Summary Review of the Geology of Greenland as Related to Geological and Engineering Aspects of Sampling Beneath the Inland Ice

Thomas C. Mowatt
A. S. Naidu

Fig. 378. The main geological divisions in Greenland.

Acknowledgments

Authors

Thomas C. Mowatt is a geologist in the Branch of Lease Operations, Division of Mineral Resources, Alaska State Office, Bureau of Land Management, United States Department of the Interior, Anchorage, Alaska, and also has adjunct research and teaching affiliations with the University of Alaska.

A. S. Naidu is a geologist, and a professor in the Institute of Marine Science, University of Alaska-Fairbanks.

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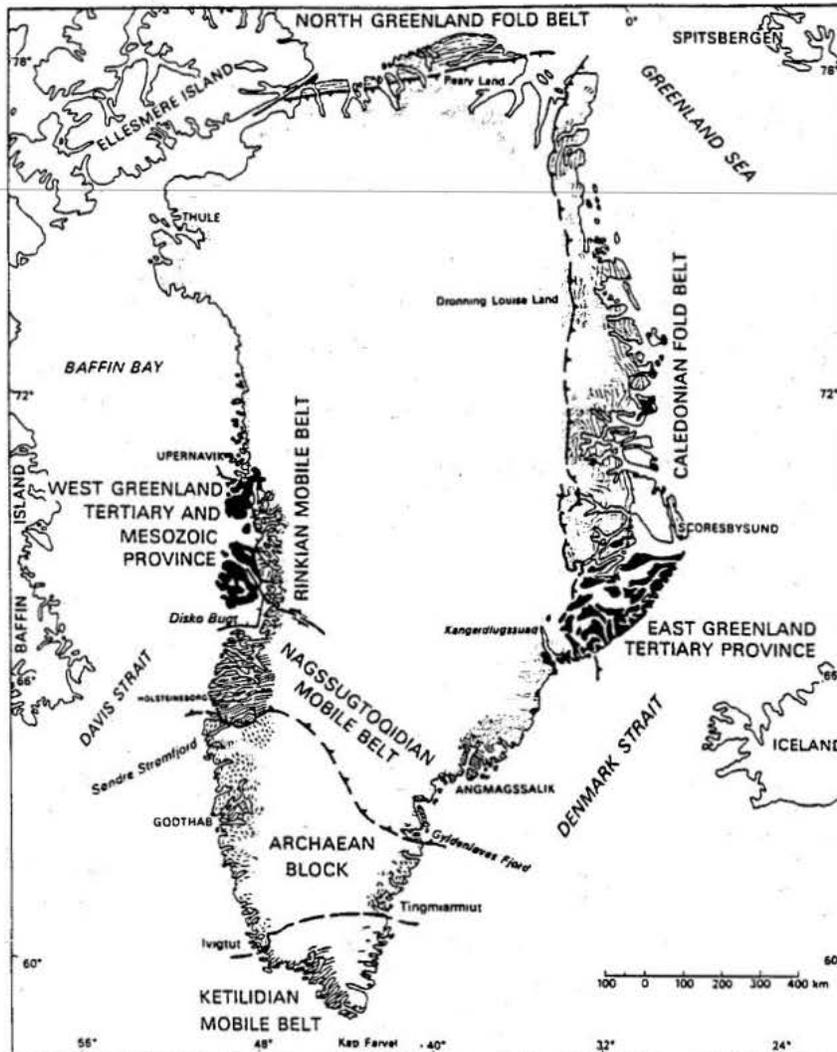
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A. S. Naidu

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Preface

Serious concerns continue as to possible significant perturbations of portions of the Earth's exogenic cycles being of anthropogenic derivation, at least in part. Foremost among these concerns is the now-familiar topic of possible "global warming", attendant upon various human activities. Suffice to say here that these concerns are of sufficiently fundamental importance to global biology- including human society- that appreciable efforts are underway, worldwide, to study this matter carefully. One aspect of this, of course, is to develop data bases sufficient for rational investigation and evaluation, as well as to indicate such courses of action as may appear to be warranted in endeavoring to rectify such deleterious activities as may be demonstrated.

An aspect seemingly of fundamental relevance is to attempt to elucidate more substantively global climate character and patterns of vicissitudes, from the present time back into the past. This involves a variety of considerations; much, in fact, devolves to studies of relatively recent geologic history.

One approach to this is to investigate the geologic record provided by geologic environments such as the present-day ice sheet- the "Inland Ice"- which covers a major portion of the world's largest island, Greenland. Programs are underway to drill into this ice mass, retrieve samples via coring procedures, and analyze them, variously, in terms of information possibly germane to the paleoclimates extant during the time periods represented by these samples from depths within the ice. The Polar Ice Coring Office, located at the University of Alaska-Fairbanks, is a principal component of this work.

Ancillary to the ice-coring work per se, it has been suggested that additional fundamental geologic information regarding the character of sub-ice materials—ie., bedrock and/or glacio-fluvial material—might be readily obtained during the course of ice-coring work, via sub-ice drilling and sampling. Such additional efforts as would be required should potentially yield incrementally far greater returns, in terms of significantly expanding geologic knowledge into areas now totally unknown. Mineralogical-geochemical characteristics of bedrock materials immediately subjacent to the ice may well yield clues as to paleo-climate/weathering conditions extant prior to the deposition of the overlying ice horizons. As well, sub-ice sampling would seem to represent an unusually attractive opportunity to efficiently add to the sum total of human knowledge regarding the geology of a region which is acknowledged as being key to a variety of global geologic concerns. These include the early history of the Earth itself, subsequent geologic events through time, and related processes. A principal aspect is that of plate-tectonic relationships, present and past, and related paleo-geography. This, in turn, of course, has decided implications in terms of paleo-climates. Thus, a project has been initiated at the University of Alaska-Fairbanks, in collaboration with investigators from other organizations, to delve into the matter of sub-ice sampling. A fundamental aspect, of course, is that of engineering methods and equipment required. The focus of the work reported on herein has been to endeavor to provide a geologic context, in terms of types of geologic materials likely to be encountered during sub-ice drilling in Greenland, and the facilitation of recovery of such materials.

The Bureau of Land Management, U. S. Department of the Interior, (BLM), is strongly advocative of research in the environmental and geo-sciences. One of a number of current interests regards worldwide concerns as to possible global-warming attendant upon various human activities. Within the mandates of its' principal programs of land and resources management, the Bureau strives to support such research activities at every opportunity, as exemplified by the presentation of this BLM-Alaska Open File Report.

This report represents in part a contribution by a Bureau scientist to contemporary research related to the postulated phenomenon of global-warming. This work was carried out via informal collaboration with the University of Alaska-Fairbanks.

Note Added in Press

This report was compiled during 1991-2, and originally prepared in January of 1992. Prior to 1991, only two ice cores had been drilled through to the underlying bedrock, at the Camp Century and Dye 3 sites (Langway and Oeschger, 1989). There is an ongoing effort in Greenland, under the NSF-sponsored GISP2 project, to obtain samples of continuous ice cores down to the bedrock. As part of this project, in July, 1993, drilling through a record thickness of 3054 meters of ice was accomplished near the Summit site in central Greenland. Additionally, a 1.5-meter-long core sample of the subjacent bedrock was retrieved—a most significant technological achievement, as well as one of great scientific import. Analysis and characterization of these materials should aford information of uncommonly great value to geological science.

Preliminary examination of this core sample indicates that it consists of rocks of leucocratic granitoid gneissic character, with readily discernible variations in color, composition and structure throughout the length of the core. There also appear to be manifestations of weathering exhibited over some 40 centimeters downward from the top of the core. Thus our predictions, as developed in the present report, as to the nature of bedrock most likely to be encountered below the Inland Ice in the study area in central Greenland appear to have been borne out.

Summary Review of the Geology of Greenland as Related to Geologic and Engineering Aspects of Sampling Beneath the Inland Ice

Abstract

One hundred forty-one papers, representing a selected portion of the enormous extant technical literature dealing with various aspects of the geology of Greenland were reviewed to provide background information for speculating on the character of geological materials beneath the Inland Ice in central interior Greenland.

An attempt was made to evaluate "likelihoods" of the potential sub-ice materials within the general environs including a defined study area. In terms of decreasing likelihood, a "hierarchy" is suggested—with appreciable reservations. Estimated as most likely are "crystalline" metamorphic, and/or igneous, rocks—essentially the gamut of Archaean and younger such terranes as have been recognized in exposures elsewhere in Greenland. Principal lithologies include quartzo-feldspathic gneisses, with subordinate granitoids, amphibolites, mafic-ultramafic rocks, meta-volcanic/meta-sedimentary "supracrustals" and metamorphosed doleritic (or variants) dikes/sills. Metamorphic grades range from granulite—greenschist facies, with amphibolite facies being most common, in the known terranes.

Five other groupings are presented and considered, similarly, in the text of the report, in terms of likelihood of occurrence.

A brief summary is presented, including discussion of physical characteristics of rocks and minerals, with particular regard to engineering properties and concerns.

1. Introduction

General Comments

A formidably large body of international technical literature has been developed dealing with various aspects of the geology of Greenland. Much of this represents work carried out by, or under the aegis of, the Geological Survey of Greenland (Gronlands Geologiske Undersogelse—"GGU"). We have followed this development for many years, during the course of other work. Our recent computer-assisted search of this literature resulted in a listing of 9,380 references dealing with the geology-geomorphology-glaciology of Greenland. Three thousand seven hundred and fourteen of these were dated 1980 or more recently; 91 between 1990 and 1992 alone. It is somewhat daunting to consider attempting any sort of meaningful summarization of this vast amount of accrued knowledge. We make no claims as to the completeness of our review. Our intent was to glean information relevant to the project at hand, availing ourselves of the reasonably readily available materials. We have read 141 selected papers for the purposes of the present report.

A concise contemporary summary of Greenland's general geological setting and character is provided by Funder (1989). In order to provide a background framework of reference for more detailed considerations, the following material from Funder (pages 744-746) is presented below:

"The largest part of the country, probably including areas under the Inland Ice, is made up of Precambrian crystalline rocks-gneisses and migmatites with interbedded supracrustal and various plutonic rock types

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(e.g., Kalsbeek, 1982). Several mobile belts are recognized in this Precambrian Shield which was established as a craton by middle Proterozoic time...

Along the northern and eastern margins of this stable block, sedimentary basins began to develop in mid-late Proterozoic time, and thick piles of sediment accumulated on the subsiding continental crust. In East Greenland, sandstone, pelites, and carbonates accumulated in the basin in Late Proterozoic and Early Paleozoic times and during the Caledonian Orogeny (Early Silurian); these sediments were folded, thrusted, metamorphosed, migmatized, and locally intruded by granite (Henriksen, 1985; Hurst et al., 1985). In North Greenland the sedimentary basin was occupied by a shallow shelf sea to the south, with mainly carbonate sedimentation (Peel, 1985), and a deep water trough to the north, with a sequence of mainly turbiditic sandstone and shale (e. g., Dawes and Peel, 1981; Surlyk and Hurst, 1984; Higgins et al., 1985). During the Innuitian Orogeny (Late Paleozoic) the deep water basin was deformed and the sediments folded and progressively metamorphosed up to amphibolite facies in the north, while the carbonate platform to the south escaped major deformation and metamorphism.

Following the Caledonian Orogeny, Greenland was part of a single North Atlantic landmass, comprising the North American and North Eurasian plates. In East Greenland thick deposits of Devonian and Carboniferous terrestrial sandstones were deposited in intramontane basins and testify to crustal instability and rapid downwasting of the newly formed mountain range (e. g., Birkelund and Perch-Nielsen, 1976). Later, especially in Mesozoic time, a new complex sedimentary basin arose by block faulting along lines parallel to the present coast (Surlyk et al., 1981). This basin was filled with continental and marine-epicontinental sandstone and shale. At right angles to the main direction of faulting, crossfaults with a northwest-southeast strike formed. Much later these determined the location of the spectacular fjords of East Greenland.

The Precambrian Shield in West Greenland also began to fragment in Mesozoic time, and a new sedimentary basin- the West Greenland Basin- was formed in the Late Cretaceous by rifting and faulting parallel to the present coastline. The sediments are exposed on land in the Nugssuaq Embayment as a thick pile of clastic marine and fluvial sandstone and shale but are mainly confined to the shelf (Henderson et al., 1981).

Thus, by Late Mesozoic time the stage was set for a decisive chapter in the history of Greenland- the history of how the country attained its present shape and physiography. This process was closely related to the formation, by active ocean floor spreading, of the Baffin Bay-Labrador Sea in the west and of the Greenland and Norwegian seas in the east. In the early Tertiary, ocean floor spreading was preceded by a period of effusive volcanism, which produced sheets of plateau basalts in the Nugssuaq Embayment of West Greenland (Clarke and Pedersen, 1976) and locally in East Greenland (Larsen, 1980; Brooks and Nielsen, 1982; Larsen and Watt, 1985).

During the ensuing period of ocean floor spreading vast amounts of terrigenous detritus were deposited in the West Greenland shelf area and in a newly formed sedimentary basin extending along the entire East Greenland coast. Seismic and aeromagnetic measurements have shown that these sediments, which were deposited mainly in the Tertiary and Quaternary, attain thicknesses of 7 km (Larsen, 1980; Henderson et al., 1981), and the record preserved in them provides an indirect record of the development of the physiography of the adjacent land."

At a somewhat more detailed level, our literature survey confirms that the volume "Geology of Greenland", edited by A. Escher and W. S. Watt, and published by the Geological Survey of Greenland in 1976, remains in a class by itself as a source of information, particularly in the context of the present summary here. This admirable volume presents a series of twenty-one succinct, cogent discussions, at technical levels quite commensurate with a work of its kind. It would indeed be presumptuous here to endeavor to do more than, capture the essence of this exemplary volume. Intended principally as a synoptic overview, in fact it does much more. It is a well-conceived and executed effort, in the classical tradition; well-written, informative, copiously illustrated. It presents a thorough, sys-

tematic, and integrated survey- insofar as this is feasible, given the incomplete state of geological knowledge of this enormous area. Overall, it achieves an excellent balance between generality and detail, quite commensurate with the principal intent of the work. Though now somewhat out-of-date in certain particulars, it nonetheless remains the fundamental keystone in the technical literature on the geology of Greenland. We have found it an excellent and informative source on previous occasions, hence resort to it once again here.

In particular, the chapter "Summary of the geology of Greenland," written by A. Escher and W. S. Watt (p. 10-16) is noteworthy for our present purpose. Providing, as it does, an effective synopsis, it seems appropriate to serve as a basis for the present project. Thus, their (p. 11) introduction is quoted here as follows:

Greenland is the largest island in the world with a surface area of 2 186 000 km(sq) about 80 per cent of which is covered by the Inland Ice. The ice-free margin is up to 250 km broad and the highest peak is 3733 m. The major units of the geological column in Greenland can be matched with rocks of similar age and lithology in North America and northern Europe, and their character and distribution are consistent with the idea that Greenland represents a fragment of a single North Atlantic land mass.

The largest part of the ice-free area is made up of crystalline rocks of the Precambrian shield. Rocks from part of the shield in the Isua region have given the oldest relaible isotopic ages of any terrestrial rocks. The shield acted as a stable block on which sediments accumulated at various times throughout the Precambrian and were deformed and metamorphosed.

In North and East Greenland sedimentation continued into the Palaeozoic and some of the deposits were involved, together with the underlying basement, in tectonic and metamorphic events in mid-Paleozoic time. Folded Palaeozoic rocks are overlain by Upper Paleozoic and younger platform sediments in North Greenland; in East Greenland Upper Palaeozoic continental and marine deposits followed by thick successions of mainly marine Mesozoic sediments lie on the folded Palaeozoic and Precambrian rocks.

Along the west coast of Greenland a sedimentary basin developed during the Mesozoic and is represented onshore by Cretaceous and Tertiary sediments. In both West and East Greenland there was considerable volcanic activity in the early Tertiary.

By way of additional introduction, we limit ourselves here to quoting the following remarks of K. Ellitsgaard-Rasmussen, then Director of the Geological Survey of Greenland, in the preface to Geology of Greenland:

Geology of Greenland aims to provide a concise modern account of nearly all aspects of Greenland's geology.

A large part of the exposed bedrock in Greenland is formed of Precambrian crystalline rocks with great similarities to the Canadian and northern European shields; Phanerozoic rocks are widely represented in North and East Greenland. The excellent exposures in the marginal, mountainous strip, up to 250 km wide and 3000 m high surrounding the Inland Ice, have permitted the unravelling of a complex sequence of Precambrian events stretching back in time for nearly 4000 m. y., including the oldest dated rocks in the world.

Subsequent to these remarks, rocks likely to be even older have been recognized elsewhere in the world. Those from Greenland remain, however, among the oldest known at present. Actually, they remain the oldest rock associations of any appreciable known geologic extent recognized anywhere on earth to date. Thus, significant knowledge of the earth's early history awaits elucidation from studies of Greenland geology (cf. a number of the papers in our listed "selected references").

In addition to featuring some of the oldest rocks, there are other compelling reasons for the widespread, intensive, and continuing interest in Greenland geology. The geology of Greenland represents a fundamental key to the understanding of regional circum-Arctic and North Atlantic geological relationships, physical as well as temporal. One area of particular interest concerns plate tectonics, and paleogeography, in the context of Greenland, from earliest Precambrian time. There is a host of papers on this theme in

the technical literature. Those listed in the references to this report from the volume "Geology of the North Atlantic Borderlands", edited by Kerr, Fergusson and Machan, are particularly relevant, as is the volume edited by Trettin, "Geology of Canada- No.3". There are many others. A number of other papers listed in our references here also deal with this topic, at least in part. To elaborate further in the text of the present report would be to stray from the principal focus of this project. Suffice to say that Greenland merits and continues to receive appreciable attention in the context of global plate tectonics, from a variety of perspectives. It is a key area to this aspect of geological science.

A further combination of circumstances is somewhat unique to Greenland, in terms of geologic research. Appreciable portions of the coastal areas afford excellent exposures - often both laterally as well as vertically- of bedrock, providing unusually good opportunities for geologic field work, facilitating the deciphering of the often-complex spatial and temporal relationships now represented by the rock associations and structural features. In particular, studies of petrologic processes are potentially very rewarding here, and a number of fundamentally significant contributions along these lines have been made to date, as attested by the extant literature. As particularly germane, some of this work is referred to elsewhere in the present report.

Thus, an uncommonly attractive natural laboratory is available in many areas of Greenland for various types of geologic studies. Given these considerations, the great interest in Greenland geology is most understandable.

However, as if to counterbalance matters somewhat, nature elsewhere has masked much of the Greenland geology from our direct view, under the cover of the thick and extensive Inland Ice. The principal focus of the present project is intended to expand the level of geologic knowledge into presently unknown regions beneath the Inland Ice—indeed an exciting concept of potentially appreciable significance.

Specific Considerations

The principal concern of the present project is with regard to the nature/character of the geological materials likely to be encountered by the drill below the Inland Ice. Emphasis is focussed on a study area termed the "radar grid" by Hodge, et al, 1990. This area consists of "...a 180 km by 180 km grid centered on the 1974 `Summit' site (lat.72 18' N., long. 37 55' W.)..." The cited reference gives further particulars. Our *figure 1* (taken from Hodge, et al, 1990, Figure 1) depicts the location. Comparison with our *figures 2 and 3* (taken from "Geology of Greenland", Figures 1 and 378) places this grid wholly within a portion of Greenland for which the sub-ice geology is presently unknown. Hence, of course, one of the paramount reasons for the intense interest in this aspect of the present project. At the same time, however, this lack of knowledge places serious constraints on rational predictions as to the nature and physical properties of the sub-ice materials likely to be encountered by the drill. This, in turn, results in decided ambiguities regarding drilling technology, in particular as to sampling and sample recovery. Thus, to the extent feasible, it is most desirable to endeavor to at least derive, via geologic inference, and extrapolation from areas of known geology, some sort of generalized conceptualization, no matter how vague, in terms of reasonable geological possibilities. This seems, at best, to devolve to an assessment of possibilities and their ranking in terms of likelihoods; use of the word "probabilities" in this context seems not quite accurate. This can hardly be essayed on more than a qualitative basis, of course, given the severely limited relevant extant knowledge.

As shown by our figures 1, 2, and 3, the "radar grid" area lies geographically nearest to the Caledonian Fold Belt of East Greenland, in terms of known geology exposed elsewhere beyond the margins of the Inland Ice. Somewhat farther away, to the southeast, is the East Greenland Tertiary Province, while to the south is the somewhat ill-defined Nagssugtoqidian Mobile Belt. To the west of the radar grid area is the similarly vaguely-defined Rinkian Mobile Belt. Thus, extrapolation is bound to be uncertain at best.
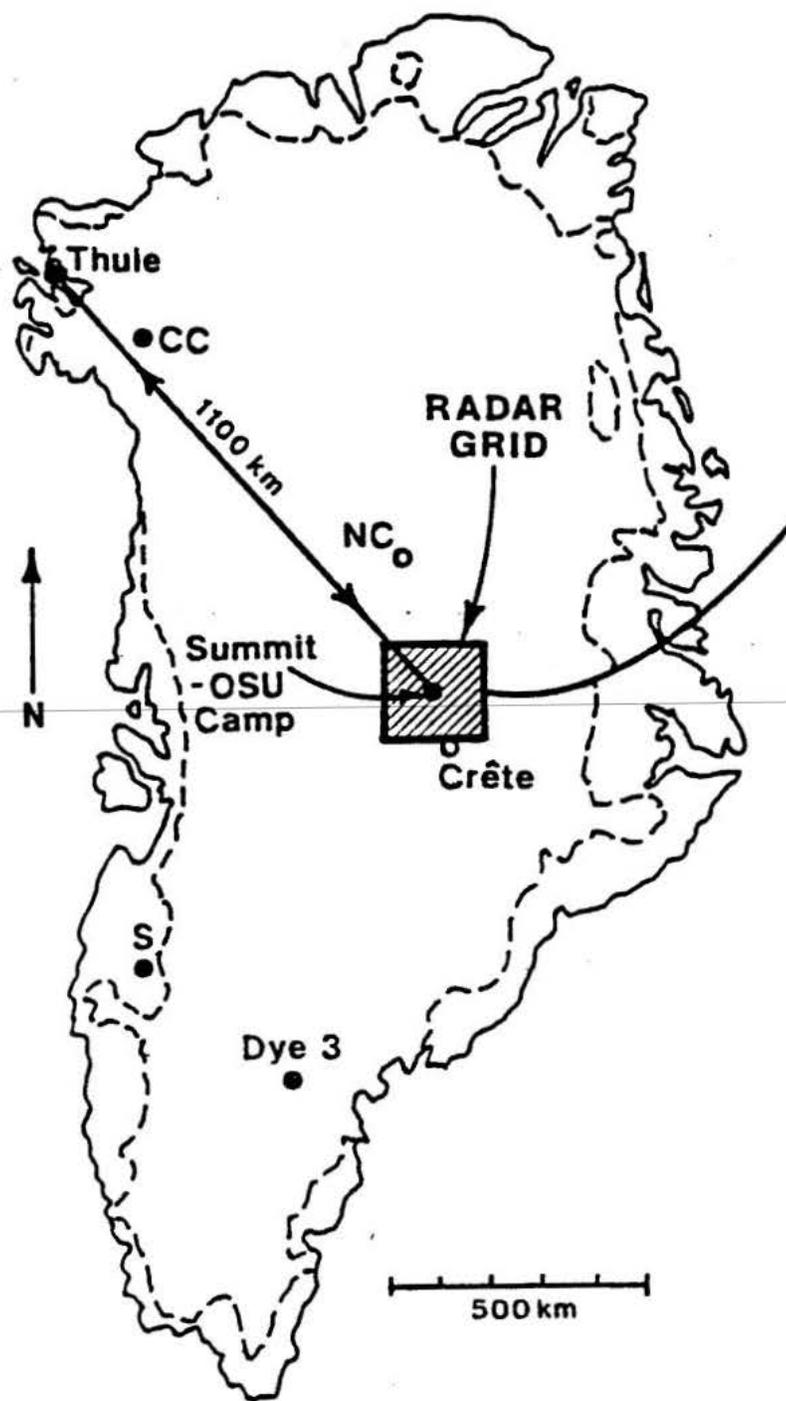
Figure 1. The location of the "radar grid" area in central Greenland (from Hodge, et al, 1990).
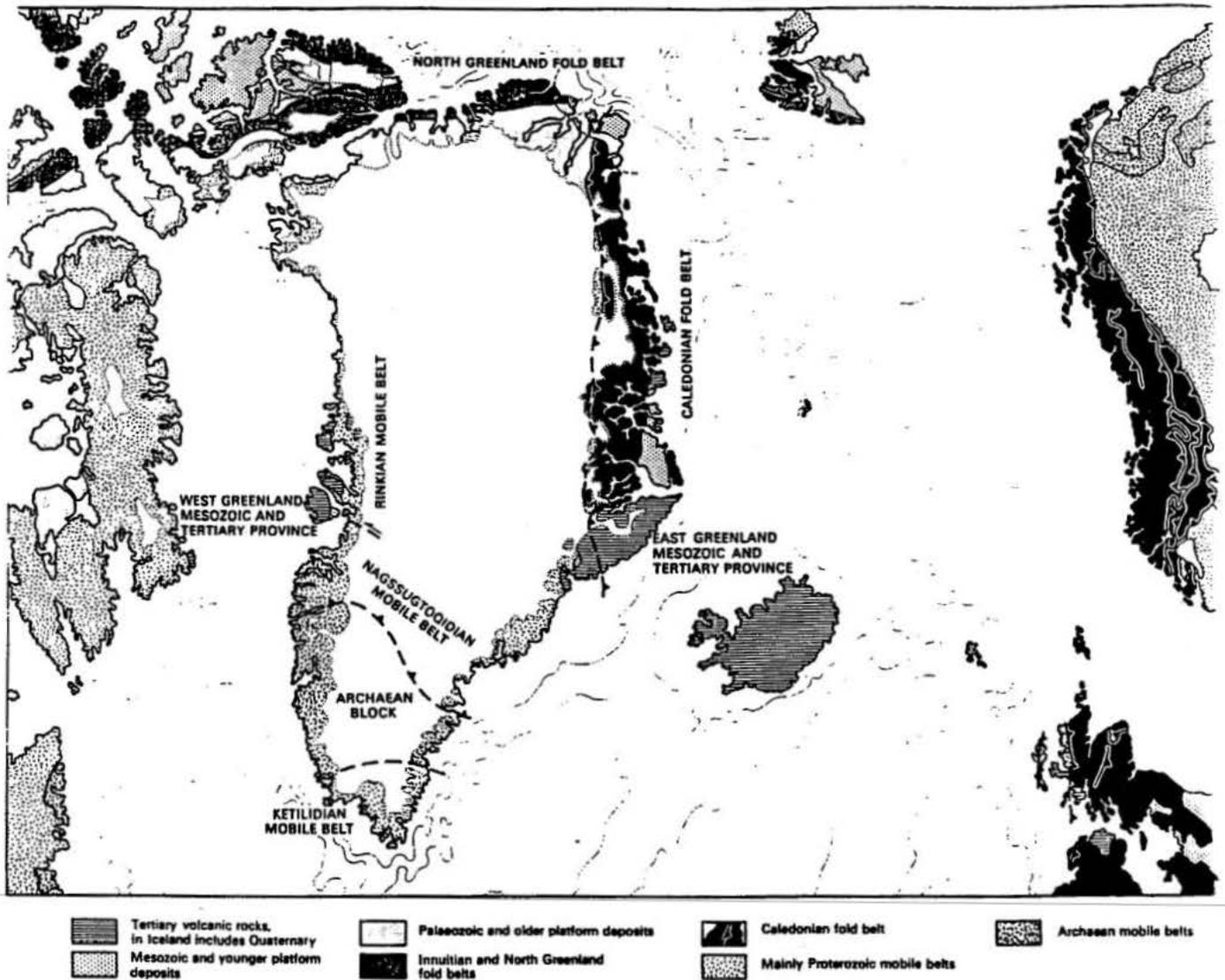
Figure 2. The structural divisions of Greenland in relation to the neighbouring land areas (from "Geology of Greenland", 1976, Figure 1).
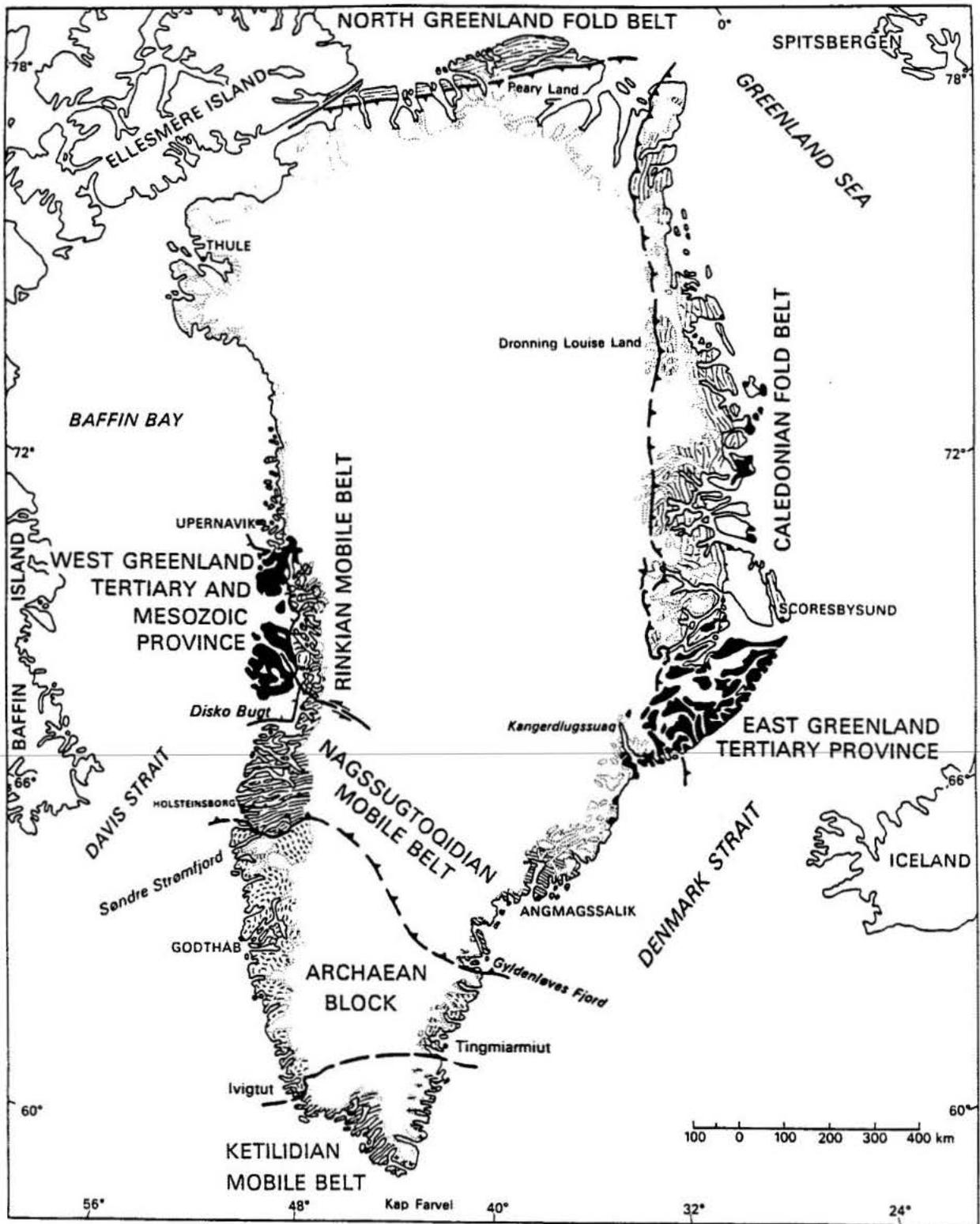
Fig. 378. The main geological divisions in Greenland.

Figure 3. The main geological divisions in Greenland
(from "Geology of Greenland", 1976, Figure 378).

An additional complication has to do with the tectonic-geomorphologic history of Greenland—in particular this central portion attendant to the development of the Inland Ice mass (es). Two scenarios seem worthy of comment here, viewing rather simplistically what undoubtedly is an appreciably more complicated actual course of geologic events. Each of these hypothetical scenarios, as well as others, will represent rather specific present sub-ice geologic situations and must be factored into any attempt at developing a hierarchy of likelihoods as to present sub-ice lithologies. The present report makes no pretense as to exploring these ramifications to any great extent. But if it is assumed that the present sub-ice rock surface elevations are due essentially to simple isostatic compensation, then extrapolation from areas of known geology peripheral to the Inland Ice would seem to be at least reasonably straightforward.

In the context of the present project, this scenario seems to represent the most reasonable one to attempt to work with, at least initially. Any complications to this somewhat simplistic scheme would appear to merely add further to an already most uncertain exercise in prognostication. While this may well be generally true, in fact there is at least one such complication which might well contribute to enhanced prediction of sub-ice lithologies. Should it in fact be the case that appreciable, and widespread, physical erosion of sub-ice materials has occurred, then the likelihood of sub-ice exposures of older materials is increased. Hence it could be anticipated that drilling would be more likely to encounter such materials beneath the ice. Such abrasion is not unlikely, thus this factor would need to be taken into account. However, the general case of the simple subsidence model seems to be the most realistic one (cf. Hodge, et al, 1990) to use here, as an initial point of departure. Reeh (1989), in discussing the "Dynamic and climatic history of the Greenland ice sheet", offers a valuable and informative summary of relevant concerns as well; pages 795-799 are particularly pertinent.

2. Geological Regions, Provinces/Terranes

Consideration of the various areas of known geology peripheral to the radar grid study area suggests a number of salient points. These are summarized next. Reference also should be made to the summaries of Escher and Watt (p. 10-16) in each instance.

Caledonian Fold Belt

This region lies geographically closest to the study area. It is treated in some detail in the chapter by N. Henriksen and A. K. Higgins (p. 182-247) in "Geology of Greenland". In summary, these authors comment (p. 183):

> The East Greenland fold belt is part of a major Caledonian structure which occurs on both sides of the North Atlantic Ocean (fig. 172). It extends from latitudes 70 to 82 N in East Greenland (fig. 173), occupying most of the wide strip of land between the coast and the Inland Ice.
>
> Metamorphic crystalline complexes dominate the fold belt throughout most of its length; these comprise gneisses, migmatites, granites and high grade supracrustal rocks, of a variety of ages. In central East Greenland the metamorphic complexes are bordered to the east and west, and partially overlain, by low grade or non-metamorphic late Precambrian and Lower Paleozoic sediments of considerable thickness. Caledonian orogenic activity can be traced throughout the region.
>
> Continental clastic deposits of Devonian and Carboniferous to Lower Permian age were laid down in central East Greenland on Caledonian folded units, locally in great thicknesses. They are succeeded by Upper Permian and Mesozoic mainly marine sediments exposed only in the outer fjord zone and coastal region (Birkelund and Perch-Nielsen, this volume). Tertiary basalts bury and hide the southern continuation of the fold belt at 70 N, and occur locally as a partial cover to the Mesozoic sediments between latitude 73 to 76 Nsediments between latitude 73 to 76 N. Peel (1982) presents additional relevant information in his paper on "The Lower Paleozoic of Greenland." Peel points out (p. 326-327):

Cambrian and Ordovician platform sediments form a number of small outcrops within the Caledonian fold belt of East Greenland (Figures 2, 14), but Silurian strata are not preserved. The sequence is best known through the work of Cowie and Adams (1957), summarised by Haller (1971) and Henriksen and Higgins (1976), with recent developments recorded by Frykman (1979), Peel and Cowie (1979) and Peel (in press. Swett and Smit (1972a, b) and Swett (1981) have described the close relationship between Cambrian and Ordovician sections in East Greenland, northwest Scotland, Spitsbergen and Newfoundland.

The Cambrian in East Greenland begins with sandstones and siltstones of the Kloftelv and Bastion formations (ca. 210 m) which are overlain by carbonates of the Ella Island (= Ella O) and Hyolithus Creek formations (ca. 300 m) of late Early Cambrian age. The carbonates and the upper part of the underlying clastic sequence are equivalent to parts of the Buen Formation and lower Bronlund Fjord Group of Peary Land, northern Greenland, but the lower clastics are of older Cambrian age (V. Poulsen, 1978; Vidal, 1979). Carbonates equivalent to the Portfjeld Formation of Peary Land are absent.

The Dolomite Point Formation (ca. 400 m) is not readily correlated with sequences in northern Greenland. A Middle Cambrian age has previously been assumed (Cowie, 1971), requiring a major uncomformity below the Early Ordovician Antiklinalbugt Formation. However, conodonts of Early Ordovician age occur in the uppermost beds of the formation (Frykman, 1979; Miller and Kurtz, 1979; Kurtz and Miller, 1981), although faunas of Middle and Late Cambrian age are still unknown. Swett (1981) suggested that the absence of fossils of this age probably reflected slow sedimentation under schizohaline conditions. The Dolomite Point Formation is loosely correlated with the Kastrup Elv, Telt Bugt and Cass Fjord formations of Washington Land, and the Bronlund Fjord and Tavsens Iskappe Groups of Peary Land (Figure 2).

Ordovician strata in East Greenland attain a thickness in excess of 3 km, three times greater than that known in northern Greenland. The former Cass Fjord Formation of East Greenland was recently renamed the Antiklinalbugt Formation by Peel and Cowie (1979), who restricted the former

name to outcrops adjacent to the type area in Washington Land, northern Greenland. Cowie and Adams (1957) noted a thickness of 212 m - 270 m and suggested an early Early Ordovician age. Strata of this age are present in the Washington Land area of northern Greenland but are not preserved beneath the sub-Wandel Valley unconformity in Peary Land and Kronprins Christian Land.

Cowie and Adams (1957) suggested a middle Early Ordovician to early Middle Ordovician age for the Cape Weber (=Kap Weber) Formation (1040 m- 1165m) of East Greenland. The formation is lithologically reminiscent of the Amdrup Member of the Wandel Valley Formation in Kronprins Christian Land, but the latter has yielded 'Ceratopea billingsi' of late Early Ordovician age which occurs in the Narwhale Sound (=Narhval Sund) Formation of East Greenland (Yochelson, 1964; Peel, 1980d). The Cape Weber Formation probably extends up into the latest Early Ordovician, where it may be equivalent to the lowest beds of the Wandel Valley Formation (Figure 2), but it is likely that most of the formation has no equivalent in the platform sequence of Peary Land- Kronprins Christian Land. There is no obvious similarity between the Cape Weber Formation and the section in Washington Land, but a general correlation with the Poulsen Cliff, Nygaard Bay and Canyon Elv Formations is expected.

The Narwhale Sound Formation (ca. 460 m) is apparently equivalent to much of the lithologically similar Wandel Valley Formation, and a late Early Ordovician to early Middle Ordovician age is suggested. Thickbedded limestones of the Heim Bjerge Formation are considered equivalent to the Borglum River Formation of Peary Land and the Gonioceras Bay, Troedsson Cliff and Cape Calhoun formations of the Morris Bugt Group of Washington Land (Figure 2). Cowie and Adams (1957) reported a minimum thickness of 320 m, but Frykman (1979) increased this to at least 1200 m. A Middle Ordovician to Late Ordovician age is postulated, but Ashgill and younger strata are apparently not present.

Blocks of various types of carbonates occur within a breccia, developed along a fault zone in Precambrian crystalline shield at 'Fossilik' in southern West Greenland (Figure 1). V. Poulsen (1966, 1967) noted the presence of poorly-preserved fossils (bryo-

zoans, brachiopods, graptolites, a trilobite, conodonts) and suggested a Middle Ordovician to Early Silurian age. Stouge and Peel (1979) described a small conodont fauna of Middle-Late Ordovician age. The conodonts are thermally unaltered and occur in limestones which are lithologically indistinguishable from equivalent strata in northern Greenland.

The locality is of considerable interest in assessing the former distribution of Ordovician strata in Greenland and the adjacent Canadian Arctic.'Fossilik' lies 1000 km east of land exposures of Ordovician around Foxe Basin on Baffin Island, although McLean et al (1977) documented subsurface Ordovician in offshore boreholes southeast of Baffin Island. Still greater distances separate the West Greenland occurrence from Ordovician outcrops elsewhere in Greenland (Figure 1).

Peel and Secher (1979) described fossiliferous blocks associated with a carbonatite complex some 130 km north of 'Fossilik', but the age of these is uncertain.

This is obviously an area of diverse and complex geology- in terms of lithologies, structural relationships, geologic history- as yet rather incompletely known. One salient point in the present context is the dominantly north-south aspect of the regional geological trends (cf. Figures 1, 172, 173, 193, 198, 199, 378, in particular, in the *Geology of Greenland* reference).

This characteristic "grain" suggests that it is rather unlikely that the terranes comprising the known lithologies of the East Greenland Caledonian fold belt would be anticipated to be present beneath the ice within the "radar grid" area to the west.

Rinkian Mobile Belt

In a manner somewhat reminiscent of the East Greenland fold belt, the Rinkian mobile belt occurs to the west of the "radar grid" area, but with regional geologic trends oriented more or less north-south, in general. Hence, similarly it seems somewhat unlikely to anticipate lithologies characteristic of the known portions of the Rinkian belt to be present beneath the Inland

Ice within the study area to the east. Though this seems reasonable, based on the overall regional geologic "grain", it should be emphasized that the Rinkian belt is by no means all that clearly-defined, as to extent or attitudes and persistence of geologic trends.

"The Rinkian mobile belt of West Greenland" is the title of the chapter in *Geology of Greenland* (p. 104-119) prepared by A. Escher and T. C. R. Pulvertaft. Their summary comments (p. 105-106) are as follows:

> In previous reviews of the Precambrian of Greenland the whole of the Precambrian of West Greenland north of the Archaean block was said to belong to a single Lower Proterozoic complex- the Nagssugtoqidian complex. However, during recent compilation of 1:500 000 maps it became clear that there is a marked difference in structural style between the Nagssugtoqidian south of Jakobshavn and the Precambrian terrain to the north. The southern region is characterised over wide areas by a fairly regular ENE trend and steep dips, while north of Jakobshavn, at least as far as Melville Bugt, there is no obvious regional strike, dips are generally low, and the most obvious structures are large domes. On account of this structural contrast the Precambrian north of Jakobshavn is no longer included in the Nagssugtoqidian, but is referred to as the Rinkian mobile belt. The boundary between the Nagssugtoqidian and the Rinkian mobile belts coincides with an important sinistral transcurrent fault zone at Pakitsoq, directly north of Jakobshavn (fig. 101).
>
> The Rinkian mobile belt can be conveniently divided into the following three areas:
>
> (1) The Ata Sund area in the south, dominated by a very large gneiss dome surrounded by a rim syncline of meta-sedimentary and metavolcanic rocks.
> (2) The central Umanak- Rinks Isbrae area, characterised structurally by gneiss domes and recumbent folds, and notable for the most extensive outcrops of metasediments in the Precambrian of West Greenland.
> (3) The Upernavik- Kraulshavn area in the north, characterised by granulite facies rocks and the occurrence of a large intrusive granite- charnockite body.

Throughout the three areas the planar structures show relatively low dips, and the plunge of fold axes and linear structures is likewise low.

Seven K-Ar age determinations have been carried out on biotites from gneisses and metasediments in the Rinkian mobile belt; these all gave ages in the range 1870-1680 m.y. (Larsen and Moller, 1968; Bridgwater, 1971)(fig. 101).

A paper by Taylor and Kalsbeek (1990) is relevant here as well. It includes radiometric age determinations of marbles of the Marmorilik Formation, placing useful constraints on the geological history of these rocks. These authors also summarize concisely other aspects of the Rinkian geological relationships.

The regional geologic trends are rather less well-defined in this belt, as compared to those of the East Greenland fold belt. Thus, there is insufficient substantive evidence to either support or weigh against meaningful extrapolation eastward into the "radar grid" area. Due to this very uncertainty, it may be suggested that this belt may extend far to the east of its presently known localities and might be present beneath the ice in the study area

Nagssugtoqidian Mobile Belt

As presently known, this region lies to the south of the study area, comprising significant areas of exposed bedrock on both the west and east margins of Greenland. Reasonable inference and geologic extrapolation indicate it continues between these two regions beneath the Inland Ice. However, the extent of this belt in a northerly direction toward the "radar grid" area is much less amenable to similar extrapolation from existing knowledge. Thus there remains the distinct possibility of its persistence into the study area, though a regional geologic "grain" oriented generally east-west tends to argue against this. Separate chapters in "Geology of Greenland" deal with a general summary (Escher and Watt, p. 12), the western (A. Escher, K. Sorensen, and H. P. Zeck; p. 76-95) and the eastern (D. Bridgwater; p. 96-103) segments of this belt.

Escher and Watt (p.12) comment:

The Nagssugtoqidian mobile belt consists mainly of Archaean gneisses which were reworked in a major tectonic zone about 300 km wide in both East and West Greenland. This zone is characterised by a pronounced regional planar fabric parallel to the boundary with the Archaean block, the so-called linear belts alternating with areas of less deformed rock.

Isotopic dates suggest that the main phase of Nagssugtoqidian deformation and metamorphism took place about 2700 m. y. ago although the belt was active until about 1700 m. y. ago.

Supracrustal rocks form thin layers interlayered and deformed together with the Archaean gneisses. The gneisses are mostly in amphibolite facies though granulite facies gneisses occur in the central part of the mobile belt. The strong deformation of Nagssugtoqidian rocks is probably partly due to horizontal shear movements associated with overthrusting of the Nagssugtoqidian block onto the Archaean block to the south. Deformation is not equally developed throughout the belt; islands of Archaean rocks occur which are almost unaffected by Nagssugtoqidian movements and show a complex pattern of dome and basin structures.

The western segment is summarized by Escher, Sorensen and Zeck (p. 77-78) as follows:

The rocks forming the northern part of the Archaean block in West Greenland are cut by dense swarms of dolerite dykes. Towards the north the dykes, together with their country rocks, are progressively deformed and metamorphosed resulting in a reorientation and parallelisation of dykes and country rock structures. These changes were the basis on which Ramberg (1949) distinguished a Nagssugtoqidian complex fron a pre-Nagssugtoqidian (Archaean) complex in West Greenland. Similar observations by Bridgwater & Gormsen (1968) in South-East Greenland made it possible to correlate the Nagssugtoqidian mobile belt from West to East Greenland. It forms a ca. 300 km wide belt characterised by a pronounced regional fabric oriented parallel to the boundary with the Archaean block (fig. 70). In West Greenland this regional fabric is cut to the

north by the wrench fault zone which separates the Nagssugtoqidian from the Rinkian mobile belt. Although K-Ar dating of Nagssugtoqidian rocks gives ages within the range 1740-1650 m. y. (Larsen & Moller, 1968), U-Pb dating of zircons (Chessex et al., 1973) suggests that the main phase of Nagssugtoqidian deformation and metamorphism is much older and probably took place at the beginning of the Proterozoic or at the end of the Archaean (fig. 71).

The eastern segment, similarly, is summarized (p. 97-98) by Bridgwater:

The Nagssugtoqidian mobile belt in East Greenland outcrops from Gyldenloves Fjord northwards to the Angmagssalik region (fig. 93) and possibly further north towards Kangerdlugssuaq (fig. 70). Compared to the Nagssugtoqidian mobile belt of the west coast little work has been done in this region. Wager (1934) gives a brief description of the gneiss complex from Angmagssalik to Kangerdlugssuaq where the Precambrian rocks are overlain by Tertiary basalts. Bridgwater & Gormsen (1968, 1969), Andrews et al. (1973) and Bridgwater et al. (1973b,c) give the main features of the rocks exposed between the southern border and Angmagssalik. A more detailed description of the area surrounding Angmagssalik is given by Wright et al (1973)(fig. 94).

Isotopic age determinations are limited to K-Ar and Rb-Sr mineral determinations (Wager & Hamilton, 1964; Turner, 1970), and a single U-Pb zircon concordia determination on zircons from an anorthosite inclusion in the gneisses west of Angmagssalik (Nunes et al., 1974). These determinations show that the area was affected by a thermal event at about 2000-1600 m. y. ago which overprinted a major event about 2800-2700 m. y. ago. The effect of the 2000-1600 m. y. event appears to have varied from place to place within the Nagssugtoqidian mobile belt. In the north there is a marked discrepancy between Rb-Sr mineral ages at 1800-1600 m. y. and K-Ar mineral ages at 2800-2700 m. y. suggesting that this part of the mobile belt was remarkably little affected by Proterozoic metamorphism.

The Nagssugtoqidian mobile belt in East Greenland consists largely of Archaean rocks comparable to those of the gneiss complex to the south (see Bridgwater et al.,

this volume). They have been partially reworked by belts of intense deformation during the early Proterozoic. Before and during this deformation the rocks were intruded by major swarms of basic dykes. A variety of syn-tectonic to post-tectonic igneous bodies are found ranging from the leuconorite-charnockite complex of Angmagssalik O to a variety of calc-alkaline diorites, granodiorites and adamellites. Subsequently this Precambrian complex was intruded by basic dyke swarms which have yielded K-Ar ages of about 1300 m. y. and by the southern continuation of the coast parallel Tertiary dyke swarm (Wager, 1934).

Taylor and Kalsbeek (1990) recently presented summary observations on the geology of the Nagssugtoqidian mobile belt. The focus of their reported work is on radiometric age determinations of marbles which occur as boudinaged layers in deformed supracrustal rocks.

West Greenland Mesozoic and Tertiary Province

The sedimentary rocks are discussed by G. Henriksen, A. Rosenkrantz, and E. J. Schiener in *Geology of Greenland* (p. 341- 362). Selected portions of their introductory remarks are as follow:

Sedimentary rocks of Cretaceous to Lower Tertiary age are present on land in an area extending from the inner part of the Ingnerit peninsula in the north to the Gronne Ejland group of islands in the south (fig. 301). This area constitutes only part of a much more extensive sedimentary basin- the West Greenland basin- that is known to extend along the entire western margin of Greenland, most of the deposits being concealed beneath the waters of Baffin Bay, Davis Strait and the Labrador Sea.

The deposits on land are present in an embayment for which the name Nugssuaq embayment is proposed, after the Nugssuaq peninsula in the central part of the onshore area. This account deals entirely with the rocks exposed on the various islands and peninsulas in this embayment.

The rocks exposed range in age from Lower Cretaceous (Barremian) to Lower

Tertiary (mainly Danian). They comprise a sequence of predominantly clastic marine and non-marine sediments deposited in an environment transitional from fluviatile to deltaic. Apart from minor oscillations the relative positions of the subenvironments did not change significantly. The transport of material was mainly from the south, resulting in a northwards change from a deltaic-fluviatile to a prodelta marine environment. Various facets of this changing environment have been studied on the Nugssuaq peninsula, where the exposures are reasonably good.

The surface on which these beds were deposited had considerable relief. For example, south-west of Kuk the pre-Cretaceous surface rises from sea level to 1800 m in the inner part of Nugssuaq. This surface was deeply weathered, in places along the north coast to a depth of 35 m (Rosenkrantz & Pulvertaft, 1969).

Seismic surveys (Sharma, 1973; Elder, 1975) considered in conjunction with the known outcrop geology have shown that the thickest sequence of sediments is in the central part of the north coast of Nugssuaq, where it amounts to about 4 km, of which 3 km of sediments are below sea level. In the central part of the Vaigat the total thickness of sediments is about 3 km of which 2 km are below sea level. Elsewhere in the embayment thicknesses of 1 km or more have been determined.

Composite sections determined by adding up thicknesses of known sections above sea level produce a maximum thickness of about 2 to 2.5 km. It thus seems very likely that the deepest sections below the Nugssuaq peninsula consist of beds older than any exposed at the surface.

The sediments are overlain by a thick sequence of Tertiary basalts, which belong to the Brito-Arctic volcanic province (Clarke & Pedersen, this volume). The onset of volcanic activity is shown by the presence of tuff layers in the Danian sediments of southern, central and northern Nugssuaq (Rosenkrantz, in Rosenkrantz et al. 1941; B. E. Koch. 1959; Rosenkrantz, 1970; Jurgensen & Mikkelsen, 1974). A thick sequence of subaquatic pillow breccias wedging towards the east-south-east marks the first major extrusive phase. The pillow breccias in turn are overlain by subaerial basalts, which are thought to be up to 8 km thick in the western part of the area.

A thin fossiliferous marine conglomerate and another conglomerate intercalated in the lower part of the volcanic sequence of south-western Nugssuaq have given an Upper Danian age. Interbasaltic non-marine sediments are known from several parts of the area. Plant remains from these show that the beds cannot be younger than Eocene.

The eastern limit of the pre-basaltic sediments is a system of faults with downthrow to the west. Some of the faults were active during the sedimentation but much, possibly most of the movement along the faults took place after sedimentation. The vertical displacement in some areas must have been in the range of 1500 m.

On both Nugssuaq and Svartenhuk Halvo basalts overlap the faults and rest directly on the Precambrian rocks to the east.

The western part of the onshore area consists exclusively of basalts, which here, in contrast to the basalts found capping the sediments in the central and eastern parts of the area, are tilted westwards and are extensively faulted.

Brooks (1973), in his paper "Tertiary of Greenland- a volcanic and plutonic record of continental break-up", discusses these relationships, similarly, though from a somewhat different perspective. As Brooks (p. 152-153) observes:

In contrast to the east coast, subbasaltic sedimentary rocks in West Greenland are thicker and more extensive, intrusions are much less common, and the older lavas are submarine and picritic. A map of the area is shown in Figure 2.

In the Nugssuaq and Svartenhuk Peninsulas and on Disko, sedimentary deposits lie on the deeply eroded Precambrian basement. They reach more than 1,000 m (3,300 ft) in thickness but pinch out toward the Inland Ice- as do the overlying volcanic rocks. Thus, data from both the west and east coasts support the view that the two areas are not related. The sediments are limnic in the southern part of the area, whereas marine beds are found in the more northwesterly occurrences. Both sedimentary types contain rich fossil assemblages. A detailed

review of the Cretaceous-Tertiary stratigraphy and tectonics was written by Rosenkrantz and Pulvertaft (1969), and a review of the marine deposits was published by Rosenkrantz (1970). Significant intrabasaltic sedimentary zones are also present in West Greenland.

Rosenkrantz and Pulvertaft (1969) can also be cited in this context. A particularly germane comment (p. 896) is:

Everywhere it is exposed, the eastern limit of the Cretaceous sedimentary basin is a fault. However, coarse conglomerate is found in the sedimentary strata in places along the fault, suggesting that locally, at least, steep slopes were nearby during sedimentation. At Ikorfat the first 400 m of downthrow occurred at the end of the Maestrichtian, but there the fault does not delimit the sediment area.

The faulting along the eastern boundary of the sedimentary beds most likely occurred intermittently during the Cretaceous and early Tertiary, defining the new sedimentary basin. That would explain the present faulted relations; the steep slopes that apparently were present locally along the boundary during sedimentation were probably fault scarps. Such faulting would also explain the total lack of Cretaceous sedimentary strata east of the boundary fault system. On both Nugssuaq and Svartenhuk, basalts overlap the faults and lie directly on the Precambrian rocks on the east. Thus it is almost certain that Cretaceous sediments were not deposited on the east. Only in the fault-controlled depression on the west did detritus accumulate, and sedimentation generally kept pace with fault movements.

A key point in the context of the present project is that current relevant geological-geophysical information strongly indicates that appreciable- if any- eastward extension of these sedimentary strata beyond the presently known exposures along the western margin of Greenland is highly unlikely. It appears, based on present knowledge, that neither these sediments, nor those known from East Greenland, are connected, sedimentologically, in terms of continuous depositional environments. Thus, it follows that there would be little likelihood of their being present sub-ice within the "radar grid" area.

"Tertiary volcanic province of West Greenland" is the title of the chapter in *Geology of Greenland* prepared by D. B. Clarke and A. K. Pedersen (p. 365-385). Some of their comments of particular relevance to the present work are (p. 365, 385, 383-384):

The Tertiary volcanic province of W est Greenland is geographically divisible into four main areas, namely Svartenhuk Halvo, Ubekendt Ejland, Nugssuaq and Disko. Other smaller exposures of Tertiary igneous rocks include Schades Oer, Hareoen, Gronne Ejland and probably parts of Upernivik O and Qeqertarssuaq (figs 323, 324). The areal extent of the province including recently discovered offshore extensions, is roughly 55 000 sq km and has maximum onshore dimensions of 125 km in width by 370 km in north-south length (fig. 323).

This volcanic area has already become widely known for its occurrences of native iron bearing basalts and the production of enormous volumes of picrites and olivine basalts. In addition, the volcanics are now recognized as a key factor in interpreting tectonic evolution in the Baffin Bay-Labrador Sea region.....

The principal structural elements of the province have been discussed by Rosenkrantz and Pulvertaft (1969) and Henderson (1973) and are summarised in fig. 323. A boundary fault system (dashed line) forms the eastward limit to Cretaceous-Tertiary sedimentation and the early phases of volcanic activity. Several of the minor picritic and major doleritic intrusions discussed under eruptive rocks are related to this fault system. A brief discussion of the structure of each major area follows....

Recent regional work on the offshore structures is given by Keen et al (1972) and Denham (1974)....

The West Greenland Tertiary lava province has long been recognized as a part of the Thulean Tertiary basalt province and as such it should be considered in relation to the neighbouring volcanic areas. Because of their similarity in age and field relations, the Tertiary lavas of West and East Greenland have been considered to be intimately related. Recently Brooks (1973) has compared the East Greenland tholeiitic

basalts with the feldspar-phyric basalts of West Greenland and noted their similarity. However, the two provinces which are separated by more than 700 km, display considerable differences. For instance, East Greenland has not produced the large pile of picrite basalts with the low concentrations of minor elements found in West Greenland. On the other hand West Greenland does not display the numerous syenitic and nepheline syenitic plutons nor a prominent coast parallel dyke swarm, so characteristic of the East Greenland province (Deer, this volume). This evidence suggests that the two areas belonged to spatially separate, but roughly contemporaneous, phases of volcanism.

Because of the strong similarities in field relations, petrology and chemistry between the Tertiary lavas of Baffin Island and those of the early eruptives of West Greenland as discussed by Clarke (1970), the two areas should be considered as genetically related. A model for the evolution of the two areas has been presented by Clarke & Upton (1971), who invoke continental rupture and sea-floor spreading to generate the magmas and create the present separation of the two lava provinces respectively. Recent discoveries of offshore extensions of the West Greenland basalt plateau by Park et al (1971) have tended to reinforce this suggestion that the two provinces initially evolved together and have since been separated by sea-floor spreading. The discovery by Barrett et al (1971) and Keen et al (1974) that the crust of Baffin Bay is oceanic lends further weight to this idea. Henderson (1973) has considered in some detail the structural evolution of the eastern half of this continental rupture and has concluded that the evolutionary history of the provinces, including the graben in Melville Bugt, may be much longer than present terrestrial exposures would suggest. Fahrig et al (1971) have also suggested that the development of Baffin Bay may have begun in the Hadrynian, some 600 m. y. ago. If these suggestions are correct, then an interesting picture is emerging of a very sluggish period, in excess of 500 m. y., in which Paleozoic and Mesozoic sediments accumulated in a slowly subsiding graben. The region of subsidence was then suddenly expanded in the late Cretaceous-early Tertiary, as evidenced by the exposures on both Baffin Island (Paleocene only) and West Greenland of sediments of this age, and culminated shortly thereafter in the massive outpourings of subaqueous breccia and subaerial flows. At this point sea-floor spread-

ing was initiated in which the new sea-floor remained coupled with both continental blocks and the two volcanic areas were soon separated.

It is now clear that the full history of development of the Baffin Bay rift and related volcanics awaits detailed oceanographic work in Baffin Bay and Davis Strait....

Among others, Brooks (1973), Clarke (1977), and Hall (1981) also discuss this geologic province. Clarke (p. 455), in particular, following Brooks (1973) and Henderson (1973), dismisses any likelihood of continuity of these igneous rocks with those in East Greenland:

The Brito-Arctic comagmatic volcanic province was first defined by Holmes (1918). It has grown to include all volcanics of early Tertiary age found in Western Scotland, Northern Ireland, Jan Mayen, Faeroes, Iceland, East Greenland, West Greenland and, more recently by implication, Baffin Island. However, the rather close spatial and temporal relationships shown by these fragments are not sufficient to define a comagmatic province. It must also be demonstrated geochemically that the various members are genetically related to a single magma producing event. As pointed out by Brooks (1973), there are considerable differences in the rock types and intrusive vs extrusive activity between East and West Greenland. Indeed, the volcanic rocks in both areas thin towards the inland ice, and it is not believed that there is any physical connection between the volcanics of the two areas beneath the ice (Henderson, 1973). Nor have rocks with primitive chemistry akin to those in Baffin Bay been found in East Greenland. In fact the parallels between Baffin Island and West Greenland (Clarke and Upton, 1971) are much stronger than those which can be drawn between East and West Greenland.

It is herein proposed that the Tertiary volcanic province of Baffin Bay be formally amputated from the Brito-Arctic Province and henceforth be regarded as a comagmatic province in its own right. The former is a province clearly related to the opening of Davis Strait and Baffin Bay, whereas the remainder of the Brito-Arctic Province appears to be related to a magma-producing event associated with the opening of the North Atlantic.

15

Hall (1981), while not disagreeing, leaves open the possibility of a more fundamental relationship between the Tertiary volcanics of East and West Greenland, in terms of plate-tectonics, and "hot-spots"/thermal plumes of mantle origin. This notion does, thus, leave some residue of possibility, on purely theoretical grounds, of the existence of similar rocks—now beneath the Inland Ice—between these two known provinces. No direct indication of this has been reported to date, yet another reason for the considerable importance of sub-ice sampling, in terms of substantively adding to knowledge of significant areas of concern to geologic science. Given present knowledge, the likelihood of such occurrence beneath the ice within the "radar grid" area seems rather low.

East Greenland Mesozoic and Tertiary Province

In two successive chapters of *Geology of Greenland*, A. Noe-Nygaard (p. 387-402) and W. D. Deer (p. 405-429) discuss the Tertiary igneous rocks of East Greenland.

Salient comments from Noe-Nygaard include (p. 387-388, 401-402):

Tertiary igneous rocks are known in two main regions of East Greenland. The southern region extending from Scoresby Sund (70 N) to Kap Gustav Holm (66 30 N) comprises plateau basalts and important intrusive centres and is described by Deer (this volume). The northern region, which is the subject of this account, extends from Scoresby Sund (70 N) to Shannon (75 30 N).

The Tertiary igneous rocks of the northern region are mainly found in a broad zone of the coast and outer fjord region. They include plateau basalts, found in the northern part of the region, numerous dykes and sills, and a line of alkaline plutonic centres. These rocks have been largely emplaced into or overlie Devonian, Carboniferous and Mesozoic strata (see Birkelund & Perch-Nielsen, this volume). In the inner fjord zone which is dominated by metamorphic complexes forming the East Greenland Caledonian fold belt (Henriksen & Higgins, this volume), Tertiary igneous rocks are known only as scattered

dykes and very locally a plateau basalt cover....

In a northern basalt province extending from Shannon (75 30 N) to the entrance of Kejser Franz Josephs Fjord (c. 73 N) the remnants of a dissected lava plateau are preserved (fig. 343). The lava sequence, which is thickest in the east and thins towards the mainland has an estimated outcrop area of 16 000 sq km (W enk, 1961)....

The youngest pre-basalt sediments are marine Cretaceous strata, which in many places show evidence of a period of deep erosion prior to outpouring of the lavas (cf. fig. 341). The sub-basaltic plateau areas are covered by a thin limnic or continental sandstone sequence. The earliest thin flows of subaerial lavas spread across a roughly levelled surface, first filling up the valleys and lowlands and finally flooding the whole region.

The flows are generally 10 to 30 m thick, similar to the lava plateau of the Faeroe Islands (Rasmussen & Noe-Nygaard, 1970). Single sheets often exhibit columnar structure (cf. fig. 342), though in the upper portions the columnar structure disappears and the flows become vesicular or amygadaloidal. In several places scoriaceous lavas and ropy surfaces have been recorded. Though no observations of the existence of pillow lavas are mentioned in the literature, Vischer (1943) is of the opinion that some of the earliest lavas near to the present coast were subaqueous.

The plateau basalts are tholeiites. Most are aphyric, while a few contain small plagioclase phenocrysts. Lavas rich in olivine (10-15 % modally) have been recorded locally.

Thin interbasaltic tuff-like sediments occur in several places. They generally contain a considerable proportion of rock and mineral components of non-basaltic origin, which are probably derived from 'islands' and ridges of the pre-basalt topography rising above the lava surface, as well as from adjacent continental areas to the west. The proportion of volcanic ash is generally a minor one, the clastic fragments bearing witness to disintegration and redeposition of pre-basaltic rocks and the older basalt flows.

The formation of the North Atlantic Ocean may have begun in the mid-Mesozoic with a fissuring and breaking up of a Laurasian landmass, and the Tertiary tectonic and igneous activity may be related to changes in ocean floor spreading patterns. In the early Tertiary it would appear that an ocean floor rift came into being east of the Greenland shield and basaltic lavas were poured out along the greater part of its length along the Greenland coast; on the opposite side of the newly formed North Atlantic Ocean lavas formed the plateaux of the Faeroe Islands and the Hebridian Province including the banks west of the Faeroes and Scotland. This volcanic episode seems to have lasted for some 10-15 m. y. in the lower Eocene.

The northern coastal plateau lavas in East Greenland between Shannon and Bontekoe O are only known in part. Samples from a profile through half of it, at Kap Stosch, have demonstrated that the lavas are saturated, low-alumina, high-iron tholeiites and thus very similar in composition to those which form the extensive lava plateau south of Scoresby Sund. The smaller northern area of plateau lavas, however, shows an evolution in chemistry with time, a feature which is not found in the southern region.

There is reason to believe that the source region for the southern and the northern plateau basalt areas in East Greenland was initially the same. The direction of the transform Jan Mayen Fracture Zone, which cross-cuts the spreading axis of the oceanic rift, is directed towards the entrance to Kejser Franz Josephs Fjord, which marks the southern end of the northern basalt plateau. If an early movement along this fracture zone has taken place, perhaps in connection with a shift of the spreading axis, this may have led to a breaking-off and isolation of the northern plateau basalt reservoir. The result would perhaps be the formation of an isolated body in the lower crust shielded from later inflow; during gradual exhaustion of this reservoir an upwards variation trend in the resulting lavas, such as that observed, would be expected to result.

Mildly alkaline lavas and minor, basic intrusions of similar composition which are met with in the Loch Fyne-Passagehoje belt stem from deeper sources than the coastal lavas, and may have been emplaced through coast parallel fissures which belong to the major system of antithetic faults disrupting the sedimentary strata east of the Caledonian fold belt. Still further inland, and probably from still deeper sources, alkali basaltic and nephelinitic lavas were erupted as are now seen on the nunataks between 73 30 and 74 N. In Traill O the sills are thicker away from the coast than near to it, which again points to the fissures of the antithetic fault system as the possible conduits for basic melts to higher levels.

The later Tertiary plutonic centres from the northern region are, however, essentially of the same nature as those to the south of Scoresby Sund.

There seems to be little clearcut evidence as to possible extents of these igneous rock associations to the west/northwest, beneath the Inland Ice. Noe-Nygaard (p. 392) also comments:

The large area of plateau basalts in the nunatak zone was discovered by Katz (1952) and is estimated to extend over an area of 2000 sq km (Wenk, 1961). The topography of the ice cap north of Hobbs Land and Arnold Escher Land suggests they continue farther to the north beneath the ice. While it can only be stated with certainty that they are of post-Caledonian age, it is very possible that they are equivalent to the basalts of the outer fjord zone (Haller, 1956).

The base of the plateau basalts occurs at an altitude of 2000 m in north-west Andree Land and on Wilkins Nunatakker, and at 2300 m in Hobbs Land and Hvidbjorns Nunatakker; it thus rises westwards. Feeder dykes ('Scholtgange') were found by Katz in Hobbs Land and Arnold Escher Land, as well as red, brown and green tuffs. These suggest that the area was the site of the volcanic activity, and that the basalts are mainly surface flows.

Three different basalt rock types, two of alkali basalt composition, are described by Katz. Numerous dykes in the Hobbs Land area are believed to be related to the flows, and their content of nepheline and phlogopite makes this highly probable. The dyke rocks are often semi-crystalline and porous, and are classified as augitites and limburgites. A dyke of fine-grained trachyandesite with brown hornblende phenocrysts has been noted from Ajungilaq

nunatak, and a greyish green phonolite sill with black idioblastic hornblendes has been recorded in central Hobbs Land (Haller, 1956). Basaltic dykes have not been traced into areas to the south.

Haller mentions the possibility that eruption of the alkali basalt lavas is related to a reactivation of the late Caledonian to Devonian rifting of the Eleonore So area.

However, this is somewhat north of the latitude of the "radar grid" area, and may have little direct bearing on the concerns of the present project.

As mentioned in our discussion of the West Geenland Tertiary Province, there seems to be little likelihood of any physical continuity, in terms of rocks, between this region and the East Greenland Tertiary igneous association. However, the geologic relationships in the East Greenland province seem to be somewhat less-well-defined, including areal extents. Hence, there does seem to be the possibility, perhaps of low probability, that rocks of this type/association might exist beneath the ice, to the west. Certainly the "radar grid" area is closer, geographically, to this East Greenland Tertiary Province than to several of the other provinces- as shown on our figures 2 and 3. Again, reference is made to Hall (1981), Clarke (1977), and Brooks (1973), among others, regarding additional perspectives on the East Greenland province. Brooks (p. 150-151) summarizes relationships as follows:

Volcanic, plutonic, and sedimentary rocks are present in East Greenland (Fig. 1), but sediments are of inconsiderable extent and thickness. Basalts with a present outcrop area of roughly 60,000 sq km (23,000 sq mi— although basaltic xenoliths in plutons outside the present basalt area indicate that the basalts once were much more extensive) extend from Kangerdlugssuaq (68 N lat.) to Scoresby Sund (70 N). Additional scattered remnants of a once probably continuous cover are found along the coast as far north as Shannon O (75 N). These are typical plateau basalts, closely similar to those in comparable areas such as the Columbia River or the Deccan. Characteristically, they have a monotonous appearance, are either aphyric or contain plagioclase phenocrysts, and, where undis-

turbed by later events, are nearly horizontal and show no signs of central-type eruption. Pyroclastic rocks are not common, but they are recorded from the upper and lower parts of the succession, which is as thick as 7 km (23,000 ft). Abrupt thinning occurs toward the inland Ice. Basalts of this type are widely believed to have been erupted from tensional fissures (Tyrrell, 1937)....

Apart from these tholeiitic basalts, other extrusives occur. Included are the greatly undersaturated basalts described by Katz (1952) and Haller (1956) from the nunataks inland from Kejser Franz Josephs Fjord and those found as pebbles in the Kap Dalton conglomerates (Wager, 1935). Mafic, somewhat alkalic extrusives are found in central volcano remnants inland from Kangerdlugssuaq (Wager, 1947; Anwar, 1955), trachytic tuffs are present on Keglin O (Wager, 1934, p. 35), and rhyolites are present in the Kialineq area (Brown, 1968).

Plutonic complexes are many, ranging in composition from mafic and ultramafic (commonly with pronounced layering) to syenitic, foyaitic, and granitic. They are present, generally along the coast, from Kap Gustav Holm (67 N) to Kap Broer Ruys (73 1/2 N). Detailed investigations have been made on the Kap Edvard Holm layered gabbros (Elsdon, 1970), the Kangerdlugssuaq quartz syenite-foyaite series (Kempe et al., 1970; Kempe and Deer, 1970), the Skaergaard layered gabbros (Wager and Deer, 1939; Wager and Brown, 1968), the Werner Bjerge syenites, granites, and foyaites (Bearth, 1959), and the subvolcanic stocks of syenite, peralkalic granite, etc., in the Mesters Vig area (Kapp, 1960). Preliminary field descriptions are available for the Kap Parry and Kap Simpson syenites and granites (Schaub, 1938; 1942) and the gabbros, granites and syenites of the Kialineq area (Brown, 1968). Relatively unknown are the intrusive rocks of Kap Gustav Holm (gabbro, syenite), Nugalik (gabbro, microgranite), Igdluktarijik (gabbro), Nordre Aputiteq (gabbro), Lilloise (syenites, nepheline syenites), and Kap Broer Ruys (?), as well as many minor intrusions such as the Bagnaesset and Kap Deichman syenites and Kangerdlugssuaq.

Swarms of dikes and sills are found in many areas- e.g. the coast-parallel dike swarm described by Wager (1934, 1947),

dike swarms associated with major intrusive centers, and the extensive sill complexes in the strata north of Scoresby Sund. A detailed study of basaltic and lamprophyric dikes in the Skaergaard area was published by Vincent (1953).

Both subbasaltic and intrabasaltic sedimentary rocks are known- of marine, estuarine, and limnic deposition. The basalts lie on sedimentary rocks at several places in northeast Greenland (Haller, 1970, p. 229-231) and in the Kangerdlugssuaq area (W ager, 1934), where they contain basalt pebbles indicating that volcanism had already started in neighboring areas. Intrabasaltic sedimentary beds are fairly common; they consist mainly of thin sandstones and zones containing silicified tree trunks. Better developed sequences are at Kap Dalton and Kap Brewster (W ager, 1935; Hassan, 1953), where they are near the top of the plateau-basalt sequence and contain rich marine fossil assemblages.

We have underlined particularly relevant portions of the above quotation. Hall's comments- especially his page 236- provide a useful summary as well. Deer presents a thorough discussion of "The Tertiary igneous rocks between Scoresby Sund and Kap Gustav Holm, East Greenland," in the *Geology of Greenland* volume (p. 404-429); this includes the classic Skaergaard area. Brooks and Nielsen (1982) present a detailed treatment of the key Kangerdlugssuaq area.

A number of other informative papers dealing with this region are listed in the "Selected References" section of the present report.

These include Gleadow and Brooks (1979), who discuss aspects of thermal histories and tectonics, based on fission track dating of sphenes, zircons, and apatites from Lower Tertiary magmatic rocks, and some Caledonian rocks as well, providing additional insights from the perspective of this technique. Brooks, et al (1991) address petrologic and plate tectonics aspects of iron-rich tholeiitic magmas, in particular as related to the "East Greenland continental margin ophiolite" and the classic Skaergaard intrusion. Their interpretation is that "iron-rich liquids similar to those deduced for the Skaergaard intrusion do exist, and, rather than being un-

usual, they may be of major importance in rifted environments." As a variation on this theme, Larsen and Marcussen (in press, 1992) present a cogent discussion of the Scoresby Sund region, in terms of flood basalts, intrusive sills, and deep crustal structure of this portion of East Greenland. These more recent papers are supportive of the earlier work, cited above, regarding the nature and extent of the East Greenland and West Greenland Tertiary magmatic provinces.

Central East Greenland Paleozoic-Mesozoic Sedimentary Associations

Escher and Watt, in *Geology of Greenland* (p. 12), summarize:

In East Greenland the Caledonian molasse deposits were followed by an Upper Permian transgression with deposition of limestone, gypsum and shale on downfaulted and tilted blocks along the eastern border of the fold belt. Triassic sediments mostly comprise marine and continental clastic rocks whereas the succeeding Jurassic clastic sequence mostly accumulated in a shallow marine shelf environment and is highly fossiliferous. Cretaceous sediments are marine and predominantly clastic, consisting of conglomerates, sandstones and shales. The composite thickness of the whole sequence approaches 7000 m. Cretaceous and early Tertiary sandstones are known further south at Kangerdlugssuaq (68 N) immediately below the Tertiary basalts.

The Jurassic rocks provide one of the most complete sequences bordering the North Atlantic Ocean and are thus of special interest for studies of the evolution of the early Atlantic Ocaen. Faulting was active throughout the Mesozoic and into the Tertiary, and has been related to crustal widening; the intense faulting in the late Jurassic may be related to the initial spreading between the North American and European continents.

T. Birkelund and K. Perch-Nielsen present a discussion in "Geology of Greenland" (p. 304-339) entitled "Late Paleozoic-Mesozoic evolution of central East Greenland". Their introductory remarks include the following (p. 304):

Upper Permian and Mesozoic sediments outcrop extensively in central East Greenland between latitudes 70 20 N and 77 N. In addition there is a limited outcrop of sediments of Late Cretaceous age beneath the Tertiary basalts further south at Kangerdlugssuaq (68 10- 68 50 N). In central East Greenland the basin is bordered to the west by the Caledonian mountain belt from which it is separated by a system of faults with a mainly north-south trend. The former eastern boundary of the basin is largely covered by the Norwegian Sea. The basin itself was formed by a series of westward-tilted fault blocks.

The Upper Permian and Mesozoic deposits of this basin (figs 270, 271) comprise the most complete accessible sequence of that age bordering the Norwegian Sea and are thus of special interest for the interpretation of the early evolution of the North Atlantic ocean. Furthermore, the affinities of the successive faunas of the basin are of great importance for the elucidation of the geological history of the northern Atlantic and for the general correlation of Arctic deposits. Mixed faunas containing European, Canadian and Siberian elements occur at several levels in the succession....

These authors also present paleogeographical maps of the Permian (figure 275), Lower-Middle Triassic (figure 281), Lower Liassic (figure 289), Middle Jurassic (figure 290), Lower Cretaceous (figure 295), and Upper Cretaceous (figure 296) for Greenland and adjacent regions. These figures depict (interpretively) distributions of sedimentary environments, products of which may yet remain within the areas shown. None of these areas appear to fall near, or within, the "radar grid" study area (cf. figure 1, this report). Hence, sedimentary rocks representing sediments deposited at these times in the geologic past seem unlikely to exist at the present time, beneath the Inland Ice.

This must be considered in the framework of present known distributions, and structural relationships. The former is given, in general fashion, by Birkelund and Perch-Nielsen in their introductory remarks (cf. the quotation above; their page 304), while they address the latter aspect on pages 335-337 of their paper in *Geology of Greenland*. Christiansen et al (in press, 1992)

discuss various aspects of the region, in the context of petroleum exploration potential.

Northern Greenland

Dawes discusses this region in a chapter of *Geology of Greenland* entitled "Precambrian to Tertiary of northern Greenland" (p. 248-303). Particularly relevant here are the following comments from this chapter (p. 249, 252-253, 258, 276):

This paper describes the bedrock geology of the northern part of Greenland from Melville Bugt (75 00 N) on the west coast to Kronprins Christian Land (80 00 N) on the east coast. The region corresponds to the geographical divisions North-West and North Greenland as used by the Survey. The larger part of this region is ice covered, either by the northern part of the Inland Ice or by smaller ice caps. About 125 000 sq km is ice free. The majority of the coast is ice locked throughout the year making logistics and field work difficult....

Northern Greenland is made up of three main geological provinces (fig. 222): a platform region in the south in which Proterozoic and Lower Paleozoic rocks overlie crystalline basement rocks, an east-west trending orogenic belt of Phanerozoic rocks in the north called the North Greenland fold belt and a north-south trending orogenic belt of Precambrian and Phanerozoic rocks on the east coast. This latter orogenic belt- the East Greenland Caledonian fold belt- is described elsewhere in this volume (Henriksen & Higgins). A sub-province in eastern North Greenland, the Wandel Sea basin of Upper Paleozoic to Tertiary rocks, overlies the junction between the older orogenic belts.

The crystalline basement rocks north of Melville Bugt are continuous with the Rinkian complex of northern West Greenland (Escher & Pulvertaft, this volume). The lowest part of the Proterozoic to Paleozoic platform sequence is continuous with the foreland rocks of the East Greenland fold belt, and all of the basement, platform and northern folded provinces are continuous with similar regions of the Arctic Islands of Canada.

The crystalline basement, exposed

mainly adjacent to the Inland Ice, is overlain with profound unconformity by non-metamorphosed Proterozoic, mainly clastic rocks. The Proterozoic section varies in thickness from over 4500 m in the west to no more than 200m in the central part in south-eastern Wulff Land. Disconformably overlying the Proterozoic rocks are Eocambrian or Cambrian, Ordovician and Silurian clastic and carbonate rocks of platform and shelf facies, a section which reaches 3500 m in thickness. The platform rocks are preserved as downfaulted blocks in the Thule region, as outliers in Inglefield Land and as extensive north dipping homoclinal areas across northernmost Greenland. Several widely separated structural 'highs' or arches transgress the platform region. The sedimentary rocks between or flanking the highs form structural basins which probably were also basinal during sedimentation.

The undeformed strata of the platform pass northward into the thicker folded rocks of the North Greenland geosyncline, where the sedimentary record extends into the Devonian. The North Greenland geosyncline is an eastern extension of the Franklinian geosyncline of the Canadian Arctic Islands.

The North Greenland fold belt trends eastward from Hall Land to eastern Peary Land, a distance of 600 km. Folding within the belt conforms to the regional trend. The junction between the platform and the fold belt is transitional: homoclines of the platform pass northward into broad open folds that, farther north, pass into the main fold structures. Asymmetrical folds, mainly overturned to the north, dominate the fold belt. The folding is thus directed away from the platform which acted as a hinterland, not a foreland.

The North Greenland fold belt is an orogenic complex. A long history of structural and metamorphic events, culminating in Devonian time, resulted in polyphase deformation and metamorphic grades as high as amphibolite facies. Calc-alkaline volcanic rocks and major thrust faults younger than the main diastrophism form a late orogenic, possibly Cretaceous-Tertiary, suite on the north coast.

Carboniferous, Permian, Triassic, Jurassic, Cretaceous and Tertiary mainly marine rocks comprise a 3000 km thick section in the Wandel Sea basin in eastern North Greenland. This basin has been deformed by late Phanerozoic movements culminating in Tertiary time and the rocks now form a northwest trending tectonic belt....

Precambrian crystalline rocks are widely exposed between Melville Bugt and Inglefield Land (figs. 223,224). Small areas of exposure are also known in south-eastern Wulff Land and on certain nunataks at the head of Victoria Fjord (fig. 267)....

The basement rocks of the large Melville Bugt-Inglefield Land region have been explored sufficiently to allow tentative subdivision into six main lithological units, the regional extent and relative ages of some of which, however, are not known. The units are: (a) gneiss, schist and granite; (b) anorthosite; (c) psammite and amphibolite; (d) marble, pelite and calc-silicate rocks; (e) gabbroic to granitoid rocks; (f) variable gneiss, melanocratic to quartz-rich....

The Proterozoic to middle Paleozoic sedimentary rocks of northern Greenland were deposited over broad areas of contrasting tectonic character: in the south, relatively thin sequences of clastic and carbonate rocks in a stable platform region; to the north, thick sequences of argillaceous limestone and clastic sediments in a geosynclinal environment. The platform region lies peripheral to the present Inland Ice, and the geosynclinal region is now the North Greenland fold belt. The platform sediments of the hinterland pass without break into the geosynclinal fill of the orogenic belt to the north, the two sedimentary areas being separated by a shelf zone of carbonate rocks with reefs and off-reefal shales. Boundaries between these depositional sites are not precise. To the east the platform strata of the hinterland become the foreland deposits of the East Greenland fold belt.

'Platform' in this paper includes all hinterland regions of unfolded strata. 'Shelf' rocks marginal to the North Greenland geosyncline are included in the platform association, and the term "miogeosyncline" is not used. The North Greenland geosyncline is the north-eastern part of the Franklinian geosyncline (Schuchert, 1923) of northern Canada and Greenland (fig. 222).

The youngest fossiliferous beds so far recognized in the platform area are of Upper Silurian age, whereas in the geosyncline

early Devonian beds are known. It seems probable that Devonian sediments extended across at least part of the platform but have been reduced or removed by erosion."

Noteworthy at this juncture is the publication by Peel (1982) dealing with "The Lower Paleozoic of Greenland." Of particular interest here, Peel mentions (p. 313):

Lower Paleozoic strata are most fully developed in northern Greenland where Cambrian-Silurian platform and trough deposits outcrop over an area of about 100000 sq. km. Scattered outcrops of Cambrian and Ordovician platform strata occur within the central part of the East Greenland fold belt (Figure 1), which also includes deposits of Silurian age at its northern termination. A former lower Paleozoic cover to the Precambrian Shield in West Greenland is indicated by relic Ordovician platform carbonates at `Fossilik' (Figure 1).

Returning to Dawes' review, several other quotations seem pertinent here (p. 288, 290-292, 296, 297, 298-301):

A geological map of northern Greenland is dominated by north-east to east structural and stratigraphic trends that form a gentle arc from Inglefield Land to Peary Land. North-westerly trends occur, however, in the Thule region, and strong northerly to north-north-easterly structures characterise the East Greenland fold belt in Kronprins Christian Land. The trends noted lie in a sub-rectilinear pattern: the huge and largely unknown mass of the crystalline Greenland Shield forms a core or block that is flanked on three sides by sedimentary basins. These basins are: the Thule basin in the southwest; the North Greenland geosyncline in the north; and the East Greenland geosyncline in the east. The stratigraphic and structural trends in each basin conform to the general coastal configuration of the northern part of the subcontinent.

It is inviting to compare these three basins, each of which contains several thousands of metres of sedimentary rock. The similarities are few, however: the Thule basin consists of mainly undeformed sandstone, dolomite and shale beds and is now a large graben; the North Greenland geosyncline is a deformed trough of mainly clas-

tic and flysch-type sediments in which the direction of tectonic transport is dominantly northward, away from the Precambrian crystalline mass; the East Greenland geosyncline is similarly a deformed trough containing a mixed series of rocks, but the direction of tectonic transport is westward, toward the crystalline mass.

The Wandel Sea basin rests upon the junction between the two geosynclinal fold belts and is deformed into a tectonic zone having mainly north-westerly trending structures....

An undoubtedly long but incompletely known history of sedimentation and orogeny is represented by the Precambrian, crystalline basement rocks of the Greenland Shield. Uplift and profound erosion of the shield preceded subsidence and renewed sedimentation in late Precambrian time. Subsequent tectonism took place at different times in the various basins across northern Greenland: late Precambrian tectonism in the East Greenland fold belt and in the Thule basin; Lower Paleozoic (Caledonian) orogeny in the East Greenland fold belt and mid-Palaeozoic orogeny in the North Greenland fold belt; and late Mesozoic-Tertiary folding and faulting in the Wandel Sea basin. This latter activity also affected the North Greenland fold belt....

Figure 268 of Dawes (our *fig. 4*) is reproduced below, presenting a "chronological summary chart for northern Greenland."

Other general references to the geology of northern Greenland include, among others, papers by Dawes and Soper (1973), Rosenkrantz and Pulvertaft (1969), and Hakansson and Pedersen (1982). Dawes and Soper (p. 133) observe:

The North Greenland fold belt was an unstable zone of the earth's crust throughout Phanerozoic time, being the site of complex Paleozoic-late Phanerozoic orogeny. The belt borders the Arctic Ocean and lies at the junction of oceanic and continental structures.

The earlier structural interpretation of intense superficial overthrust tectonism with northerly-directed nappe structures (Frankl, 1955; 1956) is refuted: the stratigraphy and

	Composite stratigraphic section		Geological event	Igneous activity	K/Ar age (m.y.) determination
T	Sandstone, shale with coal units		Faulting	Calc-alkaline effusives	32.3, 34.9 on lavas
			Thrusting, faulting, folding, mylonitisation, metamorphism		42.3, 47.1 on metasedimentary schists
C	Sandstone, grit, conglomerate, shale				66.6, 72.9 on dolerite dykes
	~~? ~~~~		Regional reheating with folding and faulting in Wandel Sea basin	Basic dykes	75.9, 84.2 on metasedimentary schists
J	Siltstone, shale				
Ħ	Sandstone, shale		Marine and deltaic sedimentation in Wandel Sea basin		
	Conglomerate, sandstone, grit, sandy shale		(Position and nature of stratigraphical breaks uncertain)		
P	Dolomite and limestone with some sandstone and siliceous rocks				
	Limestone and sandstone with shale, conglomerate and evaporites				
C	Sandstone, conglomerate, shale with coal units		Major marine transgression		
			Non-marine sedimentation		
	TROUGH	PLATFORM			
D	Greywacke, shale, siltstone, some conglomerate and limestone	Greywacke, shale, biostromal and biohermal limestones, argillaceous limestone, conglomerate, shale	Major mid-Palaeozoic orogeny – metamorphism and polyphase deformation	Basic intrusions	(No mid-Palaeozoic ages due to late Phanerozoic overprinting)
S					
O	Sandstone, shale, chert, limestone, carbonate breccia	Limestone, dolomite, conglomerate, shale, some evaporites	Marine sedimentation in the North Greenland geosyncline and on the stable platform block. Periods of regional uplift and intermittent erosion		
	?	Carbonates, shale	(Position and status of stratigraphical breaks vary from region to region)		
	Limestone, shale	Limestone, dolomite, some sandstone			
E	Dolomite, sandstone, shale	Dolomite, limestone, sandstone, shale			
€C	Sandstone	Dolomite Sandstone, tillite	Marine transgression Glaciation, non-marine deposition	?	Range of 532 to 1190 on post-Thule Group dolerites
PC2	Sandstone, quartzite, grit, conglomerate with units of siltstone, shale and dolomite with some evaporites		Faulting and regional uplift, Carolinidian orogeny in east	Basic dykes and sills Basic and acidic effusives with sills and dykes	799, 982 on pre-tillite dolerites
			Thick shallow water sedimentation in the Thule basin and in Kronprins Christian Land, thinner on platform		
			Marine transgression		
PC1	High-grade crystalline basement-gneiss, schist, anorthosite, granite with metasedimentary units, limestone, pelite, psammite and igneous intrusions of basic to acidic composition		Regional uplift, faulting	Basic dykes	1563 on dolerite dyke 1600 – 1900 +1960
			Metamorphism and polyphase deformation	Intrusion of basic to acidic complex	Rb-Sr isochron on schists and meta-igneous rocks
			Complex history with older basement and supracrustal cover		?

Fig. 268. Chronological summary chart for northern Greenland. No attempt has been made to portray sedimentary unconformities in the Lower Palaeozoic and Upper Palaeozoic – Mesozoic successions.

Figure 268 of Dawes, in Escher and Watt, 1976.

structure can be explained in terms of repeated, more or less coaxial, folding. Frankl, although recognizing the possibility of southerly movement at depth (1956), attributed the remarkable north-facing character of the fold belt to a "push from the north" (1955). Relative movement of higher crustal rocks over lower rocks no doubt took place, but it is difficult to envisage how powerful tangential stress could have been transmitted through the undeformed platform strata of the hinterland; nor is there evidence of a root zone from which northerly-directed nappes could have been derived. It seems necessary to invoke significant movements of crustal material at depth beneath the fold belt, perhaps influenced by mantle creep. Southerly movements could be the result of the underthrusting of oceanic material against the continental block of Greenland. If so, the existence of a Paleozoic Arctic ocean, floored by oceanic crust, is indicated.

This seems to make extrapolation of these terranes as far to the south as the "radar grid" area problematic- quite in keeping with other information regarding this. However, other work, including the contribution by Hakansson and Pedersen cited above, illustrates that the current status of regional geologic knowledge remains quite incomplete. Indeed, Hakansson and Pedersen point out (p. 331-333, 335-337, 346) several things:

> The right-angle junction between the Caledonian and Innuitian mobile belts constitutes an important element in the regional geology of northeastern Greenland. The relationship between the two tectonic provinces is largely concealed in the shallow Wandel Sea, where the actual junction is probably covered by thick deposits of Wandel Sea Basin sediments (Dawes and Peel, 1981). Nevertheless, the recognition of more distant, onshore interference structures plays an important role in the understanding of the structural development of the region.

> The northern part of the East Greenland Caledonides is dominated by roughly N-S-trending nappe systems with a substantial westerly transport, suggested to be in excess of 150 km by Hurst and McKerrow (1981a). The Caledonian deformation in East Greenland commenced by Late Ordovician-Early Silurian time (Henriksen and Higgins,

1976), and in Kronprins Christian Land nappe implacement continued at least into the Late Silurian (Hurst and McKerrow, 1981a) (cf. Figure 4). In the North Greenland Fold Belt, on the other hand, dominant structures trend E-W in a fold deformation referred to the Ellesmerian Orogeny of the Inniuitian Mobile Belt. The deformation is here regarded to be of Late Devonian-Early Carboniferous age (Dawes, 1976; Trettin and Balkwill, 1979; Pedersen, 1980).

> In the southern part of the North Greenland Fold Belt of Peary Land, considerable thrust movements deformed the Early Paleozoic trough sediments prior to the Ellesmerian Orogeny. This thrust fault deformation- the Volvedal Orogeny- is interpreted as the westernmost effect of the Caledonian Mobile Belt (Pedersen, 1981a).

Although as these authors state and demonstrate, the more recent work necessitates fundamental reinterpretations of regional geological relationships; such reinterpretations as offered by them make it even less likely that analogies/portions of these northern Greenland terranes would be expected sub-ice within the "radar grid" area. The latter is an appreciable distance to the south, and, apparently, likely to be geologically quite dissimilar. Though not precluded by the incomplete extant data, it is considered unlikely that terranes characteristic of the north Greenland Phanerozoic occur as far south as the "radar grid" area.

Ketilidian Mobile Belt

J. H. Allaart discusses the "Ketilidian mobile belt in south Greenland" in *Geology of Greenland* (p. 120-151). Summary comments from this source include (p. 121-122):

> The Ketilidian mobile belt occupies the region between Ivigtut in the west, Ikermit in the east, and Kap Farvel, the southern tip of Greenland (fig. 138). To the north an extensive area of Archaean rocks is exposed (see Bridgwater et al., this volume). The mobile belt comprises gneisses, granites, and metamorphosed supracrustal rocks and is characterised by the occurrence of numerous late, intrusive granite plutons covering large areas.

Rb-Sr whole rock and U-Pb zircon techniques have so far produced ages of 1830 to 1850 m. y. for early, gneissose granites and gneisses of supracrustal origin. More age work is needed to decide whether or not these ages mark the earliest major thermal event in the mobile belt. Late to post-kinematic granite intrusions have yielded Rb-Sr whole rock and U-Pb zircon ages ranging from 1810 to about 1770 m. y. (Gulson & Krogh, 1972; Van Breemen et al., 1974). K-Ar and Rb-Sr mineral ages range between 1700 and 1500 m. y. and suggest a relatively slow cooling in the mobile belt.

The mobile belt can be subdivided into several zones from the northern margin towards the south: (1) The northern border zone in the northern part of which Ketilidian sediments and volcanic rocks overlie Archaean gneisses and supracrustal rocks uncomformably. Towards the south these are progressively involved in Ketilidian metamorphism and deformation (Henriksen, 1969a). (2) A complex body of granites, diorites, and gneissose granites (Julianehab granite) in which a central zone of late intrusive granites can be distinguished. (3) An intricately folded zone of granites, gneisses and migmatised Proterozoic or earlier sediments and volcanic rocks with amphibolite facies mineralogy. (4) A flat-lying, slightly domed, migmatite complex of high-grade (cordierite-amphibolite to cordierite-granulite facies) metasediments and metavolcanic rocks, early Ketilidian granite sheets and numerous late Ketilidian granite intrusions.

Table 3 gives the most important chronological events in South Greenland. It should be noted that there are considerable uncertainties about the correlation of volcanic and sedimentary rocks from the border zone to the central part of the mobile belt.

Table 3 from Allaart is reproduced below.

In the following chapter in *Geology of Greenland* (p. 153-181), C. H. Emeleus and B. G. J. Upton discuss "The Gardar period in southern Greenland." Portions of their introduction can serve as an adequate summary, for present purposes, as follows (p. 153):

Between Narssaq and the Inland Ice in southern Greenland, faulted outliers of sandstone and volcanic rocks lie unconformably upon a pre-1600 m. y. `basement' of metamorphic rocks, migmatites and granites. Both `basement' and the supracrustal rock outliers are intruded by a variety of dykes and central complexes. The region, which is the most populated in Greenland, has received a steady flow of visitors from Europe since the beginning of the 19th century. One of the first notable geologists to visit the area was Giesecke whose record of several years of travel and investigation still finds a useful place in the geological literture (Giesecke, 1910). He was followed later in the 19th century by Steensrup, Flink, Ussing and others, all of whom paid particular attention to these younger igneous rocks, especially to the nepheline syenites of Ilimaussaq and the Igaliko region, on account of their exotic rock types and their content of hitherto unknown minerals; this was also true of the Ivigtut cryolite deposit which was mined from 1855 until recently.

...it is to a later investigator, C. E. Wegmann, that we owe the first comprehensive account of the region (Wegmann, 1938). Wegmann distinguished several geological episodes and established the basis of modern chronology; in particular he singled out the younger sediments, volcanics and unmetamorphosed intrusives as belonging to a single tectono-volcanic episode and he termed them the Gardar rocks, after the ancient Norse Bishopric of Gardur where the present day village of Igaliko now stands.

Numerous other contributions to the geological literature have been made, dealing in one way or another with this southernmost region of Greenland. Allaart, Bridgwater, and Henriksen (1969) offer the following relevant comments (p. 874-876, 878):

...Over much of the area, two plutonic episodes can be recognized- a main Ketilidian episode, during which the major structural and metamorphic character of the mobile belt were formed, and a younger Ketilidian episode (Sanerutian) characterized by renewed tectonic activity (the stress system was the same as that of the main episode), the reactivation of older granites, and the intrusion of a plutonic suite of norite, monzonite, diorite, and granite. The K-Ar age determinations from the Ketilidian mobile belt have given only the date of the second plutonic episode- between 1,500 and 1,640 m. y. The geologic events in the Ketilidian mo-

Table 3. Chronology of South Greenland

POST-GARDAR	Dykes (coast-parallel swarms)	
GARDAR	Dykes, alkaline intrusions, faulting, sandstones and lavas of Eriksfjord Formation	1000–1300

KETILIDIAN

Thin tholeiitic dykes in persistent swarms	
Closure of K-Ar and Rb-Sr mineral systems	1500
Late granites: foreland granites, intrusion of central granite zone (reactivation), rapakivi suite and appinitic suite	1770–1810
Deformation (two or three fold phases, trending NE or ENE; thrusting and faulting in the foreland), metamorphism (greenschist-granulite facies), migmatisation and formation of early granites	1840
(Is there a still older major thermal event?)	

Northern border zone	Zones of migmatites (Tasermiut, Lindenows Fjord, Kap Farvel)
Qipisarqo Group: sedimentary	
Sortis Group: volcanic	volcanic
Vallen Group: sedimentary	sedimentary (age relations unknown)

——————— major unconformity ———————

PRE-KETILIDIAN

Extensive basic dyking (Iggavik dykes) ⎰ ESE / NE / N–NW / ESE ⎱	
Folding, thrusting, metamorphism and migmatisation	2600
Tartoq Group: volcanic and sedimentary rocks	
Ilordleq Group (position uncertain)	
Ikermit supracrustal series?	
Older basement (most of the regional gneisses): four units of quartz dioritic and granodioritic gneiss with characteristic lithology and structural position (gabbro-anorthositic rocks, metavolcanic and metasedimentary rocks)	

Table 3 of Allaart, in Escher and Watt, 1976

bile belt can be correlated with the Hudsonian and Elsonian events recorded from the east coast of Labrador...

After the end of plutonic activity the basement rocks of southwest Greenland were overlain by Gardar continental sandstone and basaltic to trachytic lavas; then alkali rocks were emplaced under cratogenic conditions between 1,000 and 1,300 m. y. ago....

The intrusion of a coast-parallel swarm of basic and lamprophyric dikes, one of which has given a K-Ar age of 164 m. y., is the only geologic event recognized in South Greenland from the end of the Gardar magmatism until the beginning of Quaternary time.

The Gardar sandstone and overlying lava units (Eriksfjord Formation, Poulsen, 1964) are preserved mainly in an ENE-trending fault block (Fig. 4) although isolated outcrops and stoped blocks in younger intrusions suggest that they once extended over a larger area. The original sedimentary basins are thought to have been controlled by the east-west wrench faults. The sedimentary rocks are mainly fluvial, resulting from the rapid deposition of material from torrential but short-lived rivers. The sediments were reworked by wind action (Poulsen, 1964). Near the boundaries of the fault-controlled basins, massive fanglomerate is present and contains giant boulders of Julianhab Granite. More central areas in the depositional basins contain conglomerate units and fine- to medium-grained sandstone with locally preserved ripple marks, rain pits, and sun cracks with mudstone infillings. Most of the sedimentary rocks are red; some have been bleached by the later effects of Gardar magmatism. During deposition of the sandy sediments, a series of volcanic vents developed along the wrench faults. In many respects the sedimentary environment resembles that in modern rift valleys; although the main movement detectable on the bounding faults appears to have been horizontal, vertical displacements of as much as 2 km within the fault block have been established (Stewart, 1964)....

The Gardar sandstones (previously called the Igaliko sandstones) and lavas, although probably more widespread once, were the result of sedimentation and lava extrusion in isolated basins; any correlation between them and similar rocks in Labrador must be tentative.

The technical geological literature is replete with contributions of various types dealing with aspects of the Ketilidian region. Several examples listed among our selected references in the present report include: Dempster et al.,(1991), dealing with the petrology of granites; Upton et al., (1990) addressing the Tugtutoq Central Complex of the Gardar sub-province; and Harrison et al., (1990b) on rapakivi granites. Taylor and Kalsbeek (1990) present an interesting report on radiometric age determinations of some Precambrian marbles.

Examples of more general topics include Harrison et al., (1990a) on the subject of "Granite magmatism and extensional tectonics in Southern Greenland," and a paper by Hutton et al., (1990) dealing with a proposed "new mechanism of granite emplacement" by means of "intrusion in active extensional shear zones." Both of these latter papers exemplify the sort of research possible in favorable coastal areas of Greenland contributing both to increased knowledge of Greenland geology per se, while also having more fundamentally widespread geological implications as well. Actually, this is true of most of the papers listed in our selected references.

By way of summarizing our review of the Ketilidian, Table 1 of Allaart, et al (1969) is reproduced below *(fig. 6)*. The regional geology and structural relationships have become reasonably well-elucidated. There seems little likelihood that the Ketilidian and its associated Gardar rocks would be anticipated to be present sub-ice within the "radar grid" area to the north, particularly since the Archaean and the Nagssugtoqidian terranes occur in between.

Archaean Block

In essence, this region represents the "keystone," the fundamental underpinning of Greenland geology as presently understood. Some eighty percent or so of Greenland is covered by the Inland Ice but the circumstances may well not be quite all that clearcut. However, based on present knowledge this "Archaean

Table 1. Chronology of Southwest Greenland

	Plutonic Episodes	Major Events Recognizable Over Large Areas	Detailed Events from Local Chronologies		Isotopic Age (m.y.)
POST-GARDAR		Coast-parallel olivine tholeiitic dikes	Carbonatitic lamprophyre dikes Olivine tholeiitic dikes (at least two generations)		164
GARDAR — Late		Major alkalic complexes	Camptonitic dikes Agpaitic intrusions Saturated and undersaturated syenite intrusions, gabbros, granites		1,020 1,150
GARDAR — Middle		Major NE-trending basic dike swarms	Dolerites (several NE-trending generations), trachytes and syeno-gabbros Some major intrusive centers		
GARDAR — Early		ESE-trending dolerites Sandstones and lava extrusions Faulting (ESE-trending set)	ESE- and local ENE-trending troctolitic dikes and early syeno-gabbro dikes Lamprophyric dikes (generally NE-trending) Nepheline syenite and carbonatite intrusion Basic and trachytic lavas and sandstones Faulting (ESE-, ENE-, and N-S-trending sets): continued intermittently throughout Gardar time		1,275
KETILIDIAN — Sanerutian Plutonic Episode		Rapakivi suite Plutonic reactivation of earlier structures and rocks	Thin tholeiitic dikes in persistent swarms Diorite sills, lamprophyres, and ultrabasic intrusions Major pegmatite swarm; aplites Composite net-veined diorites Aplitic granites Synkinematic basic dikes Rapakivi granites Porphyritic ("Big-feldspar") parautochthonous granites with mobilization of surrounding material Hornblende, gabbro, and diorite intrusions Allochthonous granites Deformation; local hot-shear belts and belts with plastic-semiplastic deformation; ENE trends		1,500–1,640
KETILIDIAN	?		Basic dikes (swarms of minor dikes)		
KETILIDIAN — Main Ketilidian Plutonic Episode		Folding, thrusting, faulting; metamorphism, migmatization, formation of granites	Deformation (two or three phases of folding; dominant regional trend: NE or ENE; thrusting; faulting in foreland), metamorphism (greenschist-granulite facies), migmatization and formation of synkinematic autochthonous-parautochthonous granites and augen gneisses		Approx. 1,800?
KETILIDIAN		Extrusion of volcanics Sedimentation	*Ivigtut Region* Ilordleq Group (volcanic) Qipisarqo Group (sedimentary) Sortis Group (volcanic) Vallen Group (sedimentary)	*Tasermiut Region* Volcanic Sedimentary	
PRE-KETILIDIAN		Basic dikes	Doleritic dikes: four major generations (prekinematic in relation to Ketilidian deformation)		
PRE-KETILIDIAN	?	Folding, metamorphism, migmatization, granitization	Deformation (two or three phases of folding; dominant regional trend: NE), metamorphism, migmatization		?
PRE-KETILIDIAN			Volcanic and some sedimentary deposits (Tartoq Group)		
PRE-KETILIDIAN			? Older basement (forming part of the regional gneisses)		2,500–2,700?

Table 1 of Allaart et al., in Escher and Watt, 1976.

block" is reasonably construed as the core of the "crystalline shield" (cf. references in the literature too numerous to make citation necessary here) of Greenland. Assuming this to indeed be the case (and ample evidence exists) then the lithologies/terranes of this block might be anticipated to exist elsewhere within the interior of Greenland, beneath the Inland Ice. Modification of such Archaean lithologies, resulting from subsequent geologic processes and events is not unlikely. Appreciable portions of the Nagssugtoqidian, Rinkian, and Ketilidian terranes most likely are the result of such processes-metamorphic (principally), igneous, sedimentary. The Archaean "gneiss complex", as defined, has remained relatively unaffected by such events during the past 2,600 m. y.

In the *Geology of Greenland* chapter entitled "Archaean gneiss complex of Greenland" (p. 18-75), D. Bridgwater, L. Keto, V. R. McGregor and J. S. Myers discuss this key region in summary fashion. From the wealth of material to be found in this chapter, Table 1 *(our fig. 7)*, as well as several other particularly relevant portions (p. 19-69) are quoted here:

> The gneiss complex which extends from Itivdleq to Ivigtut on the west coast and from Gyldenloves Fjord to Mogens Heinesen Fjord on the east coast (fig. 4) has remained unaffected by major metamorphic, tectonic or magmatic events for the last 2600 m. y. Similar rocks occur in north-west Scotland (Peach et al., 1907 pp. 191-252) and Labrador (Bridgwater et al., 1973c; Bridgwater et al., 1975) and the area described here is the largest and best exposed fragment of the Archaean North Atlantic craton which was broken up by Phanerozoic continental drift. Isolated remnants of similar Archaean rocks occur within the mobile belts to the north and south suggesting that the Archaean craton was once much larger and that a large part of it was reworked to varying degrees by younger tectonic and metamorphic events....
>
> Between 80 and 90 per cent of the Archaean complex consists of granitoid quartzo-feldspathic gneisses, of which major parts appear to have been derived from acid or intermediate igneous rocks. They are intercalated with units of amphibolite (fig. 5) which appear to be mainly derived from metavolcanics, a minor amount of meta-sedimentary gneisses, and concordant units

> of meta-anorthosite and associated metabasic igneous rocks characterised by very calcic plagioclase. These units range from a few centimetres to a few kilometres in thickness.
>
> The layered nature is thought in part to be due to the extensive injection of igneous sheets and in part due to intense deformation during which it is thought that rocks of different type and possibly of widely different provenance were brought together.
>
> The Archaean rocks are characterised by high grade assemblages, chiefly in high amphibolite and hornblende granulite facies. Over large areas the main mineral assemblages appear to have formed late in the history of the gneiss complex, after the main tectonic events which produced the layering and complex folds of the gneisses. Most rocks possess high temperature, medium pressure assemblages; high pressure assemblages have rarely been seen. Most changes in metamorphic grade are gradual (Kalsbeek, in press) and suggest that gentle thermal gradients were attained during the final stages of metamorphism of the complex.
>
> A variety of igneous rocks ranging from norites to granites and small carbonatite diatremes were intruded during late Archaean time and were cut by several swarms of basic dykes between 2700 and 2000 m. y. ago...
>
> The oldest rocks so far identified in Greenland are a variety of basic and ultrabasic greenschists, metasediments and quartzo-feldspathic rocks. They occur in a semicircular arc 10-20 km in diameter around a dome of gneiss (fig. 6), near the margin of the Inland Ice at Isua, 150 km north-east of Godthab. The supracrustal belt has a maximum width of about 2 km at the margin of the Inland Ice, but is less than 1 km wide at the lake called Imarssuaq. Contacts with the enclosing gneisses are sharp and near vertical. Intrusive relationships are preserved at a few points along the contact and the quartzo-feldspathic gneisses surrounding the belt are interpreted (D. B. and V. R. M.) as derived from younger granites.
>
> Planar structures and contacts between the different lithological units within the belt dip steeply and follow the trend of the belt

Table 1. Simplified table of events from the Archaean of Greenland

(1) Early crust providing source rocks for the Isua sediments.	Early crust
(2) Deposition of the Isua supracrustals. Basic and ultrabasic lavas and intrusions, basic tuffs, quartzites, siltstones, pelites, ironstones and calcareous rocks. Acid volcanic fragments in a conglomerate.	Isua supracrustals ≥ 3750 m. y. (a, b)
(3) Intrusion of syntectonic and late tectonic granites (parents of the Amîtsoq gneisses), possibly contemporaneous with upper acid volcanic part of the Isua supracrustals.	Amîtsoq gneisses c. 3750 m.y. (a)
(4) Deformation and metamorphism of the Amîtsoq gneisses and Isua supracrustals.	
(5) Intrusion of abundant swarms of basic dykes (Ameralik dykes) during regional stress.	Ameralik dykes
(6) Extrusion of basic and intermediate volcanics (locally pillow lavas); intrusion of ultrabasic bodies and layered basic igneous bodies; deposition of sediments including pelites, aluminous quartzites, minor calcareous units (Malene supracrustals).	Malene supracrustals > 3040 m. y. (possibly 3750 m. y. or earlier)
(7) Emplacement of major stratiform anorthosites and gabbro anorthosites.	Anorthosite complexes > 3040 m. y.
(8) Major thrusting intercalating the Amîtsoq gneisses, Malene supracrustals and anorthosites.	
(9) Emplacement of ultrabasic bodies, mostly between Malene supracrustal rocks and Amîtsoq gneiss units.	
(10) Intrusion of major suites of syntectonic and late tectonic calc-alkaline rocks as subconcordant sheets (Nûk gneisses).	Nûk gneisses 3040 m. y. (c)
(11) Intense deformation with the formation of major nappes, followed by less intense deformation which produced upright folds and widespread dome and basin interference patterns. These were partly modified in sub-linear belts of very intense deformation.	Major folding 3040–2800 m.y.
(12) Emplacement of syn- and late tectonic granites, partly formed by the remobilisation of earlier gneisses during increasing regional metamorphism. Emplacement of norites, andesine anorthosites and quartz monzonites.	Late granites 3000–2800 m.y. (d)
(13) High grade metamorphism outlasting (11) and (12) and culminating in the widespread crystallisation of granulite facies minerals under late to post-tectonic conditions.	Granulite facies metamorphism 3000–2700 m.y. (e, f)
(14) Deposition (or tectonic mis-en-plas) of Tartoq Group and Sarfartûp nunâ supracrustals.	Tartoq Group supracrustals
(15) Tectonic activity mostly concentrated in distinct shear belts (particularly in northern part of craton). Widespread homogenisation of granitic gneisses under amphibolite facies conditions. Local injection of granitic sheets and late tectonic granite-diorite complexes.	c. 2700 m. y.
(16) Emplacement of potash granites associated with NE–SW flexures in the Godthåbsfjord area (Qôrqut granite). Widespread post-tectonic pegmatite swarms.	Qôrqut granite c. 2600 m. y. (g)
(17) Emplacement of at least three regional swarms of basic dykes; transcurrent movement on NE and SE faults. Plutonic activity in areas to north and south of craton.	Dykes 2600–1750 m. y.
(18) Slight metamorphism throughout Archaean block (or uplift above level at which Rb–Sr mineral ages become stable).	Rb–Sr systems closed c. 1600 m. y. (g)
(19) Intrusions of several sets of basic dykes between 1600–1000 m.y. particularly in the south of the craton (Gardar dykes). Sporadic kimberlites 600–200 m.y. on west coast. Mesozoic alkali basalt dyke swarm in south-west Greenland. Local intrusion of Tertiary basic dykes near Godthåb and Tingmiarmiut.	Minor intrusions 1600–50 m. y.

Isotope age work quoted

(a) Moorbath *et al.*, 1972   (c) Pankhurst *et al.*, 1973a   (e) Black *et al.*, 1973
(b) Moorbath *et al.*, 1973   (d) Pidgeon *et al.*, in press   (f) Gulson & Krogh, 1972
                                                        (g) Pankhurst *et al.*, 1973b

Table 1 of Bridgwater et al., in Escher and Watt, 1976.

itself. The supracrustal rocks have a strongly marked, steeply plunging, linear fabric defined by pencil-like rods and elongated conglomerate. This fabric is considered (D. B. and V. R. M.) to be an extension fabric subparallel to the main direction of tectonic transport.

Gneisses collected mainly along the contact of the belt have given a Rb-Sr whole rock isochron date of 3700+/- 140 m. y., which is identical, within analytical error, with Rb-Sr whole rock isochron dates from the type Amitsoq gneisses near Godthab (Moorbath et al., 1972). Ironstones from the supracrustals have given a Pb-Pb whole rock isochron age of 3760+/- 70 m. y. This could represent a metamorphic event that was accompanied by severe uranium depletion (Moorbath et al., 1973) or deuteric equilibration of uranium close to the time of deposition of the ironstones. No other major unit of supracrustal rocks comparable in age or lithology to the Isua succession has yet been discovered in Greenland.

Two sets of metadolerite dykes cut the supracrustal rocks and the gneisses both within and outside the dome. Within the dome they are little deformed, but 3 km south of the supracrustal belt they are recrystallised and boudinaged. They resemble Ameralik dykes of the Godthab area....

Ten to twenty per cent of the Archaean gneiss complex consists of conformable units of amphibolitic rock (fig. 24) associated with smaller amounts of pelite, semi-pelite and quartz-cordierite (+/- sillimanite) schists of supracrustal origin. These supracrustal units are commonly associated with ultrabasic layers and pods, some of which appear to be in place and to have formed part of the original successions (Bridgwater et al., 1973c). Others may represent ultrabasic material emplaced along contacts between the supracrustal units and Amitsoq gneisses during later movements (McGregor, 1973). Adjacent units may differ markedly in composition, one unit consisting dominantly of metavolcanic amphibolite, the next consisting dominantly of metasediment. No regional differences have been recognised between groups of supracrustal units from widely separated parts of the Archaean complex and for descriptive purposes they are treated as a single suite of rocks.

In some earlier accounts, the best preserved supracrustal units were described as low grade belts of mainly greenschist rocks downfolded into an older basement of high grade gneisses (Windley, 1966, 1968, 1969a; Windley and Bridgwater, 1971). Careful work in Godthabsfjord (McGregor, 1968, 1969) (fig.13) and the Ravns Storo area (Andersen & Friend, 1973) (fig. 25), together with regional studies in South-East Greenland (Andrews et al., 1973) has shown: (1) that greenschist facies rocks are restricted to isolated localities, (2) that the supracrustal rocks are cut by sheets of granitoid rocks similar to much of the gneiss around them, and (3) that both the supracrustal units and the gneisses which intruded them can be traced into areas where they were affected by granulite facies metamorphism 2800 m. y. ago. Only two groups of Archaean supracrustal rocks are now regarded as possibly younger than the major metamorphic event which affected the complex about 2800 m. y. ago, and these are described later (Tartoq and Sarfartup nuna supracrustals).

The name Malene supracrustals was given to a group of amphibolites and metasediments in the Godthabsfjord region which were derived from a variety of basic and ultrabasic volcanics, intrusives and metasediments (McGregor, 1969, 1973) (figs. 11, 13). They appear to be typical of similar units which occur throughout the craton, although they may not all be of the same age.

The Malene supracrustals were intruded by and are therefore older than the Nuk gneisses, one suite of which has yielded a Rb-Sr whole rock isochron age of 3040 m. y. (Pankhurst et al., 1973 a). They do not appear to have been intruded by the major swarm of Ameralik dykes found in adjacent units of Amitsoq gneiss and are therefore assumed to be younger than 3700 m. y. However, many contacts between Malene supracrustals and Amitsoq gneisses are tectonic and no certain primary contact relationships have been seen.

Attempts to obtain either the age of deposition of the Malene supracrustals or the possible age of source rocks of the sediments using Rb-Sr whole rock and U-

Pb zircon determinations have so far proved unsuccessful. A U-Pb diffusion age of 2800 m. y. on zircons from an intermediate volcanic unit from a supracrustal belt at Tingmiarmiut in South-East Greenland (Gulson & Krogh, 1972; Andrews et al., 1973) has been interpreted as the age of high grade regional metamorphism. More recent U-Pb zircon work by Baadsgaard (personal communication, 1974) and Rb-Sr whole rock determinations by the Oxford Isotope Geology Laboratory (Moorbath, personal communication, 1974) have given ages of about 2800 m. y. from units of Malene supracrustal rocks which are clearly older than the 3040 m. y. old Nuk gneisses in the same area....

Metamorphosed calcic anorthosites and associated leucogabbroic and gabbroic rocks form one of the most distinctive rock units in the Archaean gneiss complex. They occur as concordant layers and trains of inclusions throughout the complex in both West and South-East Greenland. They provide one of the best marker horizons for tracing out structures on a regional scale, for making lithostratigraphic correlations from one part of the complex to another, and locally they provide way-up criteria. They are of special interest, not only because of their unusual composition with extremely calcic plagioclase, but because more than any other rock group in the Archaean, they extensively preserve their primary textures and in some places primary igneous minerals. They provide some of the oldest layered igneous rocks on earth available for study.

They were first recognised in Greenland during regional mapping in the decade following 1946 (Ellitsgaard-Rasmussen & Mouritzen, 1954; Noe-Nygaard & Ramberg, 1961) and were thought to be derived from calcareous sediments (Sorensen, 1955; Berthelsen, 1957) or volcanic ash bands (Berthelsen, 1960). In 1964-65 chromite layering was discovered by Windley near Fiskenaesset and was mapped in detail by Ghisler (1966). This discovery led Windley (1966) to conclude that the anorthosites were metamorphosed gravity stratified igneous rocks similar to the Sittampundi complex of India (Subramaniam, 1956).

The types of relic igneous texture and bulk lithology of inclusions and layers of anorthosite throughout the Archaean complex are remarkably similar, and they are now all regarded as derived from stratified basic complexes although chromite has not been recognised outside the Fiskenaesset area. Large units of anorthosite are most abundant between Fiskefjord and Frederikshabs Isblink where they may form 3 to 5 per cent of the total outcrop. Individual layers can be traced in continuous outcrop for up to 25 km and are typically less than 500 m wide. Outside of this area most of the anorthosites occur as trains of inclusions within quartzo-feldspathic gneisses, some of which can be followed as mappable horizons for many tens of kilometres (Berthelsen & Henriksen, 1975). In general they are thoroughly recrystallised although primary igneous textures are preserved even in small inclusions less than 20 cm in diameter.

Primary igneous features are best preserved in the Fiskenaesset region where both anorthositic and gabbroic rocks occur together as part of a single or a small number of layered stratiform intrusions, collectively called the Fiskenaesset complex (fig.33) (Windley, 1969a). Well-developed gravity-stratified layering indicates that the anorthosites were emplaced as sub-horizontal sheets. Original contacts between the anorthosites and older country rocks are seldom preserved but show that the anorthosite complex was intruded into metavolcanics probably equivalent to the Malene supracrustals (J. C. Escher & Myers, 1975). Similar anorthosites in the Godthabsfjord area were intruded by the Nuk gneisses (c. 3040 m. y. old), but they are not seen to be intruded by Amitsoq gneisses. They are locally cut by thin basic dykes similar to those which cut the Malene supracrustal rocks and Amitsoq gneisses.

The isotopic age of intrusion of the anorthosite bodies has not yet been determined. Rb-Sr whole rock isochron ages (Eversen, in Windley, 1973b), U-Pb zircon ages (Nunes et al., 1974) and Pb-Pb ages (Black et al., 1973) from widely different localities have all yielded ages between 2700-2900 m. y. These ages are the same as the age of granulite facies metamorphism which was the last of a long sequence of intrusive, tectonic and metamorphic events which post-date the intrusion of the anorthosite complex....

The informal lithostragraphic term Nuk

gneisses (McGregor, 1973) is applied to all the quartzo-feldspathic gneisses in the Godthabsfjord region that do not contain Ameralik dykes and that have intrusive relations with the Malene supracrustals, the anorthositic rocks and the earlier Amitsoq gneisses. It is not known to what extent all the rocks grouped as Nuk gneisses belong to a single, cogenetic suite or to what extent they were intruded during periods of unrelated granitic activity separated by major time intervals.

Rb-Sr whole rock isotope determinations on a suite from a small area on Bjorneoen (Pankhurst et al., 1973a) gave a well defined isochron of 3040+/- 50 m. y. (initial Sr ratio 0.7026+/- 0.0004) which is regarded as their date of intrusion. The Bjorneoen suite is petrologically typical of the Nuk gneisses which occur over a large part of the Godthabsfjord area (fig. 1 1). However, intrusion of granitic material and deformation may have gone on intermittently after emplacement of the anorthosites into the Malene supracrustals before 3034 m. y. ago, up to about 2600 m. y. ago when the Qorqut granite was emplaced....

More than 80 per cent of the Archaean gneiss complex is made up of quartzo-feldspathic gneisses which were deformed before the 2800 m. y. regional granulite facies event. Outside the area between Sermilik and Isua, there is no definite evidence of rocks older than the main supracrustal units and anorthosites. This does not mean that older rocks do not occur but that they are difficult to recognise. However if the supracrustals and anorthosites are regarded as equivalent in age to the Malene supracrustals and anorthosites in Godthabsfjord, then a very large part (perhaps 70-80%) of the gneiss complex must have been formed, or at least remobilised, at approximately the same time as the emplacement of the Nuk gneisses....

This section describes a heterogeneous group of rocks which includes: discrete intrusive bodies of porphyritic granite emplaced before the 2800 m. y. granulite facies metamorphism; diffuse bodies of rock apparently formed by the in situ recrystallisation and partial remobilization of earlier quartzo-feldspathic gneisses during regional high grade metamorphism; discrete intrusive bodies of charnockitic granites and associated norites emplaced under or af-

fected by the 2800 m. y. old granulite facies metamorphism; and late to post-tectonic granite intrusions and pegmatite swarms which post-date the granulite facies metamorphism. One such pegmatite has yielded a Rb-Sr mineral isochron age of approximately 2600 m. y. (Pankhurst et al., 1973b).

These rocks are not regarded as a cogenetic suite, and the main reason for describing them together is that they were all formed towards the end of plutonic activity in the Archaean craton, in the period after the main regional foliation had been impressed on the gneiss complex, although many of them are affected by one or more phases of younger deformation...

The Tartoq Group are upper greenschist to low amphibolite facies greenschists and outcrop on either side of Sermiligarssuk between Ivigtut and Frederikshab (figs. 4, 65) (Higgins & Bondesen, 1966; Higgins, 1968; Berthelsen & Henriksen, 1975). They occur as refolded synforms and slices locally repeated by isoclinal folding, and over 2 km thick, interlayered with Archaean gneisses which had already passed through a complex structural and metamorphic history (fig. 66).

Contacts with the surrounding gneisses are highly deformed and have been the site of considerable granitic intrusion. They are enclosed by a zone of migmatites and agmatites, locally several kilometres wide, in which inclusions of the Tartoq Group occur within a quartzo-feldspathic matrix. The boundary was also complicated by later deformation, which impressed a foliation on the migmatites and rendered them difficult to distinguish from the surrounding gneiss complex. Slices of the supracrustals and the marginal migmatites were also detached by thrusting and interleaved with the surrounding gneisses.

No isotopic age determinations are available from the Tartoq Group. The granitic activity and metamorphism affecting them has a minimum (K-Ar) age of approximately 2500 m. y. The group is cut by basic dykes which are affected by Ketilidian (ca. 1800 m. y.) metamorphism and is overlain by Ketilidian sediments and lavas (see Allaart, this volume). It was considered that these supracrustal rocks were younger than the majority of gneisses which surround them because of their relatively low meta-

morphic grade. This would imply that the Tartoq Group was deposited at some time betweem 2500 m. y. and 3000 m. y. ago. However, it is also possible that the Tartoq Group is an allochthonous sequence of low grade rocks of any age older than 2500 m. y. which had been thrust over complexly folded gneisses.

The Tartoq Group consists largely of basic volcanic rocks interlayered with quartzitic units, with minor calcareous layers and ultrabasic bodies. Because of the fragmented nature of the outcrops a complete stratigraphy has not been worked out. Berthelsen & Henriksen (1975) describe a type section of the group 2000 m thick, on the south side of Sermiligarssuk near Tartoq fjord. There the structurally lower 1000 m of the succession consists of quartz-rich schists intercalated with basic volcanic units. This is overlain by a dominantly basic unit 1000 m thick with locally well-preserved quartz tholeiitic pillow lavas. The shape of the lava pillows locally suggests that the succession is the right way up....

The structural evolution of the Archaean block can be divided into four main stages:

(a) early vertical movements; (b) subhorizontal movements (nappes and thrusts); (c) formation of dome and basin interference patterns, and straight belts; (d) late shear movements and faulting.

Locally stages (b) and (c) can be subdivided into different episodes of deformation. The effects of individual episodes vary markedly from area to area and from one lithological unit to the next, so that rocks which preserve evidence of the earliest stages in the structural development of the complex are found adjacent to gneisses in which all evidence of the early structures has been obliterated by later movements. Zones of intense deformation once established show a tendency to be reworked during subsequent deformation episodes. Correlation of individual episodes of deformation, or even the major stages, can be problematical in the same way as there are uncertainties in making regional lithological correlations....

The Archaean gneiss complex was intruded by at least eight regional swarms of basic dykes. The dyke swarms were emplaced in the period after the end of regional plutonic activity at about 2700-2500 m. y. ago but before major plutonic and tectonic activity in the Nagssugtoqidian and Ketilidian mobile belts....

In the present context, another valuable contribution is the paper "Development of the Precambrian shield in West Greenland, Labrador, and Baffin Island," by D. Bridgwater, A. Escher, G. D. Jackson, F. C. Taylor, and B. F. Windley (1973). This paper summarizes aspects of the Greenland Precambrian terranes, from a somewhat different and complementary perspective; Table 1 from this work is reproduced below (our *fig. 8*); the West Greenland portion is of principal interest to the present project.

The relations are still rather incompletely understood, quite complicated, and involve lithologies and terranes representing very large segments of geological history, with attendant complexities.

Nutman and Collerson (1991) also present an informative summary of regional relationships of Archaean terranes in Greenland and adjacent Canada to the west. Similarly, several papers in the volume edited by Hall and Hughes (1990) entitled "Early Precambrian basic magmatism" afford more recent insights as to the Archaean of Greenland, per se, as well as in regional contexts (cf. Hall and Hughes; Cattell and Taylor; Hatton and von Gruenewaldt; Hall, Hughes and Tarney).

A substantial amount of other work has been carried out dealing principally with petrologic aspects of the Greenland Archaean. From examples far too numerous to list, the following are some representatives of the genre. Smith (1990) is an unpublished doctoral dissertation exploring in detail the geochemistry and petrogenesis of some rather unique Mid-Archaean Malene supracrustal gneisses. Liew et al. (1990) present an interesting comparative study of Archaean gneisses from Sri Lanka, Scotland, and Southwest Greenland (Nuk gneisses), in terms of isotopic contrasts, elemental geochemistry, and high grade metamorphism. Griffin et al. (1990) present an account of granulite facies metamorphism south of Ameralik, in the Amitsoq gneisses and inclusions of Akilia supracrustals. Riciputi et al. (1990) consider the

Table 1. Subdivisions of Precambrian Used by Geological Survey of Canada and Geological Survey of Greenland

		EASTERN CANADA		WEST GREENLAND			
		Events and Rock Units		**Events and Rock Units**			
AGE m.y.	Time divn. GSC	Magmatic volcanic and sedimentary	Tectonic metamorphic	Tectonic metamorphic	Magmatic volcanic and sedimentary	Time divn GGU	AGE m.y.
500	EON HADRYNIAN ERA	Lamprophyre dikes (Makkovik) Franklin diabase dikes (Baffin Island)	Southeast tension faults		Kimberlite dikes (K/Ar age)	PRECAMBRIAN V	500
1000	PROTEROZOIC HELIKIAN	Syn-tectonic intrusions GRENVILLE OROGENY Uluksen sedimentary rocks Southeast Eqalulik sedimentary and volcanic rocks faults (Northern Baffin Island and Bylot Island) Seal Group Mugford Group Croteau Group Ramah Group (sediments and volcanic rocks) Small syenite intrusions East-west faults Diabase dikes Regional argon loss (?) Adamellite plutons Anorthosite plutons Diabase dikes		Movement on east-west faults in South Greenland Loss of radiogenic argon in many areas suggesting slight regional metamorphism	GARDAR PROVINCE Peralkaline intrusions Major syenite and associated granite intrusions Major diabase and alkali gabbro dike swarms (S. Greenland) Carbonatites Sandstones and lavas Widespread north-south diabase dike swarms Rapakivi granites of Kap Farvel area. Calc-alkaline intrusions Julianehåb area	PRECAMBRIAN IV	1000
1500							1500
		Syn-orogenic porphyritic granitic HUDSONIAN OROGENY intrusions		Main phase of the KETILIDIAN OROGENY in South Greenland	Syn-tectonic granites intermediate and basic intrusions	PRECAMBRIAN III	
2000	APHEBIAN	Diabase dikes (?)		NAGSSUGTOQIDIAN Deformation in West Greenland north of 66°N Faulting in Archean craton	Deposition of the Vallen and Sortis Groups		2000
		Deposition of Kaniapiskau Supergroup. Aillik, Mary River, Hoare Bay and Piling Groups Sedimentary and volcanic rocks, and associated basic and ultrabasic rocks and anorthosite sills			Major dike swarms including syntectonic dikes in the border zone of the Nagssugtoqidian mobile belt		
2500		Major east-west and north-south diabase dike swarms KENORAN OROGENY		MAJOR OROGENESIS affecting much of West Greenland	Deposition of Tartoq Group	PRECAMBRIAN II	2500
3000	ARCHEAN	Sedimentary and volcanic rocks and intrusion of small ultrabasic plutons		Widespread granulite facies metamorphism	Late tectonic anorthosites and granites Intrusion of granites Intrusion of calcic chrome-bearing anorthosites Early sediments, lavas and ultrabasic intrusions		3000
3500					Major dike swarm Early granitic crust	PRECAMBRIAN I	3500

Table 1 of Bridgwater et al., 1973.

conditions of granulite metamorphism in the Godthab-Fiskenaesset region. Garde (1990) discusses thermal granulite-facies metamorphism, as well as retrograde effects, in the Fiskefjord region.

With a related but somewhat different emphasis, there has been appreciable effort devoted to elucidating the geochronology of the Greenland Archaean rocks. Among the numerous papers, examples include the following. In 1976 Baadsgaard et al. discussed radiometric (U-Th-Pb, Pb-Pb, Rb-Sr, K-Ar) relationships in the polymetamorphic Amitsoq gneisses from the Godthab region. Following up, two papers presented in 1986 by Baadsgaard and co-workers pursued this theme further, endeavoring to delineate more clearly geochronologic, isotopic, and petrologic relationships in the Amitsoq gneisses of the Isukasia area. Collectively, these papers represent a significant contribution, as well as exemplifying the type and quality of geological research attainable vis-a-vis the Archaean terrane in this area of Greenland.

Schiotte and Compston (1990) reported on their studies of U-Pb relationships in individual zircon grains from the Akilia association- ie., the enclaves of older rocks found within the Amitsoq orthogneisses in the Godthab region (exclusive of the Isua supracrustal belt at Isukasia near the Inland Ice). The "Akilia association" comprises a variety of rocks of dominantly volcanogenic aspect (largely now amphibolites). Ages determined ranged from 3756-3685-3570 Ma, representative of a complex geologic history dating from early Archaean time.

As an example of the application of another isotopic approach Ashwal et al. (1989) discuss their work on the Fiskenaesset anorthosite complex utilizing Sm-Nd geochemistry.

Thus it can be seen that the Greenland Archaean remains an area of intensive geological research, with commensurately important results in terms of local, regional, and global geologic knowledge.

3. Summary

By way of recapitulation, in the context of the present project, the following comments of Peel (1982) seem appropriate:

Most of Greenland consists of Precambrian crystalline rocks representing the northeastern extension of the Canadian Shield... Five subdivisions can be recognised, with an old Archaean block flanked by the late Archaean and Early Proterozoic Nagssugtoqidian and Ketilidian mobile belts. The Rinkian mobile belt lies to the north... and is succeeded by extensive exposures of Precambrian Shield rocks in northwest Greenland, to the north.

The Archaean block has been essentially unaffected by major metamorphism during the last 2500 m. y. (Bridgwater et al., 1978). Supracrustal rocks dated at 3800 m. y. have yielded supposed microfossils, but Bridgwater et al. (1981) reviewed the occurrences, dismissing them as evidence of early Archaean life. The Nagssugtoqidian mobile belt is mainly composed of reworked Archaean gneisses deformed at about 2700 m. y. The Ketilidian mobile belt contains sediments and volcanics overlying the Archaean block along its southern boundary and is extensively intruded by large granite plutons giving ages from about 1740 m. y. to 1850 m.y. The Rinkian mobile belt is characterised by large-scale folds and nappes in strong contrast to the regional planar fabric of the adjacent Nagssugtoqidian mobile belt. The complex is continuous with Rinkian-Archaean crystalline strata in northwest Greenland which can be closely compared with adjacent Ellesmere Island (Frisch and Dawes, 1982). Exposures of Precambrian Shield also occur in southern Wulff Land (Dawes and Peel, 1981) and within the East Greenland fold belt (Henriksen and Higgins, 1976; Henriksen, in press; Hurst et al., in press).

Prediction/inference as to the nature of geological materials extant sub-ice within the project study area verges on informed speculation, at best, even in such general terms as the "terranes/regions/provinces" as discussed above. To essay an attempt at greater detail- as to specific lithologies- is still more uncertain.

There is little compelling evidence to indicate that anything other than "crystalline basement"- in whatever particular guise(s) or lithologic character that may in fact be- is likely to underlie the Inland Ice, within the "radar grid" study area. Whether it, in fact, is representative of "Archaean", "Nagssugtoqidian", "Rinkian", "Ketilidian", or not is- to some degree- a moot point. Relevant to the present immediate concerns as to drilling technology, it seems sufficient to suggest that rock types characteristic of other "terranes", such as unmetamorphosed sedimentary rocks, for example, are rather less likely to be encountered by the drill sub-ice.

Thus, in keeping with present knowledge of lithologies (types, relative abundances, distributions spatially and temporally) a "hierarchy" of sorts might be tentatively offered. In order of decreasing "likelihood" of sub-ice occurrence, such a list of lithologies might not unreasonably be suggested to appear as follows:

1. Gneisses; quartzo-feldspathic, principally derived from acid or intermediate igneous precursorial "protoliths". By far the most common lithology recognized in the various "crystalline" terranes. Of hornblende granulite-upper amphibolite metamorphic facies, most commonly. These would consist principally of quartz- feldspar (plagioclase, potassium feldspars) mineralogies, with subordinate "mafic" minerals (amphibole, pyroxene, biotite, +/- lesser amounts of apatite, opaque minerals (magnetite, etc.).

Igneous "granitoid" rocks would be quite similar in most respects, though lacking the characteristic banded-foliated textures of gneissic rocks, as imposed by metamorphism. Thus, taken together, gneisses of this type, plus granitic rocks, would constitute the "most likely" lithologies- in the general sense- to be anticipated in the present context.

2. "Amphibolites" (general sense). Much less abundant, volumetrically, than the above rock types. Mineralogies include predominant amphibole(s), plagioclase, quartz in particular, as well as a variety of generally less abundant constituents (opaque minerals, sphene, micas, pyroxene; +/- garnet, epidote, etc.). Derived mainly from volcanic rock protoliths, via meta-

morphism ranging from hornblende amphibolite-greenschist facies. Rock textures range from relict igneous-schistose.

3. Meta-anorthosite/norite/gabbro; associated meta-basic igneous rocks. The anorthositic/noritic/gabbroic rocks consist principally of calcic plagioclase, with subordinate/subequal proportions of mafic minerals (principally pyroxene, amphibole,+/- biotite) and lesser amounts-generally- of opaque minerals (chromite, magnetite, etc.). The meta-basic rocks consist of predominant plagioclase and mafic minerals- pyroxene and/or amphibole, with lesser amounts of other minerals (opaque minerals; biotite; etc.). Metamorphic grades range over the spectrum hornblende granulite-amphibolite-greenschist facies. Rock textures range from relict igneous-schistose.

4. Meta-sedimentary rocks. A relatively subordinate component of the Precambrian crystalline terranes. Various protoliths. Now consist principally of quartzites, ironstones, meta-pelites/siltstones, calcareous/calc-silicate rocks. Textures range from massive-layered-schistose.

5. Rock types associated with the Tertiary igneous rock provinces of East Greenland and West Greenland. Principally extrusive mafic rocks- generally basaltic in general character and related intrusive variants. The mineralogies feature predominant plagioclase and pyroxene, with subordinate opaque minerals; amphibole, quartz, biotite are other phases not uncommonly present. These provinces also contain other types of intrusive igneous rocks, of generally "granitoid-gabbroic" character, at least texturally. Principal mineral constituents include potassium and plagioclase feldspars (+/- feldspathoids), quartz, mafic minerals (amphibole, pyroxene, micas), and a variety of other minerals-usually in minor/trace amounts. Rock textures are principally igneous in character, ranging from fine to coarse in grain sizes.

6. Sedimentary rocks. Principally sandstones, siltstones, shales; conglomerates, limestones, dolomites. Subordinate evaporites, coals. Variations are essentially infinite, texturally and mineralogically. Inferred as the least likely lithologies to be encountered sub-ice within the study area- though, of course, their possible

presence cannot be completely discounted.

The foregoing "hierarchy" assumes indurated bedrock in place as the material to be encountered below the ice. Alternatively, there is the possibility of encountering unconsolidated materials- presumably of glacial/glacio-fluvial character. Further analysis of this is deferred here, lacking reasonable data upon which to base substantive discussion. Suffice to say that such materials could run the gamut of particle sizes- clay and larger- depending upon specific conditions, processes, and substrate/source materials. Thus, the planned drilling program might well include provision for eventualiies involving encountering unconsolidated/semi-consolidated ("less-than-lithified", ie.) materials- clays, silts, sands, gravels, boulders; or more likely, a poorly-sorted mix thereof.

Appendix I presents some suggestions for future activities within the context of this project.

4. Engineering Concerns

Physical Properties of Geological Materials

Characteristics of potential interest/concern to sub-ice drilling-coring-sampling include the properties of the constituent minerals, as well as the properties of aggregates of minerals— ie., sediments, rocks. This represents, thus, mineralogy, and texture, respectively. Though significant variations from "average" values/qualities may be important in many instances, in general some of the material to be found in the following references may be useful in the present context.

Among numerous similar sources, much information is available from the textbook *Principles of Engineering Geology and Geotechnics*, authored by D. P. Krynine and W. R. Judd (1957). Chapter 2, "Engineering Properties", Chapter 3, "Foundation and Engineering Use of Soils", and Chapter 4, "Elements of Soil Mechanics" are particularly relevant.

F. Birch, in Section 7, "Compressibility; Elastic Constants" of the volume "Handbook of Physical Constants" (Geological Society of America Memoir 97, 1966) presents additional information of potential interest in this regard.

Also of fundamental importance is the physical property termed "hardness", of each mineral species. Though rocks are aggregates/composites of minerals, and much of their physical nature in bulk may well be principally functions of textural/lithologic factors (ie. cementation, intergrowth of grains, etc.), rather than of the constituent minerals per se, this latter aspect is most important as well. Often it may be the dominant factor. Any comprehensive textbook of mineralogy will include hardness- and other possibly relevant- information for common mineral species. Mason and Berry (1968) is one example, in which a brief but informative discussion of hardness is also presented, in terms of theoretical and quantitative aspects (p. 117-119).

Bulk Rock Samples

Two bulk rock samples were obtained and sent to Fairbanks for use as test materials in the development of sub-ice sampling devices. One, weighing 61 pounds, is a quartz-bearing diorite/quartz diorite from Eklutna, Alaska; the other, weighing 47 pounds, is a porphyritic andesite from Unalaska, Alaska.

Appendix II is a report presenting results of our petrographic analyses of portions of these samples, including observations regarding engineering aspects of their characteristics. Petrographic analysis is in progress of a suite of quartzo-feldspathic bedrock samples collected from the Nagssugtoqidian terrane of West Greenland. The objectives of this work are to obtain further insights as to the nature and properties of rock types likely to be encountered beneath the Inland Ice within the study area.

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APPENDIX I
Suggestions for Further Work

Introduction

We wish to offer the following comments regarding a proposed program of research in geological science. It is our understanding that engineering capability and technology recently have been developed sufficient to facilitate the efficient and effective recovery of consolidated and unconsolidated rock materials from beneath and/or within the basal zones of continental ice-sheets such as the Inland Ice of Greenland. Such innovative technical capability affords unique and attractive opportunities to add significantly to our knowledge in a number of areas of geological science.

The opportunity to sample sub-ice regions whose bedrock geology is presently totally unknown (or only vaguely inferrable) merits, in our opinion, a serious concerted effort of sub-ice sampling, and subsequent analyses utilizing state-of-the-art techniques and knowledge. Recognizing this, we have continued to develop and expand an informal consortium, and have been carrying out background work regarding Greenland in particular, though our interests extend as well to other regions such as Antarctica, and the Himalayas where extensive thick ice-sheets presently exist. We feel that such a program is well-merited, and in the following indicate our reasons, as well as suggestions as to types of analyses warranted, and resultant information to be anticipated.

General Considerations

Recent review of the technical literature, and this subsequent report summarizing known aspects of the geology of Greenland provide a basis for observations regarding future research. Such research would be directed toward the sampling of sub-ice geological materials (bedrock, and/or unconsolidated materials) beneath the Inland Ice, and their subsequent analysis, characterization and interpretation.

This work could readily be keyed to the ice-coring program, at least initially, since there are no clearly-defined areas of particularly compelling principal interest as regards the sub-ice geology- it all is essentially unknown. Subsequent to obtaining sufficient knowledge of sub-ice geology, future drilling locations would be predicated on such increased understanding of the sub-ice geological relationships

Reasons for Such Research

The enormous extant technical literature dealing with the geology of Greenland is ample testimony to the significance of this portion of the earth to the geo-sciences. Further, this intense interest continues, as demonstrated by the amount and high quality of recent-contemporary research activities.

Thus, any efforts to expand the geological data base into presently unknown areas- ie. via sampling beneath the Inland Ice- would be quite in keeping with this, and potentially represent a most substantial contribution- somewhat akin to "moon rocks"/lunar sampling- to scientific knowledge.

1. Geological information per se. Greenland is, in large part, a "great unknown", geologically. As such, together with its' geographic location, it is a potential key to regional-global aspects of geo-science.

  A. Petrology

  B. Geochronology

  C. Regional geological relationships

  D. Information as to Earth's early(iest) history

  E. Plate tectonics and geologic history

  F. Global geological relationships

  G. Implications regarding paleogeography/paleoclimates

2. Information as to potential mineral/energy resources

A. Directly, via sub-ice sampling

B. Indirectly (via 1 A-G, above), due to increased geologic knowledge

Outline of Suggested Course of Action

1. Develop a current working knowledge as to the general geological relationships/framework of Greenland and environs.

   A. Review of technical literature

   B. Personal communications

   C. Summary report (this report)

   D. Continuing research activities

2. Develop engineering techniques and equipment to facilitate effective recovery of samples of sub-ice geologic materials-bedrock, and/or unconsolidated sediments (embracing the gamut of particle-sizes: clay-size and larger, including boulders).

   A. Obtain/characterize-analyze bulk rock samples to use for testing/experimentation purposes (this report)

   B. Develop appropriate technology

   C. Test procedures, equipment

   D. Obtain sub-ice geological samples

   E. Reports dealing with methods, techniques developed/utilized for sub-ice sampling

3. Detailed analyses/characterization of recovered materials (as appropriate to the nature of such materials).

   A. Megascopically, to include descriptions, photographs

      1. General aspect

      2. Structures

      3. Particle sizes

      4. Paleontology

   B. Microscopically

      1. Petrography

      2. Fabric-texture

      3. Mineralogy, to include x-ray diffraction, microprobe, electron microscope analyses, as appropriate

      4. Paleontology/paleobotany

   C. Chemically (bulk samples; selected portions- minerals, particle-size fractions)

      1. Major, minor, trace elements

      2. Isotope chemistry stable radiogenic

4. Interpretations/geological significance

   A. Petrologic

   B. Regional relationships; physical, temporal

   C. Implications

      1. Earth history

      2. Plate tectonics

      3. Possible relevance to mineral/energy resources

      4. Possible relevance to contemporary geological/environmental science concerns

      5. Suggestions/impetus for future drilling and ice/sub-ice sampling: Methods/equipment, Drilling locations

APPENDIX II
Petrography/Petrology of Bulk Rock Samples Selected for Engineering Testing, University of Alaska-Fairbanks Sub-Ice Sampling Project

Abstract

Petrographic analyses have been performed on portions of two bulk rock samples submitted by us to the University of Alaska-Fairbanks sub-ice sampling project for consideration as test materials in the development of sub-ice sampling technologies.

One of these samples (TM 92-4-24-2) is a quartz-bearing diorite/quartz diorite, relatively free of through-going fractures, as well as showing only moderate alteration of constituent mineral grains. The other sample (TM 92-4-20-1) is a porphyritic two-pyroxene andesite, essentially devoid of persistent fractures, and exhibiting very little alteration of constituents, except for a relatively thin oxidized crust on a portion of the surface of the specimen.

Our analyses indicate that these two samples represent reasonably coherent igneous rocks, with characteristics similar in relevant physical and engineering properties to varieties of rocks likely to be present beneath the Inland Ice within the study area under consideration in central Greenland.

Introduction

In order to assist in the development of engineering technologies and equipment appropriate for the recovery of sub-ice rock materials- in particular, bedrock-, representative bulk test samples were requested by the Fairbanks working group of the University of Alaska-Fairbanks Sub-ice Sampling Project. Two such samples were selected and submitted by us. They were selected as representing rock types similar in relevant physical and engineering properties to types of rocks deemed likely to be encountered by the drill beneath the Inland Ice within the project study area in central Greenland.

In addition to megascopic study, portions of these two samples also have been analyzed in thin-section with the petrographic microscope. The results of our analyses are described below, together with other comments as appropriate. These are summary descriptions, emphasizing those characteristics most germane to the engineering concerns of the present project. Rock classification follows Streckeisen (1967). Additional nuances/perspectives were derived from Cox, Bell and Pankhurst (1979); MacKenzie, Donaldson and Guilford (1982) and Moorhouse (1959). Reference also should be made to the body of this report dealing with general aspects of the geology of Greenland for a broader perspective as well as for comments on related concerns as to physical and engineering properties of minerals and rocks.

Sample Descriptions

I- TM 92-4-24-2

This was a sample weighing approximately 61 pounds, collected by us from a site near the village of Eklutna, Alaska, north of Anchorage. This material is representative of intrusive igneous rocks of Jurassic-Cretaceous (?) age presently exposed in outcrop in this area to the west of/within the zone (?) of the Border Ranges Fault.

Megascopically, the material exhibits a low density of either persistent or local fractures, with epidote often evident lining these fracture surfaces. In gross aspect, the sample is essentially isotropic, in terms of fabric and structures. Rare small scattered xenolithic inclusions of more mafic appearance occur. In general, the sample has a relatively coherent, unaltered/unweathered character (our specimen was from quarried materials), suggesting that it would be a good candidate for the proposed engineering testing/experimentation purposes. Certainly the sample proved quite resistant to being physically broken by means of hammer, sledge and chisel.

Microscopically, in thin-section this sample is seen to be a medium-grained quartz-bearing diorite/quartz diorite. It has a granitoid- ie. hypidiomorphic granular- texture; an interlocking mosaic of intergrown crystals of igneous origin.

Principal mineral constituents (quantitative modal analysis) and petrographic characteristics are as follow:

1. Plagioclase feldspar
-comprises approximately 52% by volume of this thin-section
-subhedral-anhedral
-grains are 3.2 mm and smaller
-zoned and twinned
-"average" composition = An 42 (ie., "andesine")
-moderately-strongly altered (sericitization)

2. Quartz
-comprises approximately 17% by volume of this thin-section
-anhedral
-grains are 2.2 mm and smaller
-some slightly myrmekitic
-most shows slight to moderate degree of undulose extinction
-some shows more patchy undulose/composite extinction; these grains are proximal to the few fractures in the thin-section
-unaltered

3. Amphibole
-variety: hornblende
-comprises approximately 19% by volume of this thin-section
-subhedral-anhedral-poikilitic
-grains are 4.7mm and smaller
-often encloses plagioclase, quartz, biotite,
-opaque minerals
-slightly altered, to chlorite +/- "mica" (deuteric/hydrothermal)

4. Biotite
-comprises approximately 6% by volume of this -thin-section
-subhedral-anhedral
-occasionally somewhat poikilitic
-grains are 3.2 mm and smaller
-often with interfoliate lenses/layers of other minerals- chlorite, zoisite/clino-

zoisite, muscovite-as alteration products (deuteric/hydrothermal)
-includes (sometimes) plagioclase, opaque minerals
-exhibit rims of opaque mineral grains (magnetite/ilmenite) where biotite grains are adjacent to quartz grains

5. Opaque minerals
-magnetite/ilmenite
-comprises approximately 6% by volume of this thin-section
-subhedral-anhedral
-grains are 1.0 mm and smaller
-generally intergranular to plagioclase; often intergrown with the mafic minerals

The overall aspect of this thin-section is that of a medium-grained "granitoid" intrusive igneous rock. There are few indications of appreciable post-crystallization stresses of significant consequence having been imposed, other than those effects attendant upon the cooling/unroofing of an intrusive igneous body. The few fractures are filled/"healed" with epidote (+/-?). There is no evidence of significant metamorphism and/or deformational stresses.

Salient features of this rock are shown in the following photomicrographs (figures A-1 to 4)

4 II- TM 92-4-20-1

This was a sample weighing approximately 47 pounds, donated to us by John W. Reeder, Director of the Geological Materials Center, Alaska Division of Geological and Geophysical Surveys, Eagle River, Alaska. It was collected from outcrop by Dr. Reeder from Unalaska Island, Alaska, and represents a shallow intrusive sill of igneous rock from the volcanic/sub-volcanic environment of that portion of the Aleutian Islands. The rock is of Miocene or younger age (Reeder, personal communication, 1992).

Megascopically, the sample exhibits no significant fractures, although a portion of the surface consists of a "rind/crust" of somewhat indeterminate oxidized/weathered material. In thin-section this rind was seen to be no more than 20 mm in thickness below the original specimen surface. In gross aspect, the rock is es-

sentially isotropic, in terms of fabric and structure. In general, except for the "rind" portion, the sample has a relatively coherent character, suggesting that it would be useful for engineering test purposes.

Microscopically, in thin-section, this sample is seen to be a porphyritic two-pyroxene andesite. There is a tendency for patchy clustering of the phenocrysts- ie., a glomeroporphyritic texture. Associated with the groundmass are occasional scattered amygdule-like areas as well, generally rimmed with inwardly-projecting crystals of matrix minerals, with the remainder of the original apparent cavity filled with a mosaic of silica and carbonate minerals (+/- zeolites ?). Principal mineral constituents (quantitative modal analysis) and petrographic characteristics are as follow:

A. Phenocrysts (39% of total rock volume)

1. Plagioclase feldspar
-comprises approximately 25% by volume of this thin-section
-subhedral-euhedral
-grains are 4.4 mm and smaller
-twinned, zoned
-"average" composition = An 50 (ie. "calcic andesine- sodic labradorite")
-slightly altered; cracks, lined with hematite/glass
-some crystals contain pyroxene inclusions

2. Pyroxene
-comprise, collectively, approximately 8% by volume of this thin-section (clinopyroxene = 3%; orthopyroxene = 5%)
-clinopyroxene is diopsidic/augitic (?); twinned
-orthopyroxene is hypersthene; pleochroic, biaxial (-)
-subhedral-euhedral
-zoning present
-grains are 1.3 mm and smaller

3. Quartz
-comprises approximately 4% by volume of this thin-section
-probably originally B-quartz
-subhedral-euhedral (original crystals); some are partially resorbed and/or skel

etal
-original crystals on the order of 0.6 mm and smaller
-now consist of pseudomorphs, each made up of composite mosaics of SiO2 (quartz, +/- ?) microcrystals, carbonate materials, micas (?), +/- brown glassy material
-perhaps originally xenocrysts (??)

4. Opaque minerals
-comprise approximately 2% by volume of this thin-section
-magnetite-ilmenite
-subhedral-anhedral
-often associated with pyroxene grains (especially in core zones)
-grains are 0.8 mm and smaller.

B. Groundmass/matrix (61% of total rock volume)
-comprised of crystals on the order of 0.1 mm and smaller
-moderate tendency for sub-parallel alignment of crystals (flow texture)
-some crystals show "swallowtail" morphologies, ascribable to rapid cooling/quenching of parent magma, and attendant imperfect crystallization of such grains
-much of this groundmass is not resolvable with the optical microscope at 400X magnification
-principal phases recognized are:

1. Plagioclase feldspar
-subhedral-euhedral, often "lath-like" morphology
-some crystals exhibit "swallowtail" morphologies
-twinned
-"average" composition = An 42 (ie. "andesine")

2. Opaque minerals
-magnetite-ilmenite

3. Pyroxene (s)
-probably both clino- and orthopyroxenes

4. Glass

5. Quartz
-probably originally B-quartz (?)

The overall aspect of this thin-section is that of a "volcanic" igneous rock. The only evidence of appreciable post-consolidation effects upon this material consists of the relatively thin oxidized/weathered "rind/crust" along one side of the sample, and some associated minor fractures. The alteration within this material features principally the development of hematite; there is moderate alteration of plagioclase phenocrysts as well, involving carbonate +/- other (?) minerals. There is no evidence of significant metamorphism and/or structural deformation.

Salient features of this thin-section are shown in the following photomicrographs (figures A-5 to 8).

Conclusions

As anticipated when they were selected for this study, these specimens represent two somewhat disparate types of igneous rocks.

The quartz-bearing diorite/quartz diorite (TM 92-4-24-2) may be considered an example of the "granitoid" type, consisting of a medium-grained interlocking mosaic of common rock-forming silicate minerals (ie., feldspar, quartz, amphibole, biotite) which formed by crystallization from magmatic material. As such, it has physical and engineering properties rather typical of a broad spectrum of "granitoid" rocks, encompassing granites-granodiorites-diorites, as well as, in general aspect, metamorphosed/gneissic varieties/equivalents of such rocks. As discussed above, these are the lithologies inferred as being most likely to be present beneath the Inland Ice within the central Greenland study area.

The porphyritic andesite (TM 92-4-20-1), on the other hand, is representative of "volcanic" igneous rocks. In terms of general physical and engineering properties this can be taken to encompass the spectrum of "mafic"/basaltic-"intermediate"/andesitic-dacitic lithologies. As discussed in the above report, such rock types might also be anticipated, alternatively to, or in association with, the "granitoid" type, beneath the Inland Ice within the project study area of central Greenland.

Thus, these two specimens seem to be reasonable materials for purposes of developing engineering methodologies and equipment to facilitate sub-ice rock sampling, in the context of the present project.

Petrographic analyses are in progress on a suite of "granitoid" samples collected from outcrops within the Nagssugtoqidian terrane of western Greenland, in order to provide additional insights as to rock characteristics related to engineering as well as geological aspects of this project.

6. References

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FIGURE A-1. Photographed at 1X magnification, in plane polarized transmitted light. Presents an overview of fabric and textural relationships. Dark grains principally hornblende or biotite. "Dusty" aspect of many of the other grains represents alteration of plagioclase feldspars. Quartz grains are clear and colorless. Note especially the "interlocking crystalline aggregate" aspect of this specimen as viewed in thin-section. The relatively few fractures to be seen trend approximately parallel to the shorter edges of the photograph. Printed photograph = 4.4X

FIGURE A-2. Photographed at 1X magnification, in transmitted light, using crossed polarizing filters. Same view as figure A-1. Hornblende and biotite appear, variously, orange-greenish-brownish. Twinned, zoned plagioclase grains in various shades of white-grey-black. Quartz grains range white-grey-black. Note the "interlocking crystalline aggregate" character of the specimen. The relatively few fractures in this thin-section trend at a slight angle to/sub-parallel to the shorter edges of the photograph. Printed photograph = 4.4X.

FIGURE A-3. Photographed at 12.5X magnification, in transmitted plane polarized light. Hornblende (greenish-brownish), plagioclase ("dusty" grains), quartz (clear) and opaque magnetite/ilmenite (black) intimately intergrown. The hornblende shows apparent poikilitic aspects here. Printed photograph = 55X.

FIGURE A-4. Same view as figure A-3, photographed in transmitted light using crossed polarizing filters. Shows the moderate alteration (principally sericite), as well as the twinning and zoning of the plagioclase feldspar grains. Printed photograph = 55X.
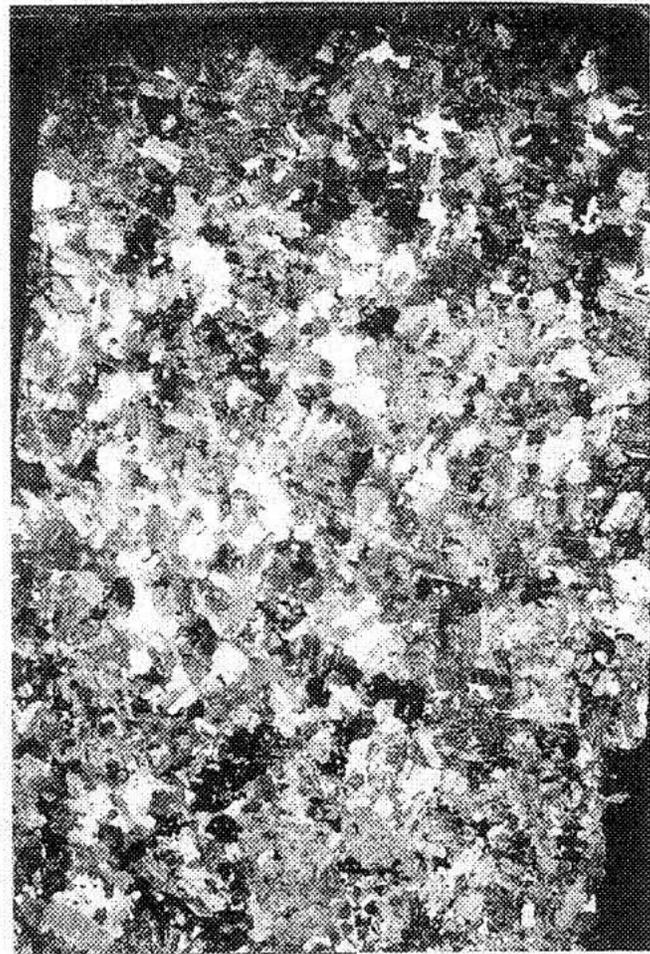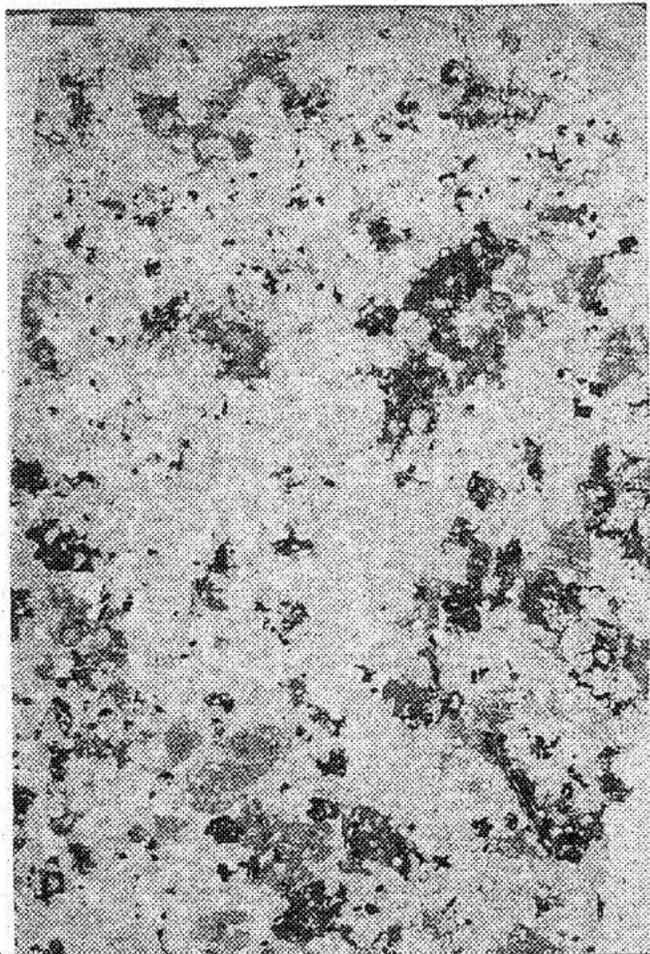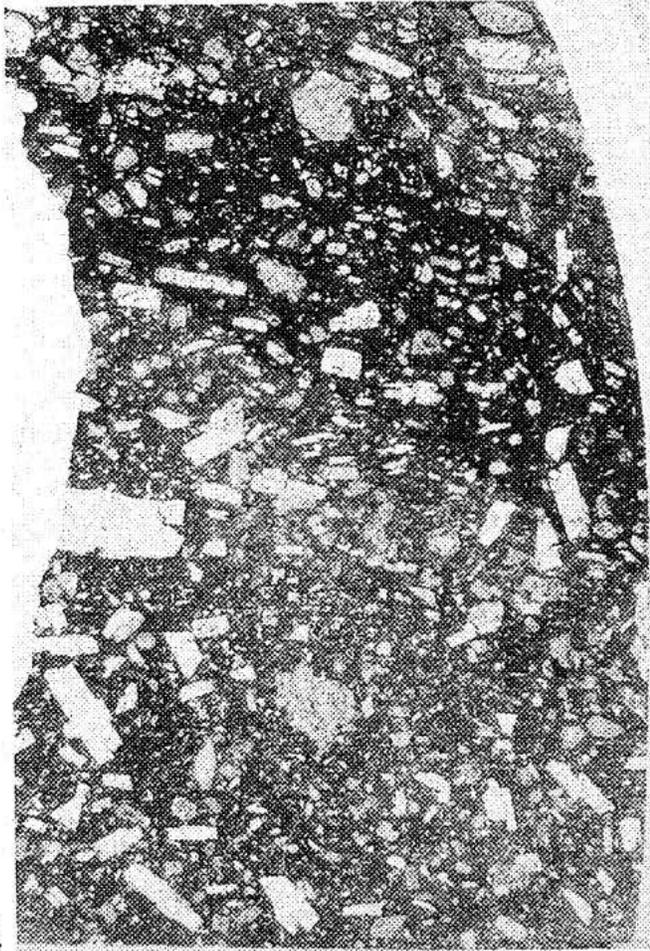
1.

3.

FIGURE A-5. Photographed at 1X magnification, in transmitted plane polarized light. Printed photograph = 4.4X. An overview, illustrating the general fabric and textural aspects of the sample. Phenocrysts readily evident are predominantly plagioclase (clear, subhedral-euhedral), with subordinate pyroxenes ("clouded"- colored aspect). Note the darker character of the sample on the left side of this thin-section photomicrograph. This is the "rind/crust" where the rock has undergone some oxidation/weathering, principally affecting the roundmass. Figures A-7,8 depict areas within the lighter portion of this thin-section.
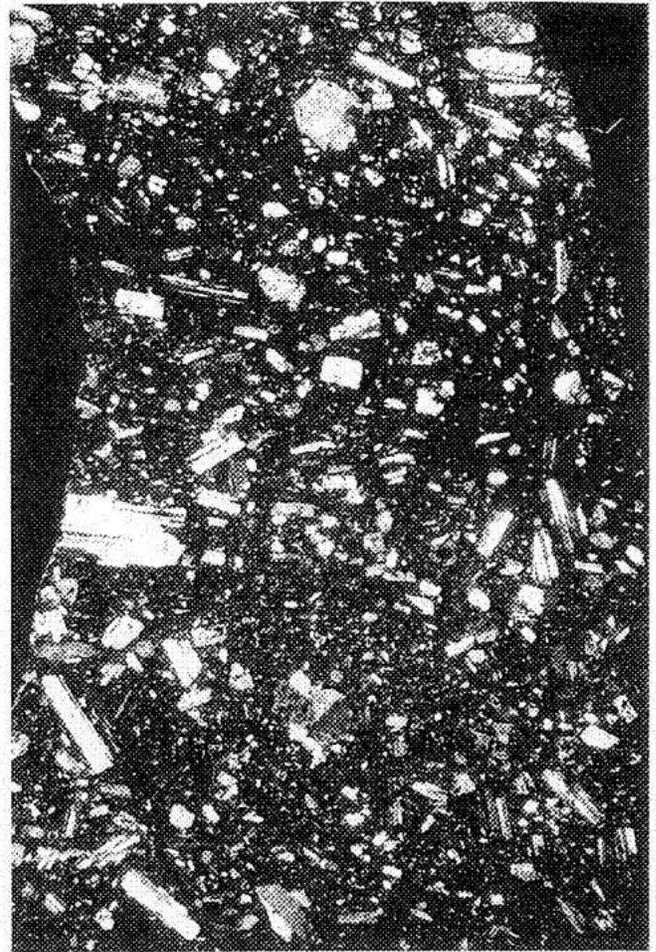
FIGURE A-6. Photographed at 1X magnification, in transmitted light, using crossed polarizing filters. Printed photograph = 4.4X. Same view as figure A-5. Groundmass is dark. Plagioclase crystals appear variously white-grey-dark. Pyroxenes appear in shades of orange-yellow-red-blue.

FIGURE A-7. Photographed at 12.5X magnification, in transmitted plane polarized light. Printed photograph = 55X. Groundmass dark, with disseminated crystals of plagioclase and pyroxene evident. Phenocrysts of pyroxene (note characteristic crystal outlines, cleavage) and plagioclase (slightly altered- "dusty" appearance).

FIGURE A-8. Same view as figure A-7, photographed at 12.5X magnification, using crossed polarizing filters in transmitted light. Printed photograph = 55X. Groundmass dark, except for scattered birefringent crystals resolvable at this magnification (plagioclase, pyroxenes). The phenocrysts of pyroxene (red-orange = clinopyroxene; yellow = orthopyroxene) and plagioclase (twinned; in shades of white-grey-black) are clustered in typical glomeroporphyritic textural relationships.
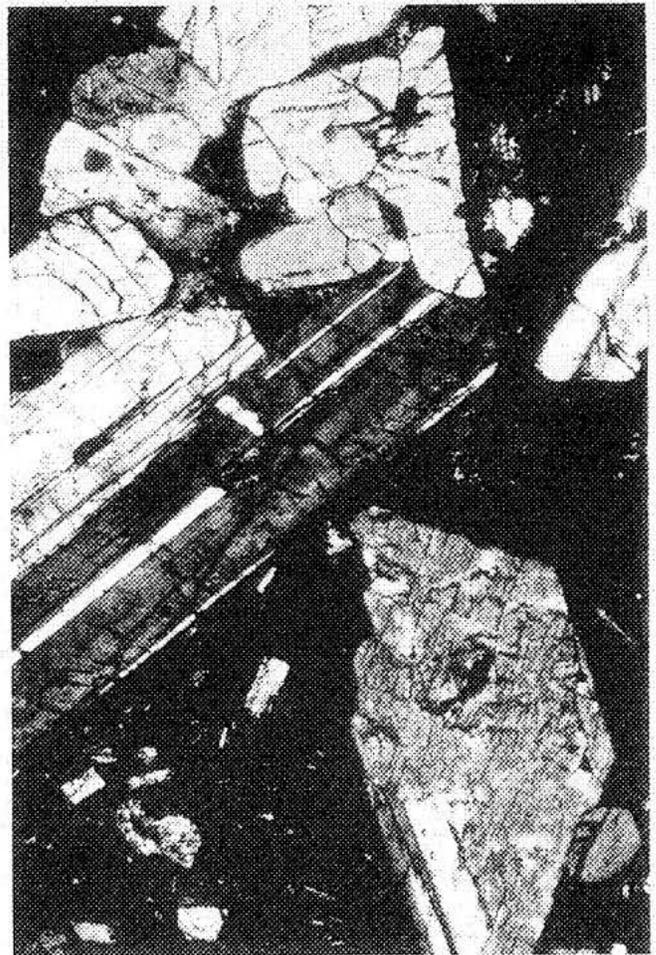
5.

6.

7.

8.