GEOLOGY OF GREENLAND SURVEY BULLETIN 188 · 2000

The structure of the Cretaceous–Palaeogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

Geology of Greenland Survey Bulletin 188

Keywords
Basalts, basin development, central West Greenland, Cretaceous–Palaeogene, extensional faults, Svartenhuk Halvø, transfer faults.

Cover
View of the 1160 m summit north-east of Simiuttap Kuua seen from the east; relief shown is about 1050 m. The view shows the striking contrast between the thick, brown-weathering flows of the Svartenhuk Formation forming the upper part of the mountain and the thinner, grey-weathering flows of the Vaigat Formation below. This contrast greatly facilitates mapping of the boundary between the formations over much of Svartenhuk Halvø. Near the bottom of the slope in the central part of the photograph, the contact between a cross-cutting dolerite sheet and the underlying sediments interbedded with hyaloclastite breccias can be seen. The poor outcrops at the foot of the slope to the right are of Precambrian gneiss.

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Chief editor of this series: Peter R. Dawes
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Drawing work: Jette Halskov, Eva Melskens and Gurli Ellis Hansen
Photographic work: Benny M. Schark
Graphic production and reproduction: Knud Gr@phic Consult, Odense, Denmark
Manuscript submitted: 26 April 2000
Final version approved: 14 September 2000
Printed: 16 November 2000

ISBN 87-7871-080-2
ISSN 1397-1905

Geology of Greenland Survey Bulletin
The series *Geology of Greenland Survey Bulletin* is a continuation of *Bulletin Grønlands Geologiske Undersøgelse* and incorporates *Rapport Grønlands Geologiske Undersøgelse*.

Citation of the name of this series
It is recommended that the name of this series is cited in full, viz. *Geology of Greenland Survey Bulletin*.
If abbreviation of this volume is necessary the following form is suggested: *Geology Greenland Surv. Bull.* 188, 40 pp.

Available from
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or
Geografforlaget ApS
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Frontispiece. **Above**: View of the western margin of the flexure zone between Usuit Kuussuat and Ulissat where it emerges at the coast 4 km south-west of Ulissat. Faulted lavas of the Vaigat Formation cross-cut by *c.* E–W-trending dykes. The height of the cliff on the right is *c.* 300 m. **Below**: View of part of the coast 3.5 km east of Tartuusaq showing lavas dipping south-west cut by dykes and faults dipping north-east. One fault (shown on Fig. 2) runs diagonally across the slope and has downthrow to the north-north-east. To the left (i.e. just left of centre of the picture) a dyke follows another fault that dips and throws down to the north-east. The height of the mountain on the right is 544 m.

Abstract

Larsen, J.G. & Pulvertaft, T.C.R. 2000: The structure of the Cretaceous–Palaeogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland.
Geology of Greenland Survey Bulletin 188, 40 pp.

Svartenhuk Halvø ('halvø' = peninsula) lies at the northern end of the exposed part of the Palaeogene volcanic province in central West Greenland. The peninsula is divided into two parts by a major NW–SE fault system, the Cretaceous boundary fault system. To the south-west lies a basinal area in which Cretaceous – Paleocene sediments are overlain by upper Paleocene basalts, whereas north-east of the fault system there is an elevated area in which Precambrian crystalline basement is exposed and is overlain by basalts, with only a few isolated pockets of Paleocene sediments in depressions in the basement surface.

Subsidence and sedimentation began in Albian time with the deposition of deltaic sandstones and mudstones. In the Turonian – early Campanian there was further subsidence and at least 1500 m of distal turbidites were deposited. During middle Campanian (?) – early Paleocene time the area was unstable, and alternating phases of uplift, erosion and subsidence resulted in the removal of all Cretaceous sediments in the uplifted Precambrian area, and the development of discordances in the basin area.

Volcanism started in mid-Paleocene time in a subsiding marine environment, so that the earliest volcanic rocks are hyaloclastite breccias. Later volcanism was almost entirely subaerial. The volcanic rocks are divided into two formations: (1) the Vaigat Formation (lower), dominated by picritic and other olivine-rich tholeiitic basalts, with a significant contaminated unit at the base of the formation in the south-east; (2) the Svartenhuk Formation (upper), characterised by plagioclase-porphyritic and aphyric basalts. In the northern part of the area about 50 m of fluvio-lacustrine sediments, tuffs and hyaloclastite separate the two formations. Mafic dykes occur throughout the area and are most numerous within the area of exposed Vaigat Formation. Thick sills and sheets of dolerite occur in the vicinity of the Cretaceous boundary fault system and within the sediments in the eastern part of the area.

Extensional faulting and tilting occurred in the basin area, both prior to, during and after volcanism. Most extensional faults trend NW–SE and throw down to the north-east, so that the rotated fault blocks dip south-west. However, there is a great difference in the degree of faulting and tilting between the northern and southern parts of the area, with few faults and generally low dips in the north, and numerous faults and dips between 20° and 40° in the south. The increase in the degree of extension and fault activity occurs at WNW–ESE- to E–W-trending transfer faults. Some extensional faults are associated with flexure zones with relative uplift on the north-east side and dips up to 60° to south-west within the zones. The regional extensional vector that gave rise to the extensional faulting could lie in any direction between NE–SW, normal to the extensional faults, and E–W, parallel to the transfer faults. The regional setting of the area suggests that extension was NE–SW. The regional structural pattern resembles closely (in mirror image) a structural pattern that has been described from the north-east side of the Gulf of Suez.

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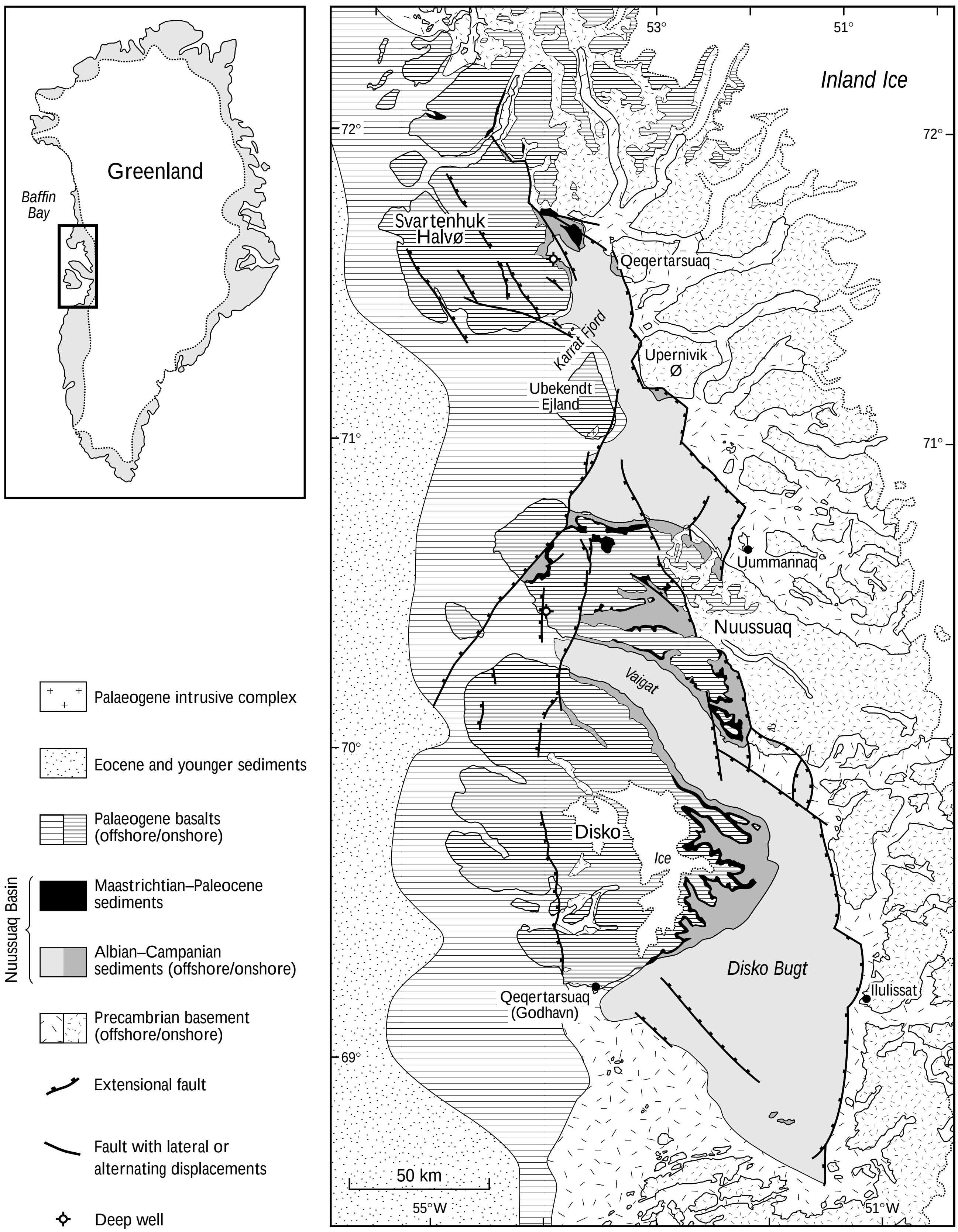

Fig. 1. Simplified map of the Nuussuaq Basin showing onshore and offshore geology and the position of Svartenhuk Halvø.

Introduction

Svartenhuk Halvø ('halvø' is Danish for peninsula) lies in the northern part of a substantial area of exposed Cretaceous–Palaeogene rocks in central West Greenland. This area extends from Disko Bugt (68°40′N) in the south through Nuussuaq to north of Svartenhuk Halvø (72°40′N) in the north (Fig. 1). It is the most extensive area of exposed Cretaceous–Palaeogene rocks in the entire Labrador Sea – Davis Strait – Baffin Bay region. Other areas of Cretaceous–Palaeogene rocks occur on the Bylot Island (Miall *et al.* 1980) and at Cape Dyer (Burden & Langille 1990), both on the Canadian side of Baffin Bay (see Fig. 14). In the Disko–Svartenhuk region the Cretaceous–Palaeogene is represented by fluvial, estuarine, deltaic, marine shoreface and marine shelf sediments of Albian to early Paleocene age that are overlain by late Paleocene – early Eocene continental flood basalts in both subaqueous and subaerial facies. In general the sediments pass from fluvio-deltaic sandstones, mudstones and coals in the south-east to distal marine turbidites in the north-west. The flood basalts overstep the margin of the sedimentary basin to lie directly on Precambrian basement to the east and north.

Previous investigations

The Disko–Svartenhuk region has been the subject of several phases of geological investigation since ammonites were first described from the area by Hoff (1865). Early work was concentrated on fossil plants (e.g. Heer 1883), invertebrate palaeontology (e.g. Ravn 1918) and coal (e.g. Steenstrup 1883). The first petrological studies of the volcanic rocks on Svartenhuk Halvø were carried out in the 1930s (Nieland 1931; Noe-Nygaard 1942). In the late 1940s and 1950s research was focused mainly on biostratigraphy and palaeontology (e.g. Birkelund 1965; Rosenkrantz 1970). In the late 1960s, however, interest in the Disko–Svartenhuk region took a new turn when the international oil industry recognised that the West Greenland shelf could have a potential for hydrocarbons. Sediments cropping out in nearby onshore areas therefore attracted attention as possible analogues of sedimentary environments and facies occurring in the shelf (Henderson 1969; Ehman *et al.* 1976). The results of studies carried out in the 1970s were summarised by Henderson *et al.* (1981), and mapping in the area resulted in the publication of five 1:100 000 geological map sheets, the northernmost two of which provide the basis of the present paper (Larsen 1983; Larsen & Grocott 1992).

Oil industry activity offshore culminated in the drilling of five exploration wells in 1976 and 1977. Results were however disappointing, and all licences were relinquished by early 1979. In the following decade studies in the Disko–Svartenhuk region were carried out largely by geologists from Copenhagen University. However, in 1990 it was decided that new petroleum-related investigations should be carried out in West Greenland, both onshore and offshore, with a view to reviving industry interest in the region, and the current cycle of multidisciplinary studies in the Cretaceous–Palaeogene outcrops onshore was initiated. When in 1992 oil and bitumen were discovered in vugs and vesicles in basalts in western Nuussuaq (Christiansen *et al.* 1994), these studies became more than analogue studies. The region was now a potential petroleum basin in its own right, and in 1994–1998 commercial exploration was carried out in Nuussuaq by the small Canadian company grønArctic Energy Inc. Six slim core wells have been drilled in Nuussuaq and Svartenhuk Halvø, four by grønArctic and two by the former Geological Survey of Greenland (GGU, amalgamated in 1995 with its Danish counterpart to become the Geological Survey of Denmark and Greenland – GEUS). Oil bled from the cores of two of these wells, traces of oil were found in cores of two other wells, and the cores of the remaining two wells, particularly that from the GGU well in eastern Svartenhuk Halvø (Umiivik-1), released wet gas (Bate & Christiansen 1996; Christiansen *et al.* 1996; Dam *et al.* 1998b). The search for oil in outcrops has resulted in seep discoveries over an area extending from northern Disko through western Nuussuaq to the south-east corner of Svartenhuk Halvø (Christiansen *et al.* 1998; Bojesen-Koefoed *et al.* 1999). In 1996 grønArctic drilled a conventional well to a depth of 2996 m in western Nuussuaq (Christiansen *et al.* 1997; Kristensen & Dam 1997).

In addition to oil discoveries, the current cycle of investigations in the Disko–Svartenhuk region has led to important advances in the understanding of the sedimentary history and basin development (Dam & Sønderholm 1994, 1998; Dam *et al.* 1998a). Until recently, however, little was known about the structure in the sedimentary basin, as only the structures affecting the flood basalts on Nuussuaq had been described in any detail (Pedersen *et al.* 1993; A.K. Pedersen, manuscript maps). The lack of understanding of the deep structure of the basin became apparent when GGU acquired a 13 km long seismic line on the south coast of Nuussuaq in 1994. This revealed that the thickness of sediments here is at least 6 km and perhaps 8 km, which is far greater than previously imagined (Christiansen *et al.* 1995). This discovery motivated a marine multichannel seismic programme that was carried out in 1995 in Disko Bugt, west of Disko, and in the fjords north and south of Nuussuaq. The results of this survey, together with gravity modelling and a compilation of onshore structures on Disko and Nuussuaq, are described in full by Chalmers *et al.* (1999). Since the marine seismic survey was not extended north of Ubekendt Ejland, Svartenhuk Halvø is not discussed in that paper.

Scope of this bulletin

The purpose of the present paper is to complement the papers by Chalmers *et al.* (1998, 1999), so that together the three papers provide an overall view of the structures in the Cretaceous–Palaeogene of central West Greenland as known today. The basis for the paper is the mapping by J.G.L. and his group carried out over four field seasons between 1974 and 1983; this work, which incorporated earlier reconnaissance mapping by Rosenkrantz *et al.* (1942), Münther (1973; mapping from 1952), Pulvertaft & Clarke (1966) and Rosenkrantz & Pulvertaft (1969), resulted in two Survey 1:100 000 map sheets: Igdlorssuit, 71 V.1 Syd (Larsen 1983) and Svartenhuk Halvø, 71 V.1 Nord (Larsen & Grocott 1992). These map sheets should be consulted for features such as dykes, sills and minor faults and fractures that could not be represented on Fig. 2 for reasons of scale.

Geological units

Svartenhuk Halvø is divided into two fundamentally different areas. The north-eastern part of the peninsula is an area of elevated Precambrian basement overlain by upper Paleocene flood basalts, with only local pockets of sediments which are entirely of late Paleocene age. In contrast, the south-western area is dominated by flood basalts which overlie sediments of Cretaceous and early Paleocene age; this area is referred to as the *basin area*. Whereas the basement area is structurally simple and largely unaffected by faults, all but the north-eastern part of the basin area is dissected by numerous faults and also zones with relatively steep dips. The two areas are separated by an irregular fault system which crosses the peninsula in a roughly NW–SE direction. The fault system is part of what is referred to as the *Cretaceous boundary fault system* in central West Greenland, because it defines the eastern and north-eastern boundary of present-day outcrops of Cretaceous sediments; it is believed that the area of Cretaceous sediments originally extended east of the fault system, and that Cretaceous sediments deposited east of the boundary fault line were removed by erosion during latest Cretaceous and early Paleocene time.

Nine geological units have been distinguished in Fig. 2 in order to illustrate the bedrock geology of the area and the structural pattern; in addition, some of the largest areas covered by Holocene fluvio-glacial deposits and ice have been shown, not least because fluvio-glacial deposits conceal some of the major faults, leaving their position as a matter of conjecture. Several more units are distinguished on the 1:100 000 map sheets, and a full description of the stratigraphy of the volcanic rocks is in preparation. A summary of the rock units and tectonic events described in this bulletin is presented in Fig. 3.

Precambrian basement

Precambrian basement outcrops in the north-east part of the area. The main units in the Precambrian are

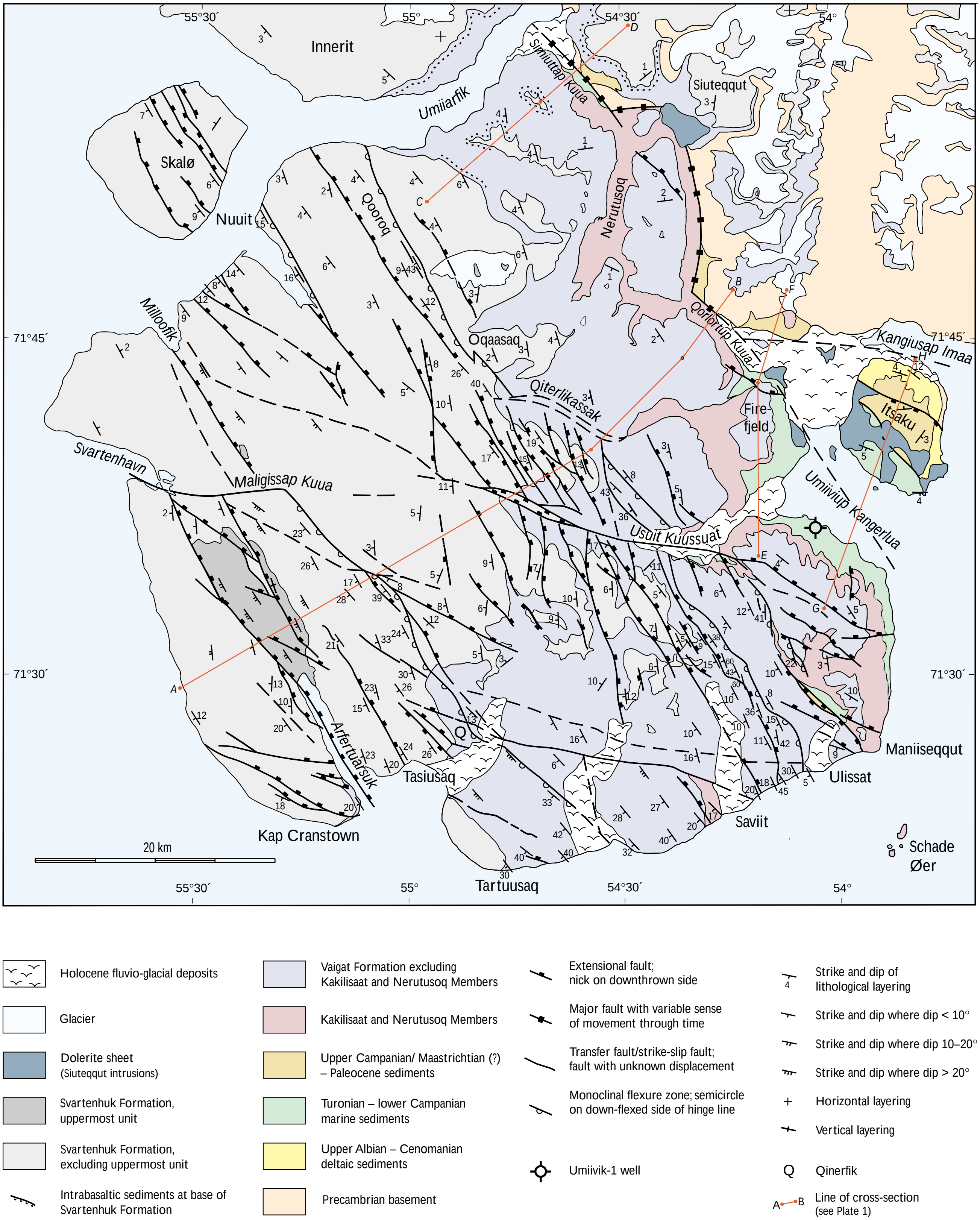

Fig. 2. Simplified geological map of Svartenhuk Halvø. For location, see Fig. 1

Archaean gneisses and Palaeoproterozoic supracrustal rocks, mainly schists and metamorphosed turbidite sandstones and mudstones, which together form part of the Rinkian (1.9–1.7 Ma) structural province in northern and central West Greenland (Henderson & Pulvertaft 1987). The structural grain (trend of foliation and fold axes) in the basement is N–S in the area north-west of the inner end of Kangiusap Imaa, swinging to NW–SE in the northern part of the area (van den Eeckhout & Grocott 1982; Grocott & Vissers 1984). Later fractures trend both NNW–SSE and WNW–ESE.

The Precambrian basement is overlain by flood basalts belonging to the uppermost part of the lower basalt formation (Vaigat Formation) and the more extensive upper basalt formation (Svartenhuk Formation). The pre-basalt basement surface is an undulating surface rising from 200 m above sea level (a.s.l.) on the north-west side of Umiiarfik to 900 m in the east, with local palaeomountains rising 700 m above this surface. Locally, in topographic lows in the basement surface, fluvial sediments with thin coals lie between the basement and the overlying basalts.

Lower–mid-Cretaceous deltaic and marginal marine sediments

These are only exposed on Itsaku peninsula in the eastern part of the area. The succession begins with a basal conglomerate in which the clasts are entirely of metamorphic rocks; this conglomerate lies unconformably on weathered Precambrian metasediments. The conglomerate is succeeded by *c.* 350 m of sediments arranged in coarsening-upwards cycles of mudstone, sandstone (the dominant lithology) and thin coal seams. These cycles are similar to those in the Atane Formation on Nuussuaq (Pedersen & Pulvertaft 1992) and were deposited from prograding wave- and storm-influenced deltas (F. Dalhoff and G. Dam, personal communication 1999). The cross-bedded sandstones that top the deltaic cycles were deposited in straight to slightly sinuous channels; foreset dip directions vary from west through north-west to just east of north, with maximum towards 305°. The deltaic succession is overlain by *c.* 70 m dark mudstones with abundant plant remains. Because of the thermal influence of the many dolerite sills on Itsaku, palynomorphs have been destroyed throughout most of the section. However, in the lowest 70 m of the section there is a pollen assemblage that bears affinity to the Late Albian – Early Cenomanian assemblages from the Cretaceous sediments on the islands Qeqertarsuaq and Upernivik Ø to the east and south-east (Croxton 1978a). The overlying dark mudstones have yielded blackened pollen assemblages that could well be of Late Cretaceous age (Croxton 1978a).

This part of the sedimentary section on Itsaku terminates at the base of a conglomerate horizon which is discussed later (see p. 12).

Turonian – lower Campanian marine mudstones and distal turbidites

Dark mudstones with thin turbiditic sandstone layers, laminae and stringers are exposed in many stream gullies in the eastern part of Svartenhuk Halvø and also in low coastal outcrops around the bay Umiiviup Kangerlua. These sediments have been studied in the core of slim core well Umiivik-1 drilled on the south coast of this bay (Dam 1997; Dam *et al.* 1998b), and they show little variation throughout the 1200 m cored (240 m of which consists however of dolerite sills). In this core there are three main cycles, each with a weak thickening- and coarsening-upwards tendency; the uppermost cycle is overlain by a unit lacking a coarsening-upwards pattern but containing a relatively large amount of slump deposits. The environment of deposition was a distal marine slope (Dam 1997; Dam *et al.* 1998b). Similar mudstones and thin turbiditic sandstones have also been cored in a number of shallow wells (maximum depth 86 m) in eastern Svartenhuk Halvø. It is significant that even in the core drilled only 1.6 km from a 700 m high, steep slope of Precambrian gneisses, the sediments retain their distal marine character. This implies that when the Turonian – lower Campanian sediments were deposited, this drill site did not lie close to a steep coast and that these sediments originally continued across the site of the boundary fault system into the area to the north-east.

The age of the Turonian – lower Campanian sediments is fairly accurately known from ammonites and dinoflagellates (Birkelund 1956; Nøhr-Hansen 1996, 1997). The oldest dinoflagellates occur at 540 m below surface in the Umiivik-1 well and indicate a Turonian age (dinoflagellates in the mudstones below this have been destroyed by heating from sills), while the youngest dinoflagellate zone, which occurs immediately below hyaloclastite basalt breccias on the west side of Umiiviup Kangerlua, is late Santonian/?early Campanian. Younger marine mudstones occur on the south side of Itsaku, where ammonites indicating an early

Period	Sedimentary and volcanic formations	Tectonic events
	Fluvio-glacial sediments	
Pleistocene	Moraines	Post-glacial isostatic uplift
	Ice caps and glaciers	
– – – 1.8 Ma – – –		
Neogene		? Regional uplift
– – – 24 Ma – – –		
		? Inversion south of Simiuttap Kuua
		Extensional faulting; reactivation of basement faults
Palaeogene	dykes – sheets Uppermost Svartenhuk Formation basalts	
	Arfertuarsuk trachyte	
	Svartenhuk Formation: plag.-porph. basalts	
	Fluvio-lacustrine sediments (Simiuttap Kuua area)	
	Vaigat Formation: picritic basalts – subaerial	
61 Ma	Vaigat Formation: " " – subaqueous;	Extensional faulting
	Kakilisaat and Nerutusoq Members at base	Subsidence
– – – 65 Ma – – –	Conglomerate and mudstone (Itsaku, Firefjeld and NE of Qorlortup Kuua)	Differential uplift and erosion
	Conglomerate and mudstone (Itsaku)	Subsidence
		Uplift and erosion
Late Cretaceous	Distal turbidites (Umiiviup Kangerlua and Firefjeld; S side Simiuttap Kuua)	Thermal subsidence
	Mudstones (Itsaku)	
– – – 99 Ma – – –	Deltaic sediments (Itsaku)	Rifting
Early Cretaceous		

Fig. 3. Summary of late Phanerozoic rock units and tectonic events on Svartenhuk Halvø. The vertical scale is not proportional to time.

Campanian age have been collected (Birkelund 1965). Since hyaloclastite breccias in some places lie directly on lower Santonian marine mudstones, the sediment-hyaloclastite contact reflects a substantial hiatus and is probably a discordant erosion surface.

Marine mudstones interbedded with thin sandstones outcrop in stream gullies on the south side of Simiuttap Kuua in north-west Svartenhuk Halvø ('kuua' is Greenlandic for river). A conglomerate layer consisting of slabs of sandstone up to 80 cm long and 30 cm thick lying with no preferred orientation in mudstones indicates that there was intermittent tectonic activity during the deposition of these sediments (Ehman *et al.* 1976). Unfortunately the age of these sediments cannot be determined closer than Cenomanian – early Campanian, which is the age range of belemnites collected from this locality (Birkelund 1956).

Mudstones and siltstones dated as Coniacian–Santonian (H. Nøhr-Hansen, personal communication 1998) occur 4 km north-west of Maniiseqqut. This occurrence is bounded by NW–SE faults, and the sediments are folded on axes parallel to the faults; axial surfaces of the folds are both steep and flat-lying. Folds with both steep and low-dipping axial surfaces are also seen in outcrops of Cretaceous sediments on the south side of the Usuit Kuussuat valley. This folding does not affect the overlying basalts, but it is not clear whether the folds were generated by gravity gliding triggered by fault movements or were the response of these ductile rocks to post-basalt fault movements.

Middle Campanian/Maastrichtian (?) – lower Paleocene mudstones and conglomerates

The summit of the Itsaku peninsula consists of dark mudstones which have yielded pollen indicating a Paleocene age (Croxton 1978a). Lower down, on the east side of the peninsula, there are two conspicuous conglomerate horizons, one at about 300 m above sea level and the other 150–200 m higher up (Plate 1). The lower conglomerate is 20 m thick in the south, thickening northwards to 70 m. A low-angle unconformity separates this from the underlying sediments. The conglomerate consists of fining-upwards beds in which the lower parts contain rounded clasts of metamorphic rocks, quartz and weathered basic igneous rocks up to 1 m in size. The upper conglomerate is poorly exposed, but can in places be studied on the north-east slope at about 670 m a.s.l., where it contains rounded boulders and cobbles of sandstone, basement lithologies, and dark fine-grained rocks that have been not yet been properly described (Ehman *et al.* 1976; Croxton 1978a). No palynomorphs or other fossils have been recorded from the mudstones between the conglomerates, so the age of these sediments can only be inferred by analogy with Nuussuaq. Here there are similar conglomerates of both middle Campanian and middle Maastrichtian age, both of which overlie unconformities and fill incised valleys and submarine canyons (Dam & Sønderholm 1994; Dam *et al.* 2000). Thus the lower conglomerate on Itsaku could be middle Campanian and the upper one Maastrichtian, or alternatively the two levels of conglomerate could be the equivalent of the Maastrichtian and early Paleocene channel-fill conglomerates and sandstones in south-western Nuussuaq (Dam & Sønderholm 1998). Dam *et al.* (1998a) suggest that these Paleocene features on Nuussuaq reflect phases of uplift, erosion and valley incision related to the arrival of a mantle plume, a phenomenon that could be expected to have affected an extensive area of central West Greenland including Svartenhuk Halvø.

On the north side of Qorlortup Kuua there is an outcrop of dark mudstones and siltstones which lie on coarse conglomerates, below which there is an unknown thickness of mudstones. The boulders in the conglomerate are angular, up to 5 m in size, and consist entirely of basement lithologies. The conglomerates are arranged in fining-upwards cycles and grade into sandstones; large boulders can however occur sporadically in the upper parts of the conglomerate beds (G. Dam, personal communication 1999). In the mudstones immediately overlying the conglomerates Croxton (1978b) recovered specimens of *Alnipollenites*, which is indicative of a Paleocene age. The mudstones and conglomerates onlap a gneiss slope which dips south at up to about 30°; in places mudstones fill palaeovalleys eroded into the steep gneiss slope. This steep gneiss slope is regarded as an eroded and bevelled fault plane (see p. 20). Hyaloclastite breccia fills a palaeovalley in the mudstones.

On the south-east corner of Firefjeld a 30 m thick pebble and cobble conglomerate overlain by sand occurs immediately below the hyaloclastite breccia. On aerial photographs this bed can be traced northwards, and 4.5 km to the north the horizon is represented by a 5 m thick fining-upwards sandy bed with cobbles. The cobbles consist mainly of basement lithologies but also lithified conglomerate clasts occur. This conglomerate may be a correlative of the conglomerate north of Qorlortup Kuua.

About 5.5 km north-west of Maniiseqqut there is a small outcrop of Paleocene sediments dipping 15° to south-south-west. The sediments consist of sandstone grading up into black tuffaceous sandstone with molluscs and *Ophiomorpha* burrows, which in turn is overlain by hyaloclastite breccia. On the basis of dinoflagellate cysts Hansen (1980) placed these sediments in the upper part of the lower Danian. The contact between these rocks and the basalts to the south-west is a fault.

Volcanic rocks

The volcanic rocks on Svartenhuk Halvø are divided into two formations: the *Vaigat Formation* (lower) and the *Svartenhuk Formation*; each formation is divided into a number of members, of which only three have been distinguished on Fig. 2, two with the same colour. A full description of the stratigraphy of the basalts by J.G.L. is in preparation.

Throughout Svartenhuk Halvø the Vaigat Formation is overlain by the Svartenhuk Formation (Plate 1). At a few localities, e.g. north-east of Simiuttap Kuua and south of Usuit Kuussuat, there is evidence of angular unconformity between the Svartenhuk and Vaigat Formations, but over much of the peninsula there is no obvious unconformity between the Svartenhuk Formation and the Vaigat Formation.

Vaigat Formation

The type locality of the Vaigat Formation is the sound Vaigat which separates Disko from Nuussuaq peninsula (Hald & Pedersen 1975). It is the lowermost volcanic formation in the type area, just as it is on Svartenhuk Halvø. The Vaigat Formation in the type area has yielded $^{40}Ar/^{39}Ar$ ages between 60.7 ± 0.5 and 60.3 ± 1.0 Ma (Storey *et al.* 1998), but the oldest lavas here show normal magnetisation (Riisager & Abrahamsen 1999) which means that they must have been erupted during magnetochron 27n or between 61.3 and 60.9 Ma in the time scale of Cande & Kent (1995). This is the time when sea-floor spreading started in the inner Labrador Sea (Chalmers & Laursen 1995) and most likely also in Baffin Bay (Chalmers & Pulvertaft in press).

The Vaigat Formation is characterised by tholeiitic picrites and other olivine-rich basalts (Clarke & Pedersen 1976). On both Disko and Nuussuaq, horizons of orange-brown- or greyish brown-weathering silica-enriched, contaminated basalt are interspersed within the olivine-rich basalts. On Svartenhuk Halvø similar brown-weathering, silica-enriched, contaminated rocks occur at the base of the formation in the south-eastern part of the area and these are distinguished as the *Kakilisaat Member*. In the north-west a different brown-weathering unit occurs at the base of the Vaigat Formation; this consists of uncontaminated olivine basalts and is called the *Nerutusoq Member*. On Disko and Nuussuaq the earliest lavas in the Vaigat Formation were erupted at the sea floor and consist of pillow lava and hyaloclastite mounds. In due course the volcanic edifice emerged above sea level but to the east and north a subaqueous environment persisted, first as a marine embayment, later as a lake. On reaching the shoreline the subaerially erupted lavas passed into subaqueous hyaloclastite breccias which built up very large prograding Gilbert-type deltas with foresets reaching a maximum of 700 m in height on Nuussuaq (Pedersen *et al.* 1993). The heights of the foresets are a measure of the depth of the basin into which Vaigat Formation lavas flowed, or in other words the minimum pulses of subsidence prior to and during initial volcanism.

On Svartenhuk Halvø the earliest eruptions in the eastern and northern parts of the basin area also took place in a submarine environment, giving rise to hyaloclastite breccias and pillow lavas. As on Nuussuaq, the hyaloclastites form Gilbert-type delta structures, with foresets up to 250 m high in the upper, picritic breccias. Water depths during eruption of the lower breccias may have been greater, but these breccias are less well exposed and their foreset bedding is less distinct. In the lower part of the breccias there is some interfingering between breccia and mudstone.

Foreset dip directions in hyaloclastite breccias are an indication of flow direction and, in favourable situations, can be used to locate centres of eruption. Foreset directions recorded on Svartenhuk Halvø indicate that there was a centre of eruption at the north-west end of Umiiviup Kangerlua from which hyaloclastites spread towards the west, and another centre close to the Cretaceous boundary fault north-east of Qiterlikassak from which hyaloclastites spread in almost all directions but particularly towards the south (Larsen 1981a). Yet another eruptive site was situated in the Nerutusoq valley, from which the Nerutusoq Member was erupted and partially blocked the north-westerly spread of the picrites. Otherwise the general flow direction during subaqueous eruption was towards north and north-east. Feeder dykes have been observed in the hyaloclastite breccias both north-west of Firefjeld and north of Kangiusap Imaa (Larsen 1981a).

The thickness of the hyaloclastite breccias and pillow lavas on Svartenhuk Halvø increases from south to north and reaches a maximum of at least 600 m along the north-east side of the basin area. Between Maniiseqqut and Umiiviup Kangerlua cross-bedded hyaloclastites alternate with subaerial lavas, indicating that subsidence here was gradual and more or less kept pace with growth of the volcanic pile. There is also evidence in the area between Usuit Kuussuat and Maniiseqqut that north-east-facing fault scarps existed during eruption of the lower part of the Vaigat Formation. Here one can see examples of subaerial lava flows that pass north-eastwards into hyaloclastites as they cross WNW–ESE or NW–SE faults, the base of the flow dropping abruptly as it crosses the fault and the rocks become hyaloclastites.

When the subsided basin became filled by hyaloclastite breccias and subaerial lavas, the lavas overstepped the Cretaceous boundary fault system and flowed northwards and north-eastwards over the Precambrian basement surface. At times, however, either phases of renewed subsidence led to marine transgressions or, in the later stages of volcanism, the lavas dammed up rivers so that ephemeral lakes developed. In either case, on entering the subaqueous environment the lavas formed hyaloclastite breccias now seen as horizons within the predominantly subaerial lavas that overlie the basement in north-eastern Svartenhuk Halvø. To the south-west the exposed part of the Vaigat Formation is entirely subaerial. The interaction between volcanism and lake development has been documented in detail on Nuussuaq and Disko (G.K. Pedersen 1989; A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998a, b).

The Kakilisaat Member is an important unit in the structural interpretation of southern Svartenhuk Halvø. As already mentioned, it occurs at or near the base of the Vaigat Formation and consists of silica-enriched, contaminated basalts including olivine-bearing types; these are mainly developed in subaqueous facies in the eastern part of the basin (the 'brown breccia' of S. Munch in: Rosenkrantz *et al.* 1942), but in southern Svartenhuk Halvø, like the rest of the Vaigat Formation here, they occur in subaerial facies. Due to faulting, the outcrops of these contaminated basalts on Svartenhuk Halvø are not continuous, but the geochemical and petrological similarity of these rocks, regardless of where they occur or whether they are in subaqueous or subaerial facies (J.G. Larsen, unpublished data), suggests strongly that they belong to a single contiguous unit. Furthermore, over a large area of south-east Svartenhuk Halvø the contaminated lavas are overlain by a characteristic massive picrite flow with large olivine phenocrysts, which suggests that all the contaminated lavas in this area belong to the same stratigraphic unit.

Chemical analyses of the Kakilisaat Member show close similarities with analyses of the Kûgánguaq and Tunoqqu Members which occur within the Vaigat Formation on Disko and Nuussuaq respectively (Pedersen 1985a, b; Pedersen *et al.* 1996). However, correlation at this level of resolution must await the results of the palaeomagnetic investigations that were initiated on Svartenhuk Halvø in 1999 (Christiansen *et al.* 2000).

The thickness of the Vaigat Formation as a whole (including the Kakilisaat and Nerutusoq Members) increases from north to south. South-west of Simiuttap Kuua the total thickness of the unit is 950–1000 m, of which 600 m consist of hyaloclastite breccias. West of Qorlortup Kuua the hyaloclastites are about 500 m thick, and the thickness of the overlying subaerial lavas has increased to 600 m. North and south of Usuit Kuussuat thicknesses are harder to estimate because of displacements on faults and fractures zones that cannot be satisfactorily quantified. However, it appears that here the subaerial component of the Vaigat Formation is more than a kilometre thick, whereas south-west of Umiiviup Kangerlua the hyaloclastite breccias are only 300–350 m thick.

It is difficult to estimate the total thickness of the Vaigat Formation along the south coast of Svartenhuk Halvø. Subaerial lavas of the formation outcrop along the entire coast from Ulissat to Tartuusaq. Along the stretch from Saviit to Tartuusaq the width of outcrop in the direction of dip is about 17.5 km and the dip is consistently to the south-west at angles between 17° and 40°. This would imply that the Vaigat Formation here is about 9 km thick as suggested by Noe-Nygaard (1942), i.e. that there is an approximately five-fold increase in the thickness of the Vaigat Formation between latitude 71°45′N and the south coast of the peninsula. This is unlikely, as already pointed out by Münther (1973) and Larsen (1981b), the latter suggesting that the thickness is of the order of 4–4.5 km. There are at least two possible explanations.

The first is that there was continuous flexure and subsidence in southern Svartenhuk Halvø during the eruption of the lavas, and that, as the lavas poured out, both the volcanic sources and the area of subsidence migrated westwards. Such a process can result in stratal shingling analogous to that seen in some pull-apart basins where stratigraphic thicknesses greatly exceed the true thickness at any point in the basin (Crowell 1982, figs 6, 7). The alternative explanation, which is based on the established fault pattern in the area, is that the south-westward dipping Vaigat Formation in southern Svartenhuk Halvø is not an uninterrupted succession but has been repeated several times along faults with downthrow to the north-east. The two explanations are not mutually exclusive, and both syn- and post-volcanic faulting can have affected a shingled succession. The problem will be discussed in the final section of this paper (see p. 34).

Svartenhuk Formation

The Svartenhuk Formation consists mainly of brownish or greyish weathering tholeiites with or without olivine; these tholeiites are commonly plagioclase-porphyritic but can also be aphyric. One significant unit in the formation is dark grey-green and olivine-porphyritic. These rocks are the stratigraphic equivalent of the Maligât Formation on Disko and Nuussuaq (Hald & Pedersen 1975). The Svartenhuk Formation is at least 2800 m thick. Flows in this formation tend to be thicker than in the Vaigat Formation, with entablature giving rise to 'trap' morphology. Near the top of the Svartenhuk Formation there is a conspicuous anorthoclase-porphyritic trachyte, the Arfertuarsuk trachyte (Nieland 1931; Plate 1), which is also noteworthy in that it contains numerous baked mudstone inclusions (A.K. Pedersen, personal communication 1999). In order to bring out the structure of the area, the Arfertuarsuk trachyte and the basalts above are distinguished from the remainder of the Svartenhuk Formation in the map Fig. 2.

In the area north-east and south-west of Simiuttap Kuua and north-west of Umiiarfik the lowermost basalts of the Svartenhuk Formation are separated from the underlying olivine-rich basalts of the Vaigat Formation by about 50 m of hyaloclastite breccias, water-lain tuffs, and fluvio-lacustrine sandstones interbedded with dark mudstones and coal seams (Fig. 2; Plate 1). These mark an interval during which this part of the area lay at the fringe of volcanic influence. Similar sediments occur farther to the north-east where they occupy depressions in the basement surface. The petrography of the sandstones shows that most of the material was brought down from exposed basement terrain. The first lavas of the Svartenhuk Formation that reached this area flowed into lakes and hence are in subaqueous facies. After this subaerial conditions prevailed, and flood basalts spread over a very large area, reaching beyond the margin of the Inland Ice to the east.

Minor intrusions

Dykes

Mafic dykes occur throughout the area. An impression of the distribution and directions of the dykes can be gained from Fig. 4, which shows as many of the dykes recorded on the 1:100 000 sheets as the scale of the figure permits. However, as explained later, most of the dykes shown in the area of exposed basalts were recorded from aerial photographs, and there is a bias towards dykes which show the greatest resistance to erosion relative to their surroundings.

In the field, dykes can be divided into four main groups: picritic, olivine-porphyritic, plagioclase-porphyritic and aphyric basalts. These correspond to the four main lava flow types that can be identified in the field, and it is assumed that dykes and lava flows of similar composition belong to the same phase of volcanism, and that many dykes are feeders to the corresponding flows.

Dykes present in the lowermost part of the Vaigat Formation that have the same appearance and chemical composition as the contaminated basalts of the Kakilisaat Member and the overlying olivine basalts are believed to be the oldest exposed dykes, because the characteristic compositions of these units are not repeated in the younger lava units. These dykes are poorly exposed, and we have no systematic data concerning their orientation.

Picritic dykes corresponding to the upper part of the Vaigat Formation are commonest in the southern part of the area. They are generally rather thin, *c.* 0.4–1 m, although master dykes several metres thick occur, some of which are up to 25 m thick. These dykes are eroded just as severely as the host picrite lavas, and the colours of weathered surfaces are the same, so that these dykes are difficult to trace on aerial photographs and only very few are included in Figs 4 and 5. They have trends mainly between NE–SW and E–W, but also NW–SE and NNW–SSE trends have been observed. In several cases picritic dykes can be seen to change direction.

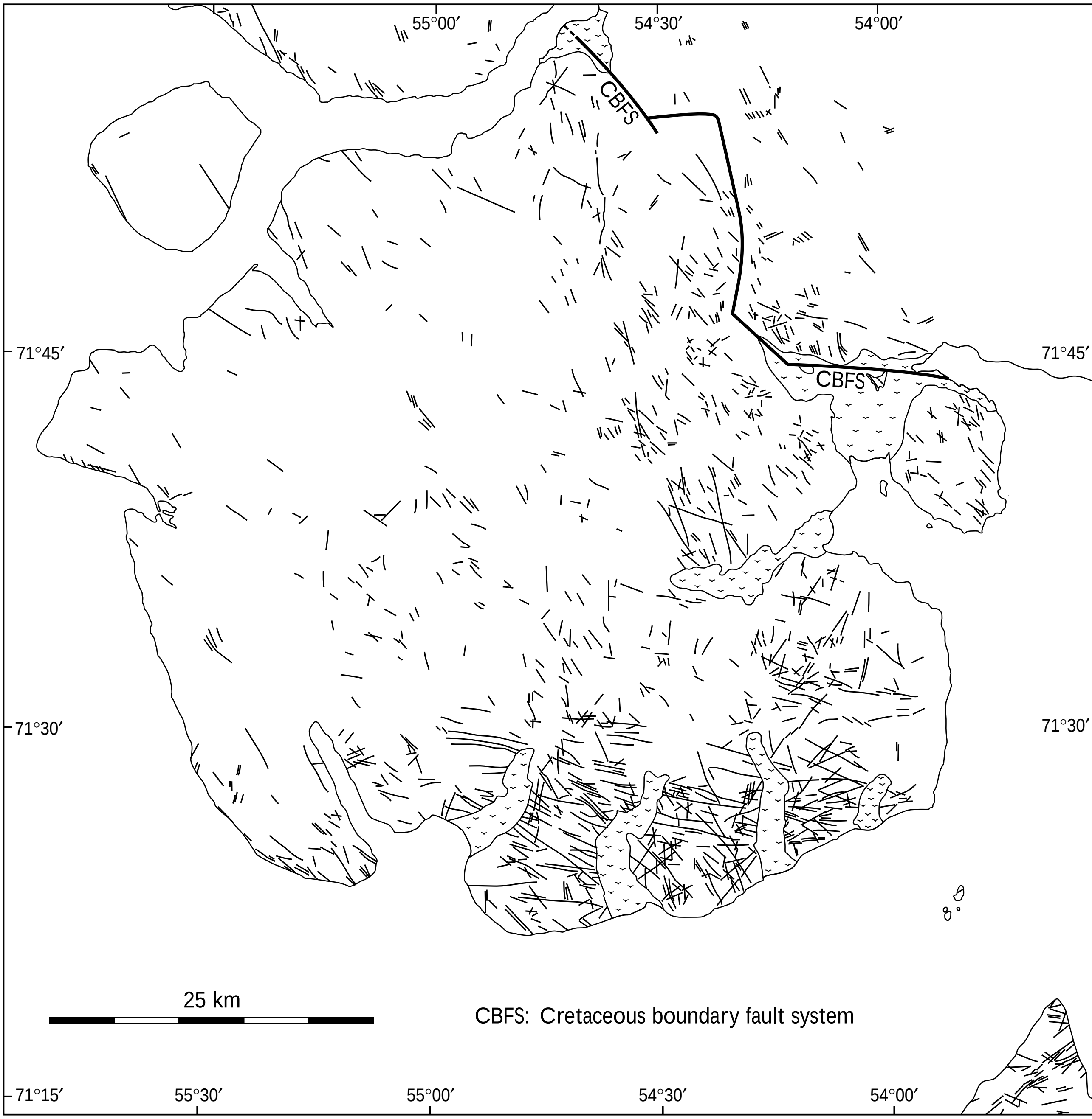

Fig. 4. Map showing dykes recorded on the 1:100 000 map sheets Svartenhuk, 71 V.1 Nord and Igdlorssuit, 71 V.1 Syd. Main areas of Holocene deposits are shown. For location, see Fig. 1.

Some NW-trending picritic dykes exposed in the steeply dipping lavas in southern Svartenhuk Halvø dip north-eastwards, suggesting that they were tilted together with the lava pile. Feeder dykes with E–W and NW–SE trends have been observed in the central eastern area.

Olivine-poor, plagioclase-porphyritic and aphyric dykes cutting the Vaigat Formation are believed to be contemporaneous with equivalent lavas in the Svartenhuk Formation, although some may be feeders to younger lavas that have been removed by erosion. These dykes stand out as resistant walls in the crumbling picritic and olivine-rich flows of the Vaigat Formation and are therefore easy to trace on aerial photographs, but within the Svartenhuk Formation there is either no topographic expression of these dykes or they may form negative features and be indistinguishable from fault and fracture features.

A photogrammetric study of the orientation of the

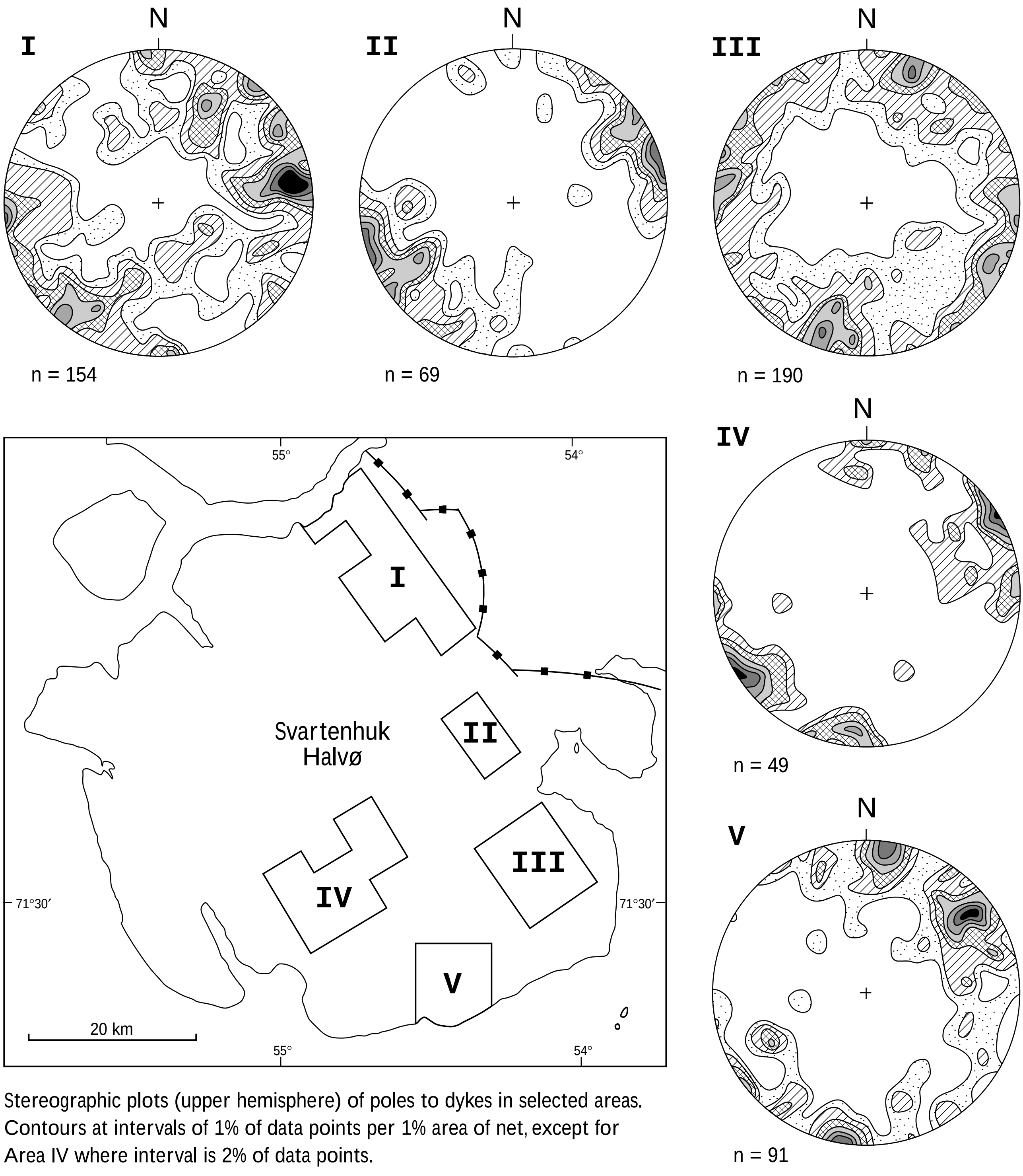

Fig. 5. Stereographic plots of poles to dykes in selected areas. The poles were plotted in the upper hemisphere so that maxima would lie in the same quadrant as the direction of dip.

dykes has been carried out in five areas which were selected to give an impression of regional variation in trend and dip patterns and how these are related to fault patterns and dip of host lavas. For practical reasons four of the five areas lie entirely within the area of outcrop of the Vaigat Formation where dykes are most easily seen in aerial photographs. In the Svartenhuk Formation only a small minority of dykes can be

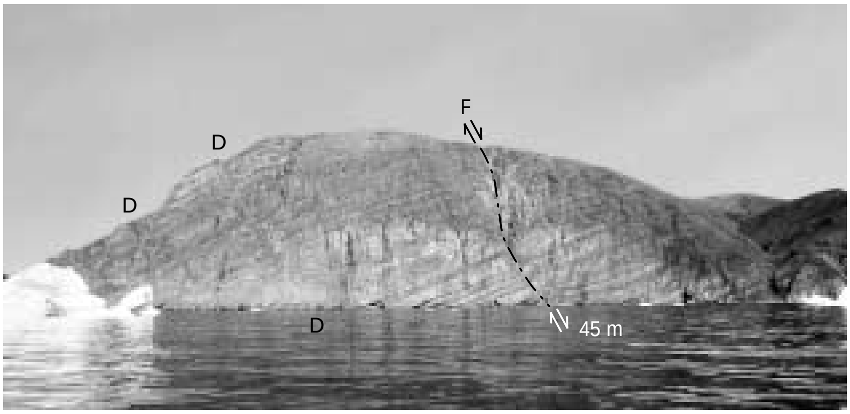

Fig. 6. View of a cliff west of Tasiusaq, showing basalts of the Svartenhuk Formation dipping south-west, cut by two dykes (**D**) and an extensional fault dipping north-east. Whether the dykes were tilted together with the basalt lavas or intruded into already dipping fractures has not been ascertained here. The height of the cliff is 300 m. For location, see Fig. 2.

seen on aerial photographs, and only in one of the selected areas, Area IV (Fig. 5), is there a substantial outcrop of Svartenhuk Formation. This method is adequate for providing a general indication of dyke orientations in an area, but is not completely reliable for determining dyke dips; a real change in dyke trend on a ridge or in a valley can be erroneously interpreted as interference between the surface of the terrain and a dipping dyke.

As can be seen from Figs 4 and 5, different areas are dominated by different trends. In the south, WNW–ESE to WSW–ENE trends dominate, together with NE–SW trends in the south-eastern area and some NW–SE- and N–S-trending dykes in the south-west. In the rest of the peninsula NW–SE and N–S trends dominate, while WNW–ESE-trending dykes form a minor group. As already pointed out, the vast majority of the dykes recorded are olivine-poor dykes post-dating the Vaigat Formation. The degree of scatter in both trends and dips of recorded dykes can best be seen from the contoured stereographic plots of poles to dykes in selected areas (Fig. 5).

In Area I, the northernmost area, dips in the basalts are less than 6° to SW. In spite of considerable scatter, there are distinct dyke maxima in trend 174°, dip 77° E and in 130/approximately vertical. These trends are approximately parallel to the trends of segments of the Cretaceous boundary fault system in this area. In Area II, where basalt dips are also very low, there is a clear dominance of *c.* NW–SE-trending dykes, approximately parallel to the Qorlortup Kuua segment of the boundary fault system and to the flexure zones (see p. 20).

In Area III in the south-east the lavas dip up to 12° SW, except locally in flexure zones where dips can exceed 45° SW (see p. 27). The scatter shown by the stereographic plot is considerable. The maximum trend is in 108°, which is approximately parallel to the transfer faults in southern Svartenhuk (see p. 29). There is also a concentration of trends in NNE–SSW.

Unlike Areas I–III, Area IV includes a large area of outcrop of the Svartenhuk Formation. As explained already, dykes are less easy to see in aerial photographs in the Svartenhuk Formation than in the Vaigat Formation, which is one reason for the low number of observations from this area. The stereographic plot shows a maximum concentration of dyke trends in 148°, which is also the dominant direction of extensional faults on Svartenhuk Halvø. There are also several dykes trending between E–W and ESE–WNW, parallel to the direction of transfer faults.

In Area V the dip of the lavas is generally steeper than 25° SW and locally up to 40°. Recorded dyke orientations show maxima in 143/74° NE and 98/approximately vertical. The former trend is parallel to the dominant trend of extensional faults in the region while the latter is parallel to the transfer faults in southern Svartenhuk Halvø. If it is assumed that deviation of the dykes from vertical is largely the result of tilting, then dykes trending parallel to the strike of the lavas have not in general been tilted as much as the lavas, implying that some of the tilt of the lavas took place before the latest volcanism in this area. However, around Tasiusaq several dykes with lithologies corresponding to the Svartenhuk Formation have been observed at right-angles to the dipping lavas, i.e. with north-east dips of 60–65° (Fig. 6), indicating that the dykes were tilted together with the lavas and that the entire tilting of the lavas here took place after intrusion of the dykes. However, some NE-dipping dykes appear to have been intruded into tilted fractures after tilting of the lavas. For example, one dyke has been observed dipping 45° NE and showing a concentration of cumulate mafic minerals along its lower contact, indicating that this dyke was intruded into a fissure that was already inclined before the dyke was intruded. Both at Kap Cranstown and east of Tartuusaq there are NE-dipping dykes that follow inclined fault planes and hence their dip need not be the result of later tilting. Further evidence that some NW–SE-trending dykes were intruded late in the history of the area is provided by the dykes cutting dolerite sheets on Itsaku; these are described below.

A proper study of the age relations between different dyke swarms and between dykes and faults was more than could be achieved with the resources allocated to the regional mapping project. Furthermore, trends observed in the early picrite and olivine-rich dykes were also utilised by younger dykes, so trend alone cannot be used to establish a complete dyke chronology. Intersections also show that dyke direction is no indication of relative age. For example, NE–SW-trending dykes have been observed both cutting and cut by dykes trending approximately 155°.

Some indication of the relative ages of dykes can be obtained from relationships between faults and dykes. For example NW–SE- and WNW–ESE-trending dykes, both of which follow the trends of major fault systems, may be strongly jointed along their margins, suggesting movements later than intrusion. Offset of both NE–SW- and approximately E–W-trending dykes at faults within the flexure zones (see p. 28) suggests that these dykes are older than development of the flexure zones, while other dykes are unaffected by these faults. There are also small right-lateral offsets of dykes on faults trending 100°, parallel to the transfer faults described in a later section. However, dykes are known to side-step on meeting planes of discordance, so this evidence is not conclusive. Within the flexure zones there are only very few NW–SE-trending dykes, i.e. dykes parallel to the zones.

Sills and sheets (Siuteqqut intrusions)

Extensive, thick (up to 150 m) sills and sheets of dolerite, and at least one sheet of picrite, occur along and in the vicinity of the Cretaceous boundary fault system on Svartenhuk Halvø and are best exposed within the Cretaceous–Palaeogene sediments on Itsaku; only the largest outcrops of these intrusions are shown on Fig. 2. For convenience they will be collectively referred to here as the Siuteqqut intrusions. In addition to the outcrops shown on Fig. 2, there are important sheets on the south-east side of Innerit, on the north-east side of Simiuttap Kuua, north of Qorlortup Kuua and south of Firefjeld. A sheet on the north-east side of Simiuttap Kuua is intruded along the inclined contact between basement and sediments or volcanic rocks before it transgresses through the Vaigat Formation. On entering the sediments between the Vaigat and Svartenhuk Formations it passes into a sill from which an irregular sheet has been fed into the overlying Svartenhuk Formation. The sheet on the south-east side of Innerit also reaches the intrabasaltic sediment horizon, but does not penetrate the lavas of the Svartenhuk Formation.

On Itsaku the very large representative of the Siuteqqut intrusions is cut by NW–SE-, NE–SW- and N–S-trending dykes. It is also cut by a significant NW–SE fault.

Situated as they are in the vicinity of the Cretaceous boundary fault system, the Siuteqqut intrusions are analogous to the Tartunaq intrusions on Nuussuaq which were intruded both along the plane of the Cretaceous boundary fault in Saqqaqdalen and into sediments and gneisses on either side of the fault (Munch 1945; Pulvertaft 1989). The Tartunaq intrusions have been dated at 54.8 ± 0.4 Ma (Storey *et al.* 1998), i.e. they are younger than the Vaigat and Maligât Formations on Nuussuaq, and they are also younger than the latest movements on the Cretaceous boundary fault system (Pulvertaft 1989). As just described, some of the Siuteqqut intrusions cut across the Vaigat Formation and locally penetrate into the Svartenhuk Formation, but outcrops of these intrusions are not good enough to allow any comment on the age of these intrusions relative to movements on the Cretaceous boundary fault system. In any case any deformation of the Siuteqqut intrusions along the boundary fault could be related to later inversion on this fault (see p. 22), a feature not observed on the Cretaceous boundary fault system on Nuussuaq.

If the Siuteqqut intrusions are not only younger than the Vaigat and Svartenhuk Formations but also younger than the main phases of faulting on Svartenhuk Halvø, the dykes cutting the Siuteqqut sheet on Itsaku are amongst the youngest intrusions in the area. The occurrence of dykes that are younger than both the basalts and the main fault movements would accord with what has been observed elsewhere in the West Greenland basalt province; for example in western Disko there are intrusions up to 25 Ma younger than the youngest lavas (Storey *et al.* 1998), and some of the lamprophyre dykes on Ubekendt Ejland are at least 18 Ma younger than the youngest known basalts (Parrott & Reynolds 1975; Storey *et al.* 1998).