Etah meta-igneous complex and the Wulff structure: Proterozoic magmatism and deformation in Inglefield Land, North-West Greenland

by

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Reports

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Abstract

A hitherto uninvestigated collection of crystalline rocks from north-eastern Inglefield Land (*c.* 79°N) allow a new interpretation of the Precambrian geology of the region.

The majority of the samples – high-grade basic, intermediate and granitoid rocks – are referred to the Etah meta-igneous complex, which has been shown to be mid-Proterozoic in age in the type area in south-western Inglefield Land. In areas of high deformation there is a gradation from massive rocks of igneous aspect into folded and variably migmatised gneisses. Thus the magmatic complex provides a gauge of the nature and intensity of Proterozoic (Hudsonian) deformation and metamorphism.

In Inglefield Land Proterozoic deformation produced different structural styles; thus in the north-east the Wulff structure – a large-scale refolded isoclinal structure – characterises a region that lacks an obvious preferred regional foliation direction, while in the south-west, linear E–W trending belts with steep dips dominate the structural pattern.

The Proterozoic evolution is outlined from the formation of the Etah Group, a supracrustal sequence that pre-dates the Etah meta-igneous complex, to uplift, peneplanation, deposition and magmatism in the late Proterozoic. Inglefield Land is not part of the Rinkian mobile belt of West Greenland, and it is stressed that the obvious continuation of the Proterozoic geology is into Ellesmere Island.

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Fig. 1. Location map of northern Greenland and adjacent Canada showing outcrops of Precambrian Shield around Smith Sound and at the head of Victoria Fjord. Inland Ice is shown stippled.

Introduction

Inglefield Land (78 10′N – 79° 10′N, *c.* 10 000 km²) is underlain by Precambrian crystalline basement overlain by Proterozoic and Cambrian platform strata (figs 1 & 2). The crystalline rocks are truncated by a Precambrian peneplain surface that dips shallowly to the north-west (see fig. 5). The overlying unmetamorphosed and undeformed platform strata form large outliers along the coast producing pronounced coastal cliffs. This basic geology was recognised by Koch (1920).

Few bedrock investigations have been undertaken in Inglefield Land since Lauge Koch's pioneer work between 1917 and 1922. These have been concentrated in the extreme south-west in the region between Foulke Fjord and Rensselaer Bugt (fig. 2; Cowie, 1961; Dawes, 1972, 1979). Apart from unpublished commercial work (e.g. by Internationalt Mineselskab A/S in 1973) the only geological visits to the region north-east of Rensselaer Bugt were those in 1976 and 1977 during GGU's mapping programme in Washington Land. The time spent in Inglefield Land was mainly allocated to the study of the platform strata (Peel, 1978; Peel *et al.,* 1982), but in both 1976 and 1977 the opportunity was taken to sample the basement complex.

Recent isotopic dating of rocks around, and north of, Foulke Fjord (Etah meta-igneous complex, Dawes *et al.,* 1988), as well as field and chemical studies of the northernmost exposures of the Greenland shield at the head of Victoria Fjord (81°30′N, fig. 1) (Henriksen & Jepsen, 1985; Hansen *et al.,* 1987) focus attention on the basement in the relatively unknown intervening area – north-eastern Inglefield Land. For this reason the 1976–77 rock collection has been restudied and is evaluated here. This allows important inferences to be made about the nature and distribution of Proterozoic plutonism and deformation, and a summary of Proterozoic evolution in Inglefield Land is presented.

General geology of south-western Inglefield Land

In south-western Inglefield Land (Kap Alexander to Rensselaer Bugt) the basement is composed of three main rock groups: the Etah Group of metasedimentary supracrustals, the Etah meta-igneous complex and a variable gneiss group (Dawes, 1972, 1976).

The *Etah Group*, where examined along the coast between Foulke Fjord and Kap Hatherton (fig. 2), is composed of marble, calc-silicate rock, garnet-bearing pelitic schists with units of quartz-rich schist, siliceous gneiss and garnet-biotite (-sillimanite-cordierite) gneisses. The supracrustal rocks form steep, E–W striking belts that are generally light in colour and thus easily seen on aerial photographs.

The Etah Group is invaded on all scales by rocks of the *Etah meta-igneous complex* that is composed of a variety of plutonic rocks characterised mineralogically by the presence of orthopyroxene. The intrusions take the form of large discordant bodies as well as sheets and
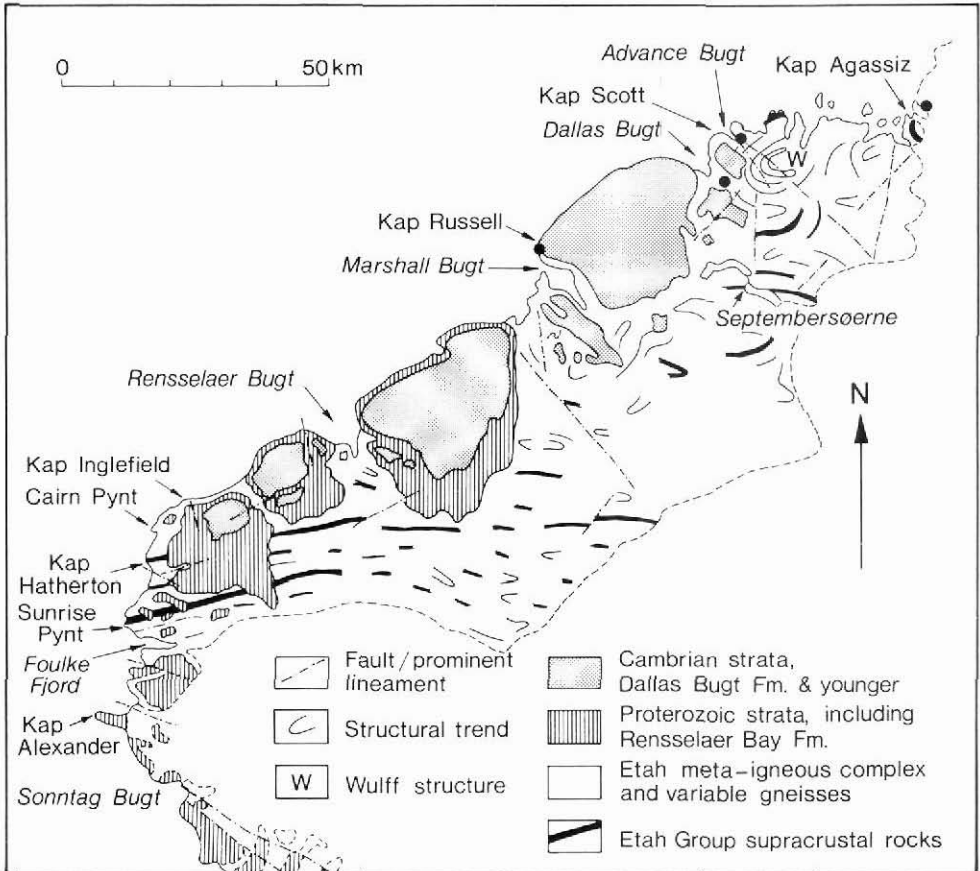
Fig. 2. Simplified geological map of Inglefield Land and northern Prudhoe Land; for regional location see fig. 1. The black dots mark the general area of four sample locations; the fifth, on the Wulff structure, is shown in fig. 6. Structures shown in the shield away from the coast are interpreted from aerial photographs. Inland areas, particularly in the east and south-east, have a heavy surficial cover. For this reason no structural trends are shown in the area immediately south of Septembersøerne, and the Etah Group farther south is shown as broken outcrops. Geology from Dawes (1976, fig. 224) with modifications from Peel & Christie (1982, fig. 3) and aerial photograph study.

veins (figs 3 & 4). Main rock types are hypersthene-bearing quartzofeldspathic granodioritic and dioritic rocks, with gradations to quartz-poor rocks. These are intruded by granitic rocks varying from leucocratic to relatively melanocratic hypersthene-biotite-garnet varieties, and also pegmatites and aplites. These plutonic rock types are generally massive to poorly foliated. The melanocratic rocks in particular have a typical greenish colour and waxy sheen, with green feldspars and commonly coloured quartz; in the leucocratic rocks feldspars can be pink to brownish red. Other rocks of the complex are thin basic metadykes, discordant to the foliation of the other rocks, and these are cut by a late generation of reddish granitic veins.

▨ Mainly red granite	▨ Metabasic rock, including amphibolite
⣿ Mainly pale granite } Etah meta-igneous complex	■ Pelitic schist, garnetiferous } Etah Group
⣿ Mainly quartz diorite	▨ Marble and calc-silicate rocks, including siliceous schist
	□ Covered
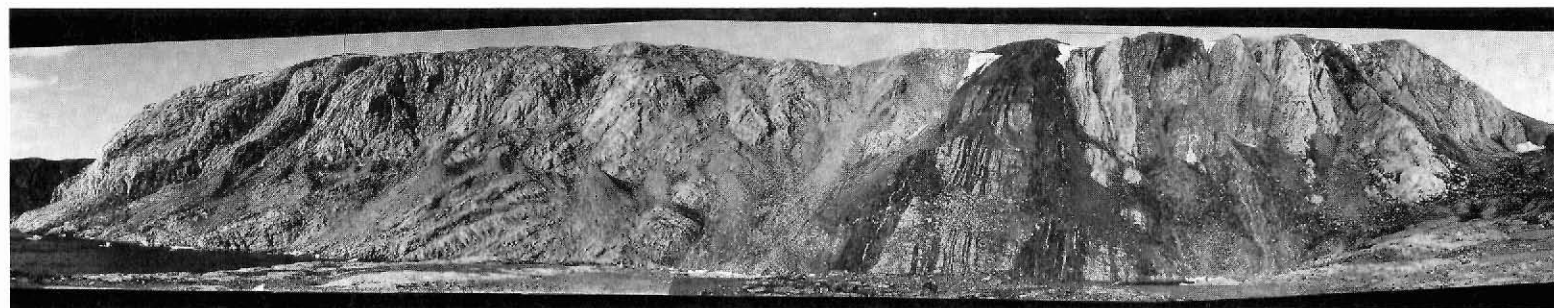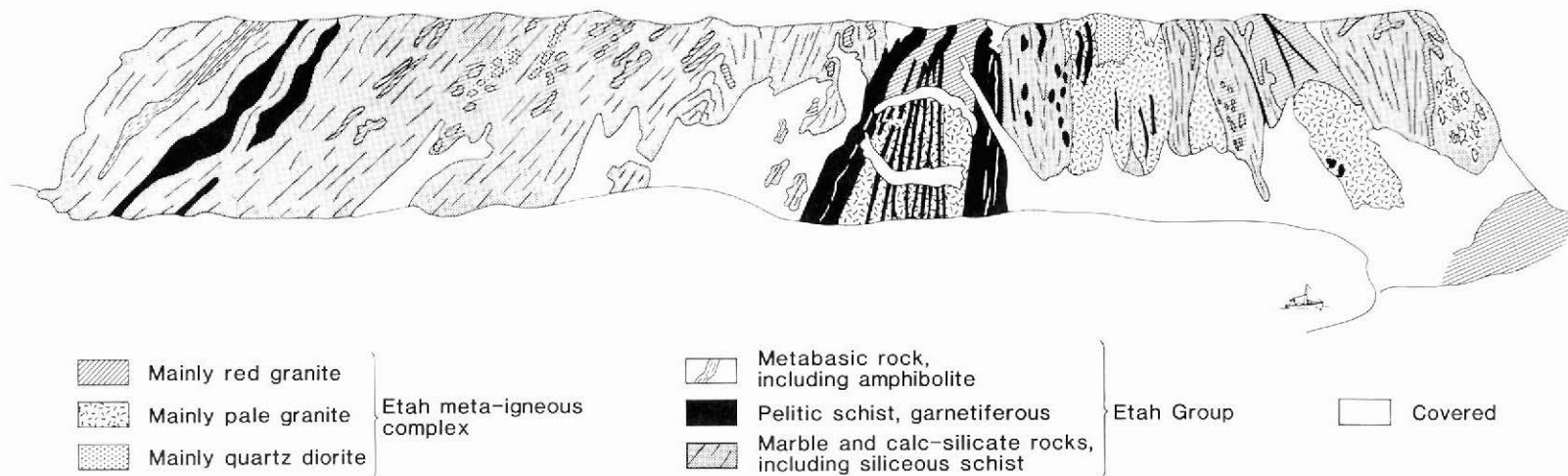
Fig. 3. Photograph and field sketch of cliff-section east of Sunrise Pynt, illustrating the intimate association of Etah Group (predominantly metasediments) and younger rocks of the Etah meta-igneous complex. Height of the cliff above fjord is approximately 350 m.

Fig. 4. Three sheets of leuco-cratic granite showing green diopside-rich reaction rims within marble and calc-sili-cate rocks. North of Sunrise Pynt, south-western Ingle-field Land.

There is a gradation from rocks of the Etah meta-igneous complex to well-foliated and banded gneisses of the *variable gneiss group*. This relationship bears witness to the complex structural history post-dating the intrusion of the igneous rocks (fig. 5).

The variable gneiss group is essentially composed of a concordant series of foliated, banded or migmatitic rocks – granulites, gneisses and schists – that generally contain both K-feldspar and plagioclase in variable ratios. Quartz-rich gneisses also occur; hypersthene and garnet are common. This gneiss group probably contains ortho- and paragneisses derived from both the Etah meta-igneous complex and Etah Group supracrustals. However, to what extent the variable gneisses also include older crustal material, i.e. a basement to the Etah Group, is at present unknown.

North-eastern Inglefield Land

Hitherto published details from the region north-east of Rensselaer Bugt include those of Koch (1933) and the petrographic descriptions of the few samples available to Callisen (1929). Of particular note is the presence of hypersthene-bearing igneous rocks at several localities (Koch's 'Etah Formation') and diverse gneisses (Koch's 'grey gneiss'). From this information, and based on aerial photograph interpretation, the Etah Group, the Etah meta-igneous complex and the variable gneiss group have been interpreted as occurring throughout Inglefield Land (e.g. Dawes, 1976; fig. 2). Earlier map subdivision of the basement by Koch had been limited to an area of 'intrusive rock' around Kap Agassiz (Koch, 1920), a feature omitted from his later, larger-scale map (Koch, 1933).

A prominent feature east of Dallas Bugt is a large horseshoe-shaped structure about 10 km across (fig. 6). This refolded isoclinal structure, illustrated earlier by Dawes (1976, fig. 230), is referred to here as the 'Wulff structure' – named after Thorild Wulff, Swedish botanist and member of the 2nd Thule expedition, who perished in the district in 1917.

Fig. 5. Proterozoic geology of south-western Inglefield Land. Steeply-dipping, crystalline rocks of the shield, truncated by a well-developed peneplain and overlain by the Helikian Rensselaer Bay Formation – sediments and cliff-forming basaltic intrusions. Metasediments of the Etah Group predominate in the cliffs to the right; more massive rocks to the left are mainly meta-igneous rocks of the Etah complex. View is eastwards from coast south of Kap Hatherton, more or less along the regional strike of the crystalline rocks. Height of inland cliff is about 350 m.

The sample collection

The rock collection forming the basis of this report comprises 30 samples from five areas of north-eastern Inglefield Land: Kap Agassiz, the Wulff structure, Advance Bugt, Dallas Bugt and Kap Russell (fig. 2). The samples from Kap Agassiz were collected by H. F. Jepsen in 1976 during a short helicopter refuelling stop en route to the south; the bulk of the collection was made the following summer by J. S. Peel and J. D. Collinson during field work on the platform sediments of the region.

Thin sections of 26 of the samples have been studied.

Kap Agassiz

Six samples are available from the Kap Agassiz area (GGU 212658–63). The rocks were collected within a stone's throw of each other on the north side of a nunatak on the south side of Humboldt Gletscher (fig. 2). The basement here is composed of generally reddish weathering and poorly foliated granitic and intermediate meta-igneous rocks.

The samples are all of massive rocks that range from medium-grained melanocratic greenish quartz diorite to greenish grey and pink fine-grained granite. The rocks are characterised by the presence of orthopyroxene or mineral replacements of pyroxene. The

Fig. 6. Aerial view of the core of the Wulff structure, north-eastern Inglefield Land; a closed isoclinal structure with steep, northerly dipping sides, refolded by an approximately E–W trending isoclinal antiform. Distance across view is about 9 km. A–B represents the traverse across the westerly dipping hinge of the antiform, along which samples have been collected. Aerial photograph 239 C, no. 80; copyright Geodætisk Institut (A200/87).

majority of the granites contain K-feldspar, often perthitic, and plagioclase. Most are fairly leucocratic and only one contains biotite in addition to orthopyroxene. Of particular note is a sample of pale weathering, hypersthene quartz diorite containing biotite that on fresh surfaces shows a greenish greasy lustre, typical of granulite facies rocks.

Wulff structure

The samples from the Wulff structure (242136–45, 242175) come from its western flank about 8 km south-east of the head of Advance Bugt (fig. 6). There a series of granitic gneiss and schists, granites and basic–ultrabasic schists have a steep westward dip folded around the main NE-trending axis of the horseshoe-shaped structure. The samples come from a traverse about 1 km long across regional strike where all the rock layers seem to form a concordant series. Field relationships noted on outcrop scale point to the polyphase nature of the rock series; discordant, pink to rusty red, granite veins (including pegmatites and aplites) are present within the acidic to basic rocks.

Many of the rocks are rusty weathering and friable; on fresh surfaces several show the greenish colour characteristic of granulite facies rocks. The rock suite is characterised by the

presence of hypersthene, with or without garnet, in both acidic and basic varieties, and by the two feldspars in the granites. K-feldspar is commonly perthitic.

In the foliated and schistose granitic rocks both hypersthene and biotite show a preferred orientation; in these rocks as well as in the more massive, fine- to medium-grained granites, both minerals show various stages of replacement.

Particularly interesting are samples of pale greenish yellow and grey, garnet-hypersthene granites in which either K-feldspar or plagioclase may be the dominant feldspar. These rocks vary in grain-size from fine to medium to pegmatitic varieties. One sample is characterised by garnets 'peppered' throughout the rock, many euhedral up to 7–8 mm across.

The only ultramafic rock in the collection is a schist composed of amphibole and ortho-pyroxene in roughly equal amounts, together with heavily replaced olivine.

Advance Bugt

A prominent feature of the crystalline basement in parts of north-eastern Inglefield Land is the occurrence of rusty yellow gossan weathered areas. Samples were collected from one such area at the head of Advance Bugt, on its south-eastern side (fig. 2).

The three samples (GGU 242135, 242176–7), all taken from the same general area, have a rusty brown to yellow weathering surface with gradation to a friable crust. The rocks are pale cream to yellow on fresh surfaces and deficient in mafic minerals. They range from rather massive, fine-grained rock to quartzitic muscovite schist, being composed essentially of K-feldspar (mainly perthite), plagioclase, quartz and pale mica, with or without sillimanite and garnet, and opaque minerals. Quartz is commonly in intergrowth with both perthite and plagioclase; garnet can be pseudomorphed by chlorite.

The primary nature of these leucocratic rocks is unclear; they probably represent psammitic metasediments. The origin of the rusty gossan products is uncertain; no concentrations of iron-rich minerals are present in the available material. The rocks have been fractured and hydrothermally altered. Thin veins rich in epidote and iron oxide (?hematite) cut the quartzofeldspathic matrix of the rock and in severely altered material feldspar is replaced by sillimanite (?contact metamorphic product) that forms a prominent mineral of the friable crust.

Dallas Bugt

The samples in the collection from Dallas Bugt come from three localities about 4 km south-east of the head of the bay (GGU 242118–22, 242172–4) (fig. 2). In this area a varied suite of meta-igneous rocks outcrops in which three main intrusion phases are recognised in the field. A complex of massive to foliated granitic, quartz dioritic and basic rocks is cut by slightly discordant, thin metabasic dykes and younger pink acidic veins.

The granitic rocks are fine- to medium-grained, generally leucocratic, containing both plagioclase and K-feldspar with or without garnet and biotite. Where present, biotite produces a foliation. In a plagioclase-rich leucocratic variety, feldspar is heavily altered. The quartz dioritic intermediate rocks have hypersthene as the dominant mafic mineral, with or without hornblende and biotite. Fresh surfaces have a greenish grey colour and a waxy sheen. The basic rock in the collection is a black schistose pyribolite composed of horn-

blende and orthopyroxene in roughly equal amounts with fresh plagioclase, biotite and opaque minerals.

The metabasic dyke material cutting the rocks above is also a pyribolite, containing both orthopyroxene and hornblende. The late acidic veins range from aplitic varieties to peg-matitic; they are commonly pink, contain plagioclase, perthite and quartz and are deficient in mafic minerals.

Kap Russell

The basement immediately east of Kap Russell (where it disappears beneath the overlying sedimentary cover, see fig. 2) is dominated by red weathering granitic and more mafic massive rocks in which ill-defined pegmatite patches and pink acidic sweats occur.

The single sample available (GGU 242129) is a pink to purplish weathering, medium-grained, two-feldspar granite. Brown to green biotite is the main mafic mineral, being partially replaced by chlorite. The plagioclase is heavily saussuritised and the rock is cut by thin veins with epidote and sericite.

Correlation

The majority of the rock samples from Kap Agassiz, the Wulff structure, Dallas Bugt and Kap Russell can be referred to the Etah meta-igneous complex. Several of the granites and hypersthene quartz diorites are mineralogically and texturally identical with the rocks around Foulke Fjord, which were initially recorded by Schei (1903) and described by Bugge (1910) and Holtedahl (1917).

In addition the field information from the sample areas strongly suggests a close similarity in igneous and tectonic chronology with the type area of the Etah meta-igneous complex. Thus a suite of acidic and intermediate rocks with some basic varieties showing evidence of varying intensity of deformation, and in which granitic rocks are intrusive into hypersthene quartz diorites, are cut by metabasite dykes and by later red pegmatitic and aplitic material.

It is concluded that the Etah meta-igneous complex has a wide distribution in north-eastern Inglefield Land. However, to what extent the metasedimentary Etah Group and the variable gneiss group are present is uncertain. The only possible metasediments in the present collection are the quartzofeldspathic micaceous rocks of the gossan zones from Advance Bugt. Other possible metasediments are the sillimanite-bearing gneisses described by Callisen (1929) from Kap Scott and Septembersøerne (fig. 2). Several white to pale grey banded zones interpreted as marble-rich sequences occur inland between Marshall Bugt and Septembersøerne. Several of these occurrences, like the Advance Bugt rocks, are character-ised by gossan weathering.

No banded gneisses or migmatitic rocks comparable to the variable gneiss group of the Foulke Fjord area occur in the present collection. The granitic gneisses present appear to represent orthogneisses, i.e. derivatives of the Etah meta-igneous complex. However, among the rocks described by Callisen (1929) are several gneisses that Koch (1933) included as part of his 'grey gneiss' terrain which he surmised to be older than the marble-rich metasediments and diorites. The questions as to whether Koch's grey gneisses are syn-onymous with the variable gneiss group and whether any of the gneisses pre-date the Etah Group must await further study.

Proterozoic magmatism, metamorphism and deformation

Two principal conclusions drawn from the present rock collection are:

(1) that the Etah meta-igneous complex forms a prominent part of the basement outcropping at least as far north as Humboldt Gletscher, and

(2) that the complex is affected by strong polyphase deformation that produced large isoclinal folds like those involved in the Wulff structure.

Results of a Rb-Sr isotope whole rock study of rocks from the type area of the meta-igneous complex in south-western Inglefield Land have been interpreted as indicating a strong mid-Proterozoic metamorphic event at around 1800 Ma (Dawes *et al.*, 1988). The low initial $^{87}Sr/^{86}Sr$ ratio (*c*. 0.7032) is taken to indicate that the complex has not passed through a long crustal history prior to metamorphism and it is considered extremely unlikely that the rocks represent Archaean material.

This Proterozoic age inference is confirmed by U-Pb age dating work on correlatable meta-intrusive rocks in adjacent Ellesmere Island where certain quartzofeldspathic plutonic rocks cutting gneiss and marble-rich metasediments have been referred to the Etah meta-igneous complex (Frisch & Dawes, 1982, see below). For example, zircon from a hypersthene-bearing quartz diorite from Cape Isabella (fig. 1) has yielded a U-Pb concordia age of 1912 ± 1.6 Ma; an age regarded as recording the time of magmatic emplacement of that particular plutonic body (Frisch & Hunt, 1988).

Field relationships both in Inglefield Land and in Ellesmere Island indicate that the Etah meta-igneous complex is composed of several generations of intrusive material. The absolute ages of the rock phases are as yet unknown and the complex in Inglefield Land may contain magmatic rocks emplaced prior to 1912 Ma. It should be noted that Frisch & Hunt (1988) present evidence for magmatic emplacement of orthopyroxene-bearing granitoid rocks from Ellesmere Island as early as *c*. 1950 Ma. Whatever the precise intrusion age of the meta-igneous rocks in north-east Inglefield Land, the folding, deformation and metamorphism of the rocks are a measure of the degree of Proterozoic (Hudsonian) plutonism and diastrophism in the region.

A common mineral assemblage of the quartzofeldspathic rocks of the Etah meta-igneous complex is plagioclase – K-feldspar (perthite) – quartz – hypersthene ± biotite ± hornblende ± garnet. Orthopyroxene ranges from fresh to altered but it appears to be essentially in equilibrium with other mafic minerals. The rocks are interpreted as having been intruded during or slightly prior to a regional granulite facies event. Break-down of orthopyroxene and biotite, and the generation of hornblende, indicate a local retrogression at amphibolite facies conditions.

The Wulff structure indicates that at least two, possibly three, phases of deformation and large-scale folding affected the igneous complex producing major isoclines and refolded structures. This has produced a structural pattern characterised by a variable regional foliation trend. This contrasts with the structural style in south-western Inglefield Land where the regional foliation has a regular, roughly E–W strike with linear and sheared belts of steeply inclined rocks persistent over tens of kilometres. This linear structure is prominent at the outer coast from north of Kap Alexander to the Kap Inglefield area; inland, definition is less distinct due to heavy cover of surficial deposits, but the straight belt structure appears to persist to the Inland Ice (fig. 2).

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The Etah meta-igneous complex pre-dates the development of the prominent E–W foliation pattern which must therefore also be of Proterozoic age. However, on outcrop scale it is evident that the Etah meta-igneous rocks (as well as the Etah Group) in south-western Inglefield Land have also passed through a complex polyphase tectonic history. Thus, in the area south of Foulke Fjord where rocks of igneous aspect grade into well-foliated and veined orthopyroxene gneisses, small-scale fold patterns resemble the structural style of north-eastern Inglefield Land (fig. 7), while in northern Prudhoe Land (south of Inglefield Land, fig. 1) large-scale recumbent isoclines characterise the granulite facies gneisses (fig. 8). Isoclinal folds are also preserved within the linear belts north of Foulke Fjord and are particularly visible causing repetitions of layers in the Etah Group. The pronounced E–W tectonic grain is regarded as a late stage in the Proterozoic deformational history post-dating the main isoclinal folding episodes (Table 1).

The gross relationship between the Etah Group and the Etah meta-igneous complex is unequivocal; in areas of low deformation, igneous bodies are profoundly discordant to the main structure of the metasediments. Towards areas of high deformation there is a gradation from such discordancies to a generally concordant interleaving of the two rock groups.

However, on outcrop scale the relationships between meta-igneous rocks and metasediments can be complex, and contact metamorphic effects and flow deformation in marble are widespread phenomena (figs 4 & 9). Where most intense the mobilisation of the carbonate rock is associated with severe folding and break-up of smaller intrusions – sheets, dykes and veins – so that boudins and fragments of granite and metabasite are isolated in marble (figs 10 & 11). Igneous bodies within marble commonly display contact metamorphic rims. The deformation effects due to magmatic injection are of more than one age; early flow folds in marble and deformed metabasic dykes are cut by later boudinaged granite veins.

The Etah meta-igneous complex represents a syn-kinematic suite of intrusions; the detailed chronology of magmatic emplacement, deformation and metamorphism must await further field study. On single outcrops it can be difficult to differentiate between folding in the Etah Group that is due to flow deformation induced by magmatic emplacement, and deformation effects that may pre-date the emplacement of the complex, or even late effects due to the main Hudsonian deformation (Table 1). The latter can be established by the
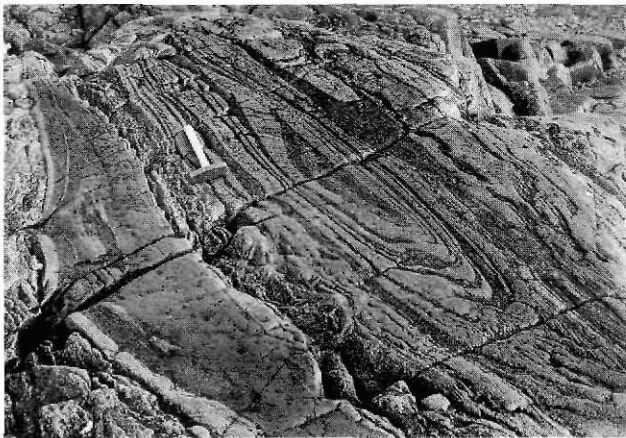

Fig. 7. Small-scale elongated dome structure in pyroxene orthogneiss. North of Kap Alexander within the area of E–W trending, steeply dipping regional foliation.

Table 1. Principal stages in the Precambrian evolution of Inglefield Land and northern Prudhoe Land

	(Basal Cambrian clastics, Dallas Bugt Formation)	
11	Uplift and erosion	
10	Hadrynian basaltic magmatism – dykes	*c.* 700 Ma
9	Helikian basaltic magmatism – sills	*c.* 1250 Ma
8	Deposition of Rensselaer Bay Formation	
7	Uplift and erosion with development of mature peneplain	
6	Faulting and fracturing connected with metamorphic retrogression	
5	Main Hudsonian orogeny, regional deformation, metamorphism and variable migmatisation producing granulite facies gneisses, polyphase structural patterns with refolded isoclinal folds (Wulff structure) and younger linear belts	*c.* 1750 – 1930 Ma
4	Etah meta-igneous complex, syn-kinematic intrusions, causing flow deformation and contact metamorphism in Etah Group	*c.* 1910 – 1950 Ma
3	Deformation, folding and metamorphism	
2	Early Proterozoic(?) Etah Group metasediments and basic rocks	?
1	?Archaean basement, part of variable gneisses. (Archaean rocks are exposed both to the south (Thule district) and north (Victoria Fjord).)	

Ages quoted are taken from Dawes *et al.* (1982, 1988), Frisch & Hunt (1988) and Larsen & Dawes (1974).

regional structural disposition of the meta-igneous complex and its occurrence in major folds like the Wulff structure.

Evidence of deformation and metamorphism prior to emplacement of the igneous complex (stage 3 in Table 1) is based on the presence of folds affecting the Etah Group that are cut by granite units, for example in the thick supracrustal belt north of Etah (Sunrise Pynt belt of Dawes, 1976). Such granites also post-date the development of a strong planar fabric in the metasediments which, in the pelitic lithologies, is developed as a thoroughly penetrative schistosity involving biotite (± garnet and amphibole). However, the relationship of this regional metamorphic and deformational event to the basic and intermediate rocks of the complex that generally are seen to be the earliest intrusion phases has not been determined.

The chronological stages numbered 3, 4 and 5 in Table 1 clearly represent a long and complex Proterozoic plutonic history, the details of which have yet to be unravelled. In south-western Inglefield Land the metamorphic peak of the Hudsonian orogeny appears to have been around 1850–1800 Ma ago (Dawes *et al.*, 1988); K-Ar 'cooling ages' on hornblende indicate waning of the metamorphism around 1750–1700 Ma (Larsen & Dawes, 1974). Retrogression of the granulite facies mineral assemblages occurred during slow uplift of the basement complex.
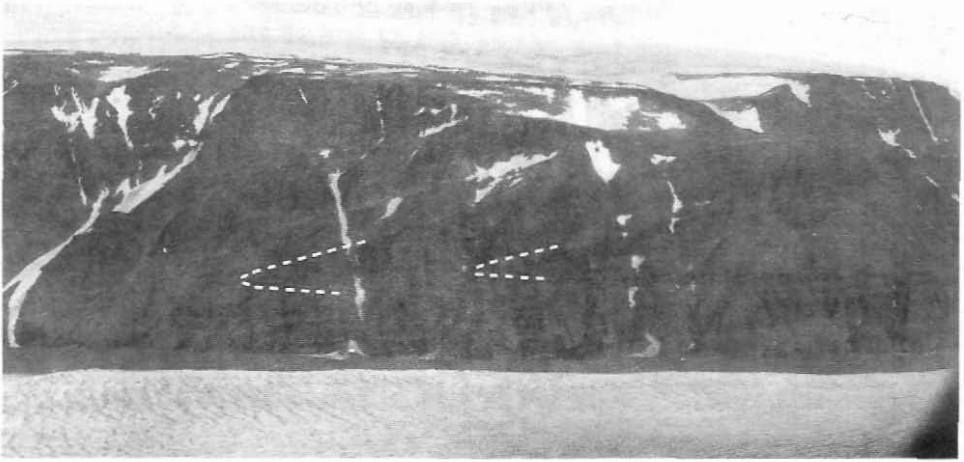
Fig. 8. Large recumbent isocline in rather massive granulite facies orthogneisses of the variable gneiss group. East side of Sonntag Bugt, northern Prudhoe Land; cliffs above Bamse Gletscher are about 400 m high.

As described earlier, the Etah meta-igneous complex in Inglefield Land (stage 4) is considered on petrological evidence to have been emplaced during or slightly prior to granulite facies metamorphism. Thus high-grade metamorphism must have existed prior to 1850 Ma. This is supported by the geochronological model from adjacent Ellesmere Island that is based on U-Pb isotopic analysis of zircon and monazite. Frisch & Hunt (1988) suggest that early intrusion at around 1.96 Ga was followed by granulite facies metamorphism and deformation, and subsequent melting and intrusion prior to 1.9 Ga. Ages of around 1.93 Ga on monazite (a mineral considered not to be capable of surviving granulite metamorphic conditions) are considered as a minimum for the granulite facies event in Ellesmere Island. How far this geochronology is regionally applicable must await comparative isotopic work from Inglefield Land, but the ages from Ellesmere Island are included in Table 1.

Another open question concerns the age range of intrusive rocks included in the Etah meta-igneous complex. Based on the isotopic age work in Ellesmere Island referred to above, it might be inferred that the complex in Greenland may contain at least two main ages of rocks: those emplaced at around 1.9 Ga (the age of the Cape Isabella quartz diorite, see above), and other material, possibly as old as 1.96 Ga. Pending renewed field and isotopic work in Inglefield Land, the Etah meta-igneous complex is used in a broad sense to include all meta-igneous rocks that post-date the Etah Group.

Many of the meta-igneous rocks in south-western Inglefield Land show a well-developed pattern of joints. Crush zones are associated with secondary mineral alteration, predominantly epidote, mica and chlorite, while feldspars can be reddened and heavily saussuritised. This alteration represents a low temperature regime associated with the end of the Hudsonian plutonism or the following cratogenic period.

This late episode of retrogression is also seen in the sample collection from north-eastern Inglefield Land. Several of the samples show retrogressive mineral alterations and a reddish mineral staining that in places are associated with fracturing and hydrothermal veining. These changes indicate a period of metamorphic alteration and late cataclasis which is taken
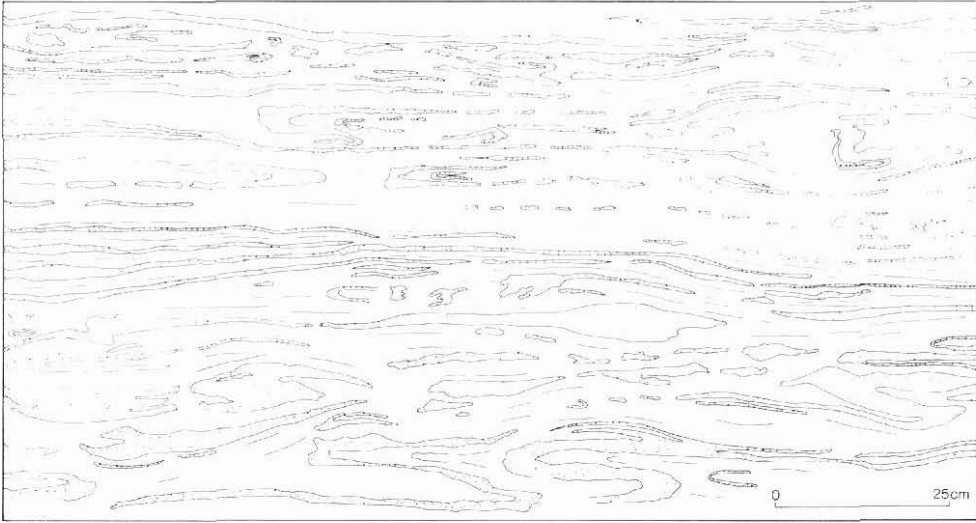
Fig. 9. Field sketch of small-scale flow deformation structures seen in calc-silicate layers (stippled – rich in diopside, scapolite and sphene) within pale marble (white). Sunrise Pynt peninsula, south-western Inglefield Land.

Fig. 10. Broken-up and discontinuous bodies of red granite (dark) with pale mobilised marble. Hammer (right) is 35 cm long. Sunrise Pynt, south-western Inglefield Land.
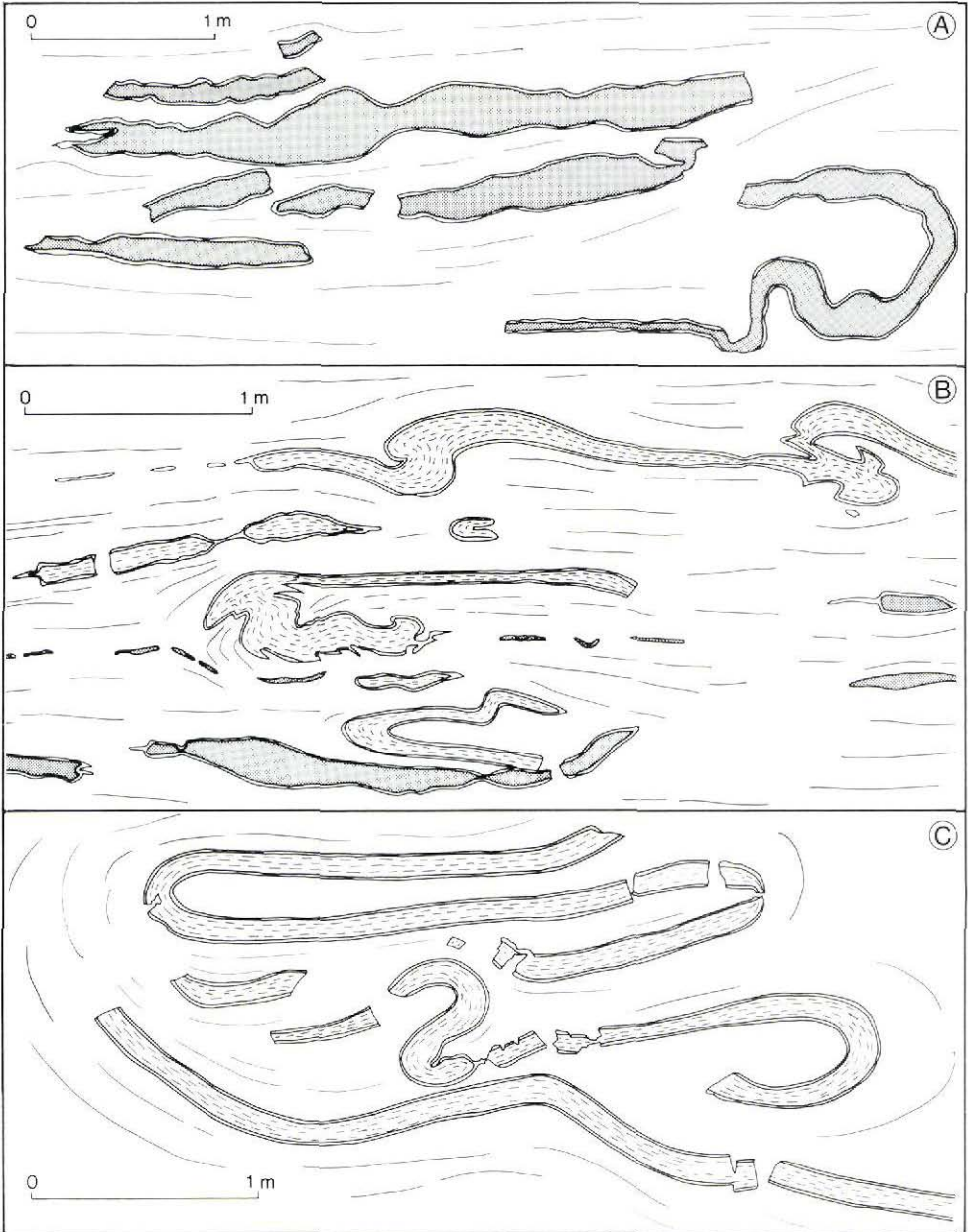
Fig. 11. Field sketches of severely deformed metabasic (dashed) and acidic (shaded) dykes within mobilised marble. Green, diopside-rich contact metamorphic rims to both rock types show varying relationships to boudinage formation and fragmentation, suggesting both pre- and syn-kinematic intrusion. Basic rock in B and C is an altered, foliated biotite pyribolite; acidic rocks are leucocratic and severely altered pink medium-grained granite (B) and pale blue-grey, pegmatitic granite (A). Sunrise Pynt peninsula, south-western Inglefield Land.

to be a Proterozoic event associated with prominent fractures that, in some cases at least, are associated with colour changes. In north-eastern Inglefield Land a criss-cross pattern of lineaments post-dating the folds is conspicuous on aerial photographs (fig. 2). The lineaments have a variable orientation with a concentration in north-west and north-east directions. One such north-west trending lineament which crosses the Wulff structure forms a prominent gully along which lakes are elongated (fig. 6). While some of these lineaments may contain basic dyke material, many do not and are vertical to steeply-dipping fractures.

The origin of the lineaments is unknown; those crossing the Wulff structure do not seem to be associated with strike-slip displacement. Whatever their origin – faults, shears, joints, crush zones – the main lineament pattern is not visible in the overlying platform cover. The structures are thus of Proterozoic age. The lineaments presumably date from the cratogenic epoch following initial uplift but pre-date the deposition of the Helikian platform cover – the Rensselaer Bay Formation, pre-1200 Ma old (Dawes et al., 1982). It should be noted that some lineaments (with trends corresponding to fractures in the basement) also affect the overlying cover, suggesting Palaeozoic (or later) reactivation of some of the Proterozoic fractures.

In gross character, however, the platform rocks throughout Inglefield Land are essentially undisturbed as witnessed by the homoclinal coastal cliffs in which individual beds can be traced over large distances. Where examined, the sporadic lineaments affecting the platform strata indicate normal fault displacements of up to a few tens of metres. The main directions of faults cutting the Proterozoic to Cambrian platform cover are: north-east, north-north-west and east-north-east (fig. 2). Faults of the last direction in south-western Inglefield Land are parallel to the main linear structure of the basement suggesting they are reactivated structures controlled by the basement geology.

The age of the fault movements that affect the platform cover in Inglefield Land is unknown. In southern Washington Land normal faults cut platform strata as young as Ordovician (Jepsen & Dueholm, 1978; Jepsen et al., 1983).

Distribution of Proterozoic rocks

North-eastern Inglefield Land represents the northernmost outcrops of the Precambrian Shield of western Greenland which is continuously exposed for over 2500 km along the coast. To the immediate north and east the crystalline basement is covered by Humboldt Gletscher and the Inland Ice; farther north the shield is blanketed by the sedimentary cover of Proterozoic and Lower Palaeozoic strata. North of Inglefield Land the shield is only visible beneath the sedimentary cover in a relatively small area (c. 1000 km^2), viz. at the Inland Ice margin around the head of Victoria Fjord (fig. 1).

The geology of north-eastern Inglefield Land contrasts with that of Victoria Fjord where the basement is essentially granitic to granodioritic gneissic terrain composed of homogeneous, veined and banded biotite orthogneisses with amphibolite bands. The gneisses are all migmatitic to varying degrees. Within the gneisses occasional supracrustal rocks occur as concordant thin bands. All the rocks, except a small late kinematic body of quartz diorite, have metamorphic textures and have recrystallised under amphibolite facies conditions (Henriksen & Jepsen, 1985).

The sample collection from north-eastern Inglefield Land described in this report contrasts markedly in lithology and mineralogy with the collections available from the Victoria Fjord arch (Dawes, 1978; Henriksen & Jepsen, 1985). Of particular note is the absence, in the latter, of orthopyroxene rocks comparable to the Etah meta-igneous complex and the lack of any evidence for a granulite facies metamorphic event, while no migmatitic gneisses like those characteristic of Victoria Fjord are represented in the Inglefield Land collection.

This difference seen in the hand sample collections is suggested to be of meaningful significance (rather than a question of inadequate representation) by the recent isotopic dating work on rocks from the Victoria Fjord exposures. U-Pb zircon and Rb-Sr whole-rock isotopic data show that the orthogneisses and later quartz diorite body represent Archaean material (c. 3000 Ma, Hansen et al., 1987). Thus, assuming that the rocks analysed by Hansen et al. adequately represent the outcrops, it can be concluded that the igneous rocks from which the gneisses of Victoria Fjord have been derived are not correlatives of the Etah meta-igneous complex.

The absolute age of the Etah Group is unknown; it is either Archaean or early Proterozoic. The marble-rich supracrustal sequence forms a distinct belt over 400 km long from Inglefield Land to southern Ellesmere Island (Frisch & Dawes, 1982). In Ellesmere Island the supracrustals are cut by meta-igneous rocks that are as old as 1.96 Ga, but the relationship to isotopically dated Archaean gneiss is unknown (Frisch, 1983). In Table 1 the Etah Group is provisionally given an early Proterozoic age assignment.

Whether any of the supracrustal rocks at Victoria Fjord represent Proterozoic material must also remain an open question. The metasedimentary units present there – like the Etah Group of Inglefield Land – contain marble, mica schists and siliceous rocks, but the age relationship to the orthogneisses is unknown (Henriksen & Jepsen, 1985).

The Rinkian mobile belt

On the tectonic/geological map of Greenland (Escher, 1970) the whole of the Precambrian Shield of western Greenland including the region between Melville Bugt and Inglefield Land is designated part of the Nagssugtoqidian orogenic complex which yields K-Ar ages between 1790 and 1650 Ma. The Rinkian mobile belt was introduced as a tectonic province by Escher & Pulvertaft (1976) to separate Precambrian terrain in northern West Greenland (c. 69°–74°N) having a distinctive structural style dominated by large-scale dome structures and recumbent isoclines, from the Nagssugtoqidian mobile belt to the south which is characterised by a prominent regional planar fabric with an ENE trend and steep dips (Escher et al., 1976). These contrasting structural styles are products of varying Proterozoic deformation.

Escher & Pulvertaft (1976) did not define a northern boundary to the Rinkian, since at that time it was unclear how far north into Melville Bugt the characteristic structural style persisted.

In recent reviews of the structural framework of the Precambrian Shield of Greenland, the northernmost part of the west coast including Melville Bugt and as far north as southwestern Inglefield Land has been included in the Rinkian mobile belt (e.g. Kalsbeek, 1986). Isotopic dating has demonstrated the presence of the mid-Proterozoic (Hudsonian) metamorphism and deformation in North-West Greenland (Larsen & Dawes, 1974; Kalsbeek & Dawes, 1980; Dawes et al., 1988).

The Rinkian mobile belt as described by Escher & Pulvertaft (1976) is composed of an Archaean basement overlain by thick and widespread supracrustal rocks of probable early Proterozoic age (the Karrat Group) that have been folded together and are now intimately associated. This geological couplet is intruded by Proterozoic intrusive rocks, notably the large Proven charnockitic granite (72°–73°N) which has a Rb-Sr age of 1860 ± 25 Ma (Kalsbeek, 1981). The Etah meta-igneous complex represents the northernmost area in western Greenland of such Proterozoic magmatism.

The variable state of the Etah meta-igneous complex demonstrates that in Inglefield Land Proterozoic (Hudsonian) tectono-metamorphic activity was intense. Isotopic data from Victoria Fjord (Hansen *et al.*, 1987) demonstrate that high-grade metamorphism at about 1850 Ma (presumably associated with much of the structural history described by Henriksen & Jepsen, 1985) also affected the crust much farther to the north. Thus, following recent usage (e.g. Kalsbeek, 1986) the Rinkian mobile belt might also be considered to extend into north-eastern Inglefield Land and even into northernmost Greenland.

However, Pulvertaft (1986) has adopted a much more restricted approach in his appraisal of the Rinkian. Hence, because of uncertainties as to the age of both rocks and structures around 69°–70°N, the Rinkian is not extended as far south as in the initial description given by Escher & Pulvertaft (1976). This approach is reiterated by Grocott & Pulvertaft (in press) who only extend the Rinkian north to just south of 75°N, the northern limit of areas of supracrustal rocks that are the supposed correlatives of the Proterozoic Karrat Group farther south. In describing the Rinkian as a mobile belt less than 500 km wide (between 71° and 75°N) these authors stress the connection to the Foxe fold belt of eastern Canada. Thus, rather than fostering the idea of a northern continuation in Greenland, the Rinkian is assessed to be the eastern part of a Foxe–Rinkian belt (fig. 12). In the most recent system of
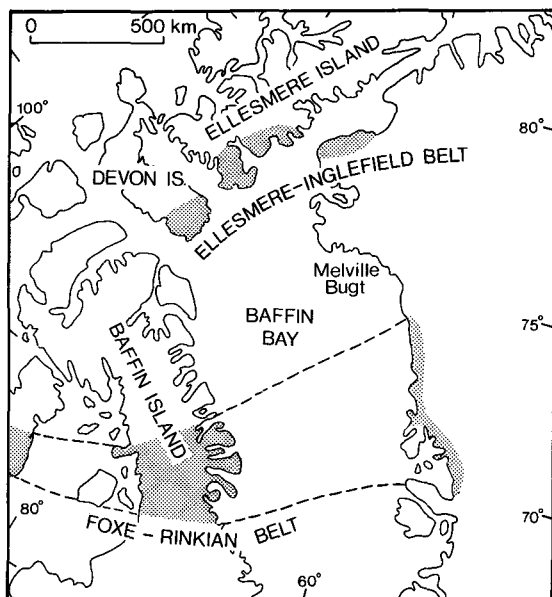

Fig. 12. Map of lands around Baffin Bay showing the location of the Ellesmere Island – Inglefield Land belt and Foxe–Rinkian belt, two major belts of Proterozoic stratigraphy, structure and magmatism that span the seaway. All exposures of Precambrian Shield within the area covered by the map, i.e. Greenland, Baffin Island, eastern Devon Island and south-eastern Ellesmere Island, have been affected by the Proterozoic Hudsonian orogeny. Location of Foxe–Rinkian belt is taken from Pulvertaft (1986); the islands west of Baffin Island and areas in Greenland, within this belt, which are shown blank on the map, are composed of younger cover rocks.

Precambrian tectonic units in North America – Archaean province, Proterozoic orogen, Proterozoic fold belt (Hoffman, in press) – the Foxe–Rinkian is a fold belt within an Archaean (Rae) province.

Melville Bugt (75°–76°N) separates the Rinkian terrain, *sensu stricto*, from the Precambrian complex of North-West Greenland (Dawes, 1976). The few isotopic age determinations available from Melville Bugt indicate the presence of Archaean crust that has been reactivated in Proterozoic time (Kalsbeek & Dawes, 1980; Dawes *et al.*, 1988). However, although there are clear similarities in Precambrian history between the Melville Bugt region and terrain to the south (Dawes & Frisch, 1981), the unifying features of the Rinkian – a characteristic structural style and the presence of early Proterozoic supracrustal rocks – cannot be substantiated. Indeed, following the initial field study, Dawes & Frisch (1981) argued, on compositional and regional correlation grounds, that the majority of the supracrustal rocks examined along Melville Bugt probably pre-date the Proterozoic supracrustals in the northern part of the Rinkian. Thus, on present evidence the extension of the Rinkian farther north than 75°N is problematic.

Accurate knowledge of the structural framework of the Precambrian of Melville Bugt (and also farther north in North-West Greenland) must await further field work and a systematic isotopic dating study. Thus, the relationship between the Proterozoic terrains north and south of Melville Bugt must, for the time being, remain speculative. One model is the presence of two distinct Proterozoic fold belts within what is essentially an Archaean province (see below and fig. 12).

In any case it is pertinent to stress here that the Proterozoic structures in Inglefield Land and environs do not conform to a particular structural style – the criteria used in West Greenland to differentiate between Proterozoic mobile belts. Thus the large-scale recumbent isoclines present in northern Prudhoe Land and the structural pattern of north-eastern Inglefield Land, characterised by large folds such as the Wulff structure and the lack of a dominant regional strike direction, resemble most the prominent style of the Rinkian. In contrast the intervening area of south-western Inglefield Land, with the regular E–W strike and pronounced steep dips, resembles the linear structural pattern of the Nagssugtoqidian mobile belt. Field evidence, including shear deformation of refolded structures, suggests that the Nagssugtoqidian tectonic style post-dates the Rinkian style in Inglefield Land.

The Ellesmere Island – Inglefield Land belt

While the structural relationship between Inglefield Land and the region to the south in Greenland remains to be determined, it is clear that the obvious continuation of Inglefield Land geology occurs in Ellesmere Island. Hence Frisch & Dawes (1982) in describing the evolution of the Precambrian Shield on both sides of northern Baffin Bay, specifically point (as anyone who sees the region must) to the occurrence of the same gneiss, supracrustal and igneous rock suites on both sides of Smith Sound. There can be no doubt that the Etah Group supracrustal rocks (characterised by marble), the Etah meta-igneous complex and the pyroxene-bearing gneiss terrain, which together form the dominant rocks in Inglefield Land and southern Ellesmere Island, are part of the same geological belt. Laboratory studies have confirmed the stratigraphic and lithologic correlations established in the field; isotopic work

has documented the comparable timing of the main metamorphic events (Dawes *et al.,* 1988; Frisch & Hunt, 1988).

The name Etah meta-igneous complex, with a type area in south-western Inglefield Land, has been extended to cover the corresponding magmatic suite in Ellesmere Island (Frisch & Dawes, 1982). This serves to accentuate the geological unity between the two lands; in both regions gradations from massive igneous rocks to isoclinally folded granulite-facies gneisses attest to the common Proterozoic deformation and metamorphism that affected the two areas. From stratigraphic, structural and metamorphic aspects the presence of a Proterozoic belt stretching for hundreds of kilometres from Inglefield Land through south-eastern Ellesmere Island (Frisch, 1981) is a reality.

The Inglefield Land – Ellesmere Island geological link is considerably more obvious than the correlation of Inglefield Land to the Rinkian mobile belt. Proterozoic (Hudsonian) plutonism affected a large part of the North American craton (fig. 12); correlation of belts of stratigraphy and structure like the Ellesmere Island – Inglefield Land and the Foxe–Rinkian belts provides a detailed indication of the primary geological units of the craton.

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