fig. 6) and petrographic studies over the past 70 years have provided key observations for universal models of igneous differentiation (Wager & Brown 1968; McBirney 1996; Irvine *et al.* 1998). However, despite or perhaps because of the extensive studies and the wealth of information available, many features of the gabbros continue to be debated, and the Skaergaard intrusion remains a primary natural laboratory for crystallisation and fractionation models for basaltic magma.

Fig. 6. The spectacular magmatic layering in the UZa (Upper Zone a) Skaergaard intrusion gabbros in the Hjemsted Bugt area (located in Skaergaard intrusion on Fig. 1).

The recognition of the Skaergaard intrusion as a world-class palladium deposit (Bird *et al.* 1991; Andersen *et al.* 1998; Nielsen 2001) adds to the interest for a better understanding of its origin and development. From 1989 to 1990 drillcores > 1000 m long were recovered from the upper part of the Layered Series of the intrusion. They provide unprecedented opportunities for analysis and quantitative modelling. The cores are now available for research projects (see below), and this has led to new research initiatives in a collaborative effort between DLC, GEUS, the University of Copenhagen (KU), the University of California Davis (UCD), Aarhus University (AU, Denmark), the Geological Survey of Norway (NGU) and in continued collaboration with the Geophysical Laboratory, Carnegie Institution of Washington (USA) and the University of Oregon (USA).

Retrieval of Skaergaard intrusion drill cores (T.F.D.N., C.E.L., J.S., J.G.)

A total of 15 km of core from 27 drill sites (*c.* 80 tons) was recovered by Platinova A/S in 1989 and 1990. Apart from selected intersects transported to Canada for further investigation, the cores were stored in the open at the landing strip in Sødalen, 10 km east of the intrusion. Recognising the scientific value of the Skaergaard drillcores, SNF supported the crating and transport of 4.5 km of selected drillcore to Copenhagen, with the permission of Platinova A/S.

The Platinova A/S exploration license had expired by the end of 1999 and the cores were transferred to ownership of Greenland, represented by the BMP who supported and confirmed the agreement to save a representative proportion of the cores. Out of the total, five long cores for research purposes (*c.* 16 tons) and mineralisation intersects from all drill sites (*c.* 4 tons) were selected for storage at the Geological Museum, Copenhagen and the core library of the BMP. Cores were airlifted to Iceland for shipment to Denmark.

The research cores cover most of the Upper Zone of the intrusion (see Wager & Brown 1968) and extend into the upper part of the Middle Zone. The core material, new detailed *EG 2000* sample profiles from all the stratigraphy of the Layered Series not covered by the cores (Fig. 7), and core material and grab sample profiles returned from Platinova A/S storage in Canada,

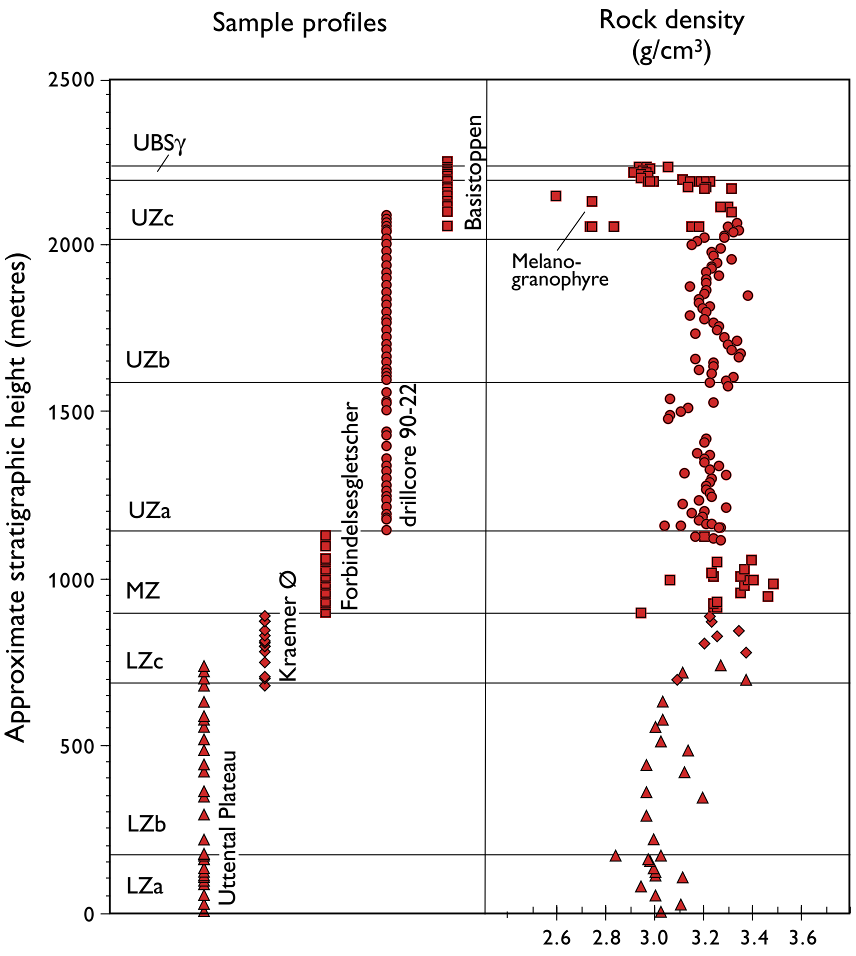


Fig. 7. **Left**: Stratigraphic coverage of the cumulus succession in the Skaergaard intrusion from LZa (Lower Zone a), through MZ (Middle Zone) and UZ (Upper Zone) to UBGγ (Upper Border Group gamma); see Wager & Brown (1968) for details of stratigraphy. Surface profiles: Uttental Plateau, Kraemer Ø, Forbindelsesgletscher and Basistoppen (all located within Skaergaard intrusion on Fig. 1). Drillcore DDH 90-22 is collared at point 312 on the north shore of Basisgletscher and covers the interval from upper MZ to middle UZc. The Skaergaard gold-palladium mineralisation is stratabound, located in the upper part of MZ and covered by the lower parts of DDH 90-22. **Right**: density profile through the stratigraphy. Modified from Nielsen *et al.* (2000).

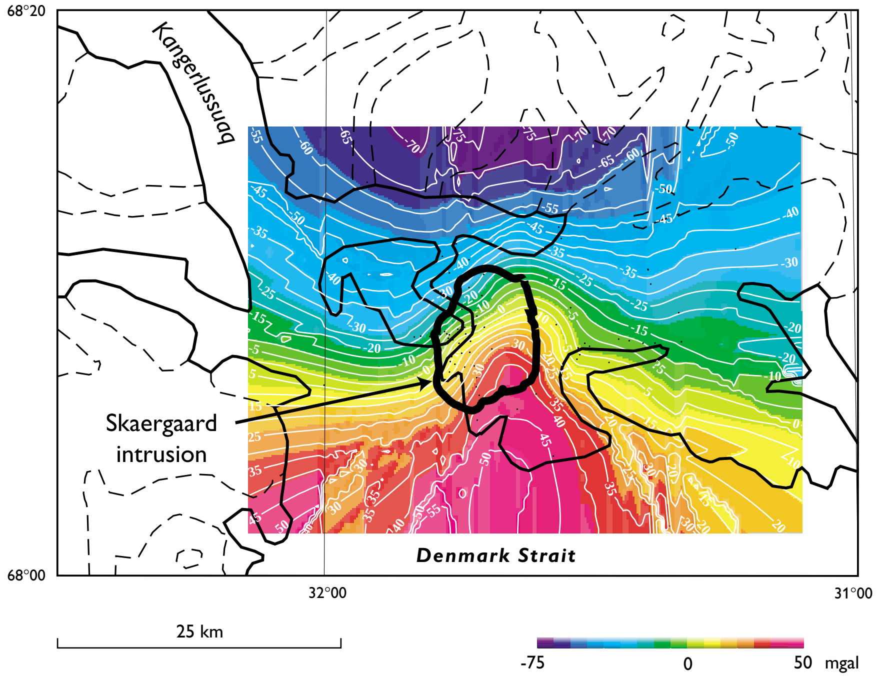
provide an unparalleled collection from the central part of the intrusion and form the basis for new Skaergaard research initiatives. These include structural modelling for mass balances for major elements and precious metals (Nielsen 2001), geophysical modelling based on gravimetry (see below), constraints on the line of liquid descent from melt inclusions, trace element studies on liquidus phases and a detailed record of modal, chemical and isotopic variations through the entire gabbro body (e.g. Tegner 1997; Nielsen *et al.* 2000) for refinement of numerical fractionation models.

Reconnaissance gravimetric survey of the Skaergaard intrusion (C.K.B., M.K.)

Pioneering gravimetric work on the Skaergaard intrusion carried out in the early 1970s was only published in abstract form (Blank & Gettings 1972, 1973). While knowledge of the regional field and the topographic effects was not available, these data have nevertheless formed the basis for numerous interpretations of the shape, depth and volume of the intrusion (e.g. McBirney 1975). The aim of the programme in summer 2000 was to determine whether new reconnaissance gravimetric data, corrected by software now available, would result in better constrained models for the shape and size of the intrusion and, in particular, better estimates of the dimensions of the hidden parts of the intrusion. The latter is a necessity for numerically constrained modelling of the development of the intrusion (see e.g. Wager & Brown 1968; McBirney 1975; Norton *et al.* 1984; Irvine 1992).

In 1986 Kort & Matrikelstyrelsen (KMS, the National Survey and Cadastre, Denmark) established a regional gravity survey of Greenland based on stations spaced approximately 25 km apart. In addition, KMS provided a digital map allowing for topographic corrections of the new gravimetric survey. Much of the new data was collected at sea level along the fjords, crossing the contacts of the intrusion by boat, using a LaCoste Romberg gravimeter (KU). A few stations were obtained with helicopter assistance in the high mountains over the central part of the intrusion.

Fig. 8. Bouguer anomaly map over the Skaergaard intrusion and surroundings based on *EG 2000* and KMS data. The intrusion is outlined in **heavy black line**, coast and glaciers in **thin black lines**. The effect from the regional field causes the negative gradient of the contour lines and the eastward displacement of the anomaly. Modified from Nielsen *et al.* (2000). For regional location, see Fig. 1.



The collected data were processed with help and software from KMS, and the Bouguer anomaly data are shown in Fig. 8. The preliminary results and models (not shown) identify a large anomaly over the Skaergaard intrusion and indicate that the intrusion continues to a depth of at least 3 km below sea level at its southern margin. This essentially agrees with models presented by Norton *et al.* (1984) and structural reconstructions (Nielsen *et al.* 2000; Nielsen 2001). The presence of two roots or feeders suggested by Norton *et al.* (1984) was not confirmed by the new data.

Late felsic magmatism and nodule-bearing lamprophyres

The Palaeogene magmatism along the coast of East Greenland is characterised not only by the voluminous flood basalts and contemporaneous gabbroic intrusions (e.g. the Skaergaard intrusion), but also by a large number of felsic and alkaline intrusions, intrusive complexes and alkaline dyke swarms (Fig. 1) emplaced over an extended period that lasted up to at least 20 Ma after the main period of flood basalt extrusion (Nielsen 1987).

Mineralisations are associated with many of these intrusions, including hydrothermal precious metals (Au, Ag), base metals (Pb, Zn) and molybdenum mineralisations. The Werner Bjerge complex (71°50′N; Fig. 1) contains a world class Mo deposit in a felsic pluton of the rifted East Greenland margin (Schønwandt 1988). Investigation of mineralisations at Amdrup Fjord (see Thomassen & Krebs 2001, this volume) and field work in the Kangerdlugssuaq intrusion in 2000 (see below) represent a coordinated effort aimed at the development of petrogenetic and mineralisation models for exploration strategies and a comprehensive description of the resource potential of the East Greenland rifted volcanic margin.

Kangerdlugssuaq alkaline intrusion: new comprehensive collections (C.K.B., D.W.P., M.S.R.)

Intrusive alkaline rocks outcrop over a large area in the Kangerlussuaq region (Brooks & Nielsen 1982b), but by far the largest contiguous body is the Kangerdlugssuaq alkaline intrusion (Kempe & Deer 1970; Kempe *et al.* 1970) and its satellites (Fig. 1). This intrusion is approximately circular with a diameter of about 33 km and covers an area of > 800 km^2, making it one of the world's largest syenitic bodies. Like many complexes of this type it contains both quartz-rich and feldspathoid-rich rocks, whose origin and mutual relationships are still under debate.

Apart from the work reported by Kempe & Deer (1970) and Kempe *et al.* (1970), very little detailed work has been undertaken on the Kangerdlugssuaq alkaline intrusion, largely due to its general inaccessibility. Wager (1965) discussed the general shape of the intrusion,

Fig. 9. Southern part of the Kangerdlugssuaq alkaline intrusion at the head of Amdrup Fjord. Telephoto view from helicopter, looking north-north-west. The summits reach > 1000 m.

Pankhurst *et al.* (1976) reported Sr- and O-isotopes, and Brooks & Gill (1982) presented analyses of the ferromagnesian minerals, together with a model for the intrusion's development.

The intrusion is largely covered by glaciers and outcrops consist of very steep-sided nunataks with frost-shattered, weathered material on the summits (Fig. 9). Fortunately, mass wastage along the glaciers provides ample amounts of fresh material, and altogether 120 samples from 42 separate localities were collected by helicopter from all parts of the intrusion.

Special attention was focused on the Astrophyllite Bay complex (Brooks & Nielsen 1982b; Nielsen & Brooks 1991), which is a mixed complex consisting of basic pillows in a syenitic matrix at the south-east margin of the intrusion. Nielsen & Brooks (1991) ascribed the origin of the syenites to *in situ* melting of the Precambrian host gneisses and chemical re-equilibration by diffusive processes. This hypothesis will now be tested in a Ph.D. project (Riishuus *et al.* 2001), using samples from precisely oriented slabs cut with a motor-driven diamond saw from the ice-polished roches moutonnées where the relationships between basic pillows, syenitic melt and basement gneiss are beautifully exposed (Fig. 10).

The Borgtinderne area (P.K., S.B.)

The Borgtinderne area along Kronborg Gletscher (Fig. 1) is an alpine glaciated terrain of extremely difficult access, and the area has only been briefly visited during reconnaissance expeditions. Kronborg Gletscher follows a N–S-trending lineament associated with abundant faulting and dyking, which separates two main structural blocks of flood basalts (Pedersen *et al.* 1997). Initial dating from the lineament shows post-plateau basalt igneous activity over *c.* 10 Ma between 50 and 40 Ma ago (C. Tegner, personal communication 2000).

The Borgtinderne syenite intrusion proved to be much more complex than described by Brown *et al.* (1978), with leucocratic syenite intruding an older, more mafic pluton of gabbro, diorite and pyroxenite. As observed in many other felsic intrusive complexes in East Greenland (Nielsen 1987), there is ample evidence for coexisting mafic and felsic magmas in pillowed dykes; these cut most lithologies in the Borgtinderne intrusion. A suite of plutonic rocks from the intrusion and samples of dykes cutting the syenites were collected for detailed studies and analyses.

A series of N–S-trending vertical lamprophyre dykes represent the youngest magmatic phase, and one of these dykes was found to carry small, but fresh, mantle xenoliths. These xenoliths appear to be finer grained than mantle xenoliths from basanitic dykes at Wiedemann Fjord, some 35 km further to the south (e.g. Bernstein *et al.* 1998).

A new ultramafic intrusion was located on the lower north-east slope of Ejnar Mikkelsen Fjeld. Seen from Borgtinderne the intrusion appears as an orange to yellow-brown weathering area of steep ridges. During two short helicopter visits the intrusion proved to be composed of dunite, with a few veins of pyroxenite and chromitite, which above 1900 m a.s.l. give way to pyroxenite. Whereas the plateau basalt host rocks are cut by a large number of mainly N–S-trending dykes, only two dykes were found to cut the ultramafic intrusives. The 'Ejnar Mikkelsen intrusion' – named after the massif in which it is found – shows similarities with the Lilloise intrusion (Brown 1973) situated 40 km to the south (Fig. 1).

The Borgtinderne syenites, the swarm of N–S-trending lamprophyre and basanite dykes, the nephelinite diatremes (Brooks & field parties 1996), the ultramafic 'Ejnar Mikkelsen intrusion' and the Lilloise intrusion all testify to the importance of the Kronborg Gletscher lineament as a major crustal structure that localised magmatism during a protracted period of *c.* 10 Ma after continental break-up along the coast of East Greenland.

The NEAT seismic project (O.G., H.B.)

The aim of the *NEAT* (**N**orth-**E**ast **A**tlantic **T**omography) project is to use seismic surface waves crossing the North Atlantic Ocean to map the structure of the upper mantle beneath the region around the proposed Iceland hot spot. *NEAT* is a collaborative project between DLC and the University of Cambridge, UK. The project requires observations from a large number of permanent seismic observatories on both sides of the ocean as well as a number of temporarily deployed seismographs in the region. The latter were deployed at remote sites in East Greenland during *EG 2000*.

Temporary seismographs were deployed at Hjørnedal (70°21.1′N, 28°09.85′W), in Sødalen (68°12.20′N, 31°22.62′W), and in Kassortoq fjord (63°14.91′N, 42°02.09′W); all three sites are located at STOL air strips. Other temporary stations have been established at Danmarkshavn, Scoresbysund and Narsarsuaq (Fig. 1). These temporary stations supplement the three permanent observatories in Greenland operated by KMS.

Each of the remotely deployed stations consists of a Guralp 3T broadband seismograph, a RefTek acquisition system (16 bit, 4 Gbyte storage capacity), a large panel of solar cells (180 W), lead-acid batteries of 700 Ah capacity, and a windmill generator. All the equipment, apart from the solar cells and windmill generator, was placed in well-insulated boxes (20 cm thick insulation) and buried beneath a layer of sand bags. The sites will be visited annually for the next few years for data retrieval and maintenance.

Perspectives

The Palaeogene magmatic province in East Greenland represents the most voluminous and best exposed part of the onshore North Atlantic province. Since the earliest regional investigations in the 1930s (e.g. Wager 1934) the region has attracted international research activities. The participation of members of the international geological community in *EG 2000* confirms the continued interest as well as the educational potential of the Kangerlussuaq region (Table 1).

The logistic platform established by the grant from SNF for the retrieval of drillcores from the Skaergaard intrusion was used during *EG 2000* to carry out many and varied projects. The Sødalen base and air strip, the huts and the presence of fuel and depots, will facilitate continued field operations in the future and ensure access to the Kangerlussuaq region for both research and company interests.

Fig. 10. Basic pillows in syenite from the Astrophyllite Bay complex (located on north shore of Amdrup Fjord, Fig. 1). Slabs have been cut from crystalline basement (at bottom in foreground) and into the basaltic melt pillows at locations nearby for study of diffusion between felsic and basic melts. Hammer for scale. Colour version of figure from Brooks & Nielsen (1982b) and Nielsen (1987).

With the completion of the DLC regional sampling programme in the flood basalts, the foundation has been laid for comprehensive modelling of the magmatism, plume involvement and the effects of crustal attenuation. The comprehensive sampling of the Skaergaard intrusion, the retrieval of drillcores for research purposes and gravimetric studies, provide opportunities for revival of studies of the structure and emplacement history of the Skaergaard intrusion and fundamental features of solidification and fractionation of basaltic magma in crustal magma chambers. The increasing focus on late mafic to felsic intrusions, and the finds of mantle nodules brought to the surface by the late magmatism, provide insights into, and open up opportunities for, studies of the complex interaction between mantle-derived magmas and the continental crust and the history of the underlying mantle during the plume-related continental break-up.

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