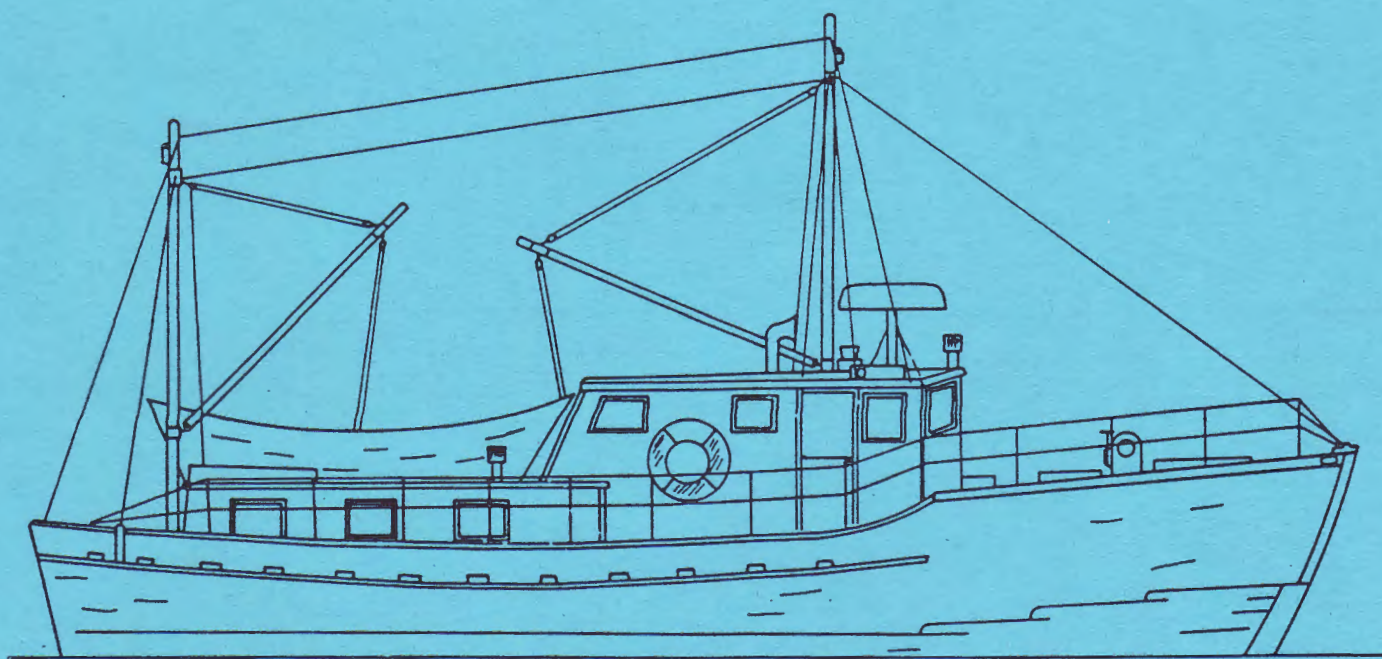


THE NAIN ANORTHOSITE PROJECT, LABRADOR: FIELD REPORT 1971

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THE NAIN ANORTHOSITE PROJECT, LABRADOR:

FIELD REPORT 1971

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INTRODUCTION

The anorthosite problem poses great challenges both to petrologic theory and to the study of field relations. Past speculations on anorthosite have suffered from a lack of information about anorthosites in areas where they are not metamorphosed. Both logistics and the understanding of field relations are made difficult in these terranes by the large physical scale of the anorthositic massifs. In recognition of this, a field facility for crustal studies near Nain, Labrador, was established in 1971 with NSF support, and a pilot season of coordinated geological field and laboratory research was successfully completed. This report describes the inception and first season's operation of the Nain Anorthosite Project as a vehicle for scientific discovery and the training of students.

Anorthosites are prominent among the igneous rocks of Central Labrador, and a forthcoming guidebook (Emslie, Morse, and Wheeler, 1972) furnishes a review of their geologic setting, salient problems, and field relations. Anorthosites and their associated intrusive rocks form the only deep-seated intrusive bodies of batholithic size apart from those of the granite kindred. Unlike granites, however, anorthosites appear to occur only in special places and within a special time interval in the geologic record. For example, in North America they occur chiefly in a belt from Labrador through the Adirondacks to Virginia, and in India, in a belt along the Eastern Ghats; their worldwide age distribution is chiefly in the interval 1100 to 1500 million years.

The central problem of anorthosites is that they appear to have compositions unmatched by any known lava, yet they are demonstrably igneous rocks. The alert reader may well ask whether we know the actual composition of anorthosites, not to mention their parent magmas, and the answer is, of course, that we do not. Accurate mapping is a prerequisite to determination of their composition. Although argument has raged for more than half a century over the origin of these rocks, few detailed maps of them have ever been published, because of their enormous size, complexity, and inaccessibility. Those detailed maps which do exist treat the more readily accessible bodies which happen to be metamorphosed and of small size. In North America only the major bodies of central Labrador have

escaped the 1-billion year old Grenville orogeny which elsewhere has compounded the complexity of field relations. The more southern of the unmetamorphosed Labrador bodies at Michikamau and Harp Lakes are under study by Emslie (1970, 1972). The Nain anorthosite has been studied over a period of more than 40 years by Wheeler (e.g., 1968), whose manuscript mapping now serves as the basis for this Project.

Rocks of the Nain area are superbly exposed along shorelines of the myriad islands lying off the mainland, and in the deep bays. This setting commends the use of a research vessel for logistic support, laboratory studies, and coordination of diverse research projects over a wide area. R.V. Pitsiulak was therefore constructed for the purpose, and used to good effect as soon as she was available. The operational section of this report describes these activities in more detail.

The origin of anorthosite and related rocks can be viewed as a focal point in the much broader problem of the evolution of continental crusts in general and of the mid-Precambrian in particular. Without being extravagant in our predictions, we can at least assert that an understanding of anorthosite genesis is necessary to an understanding of crustal evolution. Furthermore, in coming to understand anorthosites, we shall need to understand their geologic setting in all its variety. The recent discovery in Greenland of the earth's oldest known rocks, formed nearly 4 billion years ago (Oxford, 1971) and by restoration nearly on strike with the country rocks of the Nain anorthosite, carries with it the outside chance that our studies may span some three-quarters of the earth's recorded geologic history. It is therefore fitting that our scientific report begin with de Waard's description of the country rocks and anorthosite contact relations near Ford Harbour, in an area of excellent shoreline exposure. This is the first systematic study of the stratigraphy, structure, and petrography of the rocks into which the Nain anorthosite was emplaced, and it promises to serve as a useful anchor onto which field relations in this region may be tied. De Waard recognizes in what he names the Ford Harbour Formation a variety of metasedimentary units containing cordierite, hypersthene, garnet, and sillimanite, as well as ultramafic remnants and pyroxene granulites. The formation as a whole is a migmatite of enderbitic (hypersthene tonalitic) nature. A structural analysis of the formation reveals intense folding away from the anorthosite, but surprisingly simple folding near the

generally conformable anorthosite contact. This unexpected result leads de Waard to the conclusion that complexity of folding in the country rocks was acquired after the anorthosite contact was established.

Against the Ford Harbour Formation, de Waard has mapped a well-exposed anorthosite contact over a distance of some 10 km, and this appears to constitute the world's first good view of an uncomplicated and undisturbed anorthosite contact. The contact is sharp and clearly intrusive. Working inward from the contact, de Waard was able to establish a sequence and a classification of marginal anorthosite facies based on average grain size and texture. Age relations among the various facies testify to the complexity of the emplacement history, and furnish much promise for an understanding of magma evolution and igneous depositional history within the anorthosite complex. A layered intrusion in the northern part of de Waard's area (West Red I.) cuts anorthosite and intersects structural trends in the country rocks.

Wheeler, in a season largely devoted to peripatetic consultation on research problems, was nevertheless able to extend his mapping to critical areas not illuminated by past work, and to initiate a regional study of giant pyroxenes, which appear to pose some uncomfortable paradoxes between composition and inferred relative age. His work on the outer islands of the eastern contact zone revealed yet another anorthosite contact zone encumbered by younger, dioritic rocks of the adamellite series, as well as an agmatite of pure anorthosite blocks in a noritic anorthosite matrix. Some of the contact locations in this region agree with the hypothesis of left-lateral displacement on the east-west linears which cross the Nain area.

An unusual and puzzling layered intrusion was discovered by Woodward on the southern end of Aulatsivik (Newark) Island. The western part of the island is underlain by anorthositic rocks, which occur in contact with country rocks at the southeastern extremity of the island. The eastern part of the island is underlain by the new layered intrusion, which is characterized by nearly vertical layering, a locally high mafic content (augite, olivine, and opaques), and intermediate mineral compositions such as andesine, hortonolite, and hypersthene. The intrusion appears to be noritic in the west but of melanocratic ferrodiorite composition in its eastern part. Top determinations from igneous layering are conflicting, and yield no unambiguous conclusions as yet. The intrusion appears to have

a mineralogical and chemical composition unlike any previously discerned in the Nain area, and may be expected to extend the range of magma compositions associated with the Nain anorthosite if sufficient exposure exists for a reasonable assessment to be made.

The central contact zone of the Nain anorthosite occurs along a southerly-protruding tongue of country rocks enclosed by anorthosite. The Barth Island troctolite body occupies the southern part of this zone, and the relations among granulites, anorthosite, troctolite, and adamellite associated with this body form the substance of a doctoral dissertation in preparation by Rubins. In the present report, Rubins summarizes the evidence for a three-fold classification of granulites around the southern part of the Barth Island body and extends his work across Nain Bay to the northern margin of the body. The 1971 work reveals an intimate relationship among all the rocks which cut anorthosite, most spectacularly seen in the confinement of the later adamellite to a narrow outcrop belt marginal to or slightly within the troctolite. A fine-grained norite margin of the troctolite also occurs, and it, too may be a later intrusion. Rubins was able to confirm his earlier assignment of enderbitic granulites to the country rock sequence, both on petrographic and structural grounds. The sum of this work provides valuable insight into criteria for recognizing granulites of diverse origin but similar field aspect, and into the mechanics of emplacement of rocks cutting anorthosite.

A somewhat different but closely related type of marginal granulite problem was encountered by Berg in the Hettasch Lake area, well to the north of Rubins' area and on the eastern flank of the central tongue of country rocks. Working from his master's thesis conclusions regarding the paradoxical Outer Border Zone of the Kiglapait layered intrusion, Berg began a comparative study to trace the suspected extension of this unit southward along the anorthosite margin. An unambiguous correlation proved elusive, owing either to faulting, termination, or lateral gradation of the diagnostic OBZ lithology. The anorthosite margin, however, contains a new and highly interesting sequence ranging inward from a very narrow, very fine-grained gabbroic margin, to a subophitic olivine gabbro, to a layered troctolite, to very coarse-grained noritic anorthosite. If petrographic evidence should show this to be a temporal as well as a stratigraphic sequence, which appears possible from the field relations, this would

strengthen the evidence that anorthosite was produced by a magma which also produced troctolite at another time or place. Despite an abbreviated field season, Berg was able to map an extensive region of the anorthosite margin, and to lay the basis for a very promising comparative study.

The internal parts of the Nain anorthosite locally exhibit layering on several scales. A conspicuous but hitherto little-known layered zone near The Bridges Passage was examined by Planansky, and his work shows this zone to be highly complicated in its age relations to the anorthosite. The zone is essentially a homoclinal, noritic layered series, but one which varies from pristine igneous cumulate textures in some places to highly granulated and deformed layering in other places. Relations of the zone to anorthosite are both conformable and cross-cutting, depending on locality. Although much evidence remains to be assessed, Planansky's field work has led him to suggest, among other models, a hypothesis that this zone represents a partly older but allocthonous layered series which slid cohesively into contemporaneously crystallizing anorthosite. Whether it survives detailed scrutiny or not, this interesting plutonic analogy of well-known supracrustal tectonic and stratigraphic problems currently appears attractive, and furnishes a fresh outlook on some of the perplexing age relations among intrusive rocks of the Nain massif.

Rhythmic layering in anorthosite itself was confirmed for the first time in the Nain area during the 1971 season, in the course of logistic operations with R.V. Pitsiulak. A brief report on this discovery is given by Morse in a section on Miscellaneous Topics.

An elongate layered intrusion of modest size crops out on the south part of Nukasorsuktokh I. Troctolite dominates the rock types and grades upward into norite pegmatite. Weakly developed layering suggests that the intrusion is upright. The existence of a fine-grained margin against anorthosite, coupled with a generally fine to medium grain size, give some hope that the bulk composition of the intrusion can be specified, leading to a further characterization of the magma types which were associated with late stages of the Nain massif. A brief report by Speer and Morse serves to state the problem as it is now known, and to illustrate some of the petrographic problems which make laboratory control of field work essential in this area.

It is interesting to note that seven hitherto unstudied layered intrusions or parts thereof were examined in the 1971 field season, and of these only two were known to be layered or to exist prior to the season. The seven intrusions studied are located at Aulatsivik, Barth, Bridges, Hettasch, Nukasorsuktokh, Tikkoatokhakh, and West Red I. The two previously known to be layered are Barth and Bridges, and of the others, only Nukasorsuktokh was known with any clarity. The layered bodies range from anorthosite to dark ferrodiorite in composition, with troctolite and norite being the most common. One or two (Bridges and perhaps Hettasch) appear to be slightly older than anorthosite, and the rest are younger minor intrusions. The existence of layered anorthosite itself provides an important link with Michikamau and Harp Lake (Emslie, et al, 1972), and may help to clarify the gross internal structure of the anorthosite massif as well as to provide stratigraphic control on mineral variation. The mineral variation in turn should help in evaluating various flotation and accumulation hypotheses for anorthosite. The younger intrusions can probably be regarded as indirect samples of the mantle source regions of the anorthosite suite as a whole, and they should ultimately provide important boundary values for these regions. Together, the layered bodies serve to emphasize that the anorthosite massif is composed of many plutons with complex and overlapping emplacement histories, and to encourage field workers to seek further criteria whereby anorthosite plutons themselves may be delineated from one another.

The miscellaneous topics covered in this report include Wheeler's giant pyroxene study and Morse's description of layered anorthosite, already mentioned. Upton describes a reconnaissance study of basic dikes in the region, which have importance for the characterization of late-stage volcanic and tectonic activity which may be correlated with that in Greenland. On another topic of regional interest, Morse documents the unconformity at the base of the Snyder group, a younger and distinctive meta-sedimentary-volcanic sequence resting on the Archean basement northwest of the Kiglapait intrusion. Xenoliths resembling these supracrustal rocks are described from a dike cutting the Barth Island troctolite body in de Waard's report. A small xenolith of apparently tonalitic gneiss, discovered by Berg in the Upper Zone of the Kiglapait intrusion, is discussed

briefly by Morse in terms of its implications for anatexis by basic magmas in the Nain area. In a final part of the geological report, brief comments are offered on the petrographic methods used aboard R.V. Pitsiulak.

The second half of this field report concerns operational details; it includes a narrative statement and comments on hydrography, weather, flying, subsistence, and other matters of operational importance.

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The leaders of the Nain Anorthosite Project have had two clear goals in mind. The first was to establish a modus operandi whereby effective, coordinated geological research could be carried out in a difficult environment by students and others of diverse talents. The results described in this report make it clear that we have made a running start toward this goal. The second goal was to lay a firm foundation of fact upon which reasonable theories of anorthosite origin can be built, and reasonable speculations on crustal evolution in the Precambrian entertained. The realization of this goal lies, of course, at some distance between several years and infinity, depending on the observer and the kind of detail he seeks. Again, however, the very substantial discoveries reported herein by every field worker show that we are well launched on the path of progress. An enormous amount of work remains to be done before the Nain massif and its setting can be adequately described, but with the prospect of continuing NSF support in view, we can at least say that the job no longer looks hopeless. Supporting studies, particularly in geophysics and geochemistry, will be essential, and we wish to encourage and support these to the best of our ability.

We wish here to acknowledge with gratitude the support of the National Science Foundation, our institutions, and our colleagues and others named and unnamed in this report who have helped in the initiation of this project.

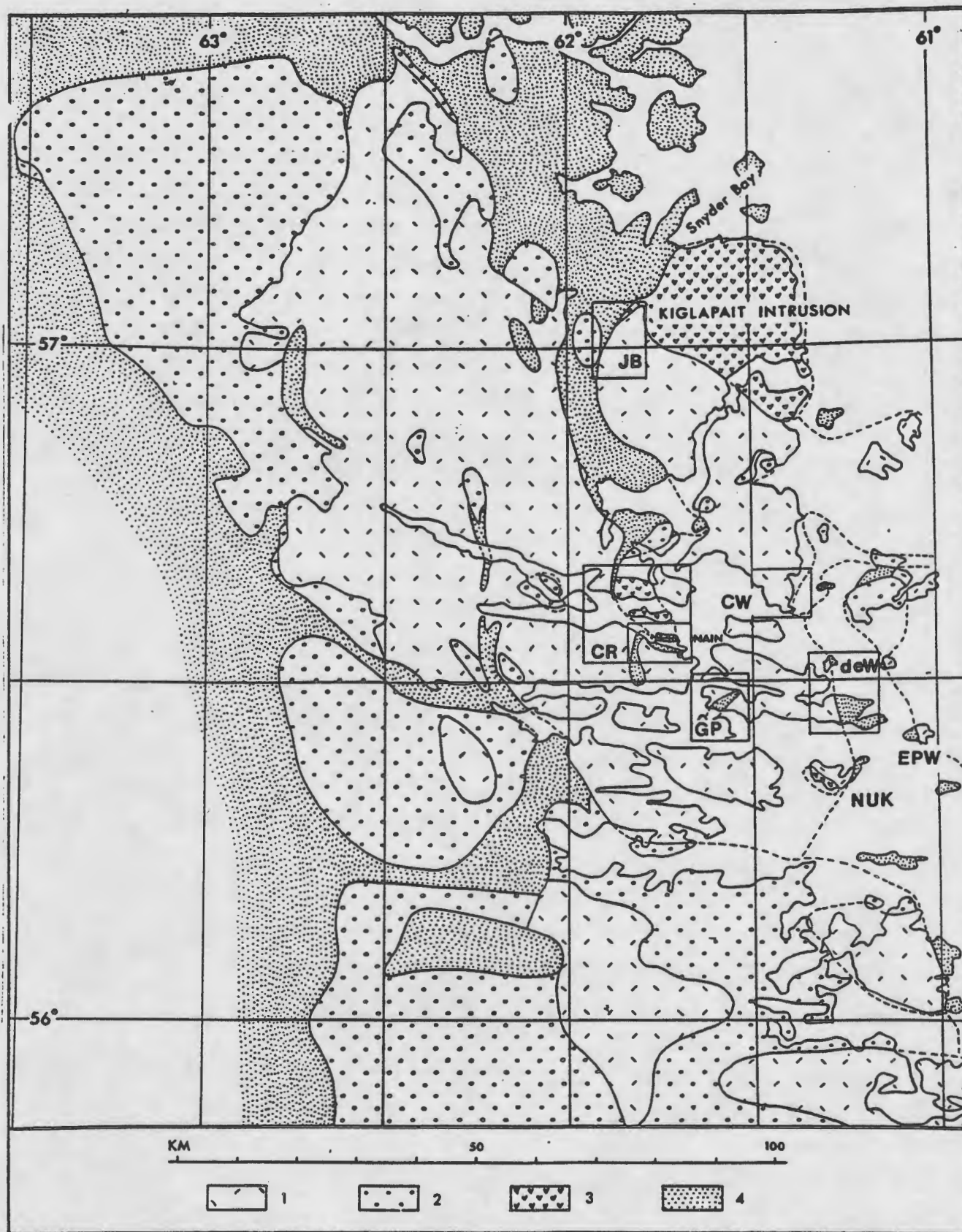


Fig. 1. Regional geology of the Nain area, after Wheeler (1968), showing locations of field areas. KEY: 1. Anorthositic rocks, 2. Adamellite series rocks, 3. Other basic intrusions, 4. Country rocks, including Snyder Group, not shown. FIELD AREAS: JHB, Berg; NUK, Nukasorsuktokh I.; GP, Planansky; CR, Rubins; TIKK, Tikkoatokhakh Rattle; deW, de Waard; EPW, Wheeler; CW, Woodward.

GEOLOGICAL REPORT

GENERAL STATEMENT

The following brief statement on the anorthosite problem in the Nain area is drawn from Emslie, Morse, and Wheeler (1972), and is included here for readers who may not be familiar with the Nain massif and its subdivisions, or with previous work in this area. For a concise discussion of the geologic setting of the central Labrador anorthosites, the reader is referred to the opening statement by Emslie in the guidebook cited above.

The Nain anorthosite complex comprises some 10^4 square kilometers of anorthosite and related basic rocks with a subequal area of intermediate to acid rocks collectively grouped by Wheeler (1955, 1960, 1968) into an adamellite series. Anorthosite in the strict sense (<5% mafics) probably forms much less than half the mass of anorthositic rocks, the remainder being noritic anorthosite (leuconorite) to norite, or more rarely troctolitic anorthosite (leucotroctolite) to troctolite. Some of the hypersthene bearing rocks are leucodiorite or diorite on the basis of plagioclase composition ($<An_{50}$).

Wheeler (1960) has defined three facies of anorthositic rocks: dark, pale, and buff-weathering. Distinction between the facies is not invariably successful, particularly with regard to the first two, but it is generally true that dark gray to black feldspar is associated with olivine as the mafic, contains the lowest K of the three facies, and gives rise to the name "dark anorthosite". Pale anorthosite contains pale gray feldspar, carries hypersthene rather than olivine as the mafic mineral, and has intermediate K content. Buff-weathering anorthosite is normally dominated by andesine and a somewhat elevated color index and K content relative to the other two. It may contain abundant apatite, and its Ca-poor pyroxene is likely to show Stillwater-type exsolution lamellae, suggesting an origin as pigeonite. The sequence dark - pale - buff represents a temporal sequence which can, in places, be demonstrated in the field, although counterexamples may occur. The use of K as a discriminator among the facies stems from the work of Gill and Murthy (1970).

Rocks of the adamellite series range from diorite to granite (norite to charnockite). A clarification of nomenclature, comparing the Johannsen system with the specialized nomenclature of hypersthenic rocks, is given by de Waard (1968, pp. 72-78). Dioritic members locally show transitional relations to anorthosite on the one hand and to more acid members on the other hand. Frequent observation of adamellite series rocks sharply cross-cutting

anorthositic rocks demonstrates the younger age of the adamellite series.

At least seven separate zones of layered igneous rocks occur among the rocks classed with the anorthosite massif. These have compositions of troctolite, norite, diorite and their mafic equivalents, and in one case, anorthosite. Some are closed synclinal structures. Others appear to be monoclinical, easterly-dipping sequences. Layering is only locally developed in some bodies. Contacts with anorthosite vary from sharp and agmatitic to gradational. A single body may show both types. Some layered zones may therefore lie between two generations of anorthosite in age. Others are more clearly post-anorthosite.

The anorthosite massif is manifestly a complex of many smaller plutons emplaced over a considerable period of time. Agmatites, xenoliths, xenocrysts, contacts ranging from sharp to gradational, igneous layered zones, magmatic slump features, and local fractionation trends all bear witness to this fact.

The Kiglapait layered intrusion (Morse, 1969) lies at the northeast corner of a mass of predominantly dark anorthosite. It appears to represent a large, independent pulse of critically undersaturated, low-K basalt magma which then differentiated in place to form a Lower Zone of troctolite and an Upper Zone ranging from olivine gabbro through ferromonzonite to ferrosyenite. The relevance of this intrusion to the anorthosite problem is two-fold. First, the continuous fractionation trend furnishes a limiting model of magmatic fractionation and crystal/liquid element partitioning for comparisons and extrapolations within the anorthosite complex. Second, the Kiglapait marginal granulite (Outer Border Zone) against Snyder group metasediments affords a potentially instructive comparison with similar mafic granulites found at anorthosite margins.

The central problem in the Nain area appears to be the identification of the magma which produced anorthosite, and the mechanism of plagioclase concentration if the magma was not abnormally feldspathic. There are several ways of approaching this problem. One is to identify the areas, volumes, and eventually masses of all rocks thought to be coeval with anorthosite, and to sum their compositions in the appropriate equation. Another is to assume a particular crystal/liquid element partition behavior and so to deduce the nature of the liquid from mineral compositions. A third is to identify chilled margins or their equivalents and analyze them directly, hoping that they fairly represent the main body

of magma. All these methods are being attempted with the Kiglapait intrusion, with hope of applying the resulting models to parts of the anorthosite.

There is disagreement about what rocks should be summed in the first approach. Morse (1968), arguing for a basalt parent magma finds that only a small portion of the exposed adamellite series area can be accommodated in the recipe, and suggests that the relative volume of adamellite series rocks may be far less than their areal extent suggests. de Waard and Wheeler (1971) propose that a single magma may have formed the troctolite-syenite suite at depth while generating the anorthosite-adamellite suite at a higher level. Morse (1972) objects to this model as requiring an oversaturated, K-rich product and a critically undersaturated, low-K product from the same parent. Instead, Morse proposes an alternative working hypothesis of a two-parent model, in which troctolite, anorthosite, and syenite are products of a low-K basalt magma, and the adamellite series rocks are the products of an andesitic magma.

Geophysics and geochemistry may help substantially to narrow the spectrum of working hypotheses. It may be possible through geophysical studies to set limits on the third dimension of both anorthosite and adamellite bodies, permitting the mass coefficients in the chemical summations to be estimated. Rb/Sr chronology, and particularly $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio studies, may help to group those rocks which could and could not be consanguinous.

Field evidence, as always, is the ultimate test of theory. There are strong suggestions in known field relations of a genetic link between at least some anorthosites and some adamellites. In particular, Wheeler (in Emslie et al, 1972) demonstrates, in the Lower Khingughutik Brook traverse, an apparent transition from buff-weathering anorthosite to fayalite-orthopyroxene adamellite. Planansky, at the Bridges, and de Waard, at Higher Bight, report the presence of interstitial quartz-K feldspar-biotite granophyre within very coarse norite pegmatite zones in noritic anorthosite. Finally, there are persistent examples, still inadequately documented, of transitions from troctolitic margins to noritic interiors near anorthosite and other basic rock contacts (see for example Berg, herein). These appear to demonstrate an important role of olivine fractionation in generating silica-saturated residual liquids. Field evidence,

then, tends to support the de Waard - Wheeler model of a genetic link among all the major rock types: troctolite (-syenite) - anorthosite - adamellite, although whether this continuum will withstand close geochemical scrutiny remains to be seen.

Collateral Studies

The oxygen isotope chemistry of Nain and Kiglapait rocks and minerals has been reviewed by Taylor (1968), who finds "normal igneous" oxygen isotope ratios throughout.

Strontium isotopes in Wheeler's collections have been briefly examined by Heath and Fairbairn (1968), who describe an initial ratio of 0.7055 for anorthosite. Several samples of adamellite show abnormally high (0.740) $\text{Sr}^{87}/\text{Sr}^{86}$ ratios, implying prior contact with a strongly rubidium-enriched source whose identity as yet escapes detection. A detailed investigation of Rb and Sr in the Nain area was begun in 1971 by J. M. Barton and C. Brooks of U. Montreal.

Potassium, rubidium, barium, and strontium abundances in Nain feldspars have been examined by Gill and Murthy (1970). These authors report high K/Rb ratios typical of anorthosite elsewhere, and find no convincing trend of K/Rb with fractionation.

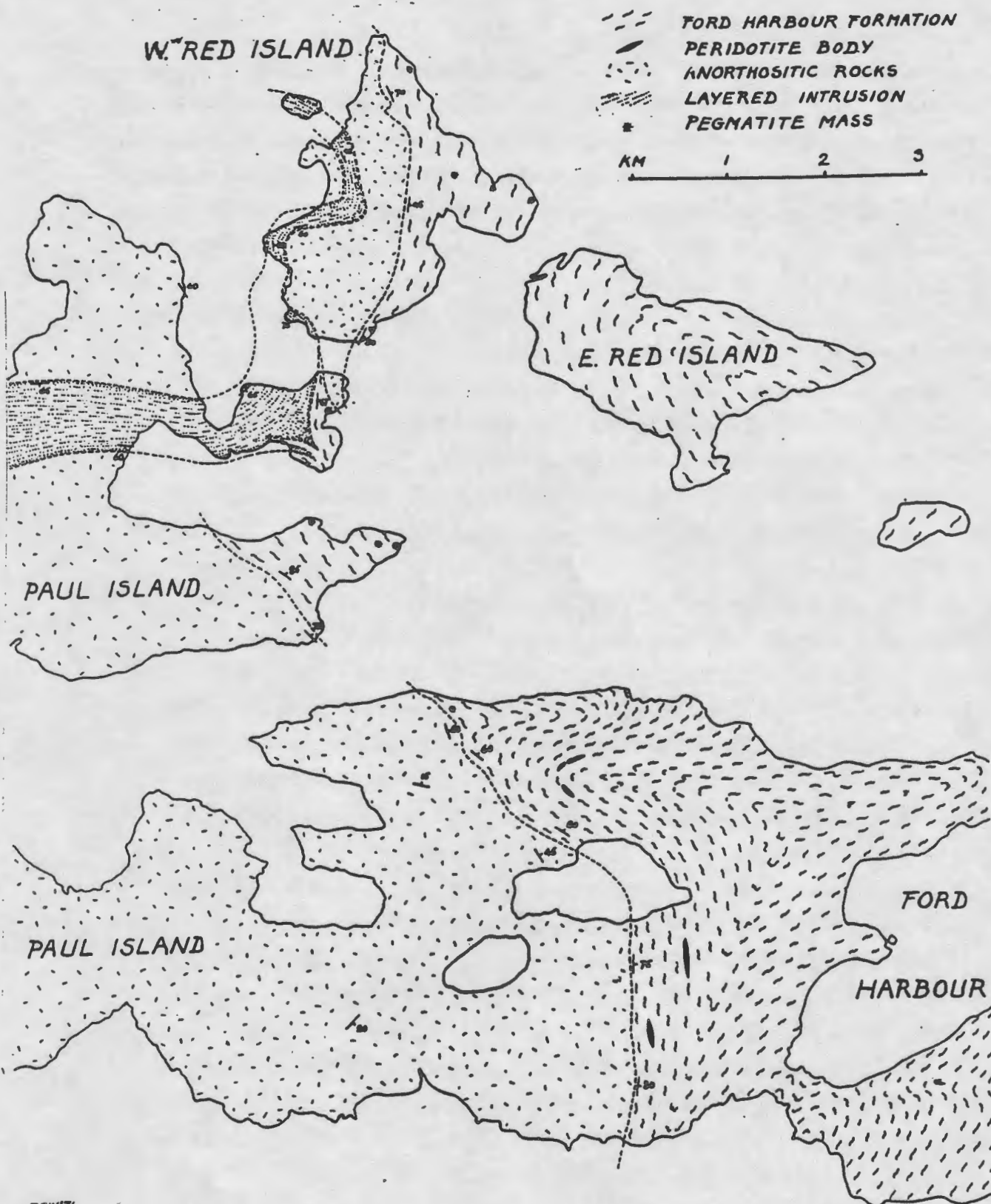
Potassium and rubidium in the Kiglapait intrusion have been studied by Morse and Davis (1969, and in preparation). Despite concentration of both elements over several orders of magnitude during fractionation, no important change occurs in K/Rb, which is high in all rocks, averaging about 1600 for the intrusion.

Iron-rich pyroxenes in adamellite, and their reaction relations to olivine and silica, have been studied by Wheeler (1965) and Smith (1971), who shows that some of the opx-cpx pairs in Wheeler's samples are the most iron-rich on record. Smith, arguing from textural considerations, concludes that the iron-rich orthopyroxenes in Wheeler's collections must have been stabilized by pressures in the neighborhood of 5 Kbar.

The oxygen fugacity during crystallization of the Kiglapait intrusion has been estimated by Morse and Stoiber (1966 and in preparation), using the Buddington-Lindsley oxygen barometer. The evidence for a closed-system model is good, and oxygen fugacities somewhat below the experimental

fayalite-magnetite-quartz buffer are inferred.

Rare earth elements in the Kiglapait intrusion have been analyzed by Haskin (Haskin and Morse, 1969). They show a normal pattern of fractionation correlated with stratigraphic height, particularly a strong positive europium anomaly at the base, yielding upward to a negative europium anomaly caused by the early extraction of plagioclase.



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Fig. 2. Geologic map of the eastern part of Paul Island showing lithologic relationships at the contact of the Nain anorthosite massif with the Ford Harbour Formation.

EASTERN CONTACT ZONE

COUNTRY ROCK OF THE ANORTHOSITE MASSIF AND ANORTHOSITE
CONTACTS IN THE FORD HARBOUR REGION

Dirk de Waard
Syracuse University

Contents

Introduction
Ford Harbour Formation
Anorthositic rocks in the eastern border zone of the Nain massif
West Red Island layered intrusion
Contact between the anorthosite massif and the country rock
Discussion and tentative conclusions

Introduction

The purpose of this study is to determine the effects of the anorthosite massif on its country rock, and the effects the country rock may have had on the intrusion. The investigation involves the lithologies, the structure, and the grade of metamorphism of the country rock east of the Nain anorthosite massif in the general region of the eastern end of Paul Island, and the contact relations between country rock and rocks of the anorthosite massif. Country rock and rocks of the massif were sampled systematically in this region in order to determine in the laboratory variations in rock and mineral compositions. The general geology near Ford Harbour is shown in Fig. 2.

Ford Harbour Formation

The country rock in the investigated area is predominantly enderbite, a leucocratic, orthopyroxene-bearing metamorphic rock, chemically of tonalitic composition. Throughout the region the enderbite is interlayered with dark-colored pyroxene granulites. Locally there are layers of quartzite, cordierite and garnet-bearing granulites and gneisses, and ultramafic rocks of various composition. In order to distinguish this group of lithologies from other rock series occurring as country rock of the Nain anorthosite massif, it is here named the Ford Harbour Formation, after the large bay at the eastern end of Paul Island, where the formation is excellently exposed. Lithologies of the Ford Harbour type extend for at least 200 km along the coast. There is a possible correlation with the very similar gneisses at Hopedale, 150 km to the south.

The enderbite is a yellowish white, medium-grained, quartz-andesine rock, containing orthopyroxene subordinately. Locally the orthopyroxene has altered to cummingtonite. The rock is characteristically layered, on the scale of centimeters, having various ratios of mineral constituents from layer to layer, with the mafic minerals inversely proportioned to quartz. Locally the rock contains cordierite, forming a cordierite-quartz-plagioclase granulite, or a biotite-cordierite-quartz-plagioclase gneiss. In a few places garnet was found in addition to the minerals mentioned. Another, more common variation is an increase in quartz content, resulting locally in the occurrence of thick layers of quartzite. In one locality the quartzite contains 1 to 5 mm-thick layers of sillimanite.

The pyroxene granulites are dark, fine-grained, pyroxene-plagioclase rocks which are commonly layered, showing intense folding similar to that in enderbite. There are at least three types of pyroxene granulites. There is the layered concordant type which grades into the layered enderbite. Secondly, there are thicker and more massive layers of pyroxene granulite which appear to be concordant, but are generally strongly boudinaged. And thirdly, there are irregular dike-like bodies of pyroxene granulite which clearly intersect the layering of the enderbite and the layered pyroxene granulite. Also this type is a metamorphic rock and shows foliation.

The ultramafic rocks are found in two types: pyroxenites which occur in decimeter- to meter-thick layers, generally boudinaged, throughout the

Ford Harbour Formation, and peridotites which occur in lenticular bodies, up to 50 m thick, apparently at a certain stratigraphic level in the Ford Harbour Formation. The pyroxenites typically have a varied composition, with one or two pyroxenes, olivine, biotite, and plagioclase. They are distinctly foliated and commonly compositionally layered. The peridotites have a more massive appearance and a specific composition in which a Mg-olivine is the predominant mineral. Bodies of this rock show foliation only marginally. They weather to a characteristic bright yellow-brown at the surface.

The structure of the Ford Harbour Formation is one of intense folding (Figs. 3 and 4). Large, plastically deformed isoclinal folds have been traced in the investigated area. Crests of the major folds are generally formed by secondary isoclinal folds. Fold axes are strongly curved over short distances. The style of deformation found regionally is reflected on outcrop-scale by the flow-folding of the finely layered enderbite. The ductile behavior of enderbite contrasts with the boudinaged nature of interlayered mafic rocks, especially of the massive pyroxene granulite and the ultramafic layers. Locally, the combined effects of rheomorphism and rock flow has given the rock an agmatitic appearance, due to blocks of various kinds of mafic and ultramafic rocks in a matrix which is essentially an almost homogenized enderbite.

High-grade metamorphism of the Ford Harbour Formation in the investigated area is demonstrated by the presence of orthopyroxene in enderbite, pyroxene granulites, cordierite and garnet-bearing granulites, and ultramafic rocks. Although cordierite is more common, both cordierite and garnet are found throughout the 12 km wide zone of Ford Harbour Formation exposed in the investigated area. Wherever occurring together in a rock they appear to coexist stably, which is diagnostic for the cordierite-almandine subfacies of the granulite facies.

Rheomorphic features, evidencing partial melting of the rock during metamorphism, are ubiquitous in the enderbitic portions of the Ford Harbour Formation. The presence of intergranular granitic melt has indubitably contributed to the flow-style of folding of the rock series. Crocyditic, dictyonitic and stromatolitic migmatites are common everywhere. Nebulitic structures are found locally, and especially near the eastern margin of

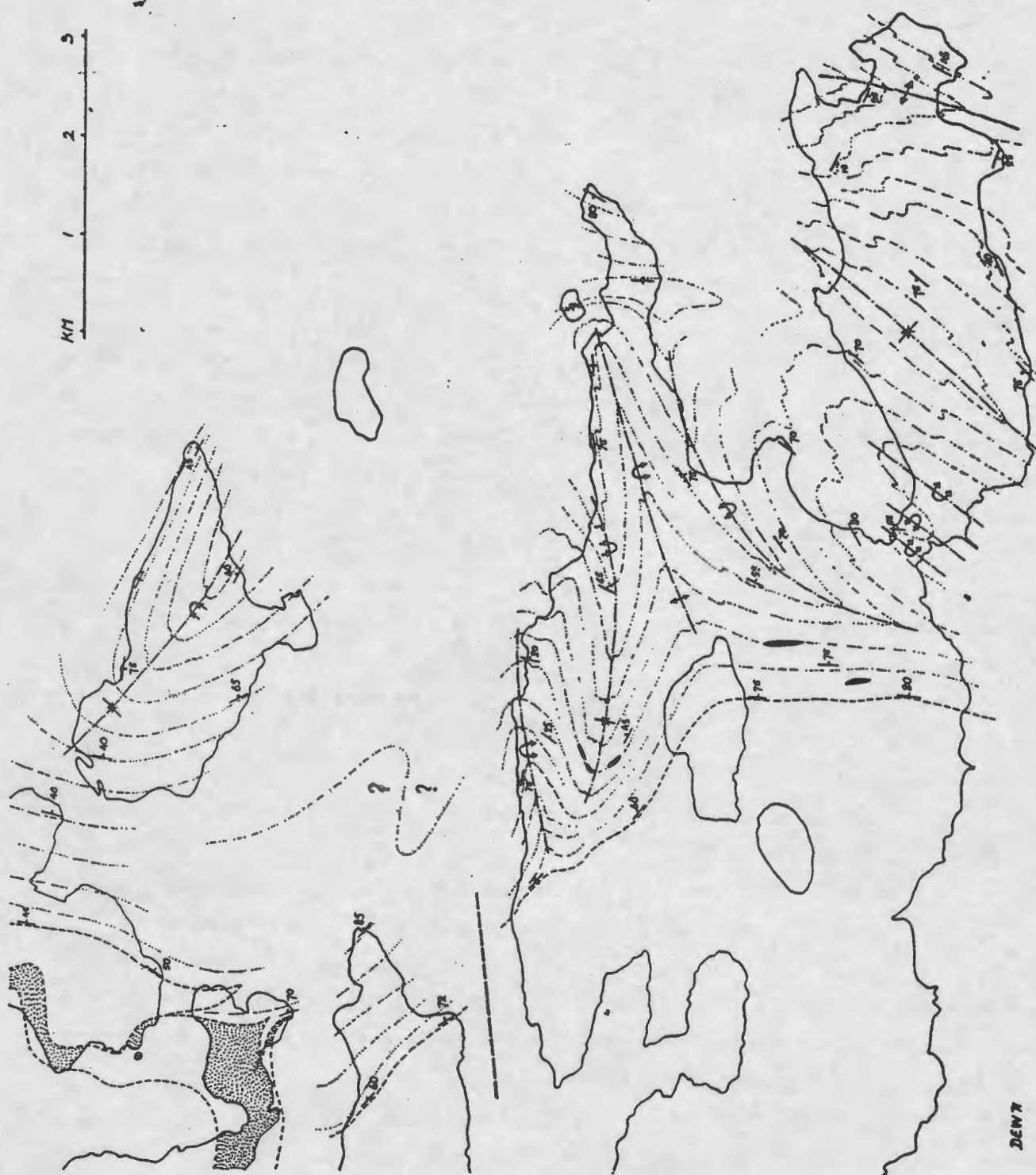


Fig. 3. Structural map of the Ford Harbour Formation at the contact with the anorthosite massif, showing the general attitude and trend of layering, and the traces of axial surfaces of folds. Layering is conformable where in contact with anorthositic rocks, but is intersected by the layered intrusion. Folding of the Ford Harbour Formation becomes more intense away from the contact.

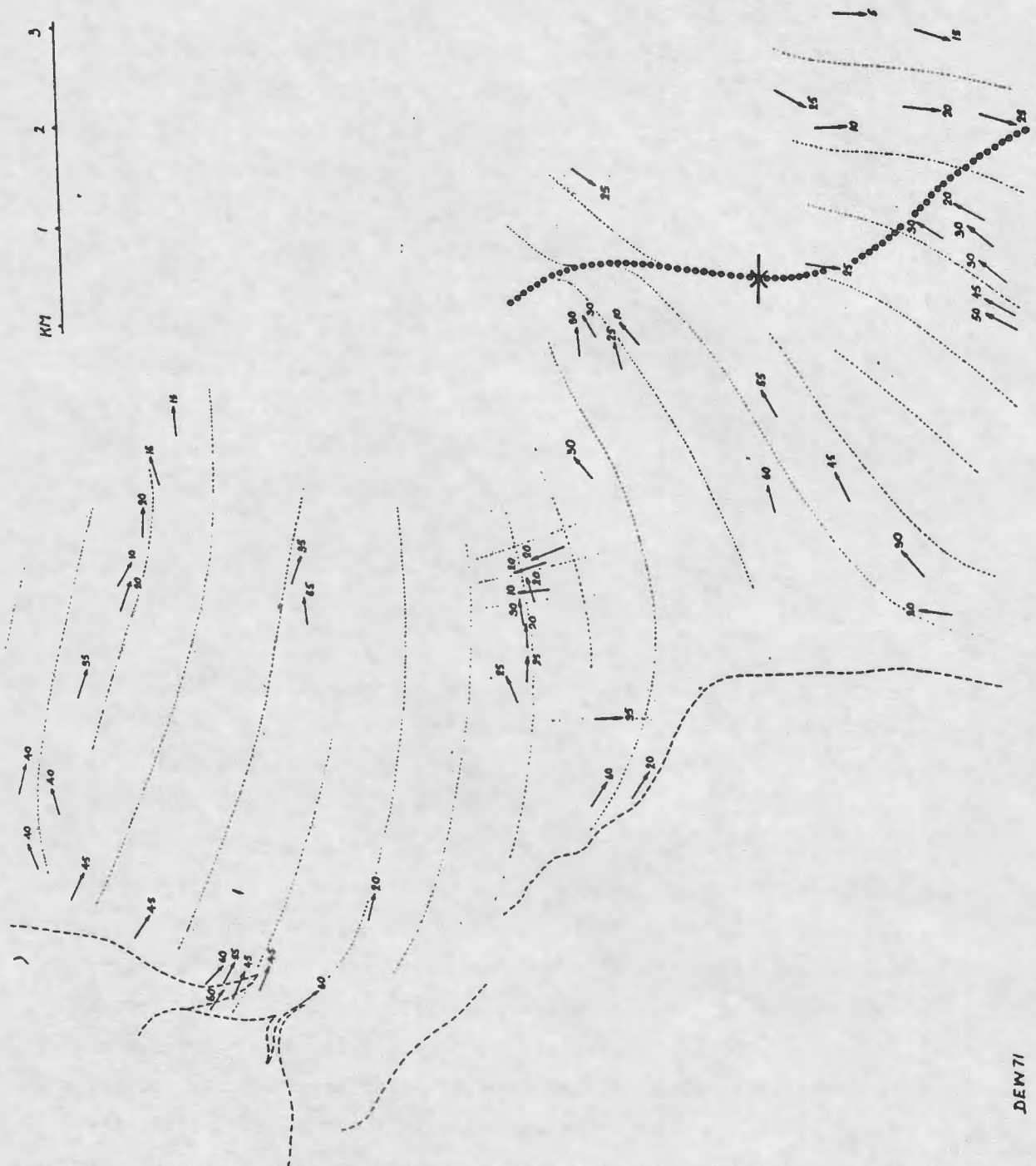


Fig. 4. Attitudes and general trend of mineral lineations, crenulations and minor folds in the same area as shown in Fig. 3. The axial depression, indicated by dots, has an open synclinal form in its southern part, but becomes V-shaped towards the north. The anorthosite massif represents an axial culmination. The structure may be explained by a wedging in of the anorthositic magma mass underneath the Ford Harbour Formation.

the investigated area, where these rocks are in contact with the anorthosite mass to the east. The nebulitic occurrences commonly contain ultraboudinaged blocks of various kinds of mafic and ultramafic lithologies, giving the rock the agmatitic appearance mentioned above.

A supracrustal origin seems indicated for almost all of the Ford Harbour Formation. The persistent, thin layering of the enderbite, effected by considerable lithologic variation, and the interlayering of enderbitic rocks with cordierite and garnet-bearing granulites, quartzite and sillimanite quartzite, speak for a sedimentary origin of the leucocratic portion of the Ford Harbour Formation. The mafic interlayers in enderbite, and possibly also part of the enderbite layers, may have been formed as volcanic tuffs. The thicker and more massive layers of pyroxene granulite are best explained as volcanic flows, sills and dikes of basaltic composition. Finely layered ultramafic rocks probably represent the calc-silicate residue of carbonate intercalations in the formation. The more massive peridotite bodies are presumably Alpine-type ultramafic lenses in the rock series.

The lithologic variability in detail expressed by the thin layering of enderbite, but the monotony of the rock series on a regional scale with the same lithologies occurring over large areas, in addition to the relative paucity of well-sorted sediments and carbonates, and the general predominance of Na_2O over K_2O in the enderbite of the series even if the granitic metatect of the migmatite is included, indicate a graywacke type of origin for the enderbitic part of the rock series. The Ford Harbour Formation may thus represent a eugeosynclinal pile of clastic and tuffaceous sediments interspersed with basic volcanics and ultramafic bodies.

Lithologically very similar to the rocks of the Ford Harbour Formation, and presumably correlative with them, though of lower metamorphic grade, are the rocks north of the Kiglapait intrusion. Here they are overlain by rocks of the Snyder group (Morse, 1969) which display a different set of lithologies, a different style of deformation, and probably a different grade and time of metamorphism. The two rock series are separated by an angular unconformity which is overlain by a basal conglomerate. The Snyder group is known to exist so far only in a narrow zone along the northwestern border of the Kiglapait intrusion. It is therefore

of interest that a large dioritic dike, cutting across anorthosite on Barth Island ($56^{\circ} 36' N$, $61^{\circ} 46' W$), was found to contain xenoliths of:

- (1) layered enderbite identical to that of the Ford Harbour Formation,
- (2) conglomerate containing rounded pebbles of 1 to 5 cm diameter of enderbite and various types of pyroxene granulite in a quartz-bearing matrix,
- and (3) quartzite closely resembling the quartzite occurring in the Snyder group.

Anorthositic Rocks in the Eastern Border Zone of the Nain Massif

The anorthositic rocks in the eastern border zone of the Nain massif in the Paul Island region display the same characteristics as commonly observed elsewhere in this massif as well as in other anorthosite massifs, viz., they are monotonous in a general sense, consisting predominantly of intermediate plagioclase and subordinate pyroxene, but they are greatly variable in detail, i.e., in grain size and in the ratio of mineral constituents. The following classification is an attempt to distinguish between commonly occurring types of anorthositic rocks. The distinctions, based upon field observations only, will be investigated further in the laboratory.

The "1 cm layered anorthosite" is conspicuously small-grained among anorthositic rocks. Layering, which is common, is expressed by planar concentrations of mafic minerals, 4 to 10 cm apart, in the plagioclase mass. The rock as a whole is anorthosite, containing generally less than 5% mafic minerals, but may grade into leuconorite with a higher content of mafic minerals. The 1 cm type was found to occur in place at the contact of the massif, having an attitude of layering concordant to the contact plane. It is also commonly found as inclusions in the following type.

The "5 cm leuconorite" is generally massive, and has a grain size varying from 2 to 8 cm. Mafic mineral content varies greatly from place to place, averaging about 10 or 15%. The mafic minerals are commonly dispersed interstitially, but may be locally concentrated, forming a clotty poikilitic texture. The 5 cm type is probably the most common anorthositic rock type of the Nain massif. It occurs both in a bluish light-gray or pale facies and in a dark gray to black or dark facies.

The "15 cm leuconorite" is the coarser grained or pegmatitic version of the 5 cm type, and commonly grades into it. It occurs in vaguely defined veins and blobs in most of the other anorthositic rock types. Both the plagioclase, commonly iridescent, and the pyroxene, generally orthopyroxene, occur in large crystals which may measure up to 1 m for the euhedral plagioclase, and up to 1/2 m for the subpoikilitic pyroxene. The 15 cm type is common, and occurs both in the pale and in the dark facies. Uncommon as a whole but found in several places are blobs of the 15 cm type which contain a core consisting of large K-feldspar crystals graphically intergrown with quartz, and locally also large quartz grains and biotite crystals.

The "1 cm leuconorite with 1 to 5 cm plagioclase" is an anorthositic rock type with a bimodal frequency of grain sizes. The bluish-gray matrix is leuconorite with 5 to 25% mafic minerals dispersed interstitially among plagioclase grains. The matrix contains darker bluish-gray feldspars of variable grain size and in variable amounts. This type was found over relatively large areas in the investigated part of the Nain massif. The rock commonly contains blocks consisting of large plagioclase crystals, and inclusions of coarse anorthosite. Locally, where inclusions are abundant, the rock has the nature of an agmatite.

Gradual contacts between the distinguished anorthositic rock types indicate that the difference in age between the types is probably not very significant, especially when considering that there is an age of mineral crystallization and accumulation, and one in which the rock consolidated. Observations have shown that the "1 cm layered anorthosite", which commonly occurs as inclusions in the other anorthositic rock types, is the oldest rock type, followed in age by the "5 cm leuconorite" and the "1 cm leuconorite with 1 to 5 cm plagioclase". The age relationship between the latter two has not been established yet. The "15 cm leuconorite", forming veins and patches in the other types, is the youngest among the anorthositic rocks.

Specimens of anorthositic rocks have been taken in a network of 12 sample locations approximately 2 1/2 km apart for a systematic laboratory study of mineral compositions in the investigated area. The study aims to determine (1) whether the observed age differences are reflected in the

compositions of the minerals, and (2) whether there is a systematic regional change in the mineral compositions, which may indicate cryptic layering in the anorthosite mass.

West Red Island Layered Intrusion

Layered intrusions, once regarded relatively rare in the Nain massif, are found to be rather common now that more detailed investigations are being done. One such body occurs on eastern Paul Island and West Red Island. It has been traced over 7 km, and continues southwestward where it has not been mapped yet, and northeastward where it goes out to sea. The body varies in width from 200 to 800 meters. It dips between 40° and 60° to the south and east. To the north and west the body is underlain by the "1 cm leuconorite with 1 to 5 cm plagioclase". Locally this rock is intensely foliated in a plane parallel to the body; shear did not affect the body itself. The lower contact of the intrusion is sharply defined. To the south the body is overlain by dark-facies "5 cm leuconorite". The contact here appears gradational within 10 meters. To the east the body is in contact with the Ford Harbour Formation and with the "1 cm leuconorite with 1 to 5 cm plagioclase" which also underlies it.

The rock types which occur in the layered intrusion range in composition from plagioclase-rich rock to ultramafic rock, with most of the rocks being rather dark, medium-grained, plagioclase-pyroxene rocks, containing locally also olivine and amphibole. Layering is common but does not occur everywhere in the body. Layers, 25 cm to 1 m thick, are the result of a variable degree of density grading, generally showing only a thin accumulation of mafic minerals at the bottom of the layer, but locally also an increasing proportion of plagioclase towards the top of the layer. The body is right-side-up with tops consistently to the south and east.

At this stage laboratory study of rock specimens of the body is needed to establish the variation in rock and mineral compositions, and to determine the possible relations with the underlying and overlying anorthositic rock types. The tentative conclusion is that magma intruded the anorthositic mass along a plane of weakness which is the shear zone indicated by the foliated anorthositic rock. Sufficient width of the body and slow cooling induced the generally weakly developed density-graded bedding of the intrusion.

Contact Between the Anorthosite Massif and the Country Rock

The contact plane between the anorthositic rock of the Nain massif and the Ford Harbour Formation in the investigated area is surprisingly uncomplicated. It runs north-south, straight and vertical on southeastern Paul Island, and, going northward, curves to the west dipping east. Further north, across West Red Island, it curves back to the north-south direction but retains an easterly dip.

The anorthositic rock tends to be finer grained and to have a higher mafic content approaching the contact. The Ford Harbour Formation shows no signs of being more affected by the proximity of the anorthositic body at the contact than away from it. Both the pyroxene granulite and the enderbite are locally found in immediate contact with anorthositic rock. Inclusions of rocks of the Ford Harbour Formation occur in a contact zone about 50 m wide, but become very scarce further away from the contact. Similarly, anorthositic rocks of leuconoritic composition occur as irregular sills and dikes in enderbite and pyroxene granulite in a zone of about 50 m wide along the contact, but are totally absent beyond that limit.

The excellent exposures along the north shore of Higher Bight present a typical section across the contact between the Nain anorthosite massif and its country rock. On the east side the Ford Harbour Formation is exposed, showing the usual alternation of enderbite, here with quartzitic and cordierite-granulite layers, and pyroxene granulite. Along this part of the contact a layered and folded pyroxene-granulite mass about 50 m thick is in contact with the anorthositic rock. The mass contains irregular sills and dikes of dark-grey leuconorite which become more abundant and more substantial approaching the contact. The contact plane with the anorthositic mass is sharply defined. The anorthositic rock at the contact is a fine to medium-grained, dark-facies norite or leuconorite which becomes coarser grained and more leucocratic within meters from the contact, and grades into dark-facies "5 cm leuconorite" about 100 m from the contact. Inclusions of pyroxene granulite are abundant near the contact but become scarce within 50 m from it. Veins and patches of dark-facies "15 cm leuconorite" occur here throughout the anorthositic mass. The cores of some of these patches consist of graphically intergrown K feldspar and quartz with or without biotite books.

One clearly visible effect the anorthositic intrusion had on its country rock is the local production of large pegmatite masses which are commonly accompanied by a discoloration of the surrounding enderbite. The pegmatite consists of large amounts of white quartz, biotite, and red K feldspar in up to 1 meter long crystals. The pegmatite occurs in irregular blobs which grade in grain size and composition into enderbite, the only rock in which the blobs appear to occur. Around the blobs the enderbite commonly has a bright red color which gradually fades with increasing distance from the pegmatite. On a regional scale the pegmatite occurrences are found within a zone which is a little over 1 km wide along the contact with the anorthosite massif. They appear to be most abundant where the contact plane dips below the Ford Harbour Formation, and least so where the contact plane is vertical. The tentative explanation for these pegmatites is that they are late-stage by-products of partial anatexis in enderbite caused by the thermal effect of the anorthositic intrusion.

Discussion and Tentative Conclusions

The lithologic characteristics of the Ford Harbour Formation favor a beginning of the formation as a eugeosynclinal pile of clastic sediments, volcanics and ultramafic rocks. Sparse age determinations (Stockwell, 1968) seem to indicate that the formation was affected by deformation and metamorphism in Kenoran time (2480 m.y.). The magma from which the anorthosite massif developed is thought to have invaded the formation at least 1480 m.y. ago (Morse, 1964).

It is surprising that the magma invasion had so little cataclastic effect on the country rock. The development of a relatively straight and uncomplicated contact plane in the now intricately folded mass of layered rock, almost without cutting across the layering, leads to the following conclusions: (1) Country rock and magma mass attained similar structural mobility. Equal ductility may explain why the two did not mix beyond a very narrow contact zone. (2) Metamorphism, partial anatexis and flow-folding of the Ford Harbour Formation are closely linked with the thermal and deformational history of the magma mass. (3) If the Ford Harbour Formation was affected by the Kenoran orogenic cycle, its effect cannot have

been very severe. The resulting structure must have been simple enough to allow magma to invade conformably, and metamorphism not strong enough to cause excessive dehydration which would have prevented partial anatexis and flow-folding during the magmatic event.

The tentative conclusion is that the magma invaded a weakly deformed Ford Harbour Formation, possibly along a pronounced stratigraphic boundary. In the thermal environment of the magma mass the formation became metamorphosed to a high grade, and underwent partial anatexis which increased the ductility of the formation. Gravitational equilibration may account for subsequent flow-folding of the formation which subsided as the lighter portion of the partially differentiated magma mass pushed its way upward.

Layered intrusions generally consist of olivine-bearing to olivine-rich gabbroic or noritic rock which as a magma invaded anorthositic rock masses. Their presence favors the concept that the anorthositic mass was underlain by undersaturated (troctolitic) magma. Zones of shear, along which intrusion took place, prove that movements occurred between parts of the anorthositic mass. The time of intrusion and crystallization is narrowed down by the observation that in the layered troctolite body of Barth Island occur (1) inclusions of small-grained anorthosite, closely resembling the "1 cm layered anorthosite" which is considered to be an early product of crystallization, and (2) an apparently rare, irregular dike of the "15 cm leuconorite", demonstrating that the surrounding anorthositic mass still contained some interstitial leuconoritic liquid at the time of consolidation of the layered intrusion.

The occurrence of quartz and K feldspar in the core of some of the pegmatitic leuconorite pods indicates that the residual magma after anorthosite production was granitic (or adamellitic) rather than syenitic in composition. The possibility that the quartz and K feldspar in the pods may have been derived by rehomorphism from enderbite inclusions seems unlikely, since enderbite in the contact zone is found unchanged in immediate contact with anorthositic rocks.

One of the final stages of magmatic activity recorded in the investigated area is the formation of large pegmatite blobs in enderbite in a zone along the contact. The blobs cut across the folded layering which demonstrates that the pegmatite was formed after all penetrative movements

ceased. The irregular transitional boundaries of the blobs, on the other hand, indicate that the enderbite was still in relatively ductile state when the pegmatite was formed. The pegmatite may represent the final residual magma of the anorthosite massif, or it may have originated by partial anatexis from enderbite. Because of the localized occurrence in the enderbite along the contact, the latter origin appears more likely. Considering the late stage and relatively low P-T conditions of formation, the pegmatite blobs are best explained as being formed by water vapor initially released by dehydration reactions during progressive metamorphism and used in the formation of anatectic fluid, and finally released during cooling and crystallization of the metatect.

Summary

The observations (1) that the contact of the anorthosite massif is relatively straight, and (2) that the layering of the Ford Harbour Formation, which is intensely folded away from the contact, becomes simply folded towards the contact, and almost everywhere conforms with the contact, lead to the conclusion that the folding of the Ford Harbour Formation became complex after the anorthosite contact was established.

The observation (3) that the metatect of the migmatitic enderbite is intimately involved in detailed folding, demonstrates that metamorphism, anatexis and deformation of the Ford Harbour Formation are largely coeval.

These observations lead to the following sequence of events. Magma intruded conformably a weakly folded Ford Harbour Formation, which acquired a state of high-grade metamorphism, partial anatexis, and high ductility. During magmatic differentiation structural adjustment took place between the lighter portion of the magmatic mass and the heavier country rock, which became intensely folded in the process.

Note 1. Extensive but relatively thin slivers of the Ford Harbour Formation occur with conformable contacts in anorthositic rocks west of Nain. Their presence, form and structure are most easily explained as being detached by the intruding magma from unfolded or weakly folded strata.

Note 2. In the Ford Harbour Formation on Nukasorsuktokh I. near the contact with the anorthosite massif occurs a lensoid sill of leucocratic norite. The rock in the center of the sill is mineralogically, chemically

and texturally similar to the leucocratic norite which occurs in the massif. Along the margins of the sill the rock is granulated and foliated, demonstrating that deformation took place in the country rock after intrusion of the norite.

APPENDIX: PETROGRAPHY OF SOME ROCK TYPES FROM THE FORD HARBOUR AREA

1. WEST RED ISLAND LAYERED INTRUSION

Microscopic examination of specimens from the intrusion demonstrate affinity with the troctolite suite of rocks occurring in the Kiglapait and Barth Island layered intrusions. Specimens NU-92 and 86, described in the table below, are representative of the intrusion. Specimen NU-83-C was taken from the intrusion at the upper contact, and specimen NU-93 is from an intercalated ultramafic layer.

2. PERIDOTITE BODIES IN THE FORD HARBOUR FORMATION

These all consist of dunite, as shown in the table below. A mosaic of olivine grains is somewhat serpentinized along generally pronounced shear planes.

MODAL ANALYSES:	WEST RED I. INTRUSION				DUNITES IN FORD HR. FM.		
	Gabbro NU-83-C	Olivine Gabbros NU-86	NU-92	Pyroxenite NU-93	NU-66	NU-68-D	NU-75
Plagioclase	69.5	48.0	62.6	7.8	-	-	-
Biotite	0.5	0.2	1.2	0.4	-	-	4.1
Hornblende	-	18.1	-	-	-	5.4	-
Clinopyroxene	15.1	18.6	10.5	7.8	-	-	1.5
Orthopyroxene	10.0	-	0.2	54.6	-	-	-
Olivine	-	13.9	17.8	-	96.8*	94.2*	93.4*
Opagues + Access.	4.9	1.2	7.7	29.4	3.2	0.4	1.0
An %	43	60	43	38	-	-	-
En %	44	-	42	45	-	-	-
Fo %	-	60	35	-	go	go	go

*Olivine partly serpentinized, varying locally in amount.

INTRUSIVE CONTACT RELATIONS IN THE OUTER ISLANDS.

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A number of prominent east-west linears cross the Nain area. Where formation boundaries intersect several of these linears in the bays and farther inland, a left lateral displacement is indicated. In the eastern contact zone near Ford Harbour (de Waard, this report), the existence of left-lateral displacement is in question. The distribution of islands and formation boundaries in the seaward part of the Nain area suggests that more complete mapping might establish this displacement if it exists, and the mobility provided by R.V. Pitsiulak provided an opportunity for such mapping. Kaghitarkhortokh Island (56-30 N, 61-05 W) and the islets southwest of it were visited with this in mind. This group of islands lies in the contact zone of the Ford Harbour Formation against an easternmost anorthosite body which is largely covered with water. The unexpected occurrence of a diorite-granodiorite complex in the area complicates the geological picture so that a test for lateral displacement is inconclusive. However, the mapping casts some light on the relations between regional granulite of the Ford Harbour Formation, anorthosite, and the diorite-granodiorite complex. This complex contains inclusions of both the other rocks. Cognate inclusions of very coarse, pure anorthosite in coarse noritic anorthosite are so abundant at the east end of Kaghitarkhortokh I. that the rock might be called agmatite. Medium-grained 2-pyroxene diorite with accessory quartz and feldspar megacrysts appears to be irregularly penetrated by coarser hornblende-bipyroxene granodiorite containing about 5% perthite and abundant quartz. This rock appears to grade over locally into an irregular network of coarsely pegmatoid dikes with pink and white feldspars, quartz, and big books of biotite. No systematic structural relations between the diorite and granodiorite have been detected.

A visit to Sioghalialuk I. (56-35 N, 61-03 W) was more gratifying, since the margin of the anorthosite against granulite proved to be in accord with the hypothesis of left lateral displacement south of the island.

Nukasorsukhtokh Island (56-22 N, 61-18 W) provides a splendid display of rock types ranging from regional granulite through anorthosite, diorite, ferromonzonite, and adamellite, to a layered troctolitic intrusion described briefly by Speer and Morse in this report. Unfortunately, not much sense has been made of this array in past short visits to the southern part of the island, and it is with good reason that this place has been chosen as a base of operations for R.V. Pitsiulak. The 1971 season provided an opportunity to visit several unmapped parts of the island where the mapped boundaries between three major formations were dangling. Granulite of uncertain origin (Wheeler, 1968), elsewhere mapped as lying between anorthosite and regional granulite, was not found around the southeast peninsula of the island, perhaps being cut out by a later mesoperthite adamellite containing olivine at least locally. This adamellite shows foliation and poor layering near and subparallel to the contact with regional granulite. A large inclusion of noritic anorthosite occurs in the adamellite near the margin, and elsewhere dark gray, blocky, oversized plagioclase crystals occur that look like xenocrysts from the anorthosite. Preliminary shipboard microscopic study of specimens from this area demonstrated that field criteria developed elsewhere for recognition of rock types need revision before they can be applied here, and suggest that a close grid of specimens will be required for successful solution of the field problems. Shipboard laboratory facilities will be invaluable in this respect in future seasons.

NEWARK ISLAND ANORTHOSITE AND LAYERED COMPLEX

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Anorthosite and leuconorite
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Introduction

The southern end of Newark (South Aulatsivik) Island is underlain by a western area of anorthosite-leuconorite and an eastern area of noritic to ultramafic layered rocks. Scraps of country rock in the southeast corner of the island reveal some contact relations with both intrusive bodies. The area is of interest particularly for its unusual layered complex of mafic and ultramafic rocks having intermediate Fe/Mg ratios and nearly vertical dips, and to a lesser extent for its internal relations of anorthosite and leuconorite. The major bodies are discussed later in this report, after a brief petrographic review of the geologic column.

Stratigraphy

Country rocks. The southeastern part of Newark Island is underlain by a small zone of granulite apparently correlative with the Ford Harbour

Formation as defined by de Waard (this report) some 20 km to the southeast. On Newark Island, enderbitic granulite predominates, accompanied by lesser amounts of impure quartzite and finely layered, mafic to ultramafic pyroxene (+ olivine) granulite. Blocks of country rock occur within the layered mafic complex as large xenoliths.

Pyroxene-hornblende granulite. This homogeneous, fine-grained mafic granulite occurs locally at the contact between country rocks and the layered mafic complex, and locally as tabular bodies and as large blocks within the latter. Petrographic evidence is as yet too scanty to permit a confident assignment of this unit to either the country rock or the layered complex; it could represent a marginal facies of the latter.

Anorthosite and leuconorite occur in an unbroken mass throughout the western part of the field area. The anorthosite is the olivine-free, pale facies variety of Wheeler (1960), consisting of coarse, pale gray labradorite (e.g. An_{53}) with subordinate hypersthene (e.g. En_{64}), minor opaques, and local biotite and augite. Very coarse zones occur locally, containing plagioclase megacrysts up to 20 cm. Blue iridescence is common. By an increase of hypersthene, anorthosite grades in many places into leuconorite (5-20% hypersthene), and the two rock types are mapped as a single unit at the scale of Fig. 5. Minor norite occurs, by extension of such local variations to mafic content as high as 30%. Green iridescence is seen in some of the plagioclase of leuconorite. Noritic members of the pale anorthosite suite are altered to hornblende gabbro near granitic intrusions.

Layered mafic rocks dominate the eastern part of the field area. These range from an ultramafic rock composed of augite + olivine + opaque oxides to norite and ferrodiorite, probably with a greater proportion of ultramafic rocks than hitherto recognized among bodies of the Nain massif. Norite is generally fine- to medium-grained, in contrast with noritic members of the pale anorthosite suite to the west. Coarse and very fine textures occur locally. Subophitic to ophitic texture is seen in places. The color index of the norite exceeds 30. The plagioclase in the few samples determined is andesine. A sample of ferrodiorite from the western part of the layered complex contains antiperthite (An_{38}) and some mesoperthite, accompanied by olivine (Fe_{40}), hypersthene (En_{50}) and augite. Hornblende and biotite are common accessories. Layering occurs locally on a scale from centimeters to meters, commonly with steep dips.

Melanocratic layers within the norite contain olivine, opaque oxides, and augite, and reach ultramafic compositions. The oxide-rich ultramafic varieties, where fresh, ring under the hammer. The proportion of dark layers increases toward the east.

Mineral compositions in the few samples examined are intermediate: An_{47-38} , En_{58} , Fe_{37} for example. One rare gabbro contains intermediate augite, andesine, abundant large apatite, and biotite.

Granite occurs in subordinate amounts throughout the field area, but particularly as small stocks with networks of dikes surrounding them, cutting the layered mafic complex. Contacts are sharp and angular where pink, leucocratic biotite granite is involved, and less angular in the case of foliated, gray granites of somewhat higher color index.

Diabase dikes from 4 cm to 15 m wide occur sparsely throughout the field area, having in general an E-W strike.

Field Relations

The contact between anorthosite and layered mafic rocks dips vertically to about 50° NE where measured. Structure in the layered complex is revealed mostly in its eastern part, where layering is abundantly developed. The dips are very steep as a rule; both easterly and westerly dips occur, with northeasterly strikes. East-west strikes occur locally near the eastern contact of the layered complex with country rocks, suggesting a sharply transgressive relationship. Near the northwesterly-striking anorthosite contact, northerly and NNW strikes are observed in layered rocks, suggesting a conformable contact.

The age relationship between anorthosite and the layered complex is suggested by several lines of evidence. Rare, discordant, fine-grained dikes of noritic appearance are found cutting less mafic rocks of the anorthosite-leuconorite mass. Also, tabular to blocky inclusions of coarse leuconorite, up to 10 m across in size, are found lying parallel to layering in certain unperturbed but inclusion-rich parts of the far eastern ultramafic layered sequence. Some of these are indicated by an "LN" symbol on the geologic map, Fig. 5. These inclusions are tentatively identified with the anorthosite-leuconorite mass, rather than with a cognate origin from within the layered complex. Both lines of evidence suggest that the layered complex solidified later than the anorthosite.

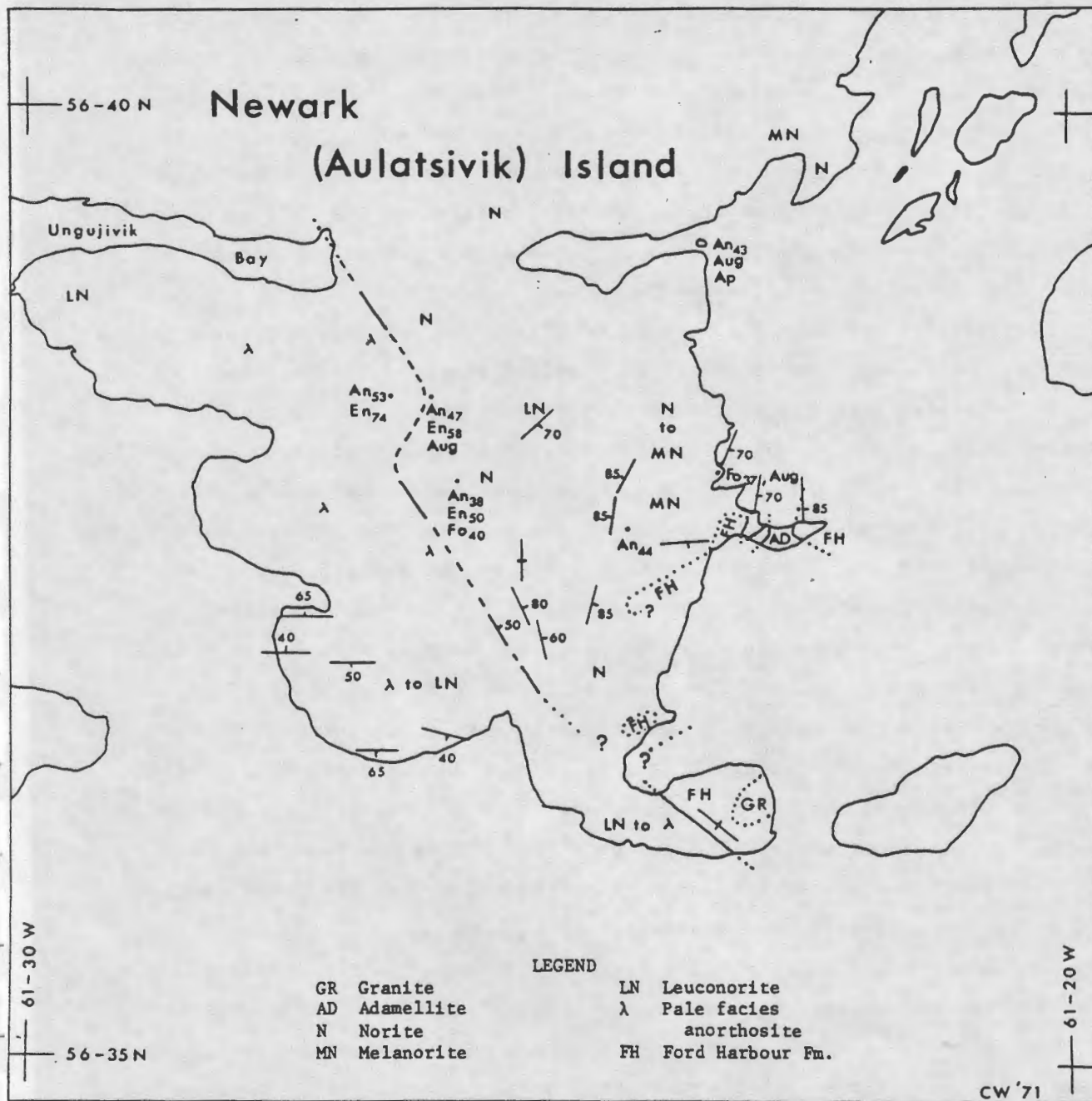


Fig. 5. Geologic sketch map of the southern portion of Newark (Aulatsivik) Island.

Mineral compositions as determined aboard R.V. Pitsiulak also support the inferred age relation, if it is assumed that the compositional difference is due to fractional crystallization and not to fractional melting at the magma source. The anorthosite percentage of the western anorthosite-leuconorite plagioclase lies in the middle 50's, whereas that of layered complex plagioclase lies in the middle to low 40's. (Of greater significance, the mafic mineral compositions are distinctly more magnesian in the anorthosite suite than in the ultramafic parts of the layered complex, showing that the compositional differences are related to cumulus rather than intercumulus effects - Ed.)

The structure within the layered complex poses problems for interpretation which cannot be satisfactorily solved at present. The nearly vertical layering dips suggest either a substantial rotation of the layered complex after deposition and solidification, or an origin of layering other than by simple crystal settling. The latter alternative seems less likely: examples of graded layering and erosional truncations occur in profusion. On the other hand, the direction of tops suggested by these features cannot be unambiguously determined in most outcrops. This was amusingly demonstrated during the August field conference, when several authorities took sides on the issue of whether tops were to the east or west at the first outcrop, and tried to maintain their arguments over other outcrops. Counterexamples were found at every locality. The graded layering undoubtedly includes both normal and reverse types, and the erosional features are not simple channel scours alone. The observed ambiguities may be so inconsistent with the expected features of bottom deposition that they will require alternative hypotheses involving steep initial dips.

Regional variation within the layered complex, from more noritic units in the west to more abundant ultramafic layers in the east, suggests that tops are to the west. Caution is required in this interpretation, however, because of the rather iron-rich mineral compositions (e.g. Fe_{37} in olivine) which occur in some of the ultramafic rocks. The latter also contain substantial quantities of opaque oxide, and abundant apatite occurs in one rock which may belong to the ultramafic group. Petrographic studies are not yet sufficiently advanced to suggest whether these are isolated occurrences in a normally more magnesian sequence, or whether indeed the ultramafic layered rocks may be more iron-rich than the associated norites farther west.

Discussion and Summary

The layered complex of Newark Island is of unknown areal extent to the north. Its noritic portion may resemble the noritic layered series of West Red Island (de Waard, this report), but the ultramafic portion appears to have no counterpart among known layered rocks associated with the Nain massif. Preliminary mineralogical studies point to an unusual composition of the ultramafic portion. Rock names such as peridotite and wehrlite suggest themselves for these rocks, but perhaps carry the wrong connotation if the ultramafic rocks are in fact "upper zone type" ferrous rich cumulates. In the nomenclature of layered intrusions, these rocks might be called "ferromeladiorites", in which case recovery of a simpler classical name may be in order.

The steep layering of the layered series, coupled with ambiguous top determinations, requires either rotation of a normal cumulate sequence after deposition (c.f. Michikamau for a similar interpretation; Emslie in Emslie, Morse, and Wheeler, in press), or an origin of layering unlike that of bottom accumulation. Resolution of these alternatives will require further mineralogical data, as well as detailed examination of internal structures, and continuation of the mapping to the north in search of helpful contact relationships. The mafic granulites in the southeast part of the field area may also have something to say about the origin of the layered complex if their relationship to the latter can be established.

The bulk composition of the layered complex may be unusually rich in ferrous iron and therefore may extend the spectrum of magma types associated with the Nain massif to new limits. If iron-richness is in fact a property of the bulk composition, plagioclase flotation may have occurred, and evidence for this can be sought among the nearby anorthosites and norites.

The anorthosite-leuconorite suite has widespread counterparts in the Nain area; it is in fact the most common type of anorthositic rock. The Newark island occurrence as yet sheds no new light on the origin of this suite, but requires further examination in detail to establish the distribution of color index and mineral compositions, and to clarify age relationships with the layered complex.

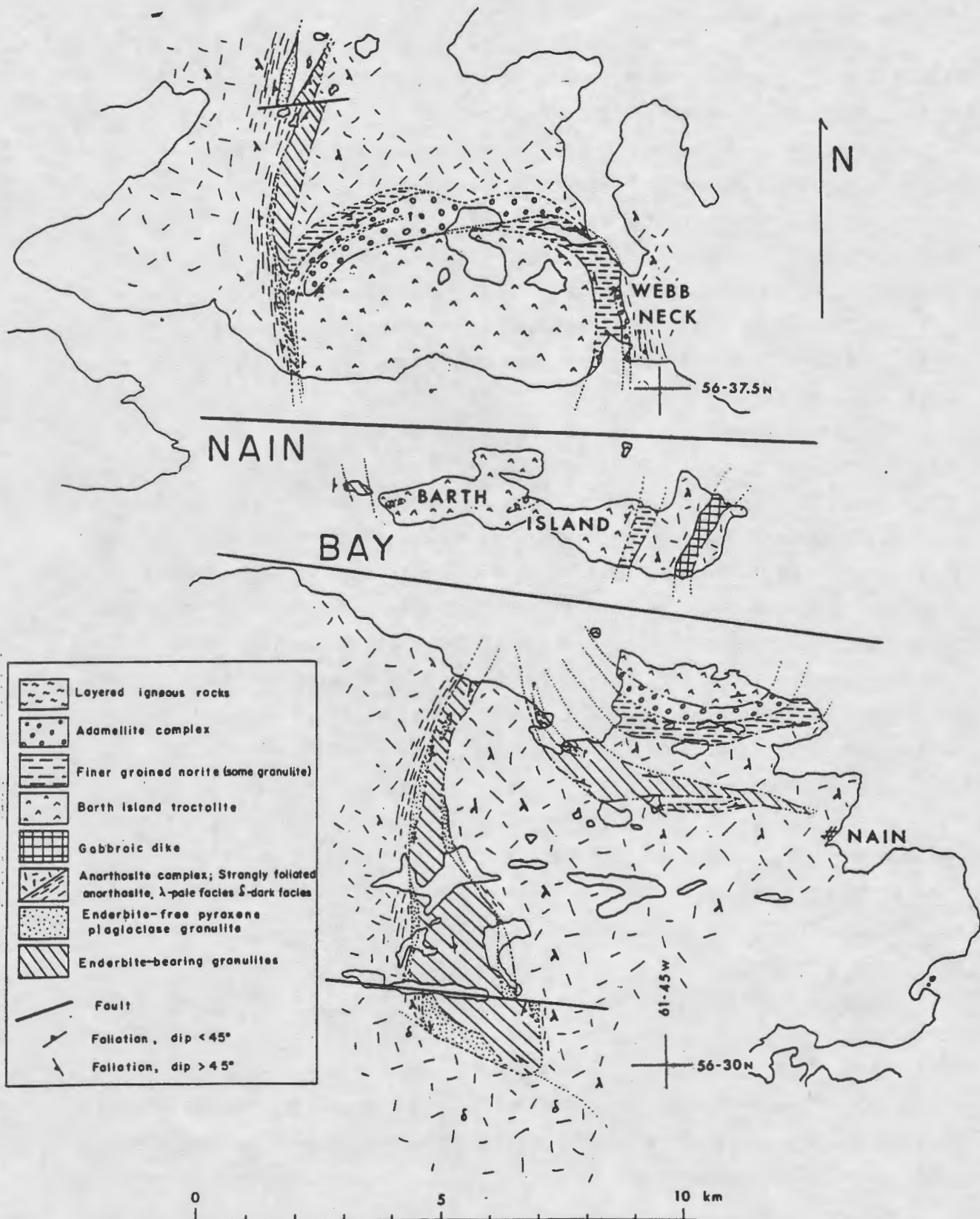


Fig. 6. Geology of the Barth Island troctolite body and surrounding rocks.

CENTRAL CONTACT ZONE

THE BARTH ISLAND TROCTOLITE BODY; GRANULITE-ADAMELLITE-
ANORTHOSITE RELATIONS AT THE NORTHERN MARGIN

Charles C. Rubins
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Introduction

The Barth Island troctolite is a nearly circular, fault-dissected intrusion, probably of lopolithic shape. The body is completely surrounded by rocks of the Nain anorthosite and adamellite complex and demonstrates an intimate connection with the events producing anorthosite and adamellite locally. Also closely associated are finer-grained rocks, mostly granulites, which are apparently of multiple origin as 1) metamorphic pre-anorthosite country rock and 2) fine-grained rocks related genetically to the anorthosite. Fine-grained rocks presumably congenetic with the evolution of the massif are apparently of more than one origin within the present area. It is possible to establish a relatively detailed time-stratigraphy based on field relations of the various rock types and with reference to previous

work along the southern margin of the troctolite.

Previous work

Work previous to the 1971 field season was concentrated on an area in the immediate vicinity of Nain, primarily to the west of the town. The mapped rocks are those associated with the Barth Island troctolite along all of its exposed southern boundary, and two enderbite-bearing granulite zones south and west of the troctolite. Figure 6 is a map of the area covered by previous work (of Rubins) as well as the present mapping in the area north of Nain Bay, and on Barth Island by de Waard (this report). Rocks encountered outward from the troctolite are adamellite, a fine-grained, pyroxene-plagioclase granulite locally grading into weakly subophitic norite, coarse-grained anorthosite and norite, two zones of enderbitic granulites separated by anorthosite and finally, more anorthosite to the west of the north-south enderbitic granulite. The two enderbitic granulites are lithologically similar and may be also connected structurally.

The granulites of this area may be divided into 3 types having presumably distinct origins. They may be differentiated in the field by the following criteria:

1. The medium grained, homogeneous orthopyroxene-clinopyroxene-plagioclase granulites adjacent to adamellite are quartz- and nearly olivine-free. They are homogeneous, showing only weak layering and relatively constant mineral proportions. The only significant modal variations are the result of local segregations of opaque oxides into pods and stringers and rare pyroxenite stringers. Occasional plagioclase megacrysts are rarely iridescent, and are reminiscent of anorthositic plagioclase. There is petrologic evidence that these rocks are a concordant intrusion along the original anorthosite-troctolite contact. The intrusion has apparently cooled from both margins inward because solid solution compositional distributions indicate that the lowest temperature assemblages (more sodic plagioclase, more iron-rich orthopyroxene and appearance of iron-rich olivine) occur near the center of the granulite.

2. The enderbitic granulites consist primarily of inter-layered, leucocratic orthopyroxene-quartz-plagioclase granulite (enderbite) and mafic orthopyroxene-clinopyroxene granulite. There are also occasional biotite and hornblende-dominant layers as well as ultramafic orthopyroxene-olivine-

serpentine units in thin (less than 1 meter) concordant bands. The granulites are also, in places, interspersed with thin layers of granular anorthositic material. These latter have been found cross-cutting foliation in the enderbitic granulites and having inclusions of the enderbite and mafic granulite within them and are therefore considered later intrusive rocks. The enderbite-mafic granulite association is more highly deformed than the rocks of the massif. The inference here and elsewhere is that they are country rock present in anorthosite as either inclusions or as wall- or roof-connected screens or pendants.

3. Within the east-west enderbitic granulite zone is an areally limited sequence of rocks which appear to have a layered intrusive igneous origin. These rocks are mafic, olivine-bearing and they show cumulate textures, density-graded bedding, and possible channel scour and fill. Tops appear to be south-facing and overturned. These rocks are distinctly later than the enderbitic granulites, showing both cross-cutting and inclusive relationships. They are presumed to have a direct relationship to the rocks of the massif because similar rocks with identical features and general chemistry are rather commonly in direct association with and gradational to anorthosite elsewhere in the Nain massif (see descriptions by Planansky and Berg in this report).

Figure 7 is a diagram of the inferred time-stratigraphic relations of the rocks of this area. Igneous structures observed in the field form the basis for each arrow drawn, but the vertical placement of each rock type is in part interpretive.

In general, foliation in the rocks adjacent to the Barth Island troctolite is parallel to the contact and dips steeply under the body. The north-south trending enderbitic granulite zone to the west appears to converge with the zone to the east. No structural relationship can be proven, but lineation in all of the granulites trends eastward or somewhat north of east at 20-40 degrees. Excepted from this is the southern terminus of the north-south enderbitic granulite where the lineations are primarily southeastward.

Current Work

Field research in 1971 was directed toward better definition of the structure and stratigraphy of rocks surrounding the Barth Island troctolite.

Initially, the enderbite-bearing granulite was traced both south to its termination near Annakhtalik Bay and north toward Webb Bay. The latter, major portion of the summer was spent in detailed mapping of adamellite and fine-grained norite or granulite which occur concentrically around the troctolite contact. Field units essentially identical to those mapped south of the troctolite body are carried into the new area and criteria for their division remain the same. One exception, for the most part in terminology, is in the fine-grained norite of the present area which is almost certainly the equivalent of the enderbite-free pyroxene granulite south of Nain Bay. The distinction is textural and not mineralogic, with more evidence of subophitic textures and igneous layering north of Nain Bay.

Enderbitic Granulites

Enderbite-bearing granulites north of Nain Bay are limited to a single north-south trending zone on the west side of the map area. It is probable that this trend is the continuation of the same rocks found south of Nain Bay in two separate zones and seen at the far west end of Barth Island (Figure 6).

In some places in the present area this enderbite-bearing zone appears to be mantled on the west by enderbite-free interlayered mafic and leucocratic pyroxene-plagioclase granulites which in turn are bordered by well-foliated and crushed anorthosite. A similar sequence of rocks found in the same structural position south of Nain Bay is explained as the result of contact effects at the anorthosite-country rock margin with the enderbitic granulites representing the country rock.

The enderbitic granulites consist of at least three predominant rock types identifiable in the field. Mafic pyroxene-plagioclase granulites are most common, followed by layers of quartz-plagioclase enderbite. Also present are thin peridotitic layers. The presence of quartz in enderbite and a generally higher degree of deformation than in surrounding rocks are the major distinguishing features of the enderbitic granulites. The zone north of Nain Bay is in these respects identical to the two zones south of Nain Bay which are presumably pre-massif country rock. Possibly similar rocks are also found on the eastern margin of the massif and have been described by de Waard (this report) and named the Ford Harbour Formation by him.

Anorthosite

Anorthosite nearly surrounds the area covered during the field season. With few exceptions, the type of anorthosite encountered has been Wheeler's (1960) pale facies. Dark facies anorthosite was encountered north of Annakhtalik Bay at the southern termination of the north-south trending enderbitic granulite zone. The contact between dark and pale facies anorthosite is not exposed, but may be placed within 50 meters in at least two localities seen. Blocky inclusions of probable pale facies in dark facies near the contact is suggestive that the dark facies is here younger. The southern termination of the enderbitic granulites is near or at the dark/pale anorthosite contact, but whether this is coincidence or of great significance is undetermined because of poor exposure in critical areas. North of Nain Bay, areas of anorthosite near adamellite may be closer in character to the buff-weathering facies of Wheeler (1960), but in general no systematic separation could be made.

For the most part, the anorthosite is very coarse-grained, leucocratic, and has bimodal grain size distribution. Plagioclase up to 25 cm and orthopyroxene are common in places, often as pegmatoid segregations in less coarse material. Plagioclase is commonly iridescent in isolated localities and not obviously in all outcrops. Both plagioclase and pyroxene commonly show bent, warped and kinked cleavage surfaces.

In the western portion of the mapped area, the anorthosite is strongly foliated and granulated. Large megacrysts are rounded, have augen shapes and show crushed "tails" aligned parallel to mafic stringers and elongated crystals which give the foliation. This deformation appears rather gradually to die out westward but in places gives way very quickly to undeformed anorthosite.

Anorthosite directly east of the troctolite in Webb Neck has strong phase layering, with bands of olivine-bearing mafic and leucocratic anorthosite and occasional pyroxenite alternating a considerable distance eastward. There is some evidence that deformation has played a strong role in this area. Considerable shearing and crushing of individual grains and strong warping of layering attest to this. It is probable, however, that the layering is at least in part primary igneous phase layering and not all tectonic in character. The extent of this layering eastward and northward is not at present known but there is the interesting possibility that

there may be a correlation of these deformational features with those in the anorthosite to the west of the troctolite. Anorthosite north and south of the troctolite does not show deformation of this nature or extent.

Troctolite

The Barth Island troctolite has, as suggested by Wheeler's map (1968), a roughly elliptical shape in plan view. Mineral ratio layering at the borders dips inward; the inference is that the contacts do also. Dips at the troctolite margin are steep, except at the northeast margin where layering is dipping around 30° southwest. The margin of the troctolite is generally fine to medium-grained and relatively unweathered. These characteristics and the presence of olivine and a dark bronze-colored biotite distinguish the troctolite from the fine-grained norite which is superficially similar.

In places the troctolite is extensively intruded by adamellite near contacts. Dikes of adamellite far from a major adamellite mass are found only rarely. Adamellite emplacement did not visibly affect the troctolite mineralogy or texture even where blocks of troctolite are completely enclosed in adamellite.

Fine-Grained Norite

Fine-grained norite shares with adamellite a position between anorthosite and troctolite, nearly completely around the Barth Island troctolite. The best development of the fine-grained norite is at the northeast margin of the troctolite, where it is in direct and sharp contact. The mineralogy of the fine-grained norite is two pyroxenes and plagioclase with minor opaque oxides and possible minor olivine. Mafic content averages 20-30%. Textural variation is limited to the appearance of 1-3 cm megacrysts of plagioclase which have the bluish cast and appearance of anorthositic plagioclase. The megacrysts range from none to around 5-10% of the rock. Subophitic texture is quite prevalent if weak, but in places the unit becomes a fine- to medium-grained, homogeneous granulite. The zone is rather thick on the northeast margin of the troctolite, and is tentatively correlated with thinner granulite units on the western margin of the troctolite. Structural position and general mineralogy make correlation with the enderbite-free granulite south of Nain Bay also a likelihood.

Two possible interpretations of the fine-grained norite and granulite can be made at present. The intimate association suggests that it may be related to troctolite as a marginal facies. A second possibility is that of a separate intrusion acting as a cone-shaped sill along the anorthosite-troctolite contact in the same locus later intruded by adamellite. This latter interpretation has been suggested for the enderbite-free granulite south of Nain Bay. Mineral composition data there suggest that the plagioclase and orthopyroxene compositions are too low-temperature to be an early troctolite-related crystallizate, and that the compositional variations are best explained by a late intrusion which has cooled from the margins inward after troctolite consolidation.

Adamellite

The field term 'adamellite' is used here for rocks having the texture of a granite porphyry and consisting predominantly of two feldspars (oligoclase and K-feldspar) and quartz. Mafics are low in the mode and may consist of hornblende, biotite, pyroxene or fayalitic olivine. In the field, adamellite is generally identifiable by its coarse phenocrystic ("maggoty") texture, the deep maple sugar brown weathering and a dark green fresh surface. With a hand lens, the K-feldspar phenocrysts have a pearly luster and usually show small insets of quartz or mafics enclosed in single grains. Plagioclase is occasionally seen as phenocrysts and is often found as the predominant groundmass feldspar. Plagioclase is not iridescent in the adamellite.

The adamellite does not appear to occupy a consistent place in the stratigraphy surrounding the Barth Island troctolite (Fig. 6). There is no doubt that the adamellite is intrusive into troctolite and there is good evidence for its intrusion into at least some of the granulites marginal to the troctolite; its relationship to anorthosite is less well established. It is apparent from the map that adamellite emplacement has occurred into and along the granulite, marginal to troctolite, along the northern and northeastern border.

One of the specific questions raised by this summer's work is why the adamellite intrusion, demonstrably a late event in the history of the massif, is localized mainly within a particular horizon surrounding the troctolite. The brittle behavior of the troctolite border which produces

agmatitic contacts with adamellite indicates that the troctolite was already in place, consolidated and brittle before adamellite emplacement. The marginal granulites appear to have adjusted their foliation to the adamellite intrusion. In Webb Neck, the granulite foliation swings around the end of the small north-south adamellite body. This deformation suggests plastic rather than brittle adjustment to the intrusion, while the troctolite was reacting in a brittle manner to the same intrusion.

Summary

The Barth Island troctolite is surrounded by rocks which are related to the evolution of the Nain anorthosite massif. The troctolite itself is an intrusion which occurred, at least in the local stratigraphy, between the anorthosite- and adamellite-producing events. A fine-grained norite margin on the troctolite lopolith may or may not be directly related to the troctolite event. Petrologic considerations in a presumably correlative granulite south of Nain Bay suggest that the margin is a separate, later intrusion. All of the rocks in the vicinity of the troctolite generally conform to the troctolite border with the important exception of zones of enderbitic granulite. The enderbites, pyroxene granulites and ultramafics of this sequence are representatives of the massif country rock.

COMPARISON OF KIGLAPAIT AND NAIN ANORTHOSITE MARGINS
IN THE HETTASCH LAKE AREA

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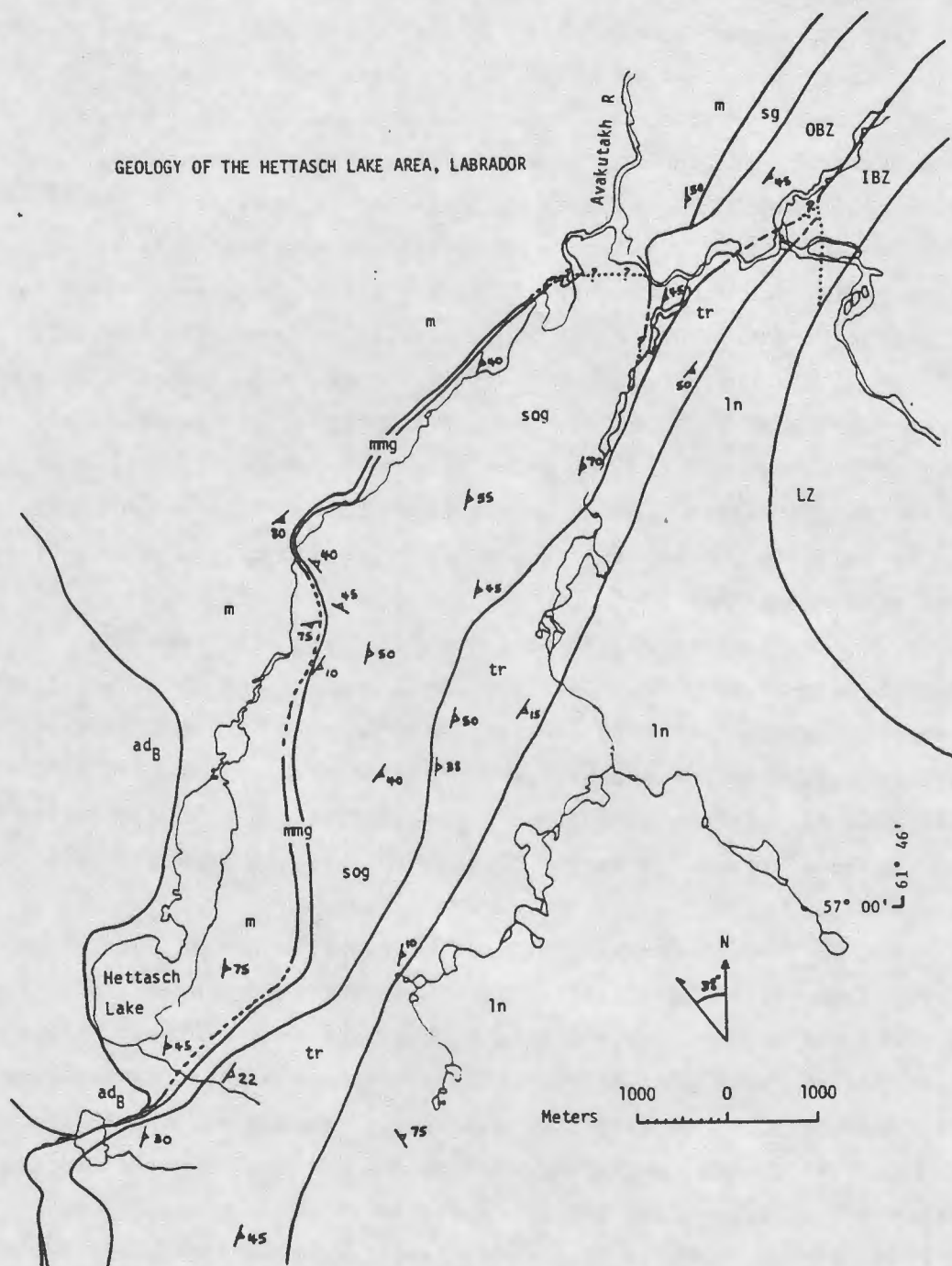
Both the Nain anorthosite and the Kiglapait layered intrusion are rimmed in part by a fine-grained, mafic, generally anhedral-granular textured rock. The origin of this marginal mafic granulite is controversial, and several genetic types probably occur (Rubins and de Waard, 1971). However, a recent study of the Kiglapait margin (Outer Border Zone) has shown it to be a layered, contaminated product of the Kiglapait magma (Berg, 1971).

Present only against metamorphic country rocks to the north and west, the Outer Border Zone (OBZ) shows considerable mineralogical variation, but generally ranges from diorite to olivine gabbro. The rocks are fine-grained, layered on a millimeter to centimeter scale, mafic, and contain primary amphibole and orthopyroxene (and locally biotite). Textures range from hypidiomorphic granular to allotriomorphic-granular. The layering, lamination, and other textural and structural features indicate that the OBZ formed as a cumulate on the sloped floor of the Kiglapait intrusion. The locally granular textures suggest that parts of the OBZ may have moved (slumped?) as a crystal mush. The primary amphibole and orthopyroxene (which never reached cumulus status in the Layered Series), along with elevated K_2O content relative to the Layered Series, reflect contamination by water and alkalis. Local silica enrichment was possibly effected by the crystallization of amphibole.

Minerals show advanced compositions near the outer margin of the OBZ (An_{40} , Fo_{30}), but become progressively more basic across the zone until they merge with the compositions of the succeeding zone (Inner Border Zone) which in turn subsequently merge with those of the Lower Zone (An_{66} , Fo_{72}).

Fig. 8. Geology of the Hettasch Lake area, Labrador. KEY, from left to right: ad_b , biotite facies adamellite; m, enderbitic and tonalitic migmatite; mmg, marginal mafic granulite; sog, subophitic olivine gabbro; tr, troctolite; ln, leuconorite; sg, Snyder Group; OBZ, Kiglapait Outer Border Zone; IBZ, Kiglapait Inner Border Zone; LZ, Kiglapait Lower Zone. The filled dip symbols denote foliation or lamination, open ones denote layering.

GEOLOGY OF THE HETTASCH LAKE AREA, LABRADOR



This trend, along with the fine grain size, broad reversed zoning in the plagioclase, and the crystallization of orthopyroxene in the expected compositional range of pigeonite suggests that crystallization occurred from magma that was super-cooled. Plagioclase zoning indicates that the super-cooling was on the order of 10 to 30° C in the outer margin of the OBZ.

With this understanding of the OBZ in hand, a similar study of the Nain anorthosite marginal mafic granulite in the region near Hettasch Lake, Labrador (57° N, 62° W) is being initiated to determine: (1) whether it has an igneous origin similar to the margin of the Kiglapait layered intrusion or is a contact metamorphic facies of the adjacent, older metamorphic basement rocks; and (2) if it is similar in origin to the OBZ, whether any chemical and petrological inferences can be made about the Nain anorthosite complex as a whole, based on an analogy of the relationship of the margin of the Kiglapait to the known chemistry and petrology of the Kiglapait layered intrusion. Added knowledge on both points would be extremely valuable to our understanding of the major problem of the origin of large anorthosite complexes.

In line with these objectives, two field projects have been undertaken during the summer of 1971. Detailed field mapping and sampling of the Nain anorthosite margin southward from the western part of the Kiglapait layered intrusion margin to the southern end of Hettasch Lake has been completed (see Figure 8). Secondly, further field studies and a more detailed sampling traverse across the margin of the Kiglapait layered intrusion have been completed.

Field mapping of the marginal mafic granulite around the Nain anorthosite has shown it to be locally intrusive into, although generally conformable with, the adjacent metamorphic rocks. These metamorphic basement rocks consist for the most part of plagioclase-pyroxene-quartz gneisses and granulites and, locally, amphibolites and biotite gneisses. The former are generally fine to medium-grained whereas the amphibolites and biotite gneisses are more commonly medium to coarse-grained.

Where mapped, the marginal mafic granulite around the Nain anorthosite is much thinner than the OBZ (30-50 meters thick, compared with up to 500 meters for the OBZ), but reconnaissance mapping by E. P. Wheeler, 2nd (unpublished maps) suggests that it thickens to the south. Because of the

marginal granulite's fine-grained, mafic nature, textures and minerals are difficult to identify in the field, but the unit appears to be much less amphibole-rich (less hydrous) than the OBZ. Olivine phenocrysts are present in at least one outcrop of the marginal mafic granulite, and a few specimens contain iridescent plagioclase. Local isoclinal folding and numerous lenses of metamorphic basement rock are present within the unit, but because of its locally cross-cutting relationships and the presence of olivine phenocrysts, the marginal mafic granulite of the Nain anorthosite is tentatively classified as igneous.

The marginal mafic granulite of the Nain anorthosite and the OBZ may not be coextensive, and, in fact, the field evidence suggests that they definitely are not coextensive. Unfortunately, the critical area is covered by Quaternary glacio-fluvial deposits; however, considering that the two units show an order of magnitude difference in thickness and do not appear to have a coincident strike (see Figure 8), it seems likely that they are separate units.

In the course of field mapping along the anorthosite margin, additional marginal units have been distinguished. These consist of a subophitic gabbro to olivine gabbro and a locally well-layered and laminated troctolite unit. The sequence of rock types encountered along a traverse normal to the margin of the anorthosite, starting from well out in the metamorphic basement rocks, is (1) generally tonalitic, isoclinally folded, layered metamorphic basement rocks; (2) fine-grained, mafic, granular olivine gabbro to gabbro (marginal mafic granulite); (3) coarse, medium, or fine-grained subophitic olivine gabbro to gabbro exhibiting local layering and abundant schlieren; (4) medium to coarse-grained layered and laminated troctolite grading to coarse or very coarse-grained, massive troctolite; and (5) very coarse-grained, massive leuconorite or anorthosite with iridescent plagioclase and large subophitic orthopyroxene. Structurally the troctolite, gabbro, and marginal mafic granulite all strike parallel to the anorthosite margin and generally dip from 55° to less than 15° under the anorthosite.

Two possible interpretations are immediately apparent for this sequence of rock types and their associated structure. The first possibility is that the troctolite is a separate body which structurally underlies the

Nain anorthosite (here leuconorite). The second possibility is that the troctolite is actually part of the Nain anorthosite complex and represents an olivine-plagioclase cumulate which may have settled out of the magma which produced the main body of the leuconorite. Structural conformity of the troctolite with the margin of the anorthosite (leuconorite) and the fact that where the troctolite-anorthosite contact is best exposed, the troctolite becomes coarse grained and massive and appears to grade into the anorthosite (leuconorite), favors the latter interpretation. In either case the subophitic olivine gabbro to gabbro probably represents an early, rapid accumulation of crystals near the margin, forming an orthocumulate.

Morse (1968) has suggested that the Nain anorthosite may be a flotation "cumulate" from a large-scale layered intrusion or from a series of layered intrusions. He suggests that for this to be proven true, geophysical data or further geologic mapping would have to show the possibility of a large troctolitic or dunitic cumulate below the anorthosite. If the Hettasch Lake troctolite is part of a deeply exposed section of the anorthosite complex and is a cumulus complement to the anorthosite (leuconorite), it would add valuable support to the flotation hypothesis.

Laboratory research and future field work on the troctolite and anorthosite should clarify their relationship. Continued laboratory and field comparisons of the mafic granulite margins of the Kiglapait layered intrusion and the Nain anorthosite are necessary as an independent source of evidence for the origin of the anorthosite. Fortunately, field mapping of the marginal mafic granulite and the troctolite can be pursued simultaneously.

INTERNAL RELATIONS

THE BRIDGES LAYERED SERIES AND ASSOCIATED ANORTHOSITES

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Introduction

The Bridges Layered Series extends in a northeasterly direction along strike from the north shore of Palungatak Island to the north shore of Ten Mile Bay on Paul Island. The series is dominantly noritic in composition, but varies between anorthosite and pyroxenitic or harzburgitic endmembers. The zone and its layering strike NE-SW and dip steeply to the SE. The wave-washed outcrops of Ten Mile Bay and the Bridges Passage give excellent sections across the Layered Series and the enveloping anorthositic rocks. Spectacular rhythmic layering, phase layering, graded bedding (tops to the SE), subophitic textures, and an igneous lamination parallel to the layering make it clear that the Layered Series is a cumulate typical of bottom deposition in large basic plutons.

At its northern end, the Layered Series (LS) is enveloped in typical coarse-grained pale facies anorthosite which grades transitionally to a marginal zone of foliated medium-grained, subophitic anorthosite or leuconorite; the foliation consists principally of igneous lamination of plagioclase tablets generally parallel to the LS layering. To the northwest this marginal leuconorite grades transitionally into the Layered Series. To the north and northeast the contact is transgressive, with xenolithic Layered Series blocks in the marginal foliated anorthosite.

To the south the LS lies in typical coarse-grained dark facies anorthosite, which grades transitionally and variously into several varieties of norite, olivine norite, and troctolite. Transgressive field relationships are present among all these rock types. Most of the rocks show variously developed foliation and layering in places. Some of the norites contain xenoliths of Layered Series and are intrusive with respect to it -- the dark facies rocks are accordingly considered younger than the Layered Series. The dark facies anorthosite locally contains pegmatoid pockets within itself; in places these contain graphic quartz - K feldspar intergrowths, biotite books, and ilmenite concentrations.

To the southeast a "giant-pyroxene leuconorite" intrudes the Layered Series. This rock may be part of the dark facies anorthosite group. Adamellite and diabase dikes are present in the field area.

Because of the contradictory and baffling transgressive to transitional contacts of some of these rock types, their genetic relationships are not yet firmly established. The Layered Series appears to be a xenolithic fragment surrounded by a congealed, foliated margin related to pale anorthosite. The dark facies rocks are later than the granulite zone and probably the pale facies anorthosite as well. Whether or not the dark facies rocks are descended from the pale facies is unclear. Some interesting speculations about the processes responsible for these rocks can already be made, in anticipation of supporting petrographic data.

Summary of Lithologic Units

Layered Series (LS) -- rhythmically layered norite, locally olivine bearing; layers vary gradationally by changing mineral proportions between anorthosite and ultramafic end members, although the extremes are



Fig. 8. Geology of The Bridges layered zone.

uncommon. Also interbedded layers of igneous laminated subophitic leuconorite, locally with gneissic texture and lenticular pyroxene clots: Stretched Fabric Leuconorite (SFL).

Pale Anorthosite group -- coarse-grained, pale facies anorthosite typical of that described by Wheeler (1960). This grades, at its margins with the LS, into medium-grained igneous-laminated leuconorite: Marginal Foliated Leuconorite (MFL), including foliated pale anorthosite. A minor but ubiquitous pale weathering pegmatoid anorthosite is intrusive into the LS and MFL.

Dark Anorthosite group -- the rocks of this group grade into one another, with anorthositic and troctolitic end members, ranging in texture from coarse-grained subophitic to fine-grained granular. Coarse-grained dark facies anorthosite typical of that described by Wheeler (1960) and medium-grained subophitic leuconorite are dominant. A fine-grained glomeroporphyritic norite with plagioclase phenocrysts is called the Snowflake Norite. Locally the rocks are igneous-laminated and layered.

Giant Pyroxene Leuconorite -- very coarse-grained, subophitic or poikilitic leuconorite. Locally finer grained. Typical pyroxenes are 30 cm long.

Adamellite dikes -- hypidiomorphic granular, quartz - K feldspar rock.

The feldspar is commonly phenocrystic; biotite is locally present.

The adamellite is commonly contaminated by the anorthositic rocks it intrudes and may grade into a hypersthene-facies member (Wheeler, 1955). It occurs as large irregular masses as well as dikes.

Diabase dikes -- fairly common, generally 2 - 4 meters thick; some chilled margins, poor columnar jointing and blocky fracture. Many of the thicker dikes contain feldspar phenocrysts.

Structure

The Layered Series trends NE-SW between Ten Mile Bay and The Bridges Passage (Fig. 9), with small extensions on their north and south shores respectively. Layering strikes parallel to the contacts, NE-SW; dips are about 45° to the SE. The foliation of the marginal pale anorthositic rocks has the same sense. Layering in the dark facies anorthosite group is irregular and much less common, and is considered unrelated to the attitude

of the LS.

Tectonically, except for vertical movements and some faulting (see below) the Nain region appears to have remained stable since the anorthosite event. The attitudes of layering and foliation in the anorthosite are considered to be unchanged since the rock solidified. Consequently, under the assumption that the LS layering was originally subhorizontal, the present steep dip of the LS is considered to indicate a tilting event during or prior to the consolidation of the surrounding anorthosite. The attitude of the foliation of the pale marginal anorthosite may be genetically related to that tilting event.

Faulting is responsible for much of the area's morphology. Because of the irregular contacts and similar appearance of the rock types the faults are usually undefineable as more than shear zones. A known left-lateral fault zone through Ten Mile Bay displaces the northern extension of the Layered Series to the west. A similar fault zone probably runs through the Bridges Passage, but no displacement is obvious.

Layered Series

The Layered Series consists of igneous laminated and rhythmically layered noritic rocks, many with olivine, which vary between anorthosite and pyroxenite end members. Some layers have basal ore-rich horizons. Individual layers are commonly very uniform, from 5 cm to 5 m thick, and extend to the limits of the outcrops (several hundred meters in places) unless interrupted by the locally extensive slumping. Some layers have distinct boundaries, while others are gradational.

Graded bedding by frequency and form, and phase layering (e.g. olivine - opaque oxide horizons through pyroxenite to anorthosite) are common and give tops to the southeast. Graded beds commonly vary texturally from massive to granular to laminated subophitic horizons; generally the more mafic layers are more granular. Troughs and scours are less common and give the same tops. Well-developed norite layers are commonly repeated in very regular rhythmic groups in the LS.

Interbedded with the layered norites are coarser, streaky, foliated layers or zones of uniform subophitic leuconorite, here called stretched fabric leuconorite (SFL). The foliation is due partly to igneous lamination of the plagioclase tablets. In addition, the formerly subophitic

pyroxenes are sheared to form lenticular, granulated clots parallel to the foliation. Locally this leuconorite and the LS norites have a lineation, apparently consistent, to the southeast. The norite layers are locally slumped in a spectacular fashion into the SFL, which is then squeezed around the mafic blocks, appearing to have been fairly mobile. Layers intermediate in character between the LS norites and the SFL are common. For example, elongated groups or clots of foliated subophitic pyroxenes may alternate with more leucocratic patches; the mafic clots can occasionally be recognized as poikilitic patches by a common reflecting surface in bright sunlight. On the other hand, lenses of granular melanorite, sub-parallel to the general layering, may be scattered in an otherwise massive anorthositic layer. Such layers are locally transitional by increasing numbers and size of the mafic lenses into massive granular melanorite horizons. Usually there is a clear boundary between the stretched fabric leuconorite layers and the more massive layered norites, and their mechanical behavior is quite different. The SFL differs from the layered norites by (1) its generally homogeneous appearance, (2) its deformational fabric, and (3) its incompetent behavior.

Pale Anorthosite Group

The Layered Series is bordered on Paul Island by coarse-grained pale facies anorthosite. Plagioclase occurs as megacrysts generally 5 - 15 cm across, up to 50 cm, locally fractured, commonly iridescent, in a matrix of finer-grained plagioclase crystals and granules. The rock generally contains very little subophitic pyroxene, generally has no sensible lamination, and may be slightly protoclastic. Close to the LS it changes its character, however, and becomes the marginal foliated leuconorite (MFL).

As the LS is approached from the west the anorthosite becomes less homogeneous and its mafic content increases. Locally there are irregular zones with coarse to giant subophitic pyroxenes, in places boudinaged and rotated, and cognate blocks and schlieren of finer-grained material. A coarse, stretched-clotted-fabric leuconorite appears, with elongated groups of subophitic (or poikilitic), foliated pyroxenes. Some granular norite layers (up to a meter thick) appear. At one locality a 10 cm boudinaged, sheared pyroxenite layer is followed one meter higher by another, phase layered with the sequence ore-pyroxenite-anorthosite. Both occur in

laminated medium-grained leuconorite. The pyroxenes are somewhat rotated, and plagioclase megacrysts in the leuconorite are rotated or streamlined in the sense of the foliation. The foliation of these rocks is parallel to the LS layering: rotation and shear is clockwise as seen from the south-west, or down-dip.

South of Ten Mile Bay, medium-grained foliated anorthosite is transitional, by decreasing grain size, increasing foliation, and pyroxene content, and more frequent layers of granular norite, into the LS.

On the north and east the anorthosite is also transitional to the MFL, but attitudes are highly irregular, the rock is more leucocratic and forms a more poorly defined zone, and contains disoriented xenoliths of variously deformed and assimilated LS material. Intrusive pale pegmatoid anorthosite is common on the east, whereas it appears to be missing on the west. Some of the LS xenoliths occur in short trains with attitudes that suggest they have sunk in the foliated anorthosite.

To the north and south the marginal rocks appear plastically deformed. The LS rocks are similarly affected, and there is in many places no clear-cut boundary between slumped or disrupted LS norites and xenoliths of LS in the marginal leuconorite. The distinction between the marginal foliated leuconorite and the interbedded stretched fabric leuconorite of the LS may not be more than one of context.

Pegmatoid Anorthosite and Giant Pyroxene Leuconorite

Coarse-grained, very pale weathering, irregular patches, dikes, and veins of pegmatoid anorthosite occur throughout the LS and in much of the marginal foliated zone. Dike and vein walls are generally sharply angular, but in places the pegmatoid material has definitely assimilated portions of the intruded rocks. Biotite books are rare. The pegmatoid material generally appears to have no source, although locally veins may diverge from a larger mass, usually along the preferred direction of the layering. Both the LS layered norites and (less obviously) the SFL are cross-cut and delaminated by the pegmatoid anorthosite.

Along the north shore of The Bridges Passage, on the southeast margin of the LS, the volume of the pegmatoid veins increases as the giant-pyroxene leuconorite is approached. Eventually, disoriented and deformed blocks of LS norite occur as xenoliths in a fairly uniform coarse-grained

leuconorite.

By an increase in grain size this leuconorite grades into giant-pyroxene leuconorite, a very coarse-grained rock with subophitic and poikilitic orthopyroxene crystals up to a meter across. Locally the pyroxenes are rounded or fractured; in places they occur as stringers or layers suggestive of recrystallized LS norite. In other places these layers, cognate anorthositic blobs, xenolithic material, and bands of finer-grained material trend roughly parallel to the LS layering and are considered primary igneous features. The plagioclase of the leuconorite occurs as large megacrysts in a matrix of finer-grained material. By an increase in proportion of the matrix plagioclase the leuconorite grades into (dark?) facies anorthosite to the east. Locally in the leuconorite there occur irregular layers of pyroxene crystals elongated perpendicular to the layering sense. Some of these have olivine cores. These may be crescumulate structures.

The giant pyroxene leuconorite could be 1) an eddy of the pale anorthosite magma chamber into which the LS (formed of an earlier magma) sank; 2) the remainder of the parent magma of the pale anorthosite and the LS, perhaps structurally isolated from them, into which the LS sideslipped; or 3) a later magma, perhaps related to the dark facies group on Palungatak.

Dark Facies Anorthosite Group

On Paul Island, spheroidal-weathering, massive, fine-grained norite occurs as multiple sills in the LS at its west contact with the marginal foliated leuconorite (MFL). The sills have locally recrystallized the LS norites forming shiny black pyroxene hornfels shells, 5-10 cm thick, in the host rock. Various assimilated LS xenoliths are present in the norite. The leucocratic portions of some xenoliths are indistinguishable from the enveloping norite. The norite coarsens, developing an igneous lamination and subophitic texture over a distance of 200 meters near its contact with the MFL. This makes the norite seem transitional into MFL; however a norite sill with chips of pyroxenite, intruded by coarser leuconorite at its margins, occurs several hundred meters westward, well within the MFL.

On the east edge of the LS, similar norite sills (?) occur close to the giant pyroxene leuconorite, and along with the LS are intruded by pegmatoid anorthosite. Some of the LS layers may be unrecognized coarse-

grained norite sills.

Coarse-grained dark facies anorthosite covers much of Palungatak Island along its shores, except by The Bridges Passage. The anorthosite has many coarser-grained patches, irregular weak layers, and cognate blocks. The plagioclase is commonly iridescent and locally the anorthosite has a striking protoclastic texture.

Scattered about are very coarse-grained pegmatoid pockets of dark anorthosite containing biotite books, ilmenite concentrations, and quartz - K feldspar intergrowths. One pocket has large pyroxenes with olivine cores.

On the northeast shore the anorthosite grades into medium-grained leuconorite with similar pockets and layers of coarser-grained material, some due to cognate blocks, and some that are clearly bona fide cumulate layers of coarser plagioclase and pyroxene in a finer-grained subophitic rock. Neither texture is subordinate and in many places the crystals are elongated perpendicular to the layering. The leuconorite also contains blocks of finer-grained rock and, notably, large blocks of finely crystalline, massive, pure plagioclase anorthosite. A similarly variable troctolite occurs close by.

The center of Palungatak Island is mainly medium-grained, subophitic to poikilitic leuconorite, transitional from the anorthosite. The dark facies rocks become finer-grained toward the LS in the northwest of the island. The LS is bordered by a massive, spheroidal weathering, fine-grained, granular norite containing variously assimilated--and in places contact metamorphosed--LS xenoliths. This is correlated with the norite sills on Paul Island. Fine-grained olivine norites and troctolites occur locally along the north shore.

At one place on the north shore an interesting snowflake norite occurs as a glomeroporphyritic variety of the fine-grained norite. The norite contains scattered clumps of 5-10 mm phenocrystic plagioclase crystals--"snowflakes"--in a fine-grained granular groundmass. There occur a few larger aggregates of such plagioclase clumps resembling chunks of snow, one of which is broken in half. The snowflake norite is flow banded with regular norite.

An extensive zone of foliated leuconorite occurs east of the LS on the northwest shore of Palungatak I.--this rock is similar to the MFL in its nature and context and is tentatively correlated with it. On its west edge

at the water level it is bordered by a series of finely layered noritic granulites, with some pyroxenitic and anorthositic layers and dunite lenses. The layers are locally intensely folded. These rocks were only seen in reconnaissance and their nature is especially uncertain, but they are tentatively considered to be a basal portion of the LS.

Genetic Interpretation

Layered Series. The LS rocks are cumulates and their layering is due to variations in the deposition of plagioclase, pyroxene, and less commonly olivine and opaque oxide cumulus crystals onto the floor of a magma chamber. Graded bedding, troughs and scours, igneous lamination and lineation indicate that the deposition was dependent on the action of currents in the magma.

The rhythmically layered norites are considered to have been deposited by intermittent, fast density currents flowing down the sides of the magma chamber and across its floor. These currents had small volumes and were caused by overturnings of a metastable zone of cooler magma at the top of the chamber, where heat loss was greatest. Cumulus minerals were pyroxene and plagioclase, sometimes olivine, rarely opaque oxide. Presumably these nucleated only near the top of the chamber. The thin, repetitive rhythmic layers, troughs and scours, and graded bedding were formed by these intermittent currents. Little intercumulus fluid was trapped by the close packing of the variously sized cumulus minerals, and the thinness of individual layers allowed rapid solidification by adcumulus growth.

The subophitic pyroxenes of the stretched fabric leuconorite (SFL) indicate that they are post-cumulus minerals. The uniformity and greater thickness of the SFL layers suggest that they accumulated steadily but rapidly from a relatively quiet magma. Such rapid and regular deposition of plagioclase cumulate effectively isolated large amounts of intercumulus liquid from the magma chamber. Thus solidification proceeded by fractional crystallization as the temperature fell and the SFL orthocumulates remained mobile considerably longer than the rhythmically layered adcumulates. The extensive slumping in the LS is due to the sandwiching of dense, brittle mafic adcumulate layers with the incompetent SFL orthocumulates. Such post-depositional deformation may be responsible for the tectonic fabric of many of the SFL layers and a consequent foliation. It is likely that the SFL

was deposited from slowly convecting magma which may have contributed to its igneous layering, and lineation.

The variety of textures in the LS is taken to be the result of the synthesis of regular deposition from the slow magma currents and the intermittent deposition of the density currents. Some layers of intermediate character are hybrids, probably involving reworked material from previously deposited layers--indeed, some of the layers resemble the flat pebble conglomerates of turbidite sequences.

The consistent slumping to the southeast, downdip by the present attitude of the LS, suggests that the LS was either being tilted in that direction during deposition or it was fortuitously tilted in the same direction as a primary dip. No progressive stratigraphic change in the LS dips is obvious.

Pale anorthosite and MFL. The pale anorthosite and the MFL are considered cumulates by their igneous lamination, layering, megacrysts, subophitic texture, monomineralic composition, and association with the LS. Models of their formation should account for the similar foliation attitudes of the LS and MFL, and for the xenolithic nature of the LS with respect to the pale anorthosite.

Four models may be considered according to whether the LS is older or younger than the pale facies rocks, and whether the pale anorthosite floated or sank in its magma.

Model 1a: LS older, anorthosite sank. Magma (presumably basaltic) was injected into the country gneisses forming a lopolith in which the LS was deposited. The lopolith and the gneiss were part of the roof of a larger chamber in which coarse pale anorthosite was accumulating, and were stopped into it. The descending LS displaced magma from beneath and the MFL accumulated as a congealed margin on its keel, laminated by the flow. The original floor of the LS is either unrecognized, stripped away, or stopped. The structure of the LS provided a plane of weakness along which the magma flowed, resulting in foliation of the same sense.

The settling of the LS into the accumulated, unfoliated coarse pale anorthosite caused further shearing and protoclastic textures. Above the LS, in the eddy region, coarse anorthosite resumed accumulating, along with suspended LS xenoliths.

This model does not explain why plagioclase should have been the

only phase to have accumulated in the lower magma chamber. Plagioclase flotation overcomes this difficulty.

Model 1b: LS older, anorthosite floated. As in 1a, the LS becomes part of a roof to a larger magma chamber. The MFL formed as an early congealed margin against the LS, foliated by magma currents. Subsequently coarser pale anorthosite accumulated underneath the MFL, partly as rafted blocks. Eventually this part of the roof foundered (or was partially stoped) en bloc, and magma flowed against the rest of the LS causing the xenolithic relationships. At this time the LS was tipped to its present attitude and juxtaposed with rafted anorthosite to the north and east. The giant pyroxene leuconorite may represent a small mass of magma trapped in the process.

This model is attractive because it leaves somewhat fractionated magma beneath from which the dark facies group may have formed.

Model 2a: LS younger, anorthosite sank. Pale anorthosite accumulated in a large magma chamber until a smaller volume of magma became isolated from the rest. By more rapid cooling and fractionation of the smaller chamber, the MFL and the LS were deposited. An event interrupted this and opened the LS to the main magma chamber, whereupon coarse pale anorthosite accumulated above the now tilted LS zone.

Such a model accounts for the similar attitudes and gradational nature of the LS and the MFL at the western contact, but it does not explain why plagioclase should have been the only mineral to accumulate in the large magma chamber.

Model 2b: LS younger, anorthosite floated. The coarse pale anorthosite accumulated at the roof of a large magma chamber while mafics sank. An event introduced magma above the anorthosite, and the MFL and LS were deposited as in 2a. Further events--perhaps all foundering of the anorthosite float, tilted the LS and intruded magma around it, resulting in the xenolithic relationships and the crystallization of the giant pyroxene leuconorite.

Either 1b or 2b are acceptable models. However a younger LS would have little time to cool before the dark facies group should engulf it, and it seems unlikely that the finer grained (chilled?) members of that group would have occurred at contacts with a relatively hot LS. It also seems unlikely that a magma chamber large enough to deposit the (restored) LS could have formed or would have been stable long enough for the very

regularly layered LS to accumulate, above an anorthosite batholith. The simplest model, of an earlier formed Layered Series engulfed by the anorthosites, appears to be the most reasonable.

Dark Facies Group. The dark facies group is later than the LS and the pale facies rocks, to judge by the relationships on Paul Island. The LS occurs as xenoliths in norite on Palungatak, and some of the cognate blocks in the dark anorthosite on the west shore of the island may be inclusions of pale facies material.

The dark facies rocks are considered cumulates; the finer-grained granular norites may be a chilled margin of the parental magma. The snowflake norite and included broken chunks of plagioclase snowflakes are considered evidence for early crystallization and accumulation of plagioclase by flotation. Similarly the large blocks of massive, finely crystalline pure plagioclase anorthosite in the leuconorite are considered floated rafts.

The generally heterogeneous nature of the dark facies group suggests proximity to a roof or wall, as do the chilled margin rocks and the nearby intrusive contacts with the LS. The subophitic and poikilitic textures, cognate blocks, and scattered coarser-grained patches indicate rapid accumulation and orthocumulus crystallization. The fractionated nature of some of the pegmatoid material is evidence for closed system fractionation of magma trapped in pockets within the cumulates. The presence of quartz-K feldspar intergrowths, biotite, and ilmenite suggests either that the dark facies parent magma was enriched in SiO_2 , K_2O , etc., relative to the parent magma of the pale anorthosite, or that it solidified under more nearly orthocumulus conditions. It is notable that fractional crystallization of the magma produced an acidic mineral assemblage, suggesting, as at Ford Harbour, a possible origin for the acidic rocks of the Nain region. However, the adamellite bodies on Palungatak I. are considered to have been introduced from outside; one large dike cuts east-west across the entire island.

Olivine, pyroxene and plagioclase crystallized as primary phases to form the troctolites. The medium-grained troctolite and leuconorite on the northeast shore of Palungatak I. and their coarser-grained layers, in the absence of igneous lamination, indicate adcumulus growth of the primary phases in a quiet magma and relatively slow deposition. The perpendicular

orientations of the crystals in some of the layers are considered examples of crescumulate growth at the top of a cumulate pile during periods of no deposition. The rafted plagioclase blocks in this leuconorite may have had a slight negative buoyancy and settled to the bottom at this quiet time. Because the troctolite and leuconorite involved the accumulation of mafic primary phases they are assumed to be bottom cumulates.

The above interpretations are consistent with a model in which the dark anorthosite crystallized from somewhat fractionated magma underneath an earlier-consolidated roof of LS and pale anorthosite. Accordingly there may be recognizable trends in the mineral compositions of these rocks.

Summary

Field relations indicate that The Bridges Layered Series is older than the Nain anorthosites, and that the pale facies anorthosite is older than the dark facies anorthosite. A reasonable model for the formation of pale facies anorthosite by plagioclase flotation above the dark facies anorthosite parent magma is consistent with the field evidence known so far.

Further investigation of The Bridges area promises to shed some light on fractionation trends and magma compositions in the Nain area during a considerable part of the anorthosite event, and should clarify the relationship between dark and pale facies rocks.

Igneous layering can be studied in the dark facies leuconorite and troctolite as well as in The Bridges Layered Series itself. Possible chilled margins of the dark facies parent magma have been identified, and a fractionation trend to acid composition and ilmenite enrichment demonstrated in the dark facies rocks of Palungatak Island. Investigation of the internal relations of the dark facies rocks should be interesting.

Field work so far has yielded the valuable recognition of critical problems in The Bridges area. Further field work and petrographic investigation of the rocks should provide a very rewarding basis for evaluating the various hypotheses.

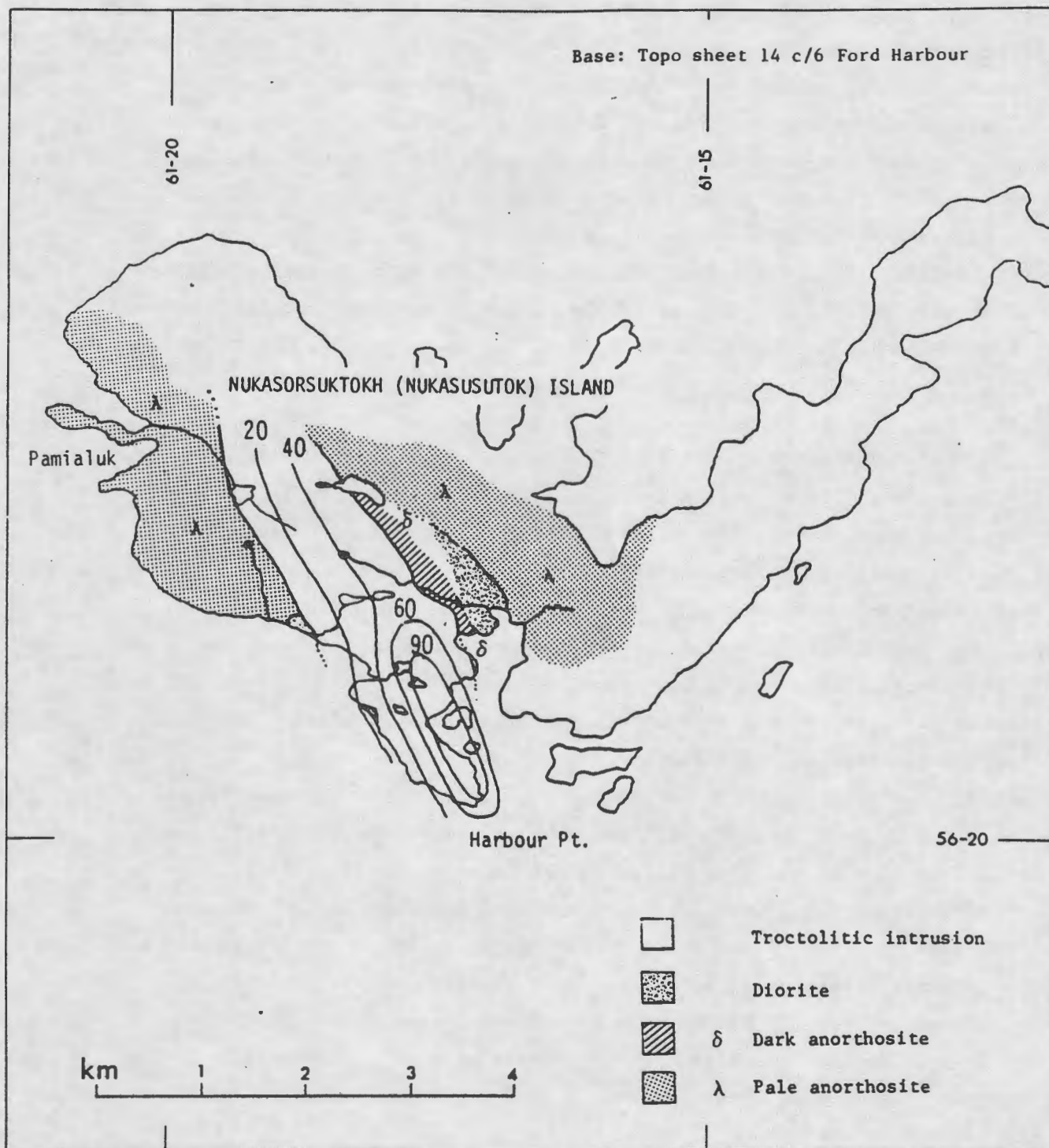


Fig. 10. Geologic sketch map of part of Nukasorsuktokh(Nukasusutok) I., showing the layered troctolitic intrusion and surroundings. Contours express percentage of stratigraphic height.

RECONNAISSANCE OF A LAYERED INTRUSION, NUKASORSUKTOKH I.

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The predominant rock of Nukasorsuktokh (Nukasusutok) Island is pale anorthosite. Near the southern part of the island, plagioclase is light gray, with compositions in the range An_{55-60} where determined. The mafic mineral is subophitic hypersthene. Numerous "15-cm" norite pegmatite zones occur, especially on the south shore, where a giant hypersthene crystal was determined to have the composition En_{70} . A sketch map, Fig. 10, shows the approximate distribution of rock types in the part of the island under consideration. Prominent among these is an elongate troctolite body, distinguished in the field by its rusty red color and weakly developed layering which dips inward along both margins. This relatively fine-grained, younger intrusive rock is of potential interest for what it may tell us about the composition and differentiation of basic magmas emplaced during the late stages of the Nain anorthosite event.

In order to use the information which this body provides, we shall have to understand its geologic setting and its bulk mineral and chemical composition. The first part of this note describes our brief and unsatisfactory efforts to understand its setting, and the second part describes, somewhat more successfully, the intrusion itself.

A body of dioritic rocks crops out near the head of the harbor, apparently cutting anorthosite. This diorite is characterized by prominent feldspar tablets on weathered surfaces locally with a pronounced lineation $320^{\circ}/40^{\circ}$. The diorite contains blocks, pods, and veinlets of anorthosite, and a small pod of opaque oxide. This body is succeeded westward along the shore by dark anorthosite, a dull, jet-black rock composed almost entirely of heavily rodded plagioclase, with a few percent of augite and a

trace of opaques. This dark anorthosite, in turn, lies in contact with the troctolitic intrusion. A similar dark rock at the intrusion contact about 1 km to the northwest and elsewhere was also confidently mapped as dark anorthosite. This rock proved, on laboratory examination, to have a variety of compositions, none of them anorthosite:

Hypersthene diorite: An_{38} , En_{66} (the hypersthene is abnormally magnesian for this plagioclase composition).

Ferrodiorite: An_{40} , antiperthite, ferroaugite, ferrohypersthene, apatite.

Ferromonzonite: An_{34} , mesoperthite, ferroaugite, apatite.

Hornblende diorite: An_{37} (heavily rodded), with fresh, prismatic, olive-green hornblende and some orthopyroxene.

This sad tale illustrates the surprises which may greet any but the most alert field worker, but more particularly it illustrates the necessity for laboratory control of field work in this area. The dark and even jet black color of feldspar in compositions as sodic as An_{34} was a surprise to us, inasmuch as the dark facies of the anorthosite carries dark labradorite elsewhere. Under the microscope, all the dark feldspar samples of the present study showed high populations of opaque rodlets, presumably Fe-Ti oxides which have exsolved from a homogeneous parent. These are so abundant as to leave no doubt that they contribute significantly to the dark color of the feldspar, although whether they are the whole cause of darkness is not proven.

The eastern contact rocks, then, can be described as dark anorthosite, possibly minor, with a variety of dark and as yet unmapped diorites to monzonites. Their relationship to any of the commoner types of anorthosite, and to the paler diorite near the harbor head, is unknown.

Genuine pale anorthosite appears to form the western contact of the troctolite intrusion.

The intrusion itself has the form of a thick dike which strikes NNW and dips about 45° to the NE. The western wall is uniform in attitude, being formed by pale anorthosite except where a block of diorite occurs at the shoreline. The internal structure of the intrusion indicates that this is its floor. The eastern contact apparently changes dip along its length, from easterly where the contact rock is genuine anorthosite, to westerly along the contact with dark diorite to the south.

Xenoliths of anorthosite, diorite, and gneiss occur in the intrusion.

Internal structures include lamination of plagioclase tablets, ratio layering of olivine and plagioclase, reverse size layering, rafts of fine-grained, apparently cognate material in medium-grained troctolite, channel scouring, slumping, and pyroxene clots at intermediate stratigraphic levels. Layering is weakly developed or absent in most places, but well-developed in a few. Fine-grained margins occur at both contacts. The color index appears to decrease northeastward. To the southeast, along the length of the body, norite pegmatite becomes increasingly abundant until it becomes a matrix rock enclosing wisps, pods, and broken layers of olivine gabbro. This transition coincides with rising topography, and the norite pegmatite zone thus appears to be stratigraphically the highest rock type.

Shipboard mineralogical examination suggests that plagioclase of composition An_{52-59} and olivine (Fo_{62-70}) are the dominant minerals in the parts of the intrusion mapped as troctolite. Hypersthene and augite are common accessories, the latter with abundant Fe-Ti oxide plates in (010) parallel to \bar{c} . Red biotite occurs in some rocks as an accessory, as it does in the Barth Island troctolite body. One sample of a fine-grained margin was examined under the microscope, and this contains little or no olivine, but abundant augite and hypersthene (En_{55}). The numerical difference between Fo and An in the troctolite tends to be about the same (8-10 units) as in the Kiglapait intrusion, and the composition range observed is equivalent to that of the Kiglapait Lower Zone and the lowermost Upper Zone.

Discussion

Contours on the map (Fig. 10) represent, crudely, the percentage of the exposed stratigraphic thickness of the intrusion, and because a roof is lacking, these cannot be regarded as percent solidified levels as in the Kiglapait intrusion. A generalized stratigraphic column of the exposed series, as we comprehend it, is shown in Fig. 11. Mineral variation promises to show a normal pattern from fine-grained margin into layered series and norite pegmatite, to wit, an abrupt increase where cumulates take over from congealed margin rocks, followed by a modest decrease.

Two features of the intrusion seem especially noteworthy at this time. The first is the upward transition from troctolite to olivine

gabbro and norite pegmatite, signifying a normal subalkaline trend away from critical silica undersaturation and toward silica saturation. The second is the abundance of norite pegmatite at high levels having plagioclase compositions in the range of pale-anorthosite. The first feature appears to distinguish this intrusion (and possibly also the Barth Island intrusion) from the "critical plane" trend of the Kiglapait intrusion wherein cumulus hypersthene fails to appear and the residuum is strictly syenitic, without quartz. Either the initial bulk composition of the intrusion at Nukasursuktokh was hypersthene-normative relative to that of the Kiglapait, or the feedback mechanisms which may have prevented silica enrichment in the Kiglapait failed to operate here. The second feature may shed light on the origin of plagioclase concentration and coarse grain size. Both features appear highly relevant to the Nain anorthosite in general, and, in fact, the stratigraphic column provides a qualitatively close analogy to models which have been invoked to account for the Nain and other anorthosites on a much larger scale. Detailed study of this small intrusion should provide very helpful models of magma types and fractionation behavior in the environment of the Nain massif.

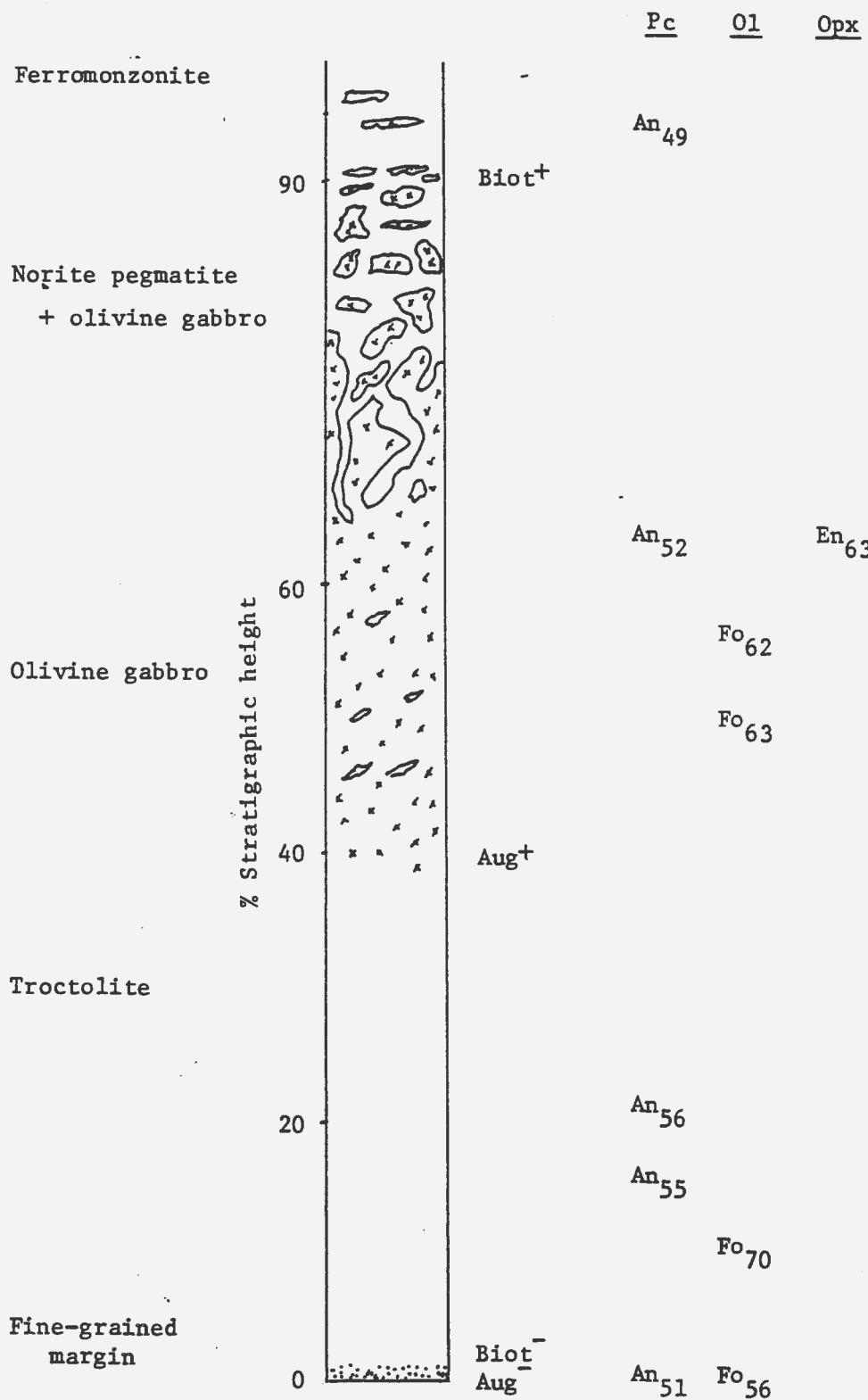


Fig. 11. Stratigraphic section of the intrusion on Nukasorsuktokh I.

MISCELLANEOUS TOPICS

Layered Anorthosite at Tikkoatokhakh Rattle (Morse). Although layered noritic, troctolite, and dioritic rocks are common in the Nain area, layered anorthosite sensu stricto has not previously been confirmed there. In early August, a 250-m-high cliff of layered anorthosite was discovered from the vessel on the south side of Tikkoatokhakh Rattle ($56^{\circ}38'N$ x $61^{\circ}58'W$). This exposure was briefly examined during the field conference in late August. The layering has a northeasterly strike, subparallel to the cliff face, and a southeasterly dip of about 30° , hence the layered anorthosite stratigraphy persists for several hundreds of meters upward. Individual layers appear to have constant thickness along strike and down dip; layers are almost perfectly parallel to each other throughout the exposure, even where slight warping is present, except in a few poorly-delineated confused zones where diffuse layering appears to have been plastically deformed. The thickness of layers ranges from about 5 cm to perhaps 80 cm. Leucocratic layers are composed entirely of pale gray plagioclase, with coarse to giant grain size. Many plagioclase crystals are euhedral, but most have white to pink granulated margins. Darker layers are composed of norite or leuconorite; in these the grain size is coarse but not extremely coarse, and the hypersthene is subophitic. Biotite is present, but may be related to nearby shear zones. All layers appear to have sharp top and bottom contacts; no graded layering or channel scours have been seen. Confused zones contain plagioclase euhedra up to 40 cm long and subophitic giant hypersthene crystals of comparable length.

Plagioclase from a crystal about 10 x 20 x 5 cm in such a pegmatitic portion of a confused zone has a composition of An_{51} ; subophitic hypersthene nearby has a composition of En_{54} . Iridescent plagioclase is present in pegmatitic zones, but cursory examination has not as yet revealed it in quieter layers. Plagioclase lamination is present in anorthosite layers, but probably not well developed.

The extent of this layered anorthosite-leuconorite complex is not known. The layered rocks may possibly extend several km along strike to the southwest, inasmuch as layering has been seen from an airplane on the

south side of Nain Bay, and the attitude of layering is compatible with that of anorthosite surrounding the Barth I. troctolite complex (Rubins, this report) to the east. An extensive sequence of layered anorthosite may therefore be involved.

The layered anorthosite complex is quite apparently an igneous cumulate, but little more can be said at present about its origin, or its implications for the anorthosite problem in general. The southeast dip is compatible with that of basic layered series studied elsewhere to the east by de Waard and Planansky. It will be important in future field work to trace this zone out to see whether it forms a closed structure, or whether it suggests a large homoclinal sequence throughout the Nain Bay-Ford Harbour region. Petrographic studies will also be necessary to establish whether the layering results from an alternation of adcumulus and orthocumulus growth. If orthocumulus growth is the cause of the noritic layers, as suggested by the presence of subophitic texture, the nature of the intercumulus material may furnish important clues as to the nature of the parent magma.

Giant Pyroxenes (Wheeler). Recent laboratory work has shown that, contrary to assumptions, not all giant pyroxene crystals in anorthosite are orthopyroxene. Moreover, some of the giant orthopyroxene is more magnesian than the orthopyroxene of the enclosing rock, indicating that the giant crystals crystallized early rather than as late, possibly pegmatoid segregations. This relationship is quite at variance with the commonly observed sequence of 1-cm grained anorthosite cut by 5-cm and 15-cm grained anorthosite or leuconorite, as described, for example, by de Waard in this report. Accordingly, a wide-ranging sampling program was undertaken in 1971 to collect giant pyroxenes and their associated matrix pyroxenes for compositional determinations. During travels with field parties early in the season, and later with R.V. Pitsiulak, pyroxene pairs were collected over an area of some 1700 km². Spot determinations aboard ship revealed no further occurrences of giant augite. Laboratory work on some of the material confirms a tendency for the giant orthopyroxenes to be more magnesian than the orthopyroxene of the enclosing rock. Most of the collection is still unexamined, and no firm conclusions are as yet warranted.

Basic Dikes (Upton). In the course of the brief reconnaissance of the Nain-Kiglapait area (Aug. 26-Sept. 3, 1971) two broad categories of

basic dikes were noted: a) metamorphosed and b) unmetamorphosed. There being no clear geographical distinction between the two it is assumed that the metamorphosed dikes are the elder. Dikes of amphibolite and garnet amphibolite, believed to have crystallized initially as diabase, were recorded on Paul Island, Barth Island, Snyder Island and Tikkegharsuk peninsula, where they cut regional gneisses and Snyder group meta-sediments. Since they were not seen cutting the unmetamorphosed Nain anorthosites and norites, or the Kiglapait troctolites, it appears that the amphibolite dikes were recrystallized at some date following the deposition of the Snyder group sediments but before the intrusion of the large basic complexes (i.e. pre approx. 1400 my).

Essentially unmetamorphosed diabase dikes were recorded from the vicinity of Nain, Paul Island, Dog Island and Port Manvers. They occur also on Barth Island (pers. comm., de Waard). The dikes are sparsely distributed, forming no well-defined swarm in the area visited. Widths of up to 30m were noted. The dikes have well-chilled sharp contacts with country rocks with no indications of rheomorphism. The principal directions of diking appear to be: a) approx. E-W, b) approx. NE-SW, and c) approx. N-S. While some dikes are aphyric, the majority contain plagioclase phenocrysts. In some, these are abundant and large (up to 5 cm); in one of the larger dikes visited the plagioclase megacrysts were concentrated in the central zone of the intrusion. Diabase dikes containing olivine or pyroxene phenocrysts were not seen.

The unmetamorphosed diabases were seen cutting the Ford Harbour Formation gneisses and also the anorthosites, adamellites and troctolites of the Nain and Kiglapait complexes. Close to Nain two intersecting diabases occur within the anorthosite; an approximately N-S (aphyric) diabase is cut by a feldsparphyric dike trending at 110° . It is not known whether any of the unmetamorphosed diabases preceded the emplacement of the Nain-Kiglapait basic complex or whether all are connected with one or more younger basaltic events.

Snyder Group basal contact (Morse). The Snyder Group consists of metasedimentary and metavolcanic rocks which were considered by Morse (1969) to lie unconformably on Tikkegharsuk migmatites (= Ford Harbour fm?) in Snyder Bay, just west of the Kiglapait intrusion ($57^{\circ}-09'N$, $61^{\circ}-42'W$).

The group is of fundamental importance to the stratigraphic and metamorphic history of the Nain area, and probably also to correlations with the Greenland geologic column. An opportunity occurred during the late August field conference to review the basal contact, and to reassess the evidence for an unconformity. The evidence deserves to be placed on record.

The mineralogy of the Tikkegharsuk migmatite in this area is essentially that of a biotite-hornblende tonalite, consisting of quartz, andesine, olive-green hornblende, and biotite. Locally the darker units are profusely injected with pale pink, cross-cutting pegmatitic material. This is notably the case at the base of the Snyder group, where the pegmatitic material amounts to some 30% of the rock.

The migmatite complex presents an uneven surface, evidently an erosion surface, at the base of the Snyder group. The ancient erosion surface has a relief of up to 1/3 meter. Cross-cutting pegmatite stringers are truncated abruptly at the contact, which has been tilted to a nearly vertical dip. Hollows in the ancient erosion surface contain 1-cm scale quartz-pebble basal conglomerate of the Snyder group. Finer-grained orthoquartzite overlies the higher portions of the erosion surface. Angular fragments of migmatite complex, locally derived, occur in the basal quartzite. The evidence for an unconformity between migmatite and Snyder group is unequivocally clear.

Quartzite forms the basal unit of the Snyder group. Beds of 2-cm quartz-pebble conglomerate occur locally near the base. The quartzite then alternates over some tens of meters with spotted andalusite-microcline gneiss and andalusite-bearing quartzite. Within some hundred meters of the base of the Snyder group occurs the first outcrop of gray breccia, a poorly understood unit of probable quartz-latitude composition. The problems of the gray breccia center around its locally abundant fragments, which are in part angular, cognate, black amphibolites and in part rounded cobbles resembling the tonalitic basement gneiss, but more or less heavily altered to epidote. Further discussion of these problems appears in Emslie, Morse, and Wheeler (1972), and need not be repeated here.

A sample of Snyder quartzite was collected for U-Th-Pb studies, and the enigmatic gray breccia was sampled by J. M. Barton for Sr isotope studies.

Gneiss xenolith in gabbro (Morse). A xenolith of tonalitic gneiss,

measuring 0.1 x 1 m, was discovered by Berg at the 86% solidified level of the Kiglapait Upper Zone during the final field conference. The xenolith occurs in layered olivine gabbro near Partridge Pt. on the south shore of Port Manvers Run. It is surrounded by a 1-cm rim of hornblende, but although the gabbroic rocks presumably were deposited at a temperature well in excess of 1000°C, it appears that no melting has occurred. Thin section studies will be needed to confirm this impression, but it is manifest that the xenolith was by no means substantially melted, and this fact sets important limits on both the thermal conductivity of the xenolith and the mechanism and rate of cooling of the Kiglapait cumulates. Furthermore, the xenolith occurs in an area previously thought to have been roofed by anorthosite, so this old assumption requires qualification.

It is probable that the process of dehydration of the xenolith to form a hornblende reaction rim acted as a temporary energy-consumer in lieu of melting. If the dehydration process were allowed to go to completion before significant melting occurred, the preservation of the xenolith is easier to comprehend, inasmuch as the "dry" tonalite solidus probably approaches that of the enclosing olivine gabbro. Nevertheless, the preservation of this xenolith appears to sound the death knell for all schemes of wholesale basic anatexis at igneous contacts, unless high aqueous pressures existed. If a hydrous tonalite will not melt when surrounded by several kilometers of hot cumulate gabbro and melt, there appears to be no chance of generating dioritic or gabbroic melts in country rocks adjacent to any gabbroic intrusion, however large. This also means that the hernias and other auto-intrusive structures seen in pyroxene granulites at Kiglapait and anorthosite margins must be regarded as primary, cooling-history features rather than metamorphic or anatectic features. The same reasoning applies to deformed layering in anorthositic rocks wherever subophitic texture occurs, and the term "protoclastic" is on firmer ground than ever according to these arguments.

Petrographic methods (Morse and Berg). The petrographic laboratory aboard R.V. Pitsiulak has been designed for rapid determination of mineral compositions by the dispersion method of Merwin (Posnjak and Merwin, 1922; Tsuboi, 1932). The application of this method has become familiar with plagioclase (Morse, 1968), but has slipped into undeserved obscurity for other minerals. We offer here a brief account of our current efforts

to resurrect it for olivine, orthopyroxene, and clinopyroxene, and to simplify it for plagioclase.

The method in general has been simplified by substitution of a substage interference filter monochromator, which is more rapid and convenient to operate than a separate monochromator with substage mirror. The plagioclase method is further simplified by the availability of a commercial, precision-dispersion "Plagioclase Dispersion Set" of refractive index liquids from R. P. Cargille Laboratories. Addition of a pocket-sized, battery-powered electronic calculator in 1972 will aid the acquisition and calculation of larger amounts of data, yielding useful mean compositions and composition ranges.

Our dispersion methods for olivine, orthopyroxene, and clinopyroxene are in their infancy, but are sufficiently advanced for reconnaissance work. Dispersion curves for high index liquids were measured by us in the winter of 1970-71, using a Gaertner minimum deviation spectrometer with direct measurement of temperature by means of a coated iron-constantan thermocouple. The beta refractive index is used for olivine, as this is obtained from both (010) and (100) cleavages. The determinative chart is based on the curve of Bowen and Schairer (1935). The dispersion of beta for a number of olivines of different composition was measured by Berg, using the immersion method with two or more intersections plotted on a Hartmann net. We were then able to plot $n_F - n_C$ for the entire olivine composition range, and to construct the dispersion net shown in Fig. 12.

In similar manner, Berg has constructed a dispersion net for gamma of hypersthene, which appears on every prismatic cleavage fragment. This net is shown in Fig. 13.

We have as yet no determinative net for augite. However, we obtain an estimate of the beta refractive index by achieving a match with variation of wavelength, and using the dispersion slopes for orthopyroxene to obtain β_D . This value can be applied to any of the familiar determinative diagrams in the literature for an estimate of $En/(En + Fs)$. By 1972, we hope to have a dispersion net yielding $Mg/(Mg + Fe)$ based on the Kiglapait augite series.

The precision and accuracy of the dispersion method is greatest for plagioclase and orthopyroxene, where a precision of ± 1 mole % in mean composition is easily attainable through measurement of many grains. The

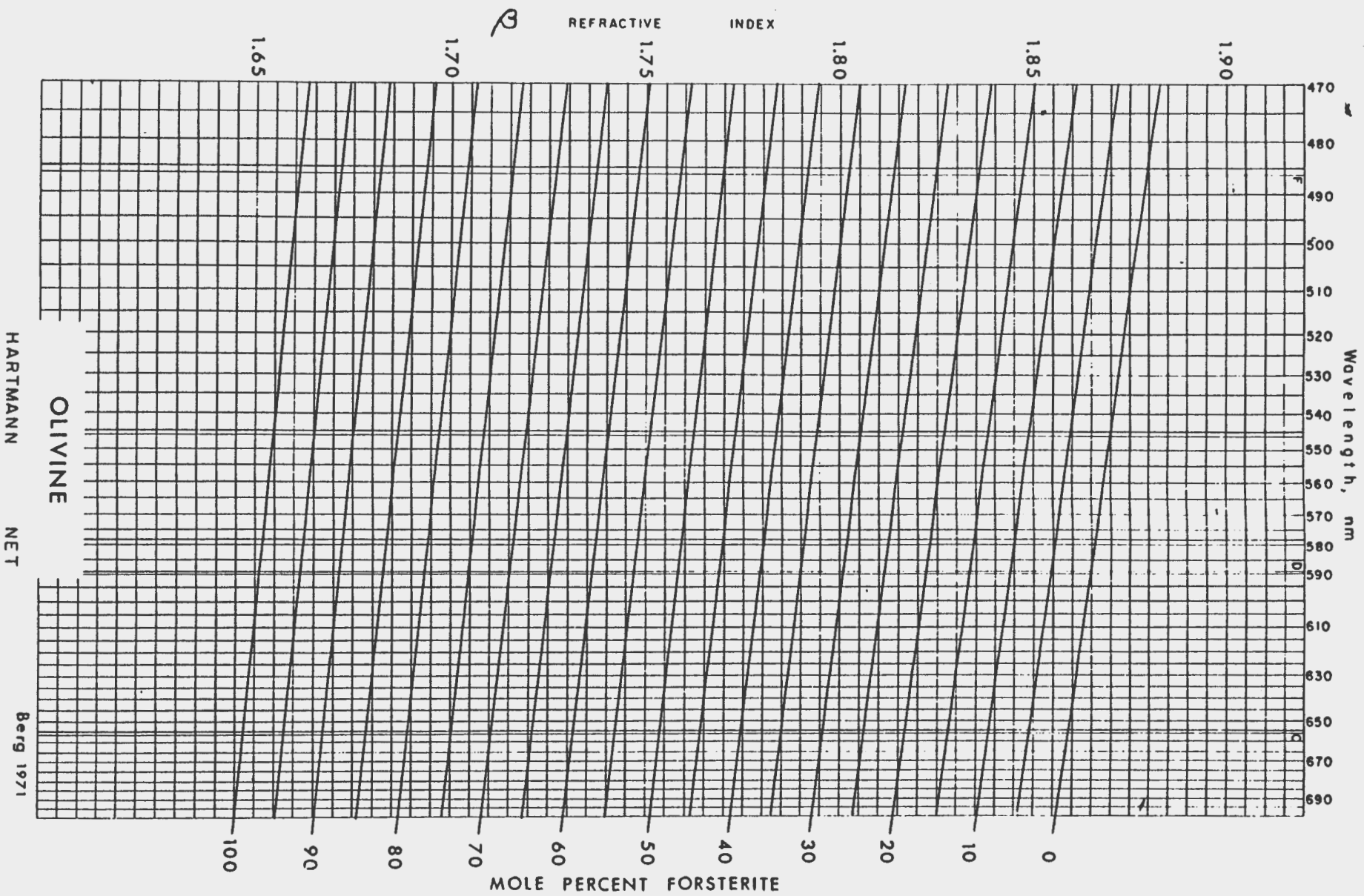


Fig. 12. Dispersion chart for olivine.

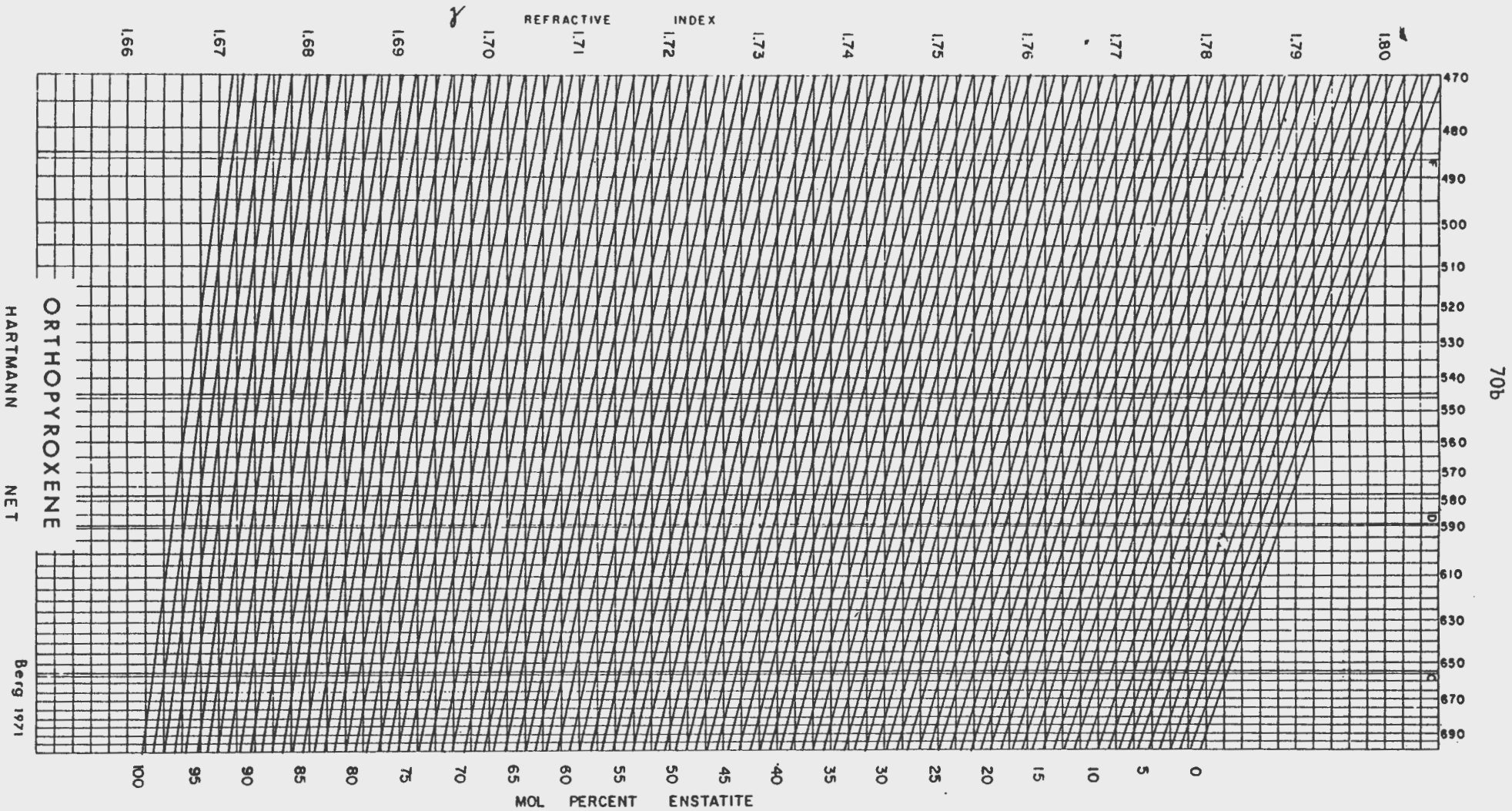


Fig. 13. Dispersion chart for orthopyroxene.

precision for olivine is roughly comparable to that for augite, and lower because of the relative scarcity of cleavages parallel to the Y indicatrix axis. In time, a valid estimate of precision will emerge from comparison of field determinations with electron microprobe grain-mount determinations on the same aliquots. For present purposes, the lower precision can be tolerated, since ranges obtained on plagioclase and orthopyroxene give a good indication of the variability within a hand specimen, and thus permit inferences to be made as to the extent of adcumulus growth.

OPERATIONAL REPORT

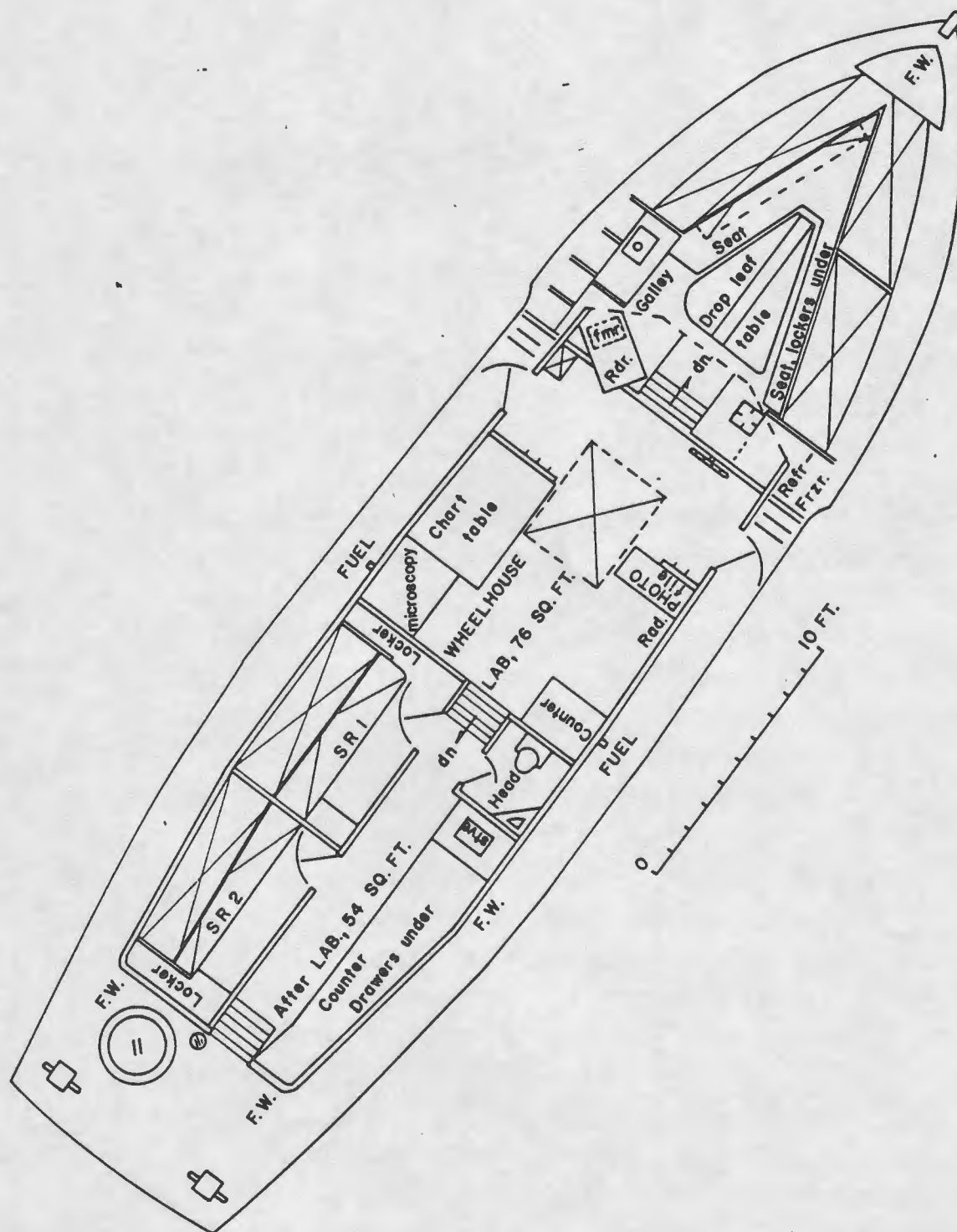


Fig. 14. Layout of R. V. Pitsiulak.

OPERATIONAL REPORT

INTRODUCTION.

This report covers the first season's operation of the Research Vessel Pitsiulak in support of geological studies in the Nain area. The first season was curtailed by late delivery of the vessel, being limited to the month of August, 1971. Despite this, it was possible to place parties in their field areas in early July by use of local boats, so we are able to report a nearly complete field season even though full use of the facility was possible only toward the end of the period. The first season's operation has provided a valuable shakedown, and has gone far toward proving the effectiveness of this type of logistic and laboratory support.

The purpose of the field facility centered around R.V. Pitsiulak is succinctly stated in the NSF Project Summary dated 24 September 1970:

"Funds are provided to establish a field facility to be used for research on the evolution of anorthosites and related crustal rocks in coastal Labrador. The facility is in the form of a floating base camp and field laboratory and is constructed on a modified design of a 50-foot Newfoundland Long Liner. In an area such as coastal Labrador where weather conditions make flying hazardous, water transportation is required for effective and sustained field operations. In addition to its use in supplying and transporting field parties, the facility will operate as a laboratory where preliminary studies of rocks can be made. It will also serve as a base for geophysical studies that must be carried out in shallow coastal waters."

The logistic function of the facility is straightforward: inasmuch as the Nain anorthosite complex is exposed along some thousand kilometers of shoreline in a deeply embayed skerry coastline, most field parties are able to work from camps at or near shoreline, accessible from a shallow-draft vessel such as Pitsiulak. The vessel is therefore able to make

periodic visits to resupply field camps or move them to another part of the field area.

The laboratory operation of the vessel is unusual if not unique, affording as it does a simple but complete petrographic facility for determining mineral compositions and processing samples for eventual mineral separation. Although the laboratory was fully operable for only about two weeks in 1971, it was nevertheless able to produce plagioclase, olivine, and pyroxene determinations, and numerous mineral identifications as well. These data were, in several cases, of material benefit in guiding the progress of mapping, and it is expected that full operation in future seasons will yield results even more closely pertinent to progress in mapping, as well as statistically useful data on regional and local composition variation.

Despite the curtailed season of R.V. Pitsiulak, it was possible to provide transportation and field guidance for limited visits by two guest investigators, who undertook reconnaissance sampling for a program of geochemical and petrological studies. The geophysical program is yet to be launched, but it is hoped that proposals for magnetic, gravity, heat flow, and seismic studies will be forthcoming, in which the vessel can play a supporting role.

DESCRIPTION OF FACILITY

R.V. Pitsiulak

The name Pitsiulak is Eskimo for the black guillemot (Cepphus grylle), a charming bird who has a habit of emerging explosively from seemingly bare rocky outcrops along shore to confound the visitor with his aerobatics and his ability to disappear whence he came, like the flash of insight which cheers the geologist at one outcrop only to vanish in confusion at the next.

The research vessel is a modified 50-ft. Newfoundland Long Liner, with quarters for 10, laboratory space, 1000-mile cruising range, ice sheathing, and standard navigational equipment. The layout is shown in Fig. 14. The design was chosen for its sturdiness, seaworthiness, modest draft, laboratory and storage capacity, ease of handling, and economy. These criteria prove to have been well met. A principal concern was to

have the vessel small enough for operation in shoal waters, with a small crew, of which the master and chief scientist could be one and the same person, at least during the first few seasons. In this way, a modus operandi could evolve favoring maximum scientific productivity and operational efficiency, while allowing the orderly development of logistic routines, including hydrographic charting, subservient to the needs of the shore parties.

R.V. Pitsiulak is of standard Newfoundland construction, to a hull design well known for seaworthiness. She measures 51 ft. overall, 13.5 ft. in beam, with a draft of 5 ft. The slightly extra length arises from raising the forward barricade somewhat to allow for greater headroom and higher bows. Further specifications are listed in Table 1.

In performance, the vessel has lived up to the reputation of the basic fishing hull design for seaworthiness and economy. Fuel consumption averages about 3.5 gal/hr at 1800 rpm, which gives a comfortable cruising speed of about 8.7 kt. Top speed is about 9.3 kt, but is achieved only with a greatly increased expenditure of fuel, to about 5 gal/hr or more. The hull has an easy motion in seas, and except in rough water it is possible to do good petrographic microscopy while under way, with the aid of a sponge rubber pad under the microscope to damp engine vibration. The only deficiencies are minor and correctable. Because of the large amount of weight forward, including stores and an oversize anchor windlass weighing nearly 1000 pounds, the vessel trims by the head, making her somewhat ungainly to steer in following seas. Most of this tendency can be corrected by ballasting aft. The present battery charger is too small to maintain peak charge during extended laboratory sessions in port, and will have to be replaced by a bigger unit. There are no major problems; the vessel is capable of hard work, as shown in the narrative portion of this report on a later page, and she is admired by the experienced seamen of Nain and the green geologist alike. The vessel is a credit to the men who built her with special pride and dedication to their craft.

The shipboard laboratory (Table 2) combines the functions of microscope petrography with rock comminution, mineral separation, slabbing and thin section preparation, and sample storage. The facilities are now completely operable at varying levels of productivity; first emphasis has been

Table 1. Specifications of R.V. Pitsiulak

Builder - Lewisporte Shipyards, Lewisporte, Newfoundland

Hull

51.0 x 13.53 x 5.3 ft. Water line 48 ft.
 Gross tonnage 24.36
 Register tonnage 16.56
 Keel - B.C. fir, 9" x 9"
 Stem - Spruce, clad with 3/16" welded steel plate.
 Extra curvature at water line for work in ice.
 Apron and keelson - Spruce
 Deadwood - Spruce
 Frames - Lower part birch, upper part spruce, 12" centers
 Planking - B.C. fir, 1 1/2"
 Deck beams and deck - Spruce
 Sheathing - South American greenheart, 1/2"
 Transom - B.C. fir, steel plated
 Rudder - Welded 3/16" steel, on 2" diameter stock

Fastenings - Galvanized steel, 5/8" in deadwoods, 1/2" bolts in clamps, shelves, floors, bilge ceiling, and planking butts. Planking to frames and decking to beams, galvanized boatnails.

Rigging - Two masts and booms for over-side lifting of boats and gear.
 Stays of 1/2" wire rope.

Steering - Hydraulic, self-activated, 20" wheel

Bilge Pump - Navy type, 15 gpm. (hand, auxiliary)

Anchor Windlass - Hydraulic, heavy duty, supplied from pump on main engine

Anchors - 100 lb., 150 lb. fisherman style; 40-lb. Danforth

Chain - 30 fm each anchor, 1/2" galvanized

Machinery - Main engine Volvo Penta MD70B diesel, 117 hp at 2100 rpm.
 Warner 73 reverse gear. Water-cooled exhaust out port side;
 silencer to be added.

Propeller 32" x 25 bronze, with spare

Shaft 2 1/2" steel

Electrical Lister 4.5 kw air-cooled diesel, generating 110 v.
 AC for after laboratory, with battery charger for main storage
 batteries. Alternator, 2 kw, off main engine for 32 v. DC
 system (engine, lights, and all auxiliary equipment)

Bilge pump Off main engine, 1 1/4" discharge overboard or to fire hose.

Fuel Tanks - 440 gal. imp., 410 useful. 1/4" welded steel, port and starboard, in engine room

Fresh Water Tanks - 130 gal.

Fire Extinguishing Equipment - Fire axe, fire buckets, foam extinguisher, dry chemical extinguisher, fire hose off bilge pump

Life Saving Gear - 16-ft dory, equipped (5 persons). Inflatable life raft (4 persons). 10 lifejackets. 2 lifebuoys.

Galley - Oil stove; bow peak day tank for water; refrigerator-freezer, 16 cu. ft., built-in.

Navigational Equipment - Magnetic compass, compensated.

Radar: Marconi, 16-mile range

Fathometer: 240-fm range, recording

Running lights, search light, electric horn, hand horn

Radio - Portable SBX-11, 10 watt, licensed as mobile station of British Newfoundland Exploration Ltd.

Quarters - Forecastle, 4 bunks, with space for another
1st cabin, 1 large bunk, 1 small
2nd cabin, 1 large bunk, 1 small

Marine Toilet - In after cabin

Storage - Galley under seats and in lockers; after laboratory in drawers; lazarette in bins.

Table 2. Laboratory Equipment

After laboratory

8" mullite plate grinder - BICO
DFC jaw crusher, small
10" diamond saw
Small lapidary set for thin sections
Sieves, stainless steel
Separatory funnels & stand
Bromoform and methylene iodide
Oil stove
Fume hood blower with portable intake on flex hose
Sample storage vials and bags

Wheelhouse laboratory

Leitz Laborlux-pol petrographic microscope, with 32-volt power supply
Interference filter monochromator, 400-700 nm
Refractive index liquids: plagioclase dispersion set, mafic dispersion set, standard set.
Thermometers and clamps
Library
Chart table and drafting machine
Filing cabinet with aerial photograph collection

placed on rapid comminution and petrographic examination, with deferred emphasis on detailed mineral separation, thin sectioning, and slabbing. K feldspar staining will be added in future seasons. Further description of the facilities and their productivity is given in the section on laboratory operations, beyond.

Shore Facilities

The town of Nain has a Government Wharf used by CNR coastal freighters, the International Grenfell Association hospital ship, fishing boats, local small craft, and visitors. The Newfoundland and Labrador government's Northern Labrador Services Division operates a 20,000 lb/day fish freezing plant near the wharf, as well as a general store and frozen food locker. An independent merchant maintains dry storage space which is used by the Project, as is the frozen food locker. The merchant, Mr. Hayward Haynes, is retained as expeditor for the Project; he acts as liaison with charter air services, receives and stores all shipments of material and food, arranges local transportation when necessary, looks after field equipment, maintains radio schedules and performs innumerable other services of great value to the smooth progress of research.

A 16' x 20' house is available for Project use in Village Bay, some 36 mi. north of Nain in the Kiglapait intrusion. This is occasionally used for storage and for quartering personnel in transit to other areas.

A part of a larger house in Khauk Harbor, 4 mi. south of Nain, is currently retained for winter storage of field equipment. It is hoped that a larger part of this house can be leased for long-term storage and as a staging area for field operations.

Field Gear

The Project has a current inventory of five kits of field gear, each consisting of tent, mattress pads, cook shelter, stove, and utensils. Four canoes are available, two 20-ft. freighters of 3000-lb capacity each, and two 16-ft. prospectors of 850-lb. capacity each. A third prospector canoe was lost from shore during a violent storm in July 1971. This will be replaced. Two 10-hp and three 6-hp outboard motors furnish power for the canoes.

The Project maintains two "GSC" model portable diamond core drills for sampling on shorelines and in other areas where precise sample location or orientation is desired. These are furnished to field parties as needed.



Fig. 14a. Route travelled by Pitsiulak, Lewisporte to Nain.

NARRATIVE REPORT

Operations prior to 1 August were conducted on two fronts; one in the Nain area and a second in the shipyard at Lewisporte, Newfoundland. The working group, headed by de Waard and Wheeler, reached Nain on 28 June, and began work soon after. The worrying group was headed by Morse, who reached the shipyard 22 June, later to be joined by his family, and on 10 July by R. B. Wilcox, Mate, and S. Andersen, Pilot-engineer.

Nain Area, July

The field parties of Rubins and Woodward comprised the initial working group under de Waard and Wheeler. The notes of Dr. Wheeler furnish the basis for the following account. The group was generously quartered by British Newfoundland Exploration Ltd. (BRINEX) in North West River between the time of their arrival at Goose Bay, Labrador by scheduled airline on 25 June, and the onset of favorable flying weather on 28 June. Chartered Otter and Beaver aircraft, operating on floats, took the group and their baggage to Nain, along with a load of early-season fresh food purchased at Goose Bay. Several days of bad weather followed, permitting organization of field equipment and purchase of supplementary items in the two local stores. Valuable assistance was provided in Nain by H. Haynes and S. Andersen.

Canoes were used for travel to the first field area, in order to test their adequacy as a transportation system for the whole group. The system proved somewhat unsatisfactory owing to the low capacity of the small canoes; these will be supplemented in the future for such work by new 17-ft. freighters of 1600-lb. capacity.

The scheme of early operations was to establish each field camp in sequence, taking the time to review local and regional geology, develop working methods, and establish familiarity with rock types and problems. Communications were established via portable radio to H. Haynes in Nain, who efficiently maintained a schedule twice daily prior to the established BRINEX schedule, and when necessary participated in the latter to pass traffic to North West River.

In Rubins' area, the threads of his Ph.D. research were picked up and followed to new outcrop localities in the period 3-7 July. The new localities included Barth I., centrally located in the troctolite body of that name.

The Rubins party was left to carry on its work on 8 July, when a fishing boat was summoned by radio from Nain to move the remaining people to the Webb Neck shore north of Barth I. Here a geological reconnaissance was made which established the existence of a contact zone involving troctolite, adamellite, granulite, and anorthosite. This contact zone has some striking similarities to that in Rubins' thesis area to the south, as well as some intriguing differences which warranted closer investigation. On the basis of the early visit by de Waard, Wheeler, and the Woodward party, it was possible to advise Rubins by radio that the area would repay detailed investigation, as anticipated. This report enabled him to plan the summer's research efficiently.

On 12 July, a fishing boat was again summoned from Nain for the longer trip to Aulatsivik (Newark) I., where Woodward's base camp was established in Ungujivik B. Again, a geological reconnaissance was made, problems were posed, and the party was left on 16 July to carry on its work.

The Planansky field party arrived in Nain 15 July, and it was arranged that de Waard would begin his independent research on the anorthosite margin at Ford Harbour, leaving Wheeler to assist the new team in getting started. Accordingly, on 16 July, a fishing boat from Nain moved de Waard to Ford Harbour and took Wheeler back to Nain. The Planansky party joined this excursion to get a general idea of the region and to begin conferring on geological problems with de Waard and Wheeler.

After resupplying in Nain, Wheeler accompanied the Planansky party on 17 July to Ten Mile Bay where a study was begun of The Bridges Layered Series. Wheeler remained with this party until 27 July, by which time Rubins was ready to move his base camp to the shore north of Barth I. This boat trip from Nain provided an opportunity for Wheeler to rejoin the Rubins party for discussions of work in progress and of the geological reconnaissance previously made in that area, 8-11 July. Wheeler remained with the Rubins party until joining R.V. Pitsiulak on 2 August.

Discussion

The above account helps to illustrate the intended pattern of early-season operations in the Nain Project. To be sure, the absence of the vessel caused some differences in the style of operations. In retrospect, the extended presence of senior investigators living ashore with new investigators during the initial period was beneficial, and perhaps most appropriate for the first season's operations, despite some consequent loss of individual research time by senior personnel. The pattern will be followed in revised form in future seasons, when the vessel will be available from the start. There will again be a few days' review of petrography and problems on the outcrop for each party. Experienced investigators will want less of this, and new investigators more. Accordingly, an effort will be made to emplace the experienced field parties first, so that new personnel can see as much geological variety as possible while they stay with the vessel in its rounds.

A facet of Labrador research which does not emerge in the above account is the need to learn how to live comfortably enough to make one's work effective and rewarding. The editor may be pardoned for some slight risk of embarrassment to his colleagues in suggesting that this mission was well fulfilled in 1971 by the extended presence of de Waard and Wheeler in the field camps.

Kiglapait Area, July

Original plans called for Berg's party and J. A. Speer to reach the field area on board R.V. Pitsiulak. When it became apparent that they would lose all of July by doing so, arrangements were made to get them into a field area which would be at least related to their working area, and accessible by boat from Nain. The house at Village Bay in the Kiglapait intrusion was chosen for its convenience as a base camp and its proximity to important outcrops and problems in the intrusion. The party arrived at Nain on 11 July after an enforced stay in southern Labrador due to bad flying weather. Ice conditions in Village Bay prevented landing there, and the remainder of the trip was made by boat from Nain. While at Village Bay, the party visited critical areas of the Kiglapait intrusion and succeeded in securing specimens from a previously unvisited part of

the intrusion where it is hoped to find pyroxenes of intermediate composition to fill an annoying sampling gap.

Because of the remoteness of Village Bay from the Nain working area, the Berg party was not able to take part in the introductions to research going on there. Nor was it able to move to its working area on the northwest edge of the intrusion until the arrival of R.V. Pitsiulak. In retrospect, it is regrettable that it was not taken directly to Hettasch Lake or Wendy Bay, although ice conditions may not have permitted landing there without making many expensive attempts. As it turned out, these investigators lost all of July and some days of August insofar as their own research was concerned; they did at least gain some geological experience, and they made the best of a bad situation.

Lewisporte, June and July

Vessel construction was delayed by a host of causes, among them a late start. By the time of Morse's arrival in June, the crew was working an 80-hour week in an attempt to catch up with time. The scheduled delivery date of 15 June had gone by. Fuel tanks were not delivered because of a strike at the machine shop which was to make them. A rash of holidays and long weekends ensued, slowing deliveries of critical items even more. When the tanks were finally cut and welded, another long weekend intervened before they could be pressure tested (as required) in the presence of a Canadian Steamships Inspector. During all this delay, work on the after cabin house ceased, because the large tanks had to be fitted into the engine room before the cabin could be closed in.

These remarks only give the reader a taste of the complications and frustrations encountered. Many decisions and much expediting of materials were required, and 16-hour days seemed at times to produce only trivial progress. On 10 July, the work was given a large boost by the arrival of Mr. R. B. Wilcox, master shipbuilder, veteran of many Arctic explorations with the legendary Capt. R. A. Bartlett, and old friend and teacher, who had managed to get clear of numerous responsibilities at home in Maine and come to us on short notice. His talents were brought to bear with good effect in numerous departments. Also on 10 July, another boon appeared in the form of Mr. Sam Andersen, our pilot-engineer, summoned from his home

in Nain. His many talents quickly bore fruit in the engine department and elsewhere.

It is a high tribute to the spirit of the crew and the builder that they accepted all these interlopers and worked closely with them. All hands, including wife and daughters, turned to with a will to further the construction, painting, and fitting-out of the vessel.

During this time, communications were maintained with personnel in the U.S. and in Nain, the latter in part via the vessel's radio, set up in the shipyard office. Contingency plans were formulated and carried out, missing supplies were chased down by telephone, and the good progress of field operations was noted with much satisfaction.

Urgency, combined with one form after another of bad luck, forced a few changes in construction and machinery. A strike in Sweden prevented the delivery of the intended 6-kw generator altogether, and a used 4.5 kw generator was substituted, savings being applied elsewhere. The resulting 110 v. power supply is very adequate for existing equipment, although it leaves less of a reserve for later additions. An appropriate electric anchor windlass could not be obtained in time, and the only hydraulic windlass available at short notice was a large gurdy windlass designed for hauling fishing gear. This very capable piece of apparatus is a welcome aid to anchoring, but it weighs about 1000 pounds, and contributes materially to the problem of balancing the vessel.

At long last, on 22 July, the vessel was launched in appropriate style by D. F. Morse, who produced a most satisfying burst of champagne with one characteristically decisive blow. The vessel moved under her own power to the Government wharf for final fitting.

On the same day, the larger of the two copper fresh water tanks failed, despite having passed previous tests. This tank is braced against the frames of the starboard quarter, and is closed in by the counter and drawers of the after laboratory. Its replacement would have entailed extensive dismantling and reconstruction. The tank was therefore abandoned. It was decided to recover most of the lost 75-gal. capacity with two cylindrical galvanized steel tanks of 30-gal. capacity each, mounted in the after peak. These were ordered, and eventually installed and tested in place on 26 July.

Also on 22 July, a short circuit occurred in the engine control panel, destroying the oil pressure and water temperature gauges. Replacements not being available, these were bypassed, and mechanical gauges were installed on 26 July.

26 July was a busy day, beginning with compass adjustment. The vessel was swung with hand lines at the knuckle of the wharf, and simultaneously, sextant angles to known objects were measured by the Canadian Steamships Inspector while magnetic bearings on the fore-and-aft line of the ship were taken with a Brunton compass on the wharf. The placement of a single adjusting magnet sufficed to reduce the maximum compass error to 1.5 degrees. The trial run was then held and passed to the satisfaction of CSI, Builder, and owners.

Lewisporte to Nain, 27-31 July

On 27 July, provisions arrived, and most of the day was spent in stowing these and tending to the endless details of getting ready for sea. By supertime it proved possible to clear Customs with an outward report, renewable annually, and at 2136 hours we cast off for the outer parts of Exploits Bay, and for Labrador if all went well.

All did not go well: the hydraulic steering developed an air lock and its response to port helm became increasingly sluggish. We were amply forewarned of this possibility, and decided to put up for the night before correcting the problem. The entrance to Little Bridgeport Harbour was found with the help of radar, and safely if somewhat erratically negotiated to a cozy anchorage at about midnight.

The proper maiden voyage began at 0904, 28 July, after air was bled out of the hydraulic lines. A good passage was made in warm, southerly weather to St. Anthony in northern Newfoundland where we docked at midnight. Here we topped off fuel tanks on the morning of 29 July, wishing to have a wide margin for reaching Nain without further delay.

On 29 July, leaving St. Anthony at 0900, a fine run was made in fair weather past Belle Isle and across the Strait of that name to a familiar landfall at Camp Islands. From here northward to Cut Throat the quality of navigational charts has undergone a quantum jump over that of 20 years past, and with great ease and comfort we ran down to Wall I. and via a buoyed

passage through Caribou Run to Assizes Harbour, where we stopped for the required 25-hour oil change. Engine speed was limited to 1700 rpm during the 50-hour running-in period; this yielded a comfortable 8 to 8.5 kt. At Assizes Harbour, radio contact was made with Mr. Haynes in Nain, who in turn reported to the field teams our position, and predicted our running time to Nain with what turned out to be great accuracy.

Leaving Assizes Harbour after supper by the narrow northwest exit, we ran down to Red I., meeting enroute R.V. Maxwell, out of Halifax. We continued through the evening, steering for Roundhill, a familiar landmark of southern Labrador. Southeast swells made steering somewhat difficult owing to the head trim of the vessel, but we continued to make good 8 to 8.5 kt at 1700 rpm. At White Rock we hauled in for Domino Run in the early hours of morning of 30 July, but here heavy fog was encountered, and a good few large pieces of ice. Radar and fathometer were used to good advantage for position control, and radar, augmented by a sharp visual lookout, was most helpful for locating ice. On clearing Domino Pt. through Mark and Saddle I., we slowed somewhat to enter Domino Run, which appeared on the radar screen to be encumbered by a large iceberg. The "iceberg" soon appeared to be well illuminated, and proved to be the CNR coastal steamer Bonavista hanging up for the night in the Run. We turned hard under her stern and passed close aboard to enter Domino Harbour, anchoring in 4 fm at 0345 to await daylight before continuing onward.

The stop at Domino was brief; we were under way again at 0810, 30 July, for what proved to be a fair day and a nostalgic run along a classical route. To avoid the southeast swell, we elected not to cross the wide mouth of Groswater Bay, instead running westerly through the islands and past the old, nearly abandoned fishing stations in tight harbors whose heyday was a half-century past. We took the inside run through Indian Tickle, passed the long-abandoned whaling station at Grady, passed close by the entrance to Pack's Harbour (where with a big vessel you must enter hard against the fishing stages built out on the steep, rocky shore), and hauled northward to South Stag I., the lonely Tumbledown Dick I. in Hamilton Inlet, across to the Herring Islands, looming as black, surrealistic images out of the water, and heavily populated with puffins, guillemots, gulls, and numerous other sea birds. This route took us by supertime to Cut Throat on the north side of Groswater Bay.

From Cut Throat the course leads northwesterly to the Quaker Hat. Here watches were set, and we ran down to the Ironbound Islands, encountering in the darkness a fair number of icebergs with their leeward discharge fields of bergy bits. With radar and lookout, these were handily avoided, or rarely, penetrated at reduced speed. Reaching the Ironbounds at 0400, we turned westward and for the second time enjoyed the comforts of modern charting past Turnavik I., through the Hares Is. to Flagstaff Tickle and so to Hopedale, the first town of the Labrador trip passed in full view. Now we were well within Pilot Andersen's home waters, familiar enough to outsiders with charts, but subject to total recall in his memory, without charts. Passing through Black Tickle, we negotiated a small-boat route around the south end of Napartulik I. with the aid of a fathometer and a bottom watch. Thence northward through Windy Tickle we made good 11 kt. over the ground for 1/2 hour with wind and tide, the engine now running at 1900 rpm.

Cape Harrigan at the north end of Windy Tickle was avoided by passing westward through Shoal Tickle, with depth 2 fm. for several miles. Off the western end of Shoal Tickle, where the bottom is a monotonous 8 fm., the fathometer suddenly climbed abruptly, and as we stopped we recorded a depth of 1 fm. over a large, sharp rock. This rock was unknown to us or any of our subsequent informants. Bearings were taken immediately, and the hazard's approximate position plotted.

The route from Shoal Tickle leads into the skerry fringe of islands which shelters the approaches to Nain. Passing the former site of Davis Inlet, we rounded Porcupine point with steep land close aboard, and negotiated the twisting, deep-water passage to the new Davis Inlet, a handsome new town nestled in spruce trees. Then came the long evening run, landlocked at every turn, past Tunungayualok I., Akpitok I., Nokhalik I., and through The Bridges Passage to Nain, where Pitsiulak docked at 2215 hr. with 300 gal. fuel remaining.

A synopsis of the maiden voyage is given below. The trip rarely takes as little as four days time, and often takes a week if weather or ice conditions are unfavorable. The passage was a good one, testifying to the good weather and smooth operation of the vessel. As to style, suffice it to say that the cook baked bread the first day out, served three delicious

hot meals a day, and stood watch and wheel tricks to boot.

Synopsis of maiden voyage of R.V. Pitsiulak

Left Little Bridgeport Hr., Newfoundland	0904	28 July
Stopped St. Anthony 9 hr., left	0910	29 July
Stopped Assizes Hr. 2 hr., left	1810	29 July
Stopped Domino Hr. 4.5 hr., left	0810	30 July

Engine time	70 hr.
Stopped time	15 hr.
Total	85 hr.
Domino Hr. to Nain, continuous	34 hr., 305 mi., av. 9 kt.
Crew:	S. A. and D. F. Morse, R. B. Wilcox, S. Andersen; Elise, Anne, and Sophia Morse.

Nain Area, August

Vessel operations began on 1 August, immediately after arrival in Nain. By 11 August it was possible to file the following report by wire:

DR. RICHARD G. RAY
EARTH SCIENCE SECTION
NATIONAL SCIENCE FOUNDATION
WASHINGTON, D. C. USA

RESEARCH VESSEL PITSIULAK LAUNCHED 22 JULY TRIAL RUN 26 JULY DELIVERY ACCEPTED 27 JULY. MAIDEN VOYAGE EXPLOITS BAY NFLD TO NAIN LABRADOR 28 TO 31 JULY 85 HOURS LAST 34 CONTINUOUS 305 MILES AVERAGING 9 KNOTS. BEGAN OPERATIONS NAIN AREA 1 AUGUST. HAVE NOW RESUPPLIED ALL FIVE FIELD PARTIES AND REVIEWED PROGRESS WITH THEM. LABORATORY OPERATIONAL 11 AUGUST AND SEVERAL DOZEN MINERAL DETERMINATIONS MADE. DRILL CORES TAKEN TWO LOCALITIES. NUMEROUS TRACKS SOUNDED IN UNCHARTED WATERS. RESEARCH PARTIES FLOWN IN EARLY JULY FINDING MUCH OF INTEREST PARTICULARLY IN CONTACT ZONES ALSO LAYERED ANORTHOSITE AND NORITE. SEASON PROVING GOOD SHAKEDOWN AND FACILITY OFFERS MUCH PROMISE FOR FUTURE. WISH YOU WERE HERE.

S. A. MORSE

NAIN
11 AUGUST 71

The first task was to pick up Wheeler at the Rubins camp, and move the Rubins and Planansky parties to new base camps. By midnight of 3

August, we were able to reach Berg's party at Village Bay, taking them around Cape Kiglapait to Kiglapait Hr. the following day. Here a rendezvous was kept with an aircraft, which took most of Berg's base camp inland to Hettasch Lake. Berg's party then left on foot from Snyder Bay on 5 August to walk to their base camp, reviewing geology along the way. The vessel returned to de Waard's camp that day, running a sounding track through Black I. Tickle in familiar but uncharted water.

Camp moves and resupply activities occupied much of the next three days. By 8 August we were able to reach our intended operations base at Nukasorsuktokh Harbour, and to begin a hydrographic survey after putting Wheeler off for field work. The crew then watered ship, pleased to find a reasonably good watering place in this island harbor, while Morse and Speer began sampling operations with a portable core drill. Nukasorsuktokh Hr., hitherto uncharted, is very possibly the finest harbor on the coast of Labrador, and it receives further mention beyond in the section on hydrography. The geology is very complicated here, so the harbor serves a dual purpose as a sheltered operational base and research area.

The middle part of August was occupied by frequent camp visits and resupply trips as we caught up on work in arrears. Interspersed with these operations were several days devoted to activating the shipboard laboratory facilities, and to geological reconnaissance on Nukasorsuktokh I. and outlying islands. By 11 August the laboratory equipment was fully installed, and production reached a peak on the evening of 17 August, when 22 mineral compositions were determined.

Field Conferences

The first round of field conferences was begun on 20 August. Conferences involve special logistic problems, added to those of normal operations and errands. The vessel's work for 19 August, in preparation for the conference, was scheduled in advance, and was completed 45 minutes ahead of schedule. The log of that day is reproduced below to illustrate what a busy day's operations can be like.

Log for 19 August

0525	pumped ship, Nukasorsuktokh Hr.
0607	underway to Nain
0745-0757	stopped to pick up 20' canoe at Bridges

0835 docked Nain. Put stores aboard.
 1000 underway to Khauk Hr. with owner of house to be used
 for storage.
 1040 arrived Khauk, left owner to work on house.
 1102 underway to Sachem Bay, Rubins party.
 1307 arrived Sachem Bay, hove to while picking up party.
 1330 underway to Khauk Hr.
 1526 arrived Khauk; anchored. Left 16' canoe, ship's lumber,
 excess field gear; picked up house owner.
 1605 underway to Palungatak I., Planansky camp.
 1655 arrived Pal. I., anchored in 1.5 fm. Took party aboard.
 1725 underway Nain.
 1825 arrived Nain, left off house owner at dock.
 1828 underway to W. Red I., de Waard camp.
 2007 arrived W. Red I., put field parties ashore with gear
 for night.
 2035 underway to Newark I., Woodward camp.
 2215 arrived Woodward camp. Anchored. Woodward party taken
 aboard for night. Secured.
 Lovely day for effective work.
 Engine time 14 hr.

The first conference day began at 0715 by picking up the field parties which had remained at W. Red I. overnight. Woodward's field area was reached at 0810, and examination of the geology there occupied the morning. His unusual layered complex provided much food for thought and discussion, not to mention disagreement about directions of tops of igneous layering. The scene of operations was shifted for the afternoon to de Waard's anorthosite outcrops at Higher Bight. By mid-afternoon, an hour's cold, windy rain had made further field work unprofitable, and the conferees returned on board. Supper was served to 14 people aboard. Radio contact to North West River produced a forecast from the Goose Weather Office of SE to NE winds and rain for the following day. Field personnel were returned to their W. Red I. camps during the evening.

The second conference day saw clearing skies with NW winds, happily contrary to the forecast. The morning round encompassed de Waard's layered complex, country rocks, and anorthosite on W. Red I., followed by afternoon visits to his highly interesting anorthosite contact zone at Higher Bight and to the Ford Harbour formation at the type locality. The W. Red I. camp was then broken, and the base of operations transferred to Khauk Hr.

The third conference morning, on 22 August, was devoted to Planansky's

older layered complex at The Bridges. A deterioration of weather during the day caused us to cut short the examination of this area, in order to pay an afternoon visit to Rubins' area on Webb Neck, north of Barth I. This was followed in late afternoon by a quick visit to the layered anorthosite at Tikkoatokhakh Rattle.

A final, partial conference visit was paid on 23 August to Barth I., while personnel due to leave on 24 August straightened out their gear and affairs in Nain.

The conference days were hampered by bad weather, but nevertheless furnished a good opportunity for investigators and assistants to broaden their experience of rocks, problems, and interpretations. At the same time, they showed how the laboratory facilities could be brought more helpfully to bear on field problems during a normal working season. Such conferences are an important facet of the entire research program, as they help to set the context for each investigator's individual research.

Termination of Field Season

Bad weather prevented flying during the period 23-25 August. The Woodward, Planansky, and de Waard parties were returned to field areas, while other personnel stored field gear and did local geological work. On 26 August, an Otter aircraft arrived, bringing guest investigators Barton and Upton, and a visit was made with this aircraft to Berg's camp at Hettasch Lake, to exchange field assistants. The Otter then returned to Goose Bay with those personnel who were scheduled to leave early.

The next four days were spent in rounds to the camps, field work, and visits to sampling sites of interest to the visitors. On 31 August, with all field parties now aboard, the vessel again travelled around C. Kiglapait, to meet Berg's party, who had walked out to Snyder Bay from Hettasch Lake with their remaining gear. A drill was provided for Berg's sampling in the Kiglapait Outer Border Zone, and further sampling visits were made by the visitors in the course of a roving conference in country rocks and in the Kiglapait intrusion. Once again, the work was cut short by variably poor weather, although Berg was able to collect a much more detailed suite of OBZ rocks than any previously in hand. Plans for sampling for U-Pb and Sr isotope studies in the central Kiglapait intrusion had to be abandoned,

as were plans for core-sampling for the completion of paleomagnetic studies. (One such sample was collected in anorthosite in Port Manvers Run enroute to Snyder Bay.)

The vessel returned to Nain on 2 September, and on the following day was stripped of her stores and working gear and taken to Khauk Hr., where she was moored and secured for the fall season.

On 4 September, all non-resident personnel left Nain via charter aircraft, unfortunately too late in the day to connect with their flights home, causing several days' delay.

Laboratory Operations

By 11 August, the mullite plate grinder was bolted in place and hooked up, and the jaw crusher was fastened down in a position convenient for manual operation. Use of the motor with the jaw crusher will require rearrangement of the crusher to a fore-and-aft position from its present thwartships position. The crushing, grinding, sieving, and separation facilities of the after laboratory permit full processing of normal hand specimens through comminution stages to bromoform or methylene iodide separation into heavy and light fractions. These full procedures are suitable with samples for which mass-balance geochemical studies are planned. However, even under the best of conditions, they are time-consuming, and a greater demand may arise for rapid and rough separation of mafic and light minerals for optical determinations and electron microprobe grain mounts. A simplified procedure might involve slabbing or breaking a hand specimen to get a representative fragment free of weathering; crushing, single-stage grinding, sieving on bolting cloth, and hydraulic separation in an expendable fluid such as methanol or water. Such a procedure would omit the simultaneous extraction of a whole-rock split, leaving this procedure to shore-based laboratories for those selected samples eventually chosen for whole-rock chemical studies. The details of such a rapid separation procedure have not yet been worked out, but the 1971 experience suggests that a rapid procedure will be preferable for shipboard studies in the future.

Although logistical priorities prevented attainment of high laboratory productivity in 1971, we did manage to make some 70 mineral composition determinations and several dozen routine identifications as well,

using methods described on an earlier page of this report.

Navigation

On long runs or in fog, dead-reckoning navigation is used and augmented by radar ranges and fixes and by fathometer readings. The accuracy of existing charts is adequate for position control by radar ranges and tangents to land, even though bathymetry is lacking in places. For shorter runs in good visibility, visual piloting is used, but DR tracks are set whenever it is convenient to do so in order to keep a record of any abnormalities in magnetic compass variation. The availability of radar has enabled the vessel to make many runs at night and in fog which would be impossible or dangerous without radar. Some runs under these conditions have even been made in uncharted waters, using Mr. Andersen's encyclopedic local knowledge backed up by the fathometer.

Particularly difficult waters are avoided except in conditions of good visibility, which allow observation of the bottom from deck.

Hydrography

Hydrographic work in 1971 consisted of a harbor survey, several sounding tracks, and numerous informal investigations of shoals or unknown areas. Sounding tracks were run whenever possible in uncharted waters, and tied to published bathymetry. Dead-reckoning tracks were controlled by conspicuous landmarks, bearings abeam to tangents of land, and radar ranges. The tracks are summarized below.

A detailed survey was made of "Nukasorsuktokh Harbour" and its approaches in the period 8-9 August at low water springs, and on 18 August. The resulting field sheet is reproduced here as Fig. 15. It is remarkable that no prior survey has been made of this wonderful harbor. We know from Wheeler (pers. comm., 1971) that Cdr. Wyatt of the Challenger recognized in 1932 the value of this harbor and the larger, northeastern bay of Nukasorsuktokh I., asserting that the entire British Navy could be accommodated there. Possibly the pressures of more urgent work prevented his making a survey at that time. Because of its importance as a base for Project operations, and its attractiveness as a shelter for vessels passing along the coast, a formal description and sailing directions are included herewith.

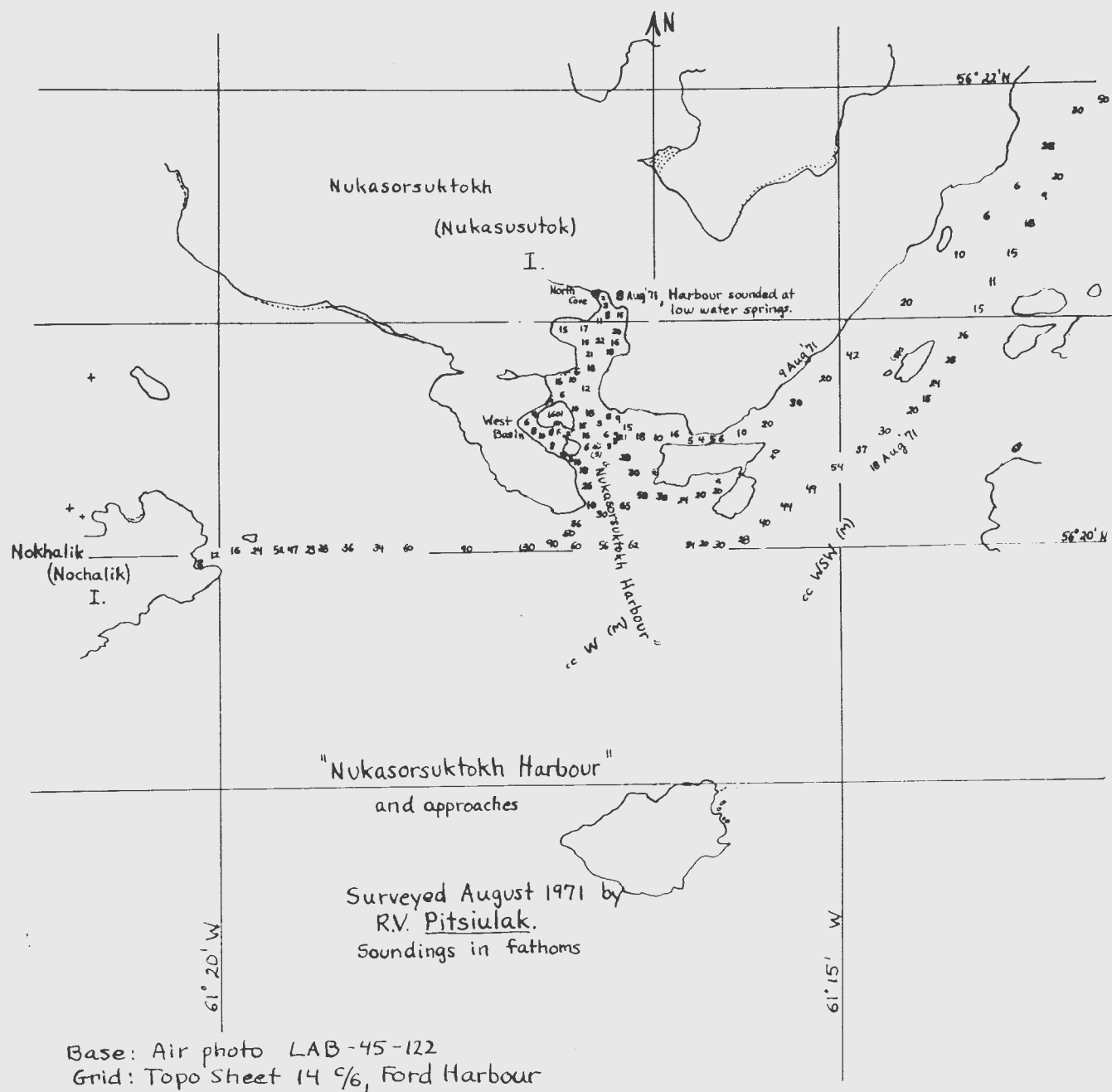


Fig. 15. Field sheet of "Nukasorsuktokh Harbour" survey. The name of the harbor is temporary; the name "Wyatt Harbour" will be proposed as a formal name.

The name is supplied in inverted commas to signify its unofficial status. Another name may eventually be submitted for approval by Canadian authorities. The spelling of the island is that used by Wheeler (1953); it appears as "Nukasusutok" on chart BA 265 and current maps.

"Nukasorsuktokh Harbour"

56° 21' N, 61° 17' W

"Nukasorsuktokh Harbour" on the south corner of the island of that name is among the finest on the coast of Labrador. The Harbour is surrounded by high land affording protection in any wind, and offers a wide choice of anchorages for any but the largest vessels. Water may be obtained at the head of the harbour (North Cove) or from the brook draining a small pond on the west side. The Harbour is entered from the south, but small vessels may enter from the east through a narrow tickle with a least depth of 4 fm. Two rocks (5 and 2 feet) straddle the entrance to the inner harbour, but these have only small shoal areas around them. Small vessels may use either North Cove or the West Basin for anchorage.

Directions. When entering from the south, a vessel should keep the easternmost of the two rocks to port for deepest water, and when this is abeam steer close along the bold eastern shore into the inner harbour. A least depth of 8 fm. is obtained along this route. When entering between the two rocks, a vessel should favor the right hand side of the channel, where a least depth of 3 fm. is found somewhat to the north of the rocks. By keeping the westernmost of the two rocks to starboard, and favoring the western shore of the harbour, a least depth of 6 fm. is encountered.

When entering from the east, a vessel should hold to the center of the narrow tickle between Nukasorsuktokh I. and the small island directly to the south. A least depth of 4 fm. is obtained in this channel.

The West Basin may be entered by small vessels either through the very narrow south channel or the somewhat wider middle channel between two small islands. The North Channel can be entered by motorboats. Both the south and middle channels have least depths of 2 fm. When entering the south channel, a vessel should steer close to the bolder northern side. The middle channel should be entered through the center, avoiding shoal points on both hands. Anchorage may be found in a 10-fathom hole near the middle of the basin, or in 6 fm. near the western shore.

North Cove affords good shelter for small vessels, but swinging room is limited and it may be necessary to moor. Anchorage in 3 fm. is obtained by favoring the northeast side of the entrance. An iron pin is to be found driven into a crack in a rock just inside the entrance, on the west side.

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The following sounding tracks were made during resupply and conference operations:

- 10 August - Southeast approach to Ungujivik Bay, Aulatsivik (Newark)
I. (about 5 miles)
- 16 August - West end of Palungatak I.
- 25 August - Western approach to Ungujivik Bay, Aulatsivik (Newark)
I. (about 5.5 miles)
- 28 August - Approaches to Young's Harbour, Dog Island
- 31 August - Wilcox Pen. to Snyder Bay, NW of Kiglapait Mountains
- 1 September - Mills Harbour, Port Manvers Run

Informal investigations, resulting in short tracks or annotations to the chart, were made in several areas, most particularly south of Skull I. in an area infested with shoals.

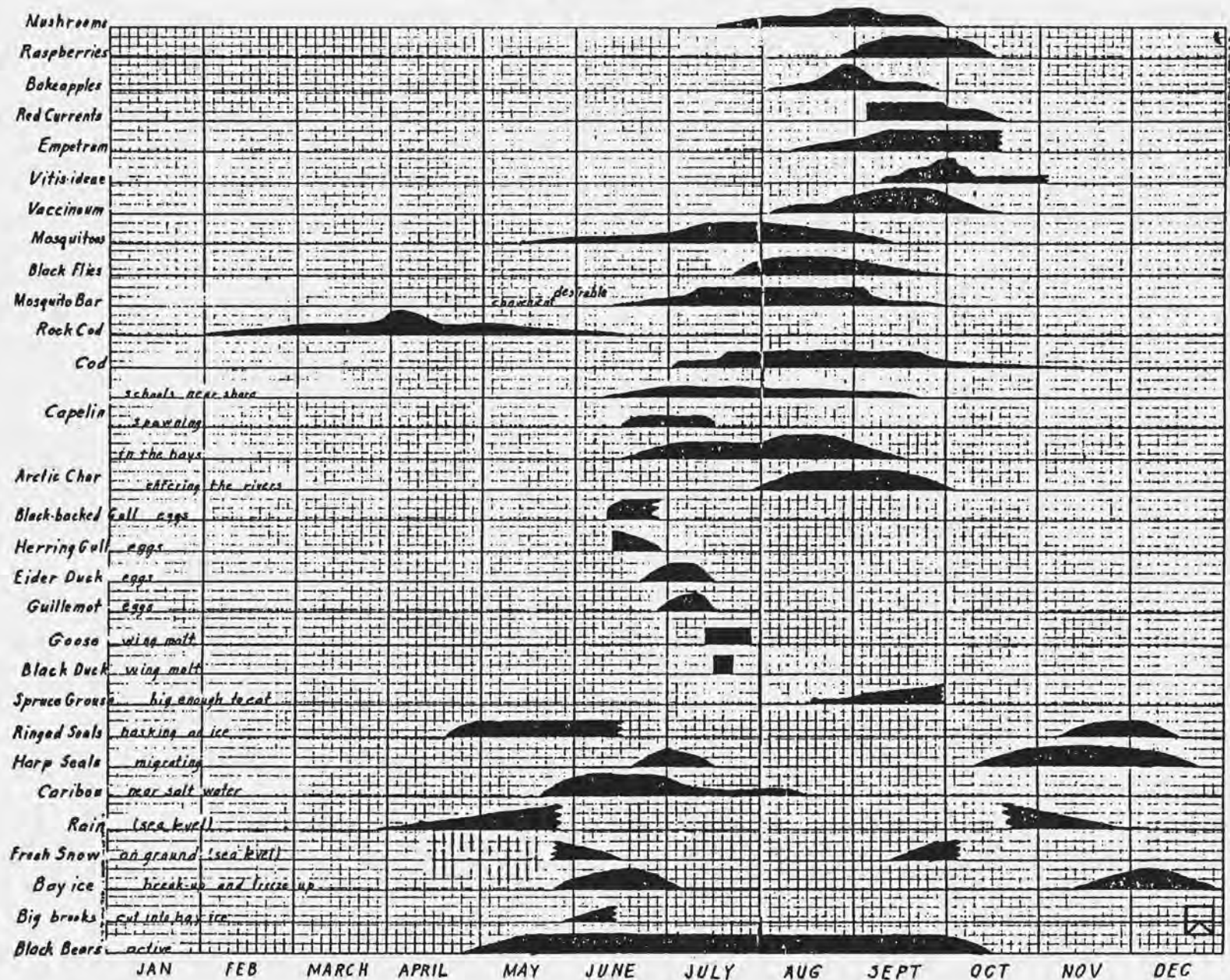
Subsistence

Food supplies in field camps centered on freeze-dried packaged meals, augmented with pilot biscuit and the common staples. Delivery of most items was effected without delay. The first supplies needed to be flown in from Goose Bay with the personnel. After the opening of navigation, supplies were shipped to Nain on coastal freighters and on R.V. Pitsiulak. The field parties used less frozen meat than anticipated, apparently in the interest of speed of preparation. More normal operations in future years with more predictable supply visits will probably result in somewhat more demand for frozen or fresh meat. Fresh vegetables are supplied from R.V. Pitsiulak when available.

In the Nain area it is possible and desirable to supplement the imported diet with a variety of fresh delicacies. Chief among these are fresh cod and arctic char, in season. Unfortunately, the past five years have witnessed an unprecedented deterioration in the summer cod fishery of Northern Labrador. The first arrival of cod in the earlier half of the century commonly fell in early to mid-July. In 1968, the first arrival at Port Manvers was 9 August, and in 1971 our first cod were obtained off the eastern end of Paul I. on 12 August. Fishing was spotty throughout August, although the fish when encountered tended to be large and of good quality. Rock cod, also of good quality and of larger than normal size in our

NAIN GOURMET'S ALMANAC

Fig. 16. "Nain Gourmet's Almanac" of E. P. Wheeler 2nd.



experience, were available throughout the season. Arctic char were available from early August. This magnificent delicacy is now being intensively fished around Nain for processing in the Nain freezer plant, whence the finest quality is shipped as steaks or smoked fillets for outside markets.

In addition to sea food, a variety of other resources are available to the initiated gourmet. The most reliable of these are the porous-gilled mushrooms and various berries, particularly the crowberry and blueberry.

For the record, it seems appropriate to include here a facsimile (Fig. 16) of E. P. Wheeler's "Nain Gourmet's Almanac", which summarizes nearly a half-century of experience in living comfortably with a minimum of imported provender. The list includes some items which today are protected and no longer figure as resources except in clear emergencies. The black bear, it should be noted, is not a resource but a gifted vandal, for whom the currently fashionable deterrent is a jam-coated aerosol can of insect repellent (or perhaps shaving cream?) to tempt his busy teeth.

Weather

The 1971 summer was devoid of meteorological disasters, such as 13-day northeast storms, which can occur in the Nain area. de Waard reports about one day out of five lost to weather during the season, which is about average for a non-disastrous season. Things can be much worse, and they are in some years better. Unfortunately, a fair share of the 1971 bad weather coincided with conference rounds, making these less productive than they would have been otherwise.

Communications

The 10-watt, 8-lb., portable, single sideband radio sets provided adequate communications. Unfortunately, the quality of signal from the vessel is not excellent, although experimentation with location and antennas has resulted in some improvement. The vessel's position is at times unfavorable for good transmission, depending on the location of the listener. On most days, apart from periods of widespread radio blackout due to ionospheric conditions, communications were feasible or even comfortable, and the diverse location of field parties usually permitted relaying of messages if direct communication was awkward or impossible.

Contact with the BRINEX base camp at North West River, 200 miles away, was very successful on most attempts. (It should be noted that the 10-50 mile range involved among our own stations is the worst range to work in radio, which is why our equipment is so expensive.) The personnel of BRINEX were very helpful, as always, in relaying messages and forwarding weather forecasts.

Limited transmissions were made, by permission, on the Provincial Government's coastal radio network, for purposes of communication with Nain or sending telegrams.

Inasmuch as R.V. Pitsiulak has little occasion to make use of standard marine frequencies, she has no marine radio, but is instead licensed to operate as a mobile station on the BRINEX net. Emergency calls, should they be necessary, would be made on that net or directly to Nain, which is connected by radio telephone to the Bell Telephone network.

Flying

The 1971 season required seven trips by charter aircraft between Goose Bay and Nain, four by Otter aircraft and three by Beaver. One Otter trip was also used for local flying (to Hettasch Lake), and a local trip to Hettasch Lake was made by a Cessna aircraft chartered from Nain. Of the seven flights to or from Nain, six were delayed by weather for periods up to four days. This ratio suggests why it was necessary to establish a reliable, sea-going logistic base in the Nain area. Had we relied on aircraft for resupply and moving operations, many days would have been lost in waiting in or near camp or in keeping frequent radio schedules.

Wintering of Vessel

It was intended to haul R.V. Pitsiulak out on the Government slip at Davis Inlet. Timbers and hardware were shipped in during the fall, and a cradle was constructed at Davis Inlet under the direction of Mr. Andersen. However, delays in delivery of material caused completion well after the highest October tides, and the vessel would not go on the cradle. The cradle was therefore shipped by freighter to Nain, where materials for constructing a slip had been assembled. Mr. Andersen returned with the vessel to Nain, where he and the townspeople and fisheries foremen, racing against

snow, freezup, and tide, built a slip with the available material. Two fisheries boats were hauled up on this with the aid of a D-4 tractor and a 1" steel cable. As it turned out, the highest November tide went by before the slip could be completed, and the Pitsiulak could not be gotten fully into her cradle. Accordingly, she was hauled out upstanding on her keel, well shored-up, and secured for the winter on 22 November. Mr. Andersen reports that the crews of M.V. Nachvak and M.V. Killinek were instrumental in carrying out these operations.

SUMMARY OF OPERATIONS

The 1971 working season lasted about two months, with support from R.V. Pitsiulak for half that time. Detailed geologic mapping and sampling was conducted in five field areas by shore-based parties, and in numerous localities by the staff of the vessel. Laboratory procedures were begun in mid-August; these yielded data of value in the conduct of field mapping, and showed the high potential of laboratory work in more normal seasons. The season began and ended with field conferences which illuminated the geologic problems and the steps toward their solution. Sampling programs were initiated by two guest investigators for geochemical studies at their respective institutions. Hydrographic surveys were made of one harbor and a number of hitherto uncharted approaches to working areas of interest. The calendar of operations below summarizes the main events.

Calendar

25 June	Early field parties to Goose Bay
28 June	Parties to Nain after delay due to weather
3 July	Start of field work, Barth I. area
7 July	Berg party to Goose Bay
11 July	Berg party to Nain after delay due to weather
12 July	Start of field work, Aulatsivik I. Berg to Village Bay
15 July	Planansky party to Goose Bay and to Nain
17 July	Start of field work, The Bridges area
22 July	<u>Pitsiulak</u> launched
26 July	<u>Pitsiulak</u> trial run and delivery
27-31 July	<u>Pitsiulak</u> Lewisporte to Nain
1 Aug	Vessel operations began
5 Aug	Start of field work, Snyder Bay to Hettasch Lake area

8-10 Aug	Harbor surveys, Nukasorsuktokh I.
11 Aug	Laboratory completed aboard <u>Pitsiulak</u>
20-24 Aug	Field conference, Aulatsivik I., Paul I., Barth I. area
26 Aug	Early departures of personnel, arrival of guests
31 Aug-2 Sept	Field conference, Snyder Bay and Port Manvers Run
2 Sept	All field operations terminated
3 Sept	Vessel moored Khauk Hr.
4 Sept	Final departures of personnel from Nain
22 Nov	<u>Pitsiulak</u> hauled out, Nain

PERSONNEL

Scientific Staff

Coordinator: S. A. Morse, University of Massachusetts, Amherst, Mass. 01002

Associate Coordinators: Dirk de Waard, Syracuse University, Syracuse, N.Y. 13210
E. P. Wheeler 2nd, Cornell University, Ithaca, N.Y. 14850

Investigators: J. H. Berg, University of Massachusetts, Amherst
G. A. Planansky, Harvard University, Cambridge, Mass.
Charles Rubins, Syracuse University
Charles Woodward, Syracuse University

Guest Investigators: J. M. Barton, Universite de Montreal, Montreal, P.Q.
W. Levendosky, Syracuse University
B.G.J. Upton, University of Edinburgh, Scotland

Research Assistants: C. D. Brauer, Vassar College, Poughkeepsie, N.Y.
F. Finley, Syracuse University
T. H. Folkomer, Franklin and Marshall College, Lancaster, Pa.
D. Russell, Syracuse University
J. A. Speer, Virginia Polytechnic Institute, Blacksburg, Va.

Operating Staff

S. Andersen, Nain	Pilot-Engineer
H. Haynes, Nain	Expediter
D. F. Morse, Amherst	Cook
S. A. Morse, Amherst	Master
R. B. Wilcox, Boothbay Harbor	Mate

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