THE NATURE OF THE GRENVILLE FRONT
NEAR LAKE TIMAGAMI, ONTARIO

Thesis by

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ABSTRACT

The Grenville Front forms the boundary between the Superior and Grenville provinces, which differ greatly in structural trends and in grade and age of major metamorphism. The Front has been claimed to be a metamorphic transition, a regional fault zone, or a combination of the two. The Lake Timagami area lies athwart the Front and is favored by good outcrop and an unusually complete geological section. Detailed mapping, petrographic and chemical studies permit tentative conclusions which are validated by Rb-Sr isochron analyses.

Early Precambrian Keewatin-type metagreywacke and metavolcanic rocks form a steeply dipping, easterly trending belt intruded successively by quartz diorite and granite. To the north, these rocks are overlain with marked unconformity by flat lying virtually unmetamorphosed Huronian strata; diabase intrudes the Huronian and older rocks. Pre-Huronian "Buchan" metamorphism of the Keewatin-type rocks predated, but was probably related to, the emplacement of the granite. Later metamorphism affected the granite and older rocks and probably the Huronian sediments and the diabase, but its macroscopic effects are only visible - by definition - south of the Grenville Front. Here one finds a migmatitic terrane in which the probable equivalents of the metagreywacke, quartz diorite and granite can be distinguished. In the west, the transition into this terrane is unfaulted, but to the east it is largely cut out by a northeasterly trending fault system. Within this terrane, the late metamorphism produced lithologies, metamorphic

grade and structures typical of the northwestern part of the Grenville province, and for this reason the metamorphism was considered to be of Grenville age.

X-ray fluorescence analyses were used to establish the range of chemical composition of the metagreywacke and the apparently equivalent schist south of the Front. Comparison of these ranges suggests that the late metamorphism was isochemical and that this correlation is permissible.

The tentative correlations from the Superior province into the Grenville province and the Grenville age of the late metamorphism cannot be proved conclusively by the mapping, or by the petrographic and chemical studies. However, the Rb-Sr analyses provide convincing evidence that these conclusions are correct.

(a) Whole rock samples of granite from the Superior and Grenville provinces define an isochron. This substantiates the correlation of these as comagmatic granites. The age derived from the isochron is 2220 m.y. ± 70 m.y. and the corresponding initial $(Sr^{87}/Sr^{86})_o = 0.703 \pm 0.001$.

(b) Mineral isochrons indicate virtually complete strontium isotopic equilibration south of the Front and partial equilibration north of the Front between 0.9 b.y. and 1.1 b.y. This is considered proof that the late metamorphism was indeed of Grenville age.

(c) The combined data from the whole rock and mineral isochron studies prove beyond all reasonable doubt that granite of the Superior province, with a primary age of approximately 2.2 b.y., was subjected to the Grenville orogeny at approximately 1 b.y.

(d) The whole rock analyses place a new maximum limit of 2.3 b.y. on the time of deposition of the Upper Huronian sediments.

The major conclusion from this work is that rocks of the Superior province were "cannibalized" during the Grenville orogeny and can be traced into the Grenville province. The Grenville Front is a metamorphic transition of Grenville age locally disrupted by faulting, and approximately defined by the southeastward transition from greenschist to amphibolite facies.

(Plate 1, the geological map of the Lake Timagami area is essential to this thesis. It has been published (Map #2048, Vogt-Hobbs area) by the Ontario Department of Mines, Parliament Buildings, Toronto 2, Ontario, Canada, from whom it may be obtained.)

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INTRODUCTION

The Grenville Front is the northwestern boundary of the Grenville province of the Canadian Shield (Fig. 1). For over 800 miles from Lake Huron to the Labrador Trough, it forms the boundary between the Superior and Grenville provinces (Gill, 1948). These and the other provinces of the Shield have been defined on the bases of differing structural and lithological characteristics, and more recently on the basis of age determinations (M. E. Wilson, 1939; Gill, 1948, 1949; J. T. Wilson, 1949; Stockwell, 1961, 1962, 1963). The several provinces are more or less internally homogeneous, sufficiently so that their characteristics may be specified. However, the relations between the provinces by comparison are major problems. This is still true of the boundary between the Superior and Grenville provinces despite the considerable attention that it has attracted. At this boundary (Fig. 1) the easterly trending volcanic and sedimentary belts of the Superior province and the overlying Proterozoic (?) rocks, in particular the Huronian Series, "disappear", being followed to the southeast by the northeasterly trending migmatitic terrane of the northwestern part of the Grenville province.

The subject of this thesis is an investigation of this boundary, the Grenville Front, as it is found in an area south of Lake Timagami, about fifty miles northeast of Sudbury, Ontario.

Previous Work on the Problem of the Grenville Front.

The contrasting characteristics of the Superior and Grenville provinces in the vicinity of the Grenville Front are summarized in Table 1. The easterly trending structures of the Superior province are truncated on the southeast by the northeasterly trending structures of the Grenville province. The former is characterized by widespread metamorphism to greenschist facies over 2 b.y. ago, the latter by metamorphism to amphibolite facies approximately 1 b.y. ago. The pre-metamorphic superficial rocks in both are known or thought to have been dominantly greywacke with associated volcanic rocks. In particular it should be noted that carbonate rocks, considered typical of the so-called Grenville Series, are conspicuous by their absence in the vicinity of the Front. Overlying these metamorphic rocks with marked angular unconformity are the sedimentary rocks of the Huronian Series: these are restricted to the southeastern corner of the Superior province (Fig. 1), although Quirke and Collins (1930) considered that Huronian relics can be discerned within the Grenville, and similar sediments appear north of the Front in the vicinity of Lake Mistassini. In the Superior province, granitic plutons are commonly discordant with contact aureoles and, where the relationships are known, pre-Huronian in age (Thomson, 1962). In the Grenville the granitic rocks are commonly gneissic and concordant, without aureoles and grade into the general migmatitic terrane.

The Grenville Front has been considered to be fault contact, a metamorphic transition zone or a combination of the two. The two extreme views of the nature of the Front are illustrated as follows.

Norman (1936, p. 120) hypothesized that the boundary is a fault zone extending from Lake Mistassini to Lake Huron, stating: "The conclusion that a fault exists in these two areas (Killarney and Chibougamau) suggests that the sudden transition from rocks of recognizable age and origin to a complex of gneisses throughout the intervening region is also due to faulting." On the other hand, Osborne and Morin (1962) do not define the northwestern margin of the Grenville province but distinguish a transitional "Grenville B subprovince" on the order of 100 miles in width. This is said to be transitional between the dominantly easterly trending structures of the Timiskaming subprovince (Superior province) and the dominantly northerly trending structures of their "Grenville A subprovince". However true this concept may be, it obscures the problem of the Grenville Front clearly shown by Fig. 1 and by the work summarized in the next section. The boundary in question here is that between their "Grenville B subprovince" and the Superior province.

A review of the literature leads one to conclude that (a) the Grenville Front exists as a line or narrow zone on the scale of Fig. 1, and (b) the boundary has a dual nature, in part fault, in part metamorphic transition. It is considered that the Grenville Front should be defined in terms of the Grenville metamorphism, that is, as a metamorphic transition, and that the faulting in the vicinity of the boundary merely disrupts this transition.

Geology.

Hewitt (1957) has reviewed previous geological work on the problem of the Grenville Front. His discussion will be amplified here with respect to certain critical areas and more recent work. The specific problems of geochronology will be discussed in the subsequent section.

Throughout much of its length, the Front is obscured by lack of outcrop, marker units and detailed mapping, or disrupted by faulting. These disadvantages are perhaps least evident in the area southeast of Sudbury, discussed by Phemister (1961) and Grant, Pearson, Phemister and Thomson (1962). Here, a metamorphic transition can be seen from low grade pre-Huronian sedimentary rocks of the Superior province to schist and gneiss of the Grenville province. The rocks to the northwest of the Front are the pre-Huronian (Thomson, 1961) Sudbury Group, dominantly quartzite, with greywacke and conglomerate. These are relatively low grade rocks, but the greywacke contains relic staurolite, now shimmer aggregates, and probably relic andalusite. The rocks are intruded by granite and gabbro, and by late olivine diabase dikes which trend northwest. The sedimentary rocks form the upper part of the monocline which extends southeastwards from the Sudbury Irruptive, but towards the Front they are folded on dominantly northeasterly axes into rough conformity with the structures at, and southeast of, the Front. Southeast of the Front one finds psammitic and pelitic schist and gneiss commonly with garnet and rarely with kyanite or sillimanite, amphibolite and garnet amphibolite, metagabbro and migmatite. Marble and calc-silicate rock are found, but are extremely rare. In this region the structure is characterized by flowage, in contrast to the style to the north, and a northeasterly trend and dip to the southeast are dominant, with a lineation to the southeast. In the north of the area the boundary is a fault contact, but southwestward the fault zone passes wholly into the low grade rocks of the Sudbury Group, and a metamorphic transition between the two provinces is exposed. Within about two hundred yards (as can be seen adjacent to Highway 69) quartzite passes into psammitic schist, greywacke into biotite and biotite-hornblende schist, with or without garnet, and the gabbro of the northwest may be the parent of at least some of the amphibolite. Granitic permeation and the development of "lits" begin to appear within this short traverse. Immediately north of the metamorphic boundary is a zone of feldspathization, up to two miles wide in the south of the area. While there may be some doubt as to the true width of the metamorphic transition, due to the probability of distributed movement in the rocks close to the boundary, there seems to be no doubt that the quartzite and greywacke of the province to the northwest appear as medium-grade metamorphic rock to the southeast. Isotopic age measurements (e.g. Fairbairn, Hurley and Pinson, 1961) demonstrate metamorphism of Grenville age southeast of the Front in this area.

The rocks northwest of the Front in the Sudbury area are, however, not typical of the Superior province; they form part of the so-called Penokean subprovince of Stockwell (1961, 1962). More typical is the area east of Lake Timiskaming, at the eastern extremity of known Huronian sedimentary rocks, described by Henderson (1936). A belt of Keewatin-type volcanic rocks and arkose and greywacke which overlie them conformably, is intruded by diorite and by granitic rocks. To the west, these rocks are overlain unconformably by Upper Huronian sedimentary rocks. To the south and southeast, the pre-Huronian superficial rocks are altered to mica schist and biotite hornblende gneiss, which contain many small bodies of granite. "At some distance from the granite masses the rocks show little granite, and are schists, but as the granite mass is approached the granite injection increases, the grain coarsens and the rock becomes a gneiss." (Henderson, 1936, p. 12). In the less altered northern part of the belt the structure trends easterly with dip to the south, turning northeast into an anticlinal nose whose plunge is southeast. There is some evidence (Henderson, 1936, p. 14) of an easterly trending monocline with steep dip to the south prior to the formation of the anticline. The rocks to the south and southeast are tightly folded and in places overturned to the north and northwest. Henderson does not mention the term "Grenville", but the rocks to the southeast are typical of the Grenville province in the vicinity of the Front (see Osborne and Morin, 1962, p. 126-129). Unanswered are the questions of the age of the metamorphic transition and the relation between the "granitic rocks" in the north and south of the area.

A metamorphic transition undisturbed by faulting is described from the Surprise Lake area, 240 miles to the northeast (Fig. 1). This transition, first noted by Norman (1936), was studied in detail by Deland (1956). The area is remarkable in that there appears to be a westward embayment of Grenville-type rocks into the Superior province. The rocks to the west are "Keewatin-type" metasedimentary rocks and metavolcanic rocks of the greenschist facies. Eastwards these pass upgrade into hornblende gneiss, amphibolite and biotite paragneiss of the amphibolite facies, the transition zone being one to two miles wide. In the south of Deland's area these rocks are intruded by quartz diorite and later (?) albite granite. "All the granitic rocks found in the southern half of the area are the same in structure and composition on both sides of the boundary.... This observation is significant for such granitic rocks have been considered characteristic of the Timiskaming subprovince." (Deland, 1956, p. 139). Both the Keewatin-type rocks and the Grenville-type gneisses strike east-west with one local exception, which Deland considers to be due to granitic intrusion (and superimposed on the east-west trend). Apparently the steeply dipping Keewatin-type rocks have been isoclinally folded, with drag folds whose axial planes strike east-northeast and are vertical, their axes plunging 40° to 80° north-east. This seems to be a demonstrable transition and was recognized as such by Norman (1936) despite his hypothesis of a faulted boundary. The area is unusual compared with most of the Front in that no transition was found in the plutonic rocks, and in that the structures are so continuous from one province to the other. Again, there is no definite proof that the observed transition is due to Grenville metamorphism rather than to some earlier event, the former being favored due to the presence of so-called "Grenville-type" gneisses.

Further evidence of a metamorphic transition into the Grenville province is forthcoming from work at the southern end of the Labrador Trough. Rocks of the Trough extend into the Grenville province, with a marked rise in metamorphic grade and superposition of northeasterly trends of the Grenville province on the northwesterly trends of the

Trough (Gastil and Knowles, 1960). That Grenville metamorphism has indeed affected this area is shown by isotopic age determinations of Lepp, Goldich and Kistler (1963) and Leech, Lowdon, Stockwell and Wanless (1963).

The most detailed discussion of faulting at the boundary of the two provinces is that of Johnston (1954). The area concerned lies immediately northeast of that discussed in this thesis, that is northeast of Timagami River. Here, the Superior province is underlain dominantly by quartz diorite or granodiorite overlain unconformably by Upper Huronian sedimentary rocks. The latter are virtually unmetamorphosed, but affected by the faulting which Johnston considers to mark the boundary. To the southeast, the Grenville province is underlain by gneisses, thought to be in part the altered equivalents of the quartz diorite and granodiorite, but characterized by potassic granite which intrudes the quartz diorite and granodiorite even north of the boundary, and is there also overlain by Upper Huronian sedimentary rocks. From his study of the quartz diorite and granodiorite, Johnston concludes that there is an increase in metamorphic grade from northwest to southeast, from the greenschist to the amphibolite facies. However, this metamorphism is considered by him to be pre-Cobalt (Johnston, 1954, plate 2). The fault zone appears as a series of northeast-trending, easterly dipping faults in a rough echelon arrangement due to right lateral offset on another fault set which trends north northeast. Close to the fault zone the Cobalt rocks are overturned to the northwest. From this and a detailed analysis of the structures, Johnston concludes that movement was east side upwards and to the northwest. In the Grenville region the foliation trends appear as arcs concave to the east-south-east, with dips in that direction. This is also the direction of plunge of the most prominent lineation, which is shown by mineral elongation, boudinage and the axes of minor folds. There is also minor wrinkling at right angles to this lineation. Both directions of lineation appear in the Cobalt rocks where they have been intensely deformed. Fabric diagrams for quartz show girdles with the major lineations as axis. Unfortunately Johnston does not state his bases for distinguishing the two subprovinces, nor does he comment on his conclusion that the metamorphism which passes upgrade into the Grenville subprovince is pre-Cobalt in age.

The conclusions from a review of previous work, illustrated by the foregoing discussion of the more critical areas, are as follows. The boundary between the Superior and Grenville subprovinces is not a through-going fault zone, nor is it an unfaulted transition on the order of 100 miles in width. Apparently there is a narrow transition from the low grade rocks with easterly trending structure to the higher grade migmatitic and northeasterly trending complex. This metamorphic transition between the Superior and Grenville provinces, the Grenville Front, may be on the order of less than ten miles in width. Further, along much of the boundary, the transition is complicated by faulting which may appear north or south of the transition or cut it out completely.

The most important question left unanswered in all but two areas (the Sudbury area and the area immediately south of the Labrador Trough, both of which lie outside the limits of the Superior province as defined by Stockwell (1963) but not as used here) is: are the reported metamorphic transitions in fact due to metamorphism of Grenville age. Johnston (1954) considers his transition to be pre-Cobalt in age, Henderson (1936) does not express an opinion as to the age of the transition in his area, and Deland (1956) considers that his transition is of Grenville age. It is apparent that geochronological work pertaining to the Front must now be discussed: this is done in the following section.

Geochronology.

The time of the "Grenville" metamorphism is well defined at approximately 1 b.y., whereas the last widespread metamorphism in the Superior province occurred at about 2.5 b.y. ago. These figures have been obtained using several different methods, and one may cite the summaries of Shillibeer and Cumming (1956) and of the Geological Survey of Canada (Leech, Lowdon, Stockwell and Wanless, 1963) to substantiate the conclusions. The figure of 1 b.y. may be considered defined within ±150 m.y., the 2.5 b.y. date is less well defined, but within ±300 m.y.

The only systematic geochronological study of the particular problem of the Grenville Front is that of Snelling (1962). Snelling discusses K-Ar age determinations on micas from the Val d'Or region in Quebec (Fig. 1). From the Grenville province southeast of Val d'Or, he reports biotite ages ranging from 850 to 1000 m.y. To the north, however, there is "an abrupt change in age across the Grenville Front (which) corresponds to a sharply defined change in degree of metamorphism" (Snelling, 1962, p. 15). One sample gave an age of 950 m.y., and is within the equivalent of five miles measured normal to the Front of another whose age is 2,205 m.y. The only intervening outcrop yielded an intermediate age of 1,695 m.y. In the interior of the Superior province, he obtained evidence of possibly two metamorphisms between 2.4 b.y. and 2.7 b.y. As he observes, two possible interpretations of these data are that (a) there was indeed an event in the vicinity of the Front at approximately 1.7 b.y., or (b) the intermediate age reflects incomplete resetting of the "clock" during the Grenville metamorphism.

Intermediate ages in the vicinity of the Front are also reported from the south end of the Labrador Trough (Hurley, et al., 1958; Lepp, Goldich and Kistler, 1963; Leech, et al., 1963), from the Mistassini area (Quirke, Goldich and Kreuger, 1960), from the Chibougamau area and from east of the present area (Leech, et al., 1963) and from the Sudbury district (Fairbairn, Hurley and Pinson, 1961). These intermediate ages range from about 1.2 b.y. to 1.8 b.y. Only Quirke, et al. (1960) and Fairbairn, et al. (1961) favor the possibility of a 1.6 b.y. event here, and Fairbairn, et al. (1961) also infer an event at approximately 1.2 b.y. in the Sudbury area. The possibility of an intermediate event is real and speculation on this is invited by the data of Goldich, Nier, Baadsgaard, Hoffman and Krueger (1961) from Minnesota, by the work of the Geological Survey of Canada from the Churchill province including the eastern Labrador Trough (Leech, et al., 1963), as well as by the papers cited above. However, it may be very difficult to resolve an intermediate metamorphism in the vicinity of the Grenville Front, for in general one can measure only the time since the last closure of the system being analysed with respect to the elements being used in the analysis.

Keeping this possibility in mind, one can at least say that ages intermediate between those commonly found within the two provinces are found in the immediate vicinity of the Grenville Front. This is in agreement with the hypothesis that the Front represents a metamorphic transition of the Grenville age.

Pertinent to the area to be discussed is the age of the Upper Huronian. Schmus, et al. (1963) report Rb/Sr determinations on granophyre from "Nipissing" diabase which intrudes the Huronian of the Blind River area, west of Sudbury. They find a minimum age of 1,755 m.y. and a probable age of 2,170 m.y. for the granophyre. In agreement with this is a K-Ar age of 2,095 m.y. on biotite (G.S.C. 61-157, Lowdon, et al., 1962) from olivine diabase, which cuts the Upper Huronian near Cobalt.

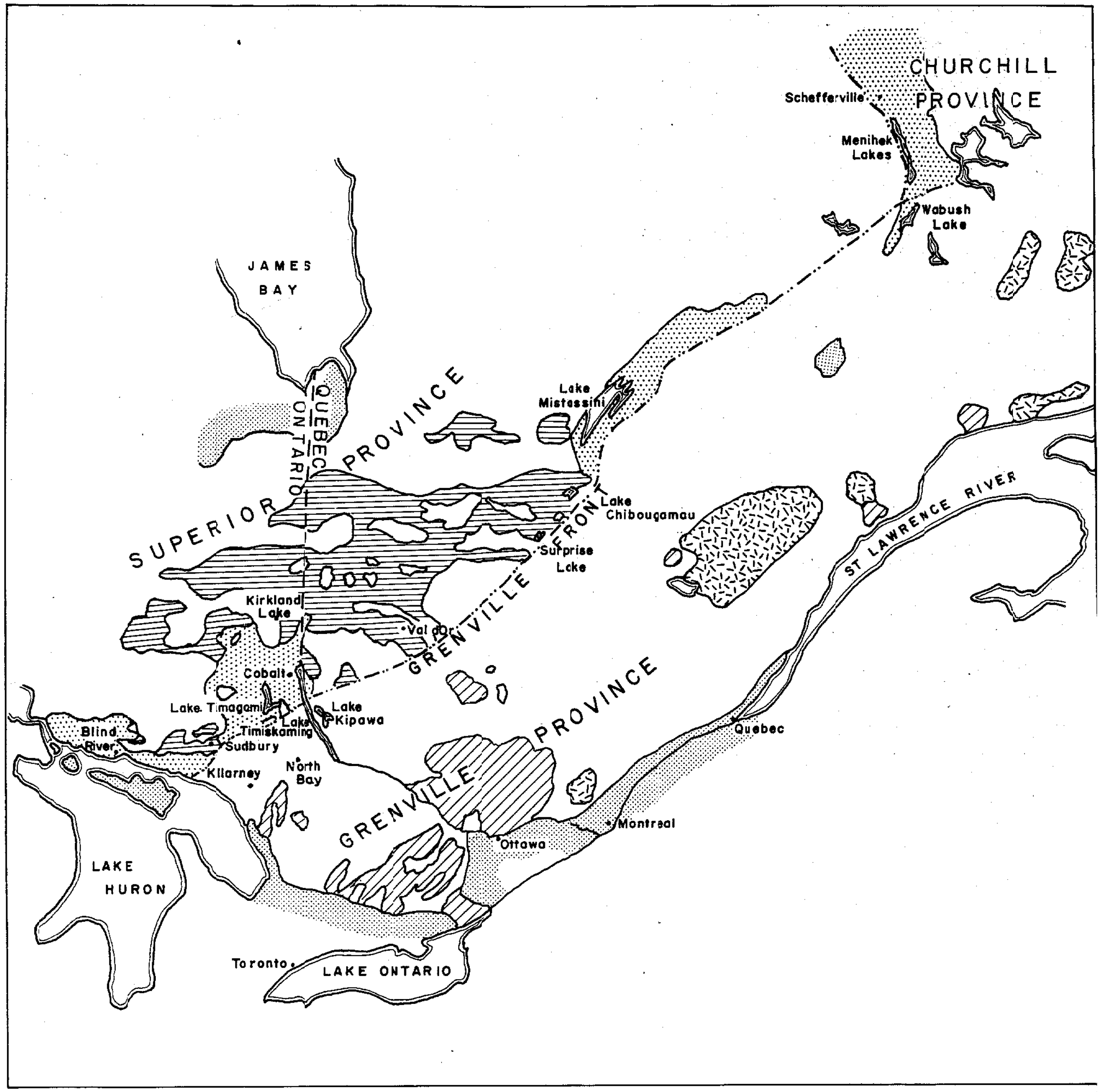
The Upper Huronian rests in part upon metavolcanic rocks and metagreywackes of the greenschist facies. It is itself virtually unmetamorphosed but has been affected by faulting in the vicinity of the boundary. Thus, neglecting the possibility of major metamorphism of intermediate age, either the 1 b.y. event was merely an overprint on a pre-Huronian (2.5 b.y.?) orogeny during which the metamorphic transition was established, or there has been superposition of a major 1 b.y. metamorphism on the pre-Huronian low grade metamorphism, with a remarkably abrupt termination southeast of the Huronian sedimentary rocks in order that the Upper Huronian be left unmetamorphosed.

Fig. 1

Sketch Map of the Grenville Front.

- Paleozoic Rocks:
- Proterozoic Sedimentary Rocks: Huronian Group, Chibougamau Series, Mistassini and Otish Mt. Groups, Labrador Trough.
- Archean Metavolcanic and Metasedimentary Rocks: Keewatin- and Timiskaming-type rocks, Sudbury Series.
- "Grenville Series": Metasedimentary and metavolcanic rocks of unknown age.
- Anorthosite.
- Granitic Rocks and Undifferentiated Gneiss.

After the Geological Map of Canada (G.S.C. map # 1045a); the Geological Map of Ontario; Quebec Dept. of Mines maps # 703A, 704A and 705A; Satterly (1943); Bergeron (1957) and Thomson (1962).



Considering the differences in structure and in degree of metamorphism on opposite sides of the boundary (Table 1) and the narrow metamorphic transitions reported from the Front, the second alternative seems the more probable.

Summary.

(a). The Superior and Grenville provinces may be distinguished in terms of lithologies, structure, degree and age of metamorphism.

(b). The northwestern boundary of the Grenville province is not a through-going fault zone, nor is it an unfaulted transition on the order of 100 miles in width. It is apparently a metamorphic transition, commonly less than ten miles in width, in part disrupted by faulting.

(c). Ages intermediate between those characteristic of the regions north and south of the Front have been obtained in the vicinity of the Front. These may represent either actual metamorphism of intermediate age or incomplete reequilibration during the Grenville metamorphism on the flank of the orogenic belt.

Outline of the Present Study.

The area chosen for a detailed study of the Grenville Front lies at the south end of Lake Timagami (Fig. 1). This area is well favored in having relatively good outcrop, good access and a remarkable complete geological section. It is one of the few known areas where it may be possible to establish a bridge between the geologies of the Superior and Grenville provinces.

The two provinces are in unfaulted contact for a distance of over three miles, the Front being defined in terms of a metamorphic transition in pre-Huronian metagreywacke. Detailed mapping has suggested that this metagreywacke and pre-Huronian quartz diorite and granite extend into the Grenville province, modified by the Grenville metamorphism. However, the correlations across the Front depend on factors such as lithology which do not yield unequivocal evidence. Moreover, it is not axiomatic that a rise in metamorphic grade to the south is due to Grenville metamorphism.

In order to support the tentative correlations and to investigate the nature of the metamorphic transition, it has been desirable to augment the field work by both petrologic and chemical means. This work, especially the chemistry, has been concentrated on the metagreywacke in which the Front is defined.

However, this can only provide supporting evidence for the correlations at best. To attempt completely independent proof of both the correlations and the "Grenville" age of metamorphism, a Rb-Sr whole rock and mineral isochron study has been undertaken, concentrating on the most favorable unit for such work, the supposedly co-magnetic pre-Huronian granites in a suite from the Superior province across the Front into the Grenville province.

Table 1. The Characteristics of the Superior and Grenville Provinces in the Vicinity of the Grenville Front.

	SUPERIOR PROVINCE	GRENVILLE PROVINCE
Original superficial rocks	Proterozoic (?) rocks: Conglomerate, greywacke, sandstone, shale, limestone and dolomite (Huronian, Chibougamau, Mistassini and Otish Mt. Groups). Archean rocks: Intermediate to basic volcanic rocks, greywacke and shale; local conglomerate, arkose, and quartzite (Keewatin- and Timiskaming-type rocks and Sudbury Series).	None of the Proterozoic Groups mentioned opposite extend into the Grenville province, except possibly in the Killarney area (Fig. 1). In general the age of the original superficial rocks is unknown. They were mainly greywacke and shale and probably intermediate to basic volcanic rocks. Marble is notably absent near the Front.
Metamorphic grade	Proterozoic rocks are virtually unmetamorphosed, except where intruded by diabase or gabbro. The Archean rocks are metamorphosed to the greenschist facies, locally to the amphibolite facies. Staurolite, garnet, andalusite and cordierite occur locally, usually retrograded.	Amphibolite facies. In general this is a migmatitic terrane in which lenses of schist, paragneiss and amphibolite and bodies of granite can be resolved. Garnet is of widespread occurrence, kyanite and sillimanite occur locally.
Plutonic rocks	Minor ultrabasic bodies, including some anorthosite. Granitic plutons, predominantly discordant, but concordant and gneissic bodies occur. Contact aureoles are common. The intrusion of quartz diorite prior to that of albite granite is common in the southwestern part of the province.	Minor deformed ultrabasic bodies, but no known anorthosite. Dominantly quartz dioritic to quartz monzonitic gneisses as concordant masses without contact aureoles, grading into migmatite.
Hypabyssal rocks	Gabbro and diabase sills and dikes are widespread in the Proterozoic (?) rocks. Later olivine diabase dikes occur.	Unreconstituted diabase or gabbro intrusions are not common.
Ore deposits	Extensive deposits: Au, Ag, Ni, Cu, Fe, Pb, Zn.	No known ore deposits of significance.
Age of widespread metamorphism	2500 m.y. ± 300 m.y.	1000 m.y. ± 150 m.y.
Structure	Proterozoic rocks are relatively flat lying. Archean superficial rocks appear in easterly trending tight folds with steep limbs and generally horizontal axes, although locally steep easterly plunges are reported. Cleavage and minor folds are common. Original features are well preserved.	Complex, with a dominant northeasterly trending foliation dipping 30-70° southeast. Lineation plunging E to SE is widespread. Flowage phenomena are characteristic, and augen gneiss is common. Original features are largely obliterated.

Chapter 2

GENERAL GEOLOGY

During the summers of 1959 and 1960, an area of about 110 square miles, centered on the south end of Lake Timagami and lying athwart the boundary between the Grenville and Superior provinces, was mapped by the writer and assistants for the Ontario Department of Mines.

The area may be reached from River Valley, on the Canadian National Railway 22 miles south of Lake Timagami, by a road which passes through the center of the area and continues eastwards to near Marten River on Highway 64. This is largely a private lumber road, and permission to use it must be obtained from Field Lumber Company, Field, Ontario. Several other lumber roads facilitate travel in the area. Canoe travel is possible on several of the lakes, on Timagami River and on some stretches of Sinton Creek. The south arms of Lake Timagami are accessible by boat and there is regular steamer service from the town of Timagami where float planes may also be hired.

Although the total relief is only about 250 feet, the area is rugged in detail. The south arms of Lake Timagami cover much of Vogt township and contain a profusion of islands and shoals. The lake is drained by Timagami River via Cross Lake. Many smaller lakes are present and several of these are linked by Sinton Creek, which drains most of Hobbs township to Timagami River.

Mapping was on a scale of 1320 feet to one inch. Pace and compass traverses were run by two men, an assistant keeping the line while the writer or his senior assistant mapped the geology, commonly on alternate traverses about one quarter of a mile apart. As much outcrop as practicable was thus visited and the mapping done directly on aerial photographs, the outcrops being generalized where legitimate. This information was then transferred to a base map drawn up by the Cartography Branch of the Ontario Department of Mines, and reduced to the scale of one-half mile to one inch. This map has been published along with a synopsis of the field work (Grant, 1964) and is included here as Plate 1 (in pocket).

General Geology.

The area lends itself to a rough threefold division. In the center appear Keewatin-type metagreywacke, iron formation and metavolcanic rocks, striking east to southeast, dipping steeply and forming the northern limb of an anticline which plunges steeply to the northeast. These rocks are intruded successively by quartz diorite and granite. The Keewatin-type rocks have assemblages typical of the greenschist facies, transitional southwards to the amphibolite facies. However, knots of white mica ± chlorite are found in the argillaceous beds, the white mica knots representing andalusite of an earlier metamorphism.

To the north these rocks are overlain unconformably by Huronian strata, largely of the Gowganda Formation, in gentle folds plunging a few degrees northwards. Within this area a striated, grooved, and polished glacial pavement is found at the base of the Gowganda, confirming the postulated Precambrian glaciation in this region. These rocks are virtually unmetamorphosed: however, sericite, chlorite, and clinozoisite are generally present in the fine grained matrix material. The Huronian rocks are intruded by diabase, the largest body of which is a sill close to the major unconformity, passing into a dike in the Keewatin-type rocks.

Southward, the metagreywacke makes a transition through phyllite to become a schist in the migmatitic complex referred to the Grenville province. Apparently the equivalents of the quartz diorite and granite are major components of the complex, modified of course by the Grenville metamorphism. In this sector the rocks have assemblages typical of the amphibolite facies, and garnet and staurolite are locally developed in the schist. The structure is dominated by evidence of distributed movement, and may be visualized as overlapping synform shingles plunging at a low to moderate angle to the southeast. A northeast trending fault zone brings the two provinces into fault contact in the eastern half of the area, but to the west the metamorphic boundary lies north of the fault zone.

Keewatin-type rocks.

The rocks referred to as "Keewatin-type" are the oldest rocks in this area and are similar to those found as the oldest unit throughout most of the mapped Superior province. However, the name implies no definite time equivalence to "Keewatin-type" rocks elsewhere. Johnston (1954) mapped the eastern extremity of these rocks and called them the Cross Lake Series. Their greatest development is in south-central Vogt and in northern Hobbs, but the belt reappears on the southeastern side of the Vogt Granite and extends eastward to the Timagami River. The succession consists of at least 10,000 feet of metagreywacke followed conformably to the north by at least 4,000 feet of metavolcanics and iron formation. One persistent band of the latter attains a thickness of 600 to 700 feet and is virtually the only distinctive marker unit in the Keewatin-type section. From Southwest Arm eastward to Timagami River the strike changes from east to southeast, the dip is steep to the north or northeast. The strata face to the north and thus the structure is the northern limb of an anticline plunging steeply east-northeast. The main intrusions in the Keewatin-type belt are the Pre-Algoman quartz diorite, the Vogt and Sinton Lake granites and the Southwest Arm diabase. To the north the belt is overlain unconformably by Huronian strata, and to the south the metagreywacke becomes a biotite-quartz-plagioclase schist.

Metasedimentary Rocks

Here "metasedimentary rocks" and "metagreywacke" are practically synonymous. The metagreywacke is typically a grey, fine-grained to aphanitic, largely recrystallized rock which, although it may be massive and monotonous, usually shows bedding marked by alterations of argillaceous and arenaceous members. These beds are from a few millimeters to a few meters in thickness. Graded bedding is common and provides abundant evidence of tops, which are to the north. Cross bedding and load casts occur locally. The grain size ranges up to about 0.25 mm., but locally a gritty bed may be found and in one outcrop half a mile east of Baie Jeanne, there are a few granitic pebbles. Rarely amphibolitic lenses are found in the metagreywacke, usually less than one meter in length. Quartz veins roughly parallel to the bedding are common. In the argillaceous beds blue-grey knots are common. These range in size from 1 mm. in the northern exposures to 6 mm. southwest of Sinton Lake where they are best developed and there have the form of andalusite.

The change in the extent of recrystallization from north to south is one of the most striking features of the metagreywacke. This involves the disappearance of relic sedimentary grains, the development of fewer and larger grains and the development of a phyllitic and then schistose texture. The metagreywacke in the extreme north is typically fine grained and laminated, showing recrystallization of micas parallel to the laminae. The grain size is less than 0.1 mm. and usually less than 0.05 mm. Rarely is biotite visible in the field. In the vicinity of the Vogt-Hobbs township line, the metagreywacke is more recrystallized, and the average grain size is about 0.1 mm. Apparently the original grain size in the arenaceous layers was in general greater than in the similar beds to the north: in these layers relic grains of quartz and plagioclase 0.25-0.5 mm. are found. Biotite flecks are more obvious than to the north. Immediately north of the Front, the metagreywacke is well recrystallized and the average grain size is 0.1-0.3 mm. The rock is phyllitic and biotite and, less commonly, white mica can be readily detected in the field.

The schistosity is in general parallel to the bedding, but locally one can detect transverse "cleavage" emphasized by recrystallization of the micaceous minerals. This is approximately parallel to the axial plane of the anticline. Minor folds, which appear as wrinkling of micaceous laminae, are approximately concordant with the major anticlinal axis.

Throughout the metagreywacke section north of the Front, there is little change in the mineralogy of the rock. It typically consists of 20-35% quartz, 30-40% plagioclase, 15-30% biotite, 0-8% white mica, 0-15% chlorite with or without minor amounts of clinozoisite, actinolitic hornblende, sphene, apatite, tourmaline, zircon, magnetite and pyrite.

The plagioclase in the central and southern metagreywacke ranges in composition from An_{19} to An_{32}, without any consistent trend. In the northern metagreywacke the very small grain size makes accurate determination of the plagioclase composition most difficult, however, one determination indicated a composition of $An_{<13}$. Commonly the plagioclase grains, where they can be distinguished, have a sieve-like texture suggesting partial recrystallization. The biotite is pale brown, with $\gamma \approx 1.628$-1.633, which suggests a ratio of Mg/Fe+Mg+Mn+Ti ≈ 0.5 (S. D. McDowell, personal communication, based on a compilation of analysed metamorphic biotites). Chlorite is present, in part intergrown with the biotite, in part as discrete flakes, and in part in the knots which are discussed below. No optical differences have been found between the chlorites of different habits. The chlorite is pale green, length fast, with a dark grey to buff birefringence, and is an Mg-Fe chlorite in the terminology of Albee (1962, p. 868). The significance of the different habits of chlorite will be discussed in the chapter on metamorphism. The epidote commonly present is clinozoisite: in only two thin sections was true epidote found. Sphene usually occurs cored by an opaque mineral, probably titaniferous magnetite or ilmenite, but may appear as dusty granules in chlorite intergrown with biotite. The amphibole is pleochroic from α-straw, β-green to γ-blue-green, with $\gamma \wedge c \geqslant 17^\circ$, 2V (-) 75°, $\gamma = 1.664$. These properties are intermediate between those of actinolite and hornblende, and the amphibole is therefore called actinolitic hornblende. The index $\gamma = 1.664$ suggests that the ratio Mg/Mg+Fe+Mn is 0.5-0.7, and in conjunction with the extinction angle, suggests that the tetrahedral substitution of Al for Si is not great. (Deer, Howie and Zussman, 1962, II, p. 257-296.)

The knots mentioned above are important in that they provide evidence of the character of pre-Grenville metamorphism. These knots, which appear in the argillaceous layers, consist of white mica with or without appreciable chlorite or quartz. Opaque inclusions are common but no plagioclase has been detected in the knots. In the south and east of the metagreywacke, the knots are dominantly of white mica, and the bedding-plane schistosity tends to swirl round the knots. Between Sinton Lake and Bass Lake these are up to 6 mm. in diameter and have the form of andalusite, although no relic andalusite is now present (Plate 2). In the north, the knots are dominantly of chlorite and white mica, and the two varieties have not been found in the same rock. These chlorite-white mica knots (Plate 3) are ovoid in shape and contain no trace of any former parent mineral. The bedding plane schistosity continues through these knots. It is possible that they are retrograde

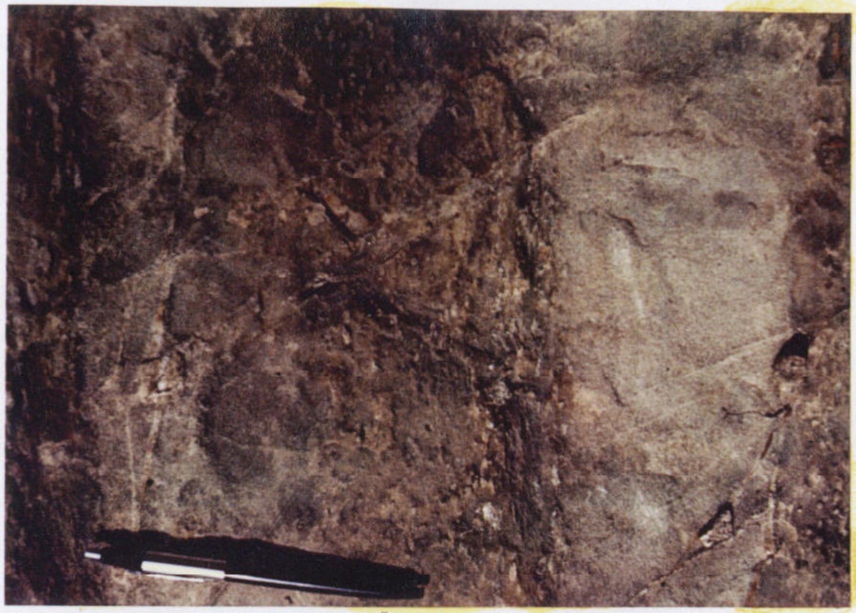


Plate 2. Keewatin-type metagreywacke, showing bedding with knots in the argillaceous layers. 0.75 miles NE of Sinton Lake.

Plate 3. Phyllitic metagreywacke, with knots of white mica after andalusite. 0.25 miles north of the Bass Lake-Sinton Lake portage.

after cordierite, according to some reaction such as:

$$15Mg_2Al_3AlSi_5O_{18} + 8K_2O + 22H_2O \rightarrow$$
Cordierite

$$16KAl_2AlSi_3O_{10}(OH)_2 + 6Mg_5AlAlSi_3O_{10}(OH)_8 + 9SiO_2.$$
Muscovite Chlorite

However, it is at least equally possible that these ovoid knots do not represent some pre-existing porphyroblast. This is supported by the continuity of the bedding-plane schistosity through the chlorite-sericite knots, in contrast to the augen-like pseudomorphs after andalusite.

The critical assemblages now found in the metagreywacke are: quartz-plagioclase-biotite-clinozoisite-white mica-chlorite, quartz-plagioclase-biotite-epidote-actinolitic hornblende. Further discussion of the assemblages will be deferred to the chapter on metamorphism. It is sufficient to observe here that except for the composition of the plagioclase, which may be relic from previous metamorphism, the first assemblage is characteristic of the greenschist facies, while the second may occur in either greenschist or amphibolite facies.

The other metasedimentary rock consists of one outcrop of limestone, on the west shore of the narrows on Timagami River north of Lone Arm. It is a grey, aphanitic, thinly-bedded rock with the assemblage calcite-tremolite-quartz-clinozoisite-talc (?) - plagioclase.

Metavolcanic Rocks

North of the metagreywacke and stratigraphically above it lie at least 4,000 feet of metavolcanic rocks and iron formation, which extend under the Huronian cover to the north and west. The metavolcanic belt extending from Southwest Arm to Lone Arm on Timagami River is split into four segments by Huronian cover in the west, the Southwest Arm Diabase in central Vogt, and the Vogt Granite in the east.

The metavolcanic rocks include metamorphosed lava, tuff and tuffaceous sedimentary rocks, and agglomerate. Differentiation of mappable units in these rocks is hampered by the small range in composition, the overprint of metamorphism and the small scale of interbanding of, or transition between, the several rock types compared with the scale of mapping. On the map, "tuffaceous metasedimentary rocks", "intermediate metavolcanic rocks", and "acid metavolcanic rocks" have been separated as far as possible. The distinction between "acid" and "intermediate" rocks is based largely on color index, the former having less than about 25% mafic minerals and usually less than 10%.

The "acid" metavolcanic rocks are dominant in the western segment, tuffaceous metasedimentary rocks in the eastern; in the central segment "intermediate" metavolcanic rocks predominate but all three units are well represented.

The "intermediate" metavolcanic rocks are commonly referred to as "andesites". They are greenish-black, aphanitic to fine-grained, fairly massive rocks; locally micaceous clots are apparent on the weathered surface. Pillow lavas occur in a number of outcrops, but none exhibit clear evidence of tops.

The texture typically consists of anhedral plagioclase grains in a poorly- to well-developed felt of amphibole and biotite or chlorite with aggregates or discrete grains of clinozoisite. Relic ophitic texture is rare. A slight foliation is commonly developed. The rock consists typically of 40-50% plagioclase (albite), 10% biotite, 30% actinolitic hornblende, 0-10% chlorite, 5-10% clinozoisite, with up to 2% each of sphene, apatite and opaques. A trace of quartz was found in one specimen, and quartz veinlets with or without carbonate may be found.

The mineralogy of the tuffaceous "intermediate" metavolcanic rocks is similar to that of the flow rocks, but these rocks are laminated, with a highly variable tenor of the various minerals in the different bands.

The typical "acid" lava is a grey, porphyritic, somewhat foliated rock with megacrysts of albite in a felted groundmass dominantly of albite, with minor mafic minerals. Recrystallization has not obliterated the original igneous (trachytic) texture. The rock consists of 15-25% phenocrysts of albite in a groundmass composed of 60-70% albite, about 5% clinozoisite, 0-5% biotite, 0-15% chlorite, and less than 3% each of sphene and opaques. Occasionally a trace of quartz or carbonate is present, but both of these are usually only in veinlets where they may be accompanied by chlorite and epidote. Chalcopyrite and pyrrhotite are of possible economic importance in the "acid" metavolcanic rocks southeast of Austin Bay. Three quarters of a mile south of Northwoods Camp, pillows can be seen in the "acid" lava. These are sufficiently well preserved on a small island to allow the determination of tops. Top is to the north, as is the case throughout the metagreywacke section.

The tuffaceous metagreywackes are laminated, greenish-grey rocks with quartz, epidote or biotite dominant in different layers. They are well developed south and east of Austin Bay and east of the Vogt Granite. The rock has recrystallized, and contains the assemblage quartz-albite-biotite-clinozoisite-actinolitic hornblende with sphene and opaques, and occasionally chlorite, carbonate and tourmaline. The proportions of the various minerals vary drastically from band to band, but a mode recalculated from a chemical analysis (G135, see Table 3) yields 30% quartz, 9% plagioclase, 24% biotite, 8% actinolite, 25% epidote, 3% magnetite, 1% sphene

The mineralogy of the various metavolcanic rocks is similar, the main difference being in the relative abundances of the various minerals. The biotite is pale brown, with a tendency to aggregation in the flow rocks. It shows slight alteration to chlorite. Chlorite, however, is often present as discrete grains, and ranges from rock to rock from length fast with grey-buff birefringence to length slow with anomalous blue birefringence. This indicates slight variation in the Mg/Fe ratio about a value of unity (Albee, 1962). As in the metagreywacke (see p. 23), the amphibole is intermediate in its properties between actinolite and hornblende. The epidote is clinozoisite (except in veinlets where it is strictly epidote), and the sphene may contain cores of an opaque mineral.

The general assemblage found in the metavolcanic rocks is quartz-albite-biotite-chlorite-clinozoisite-actinolitic hornblende. Carbonate is a possible additional phase, but is thought to be secondary and associated with the common veining noted above. The major assemblage is typical of the greenschist facies.

There is no definite evidence here of two metamorphisms: no pseudomorphs comparable to those after andalusite (and possibly cordierite) in the metagreywackes are found, nor would such be expected considering the composition of these rocks and the postulated grade of the early event. However, in stating this one must not overlook the fact that these rocks, and the immediately underlying metagreywackes metamorphosed to the greenschist facies, are overlain unconformably by virtually unmetamorphosed Huronian strata. Thus there is no doubt that there was pre-Huronian metamorphism in the area. The inference is that no new phases were formed as a result of the later metamorphism.

Iron Formation

Banded siliceous iron formation is interbedded with the metavolcanic rocks. In the area south of Austin Bay, a band 600-700 feet thick, with some interbedded metavolcanic rocks, extends westwards from the Southwest Arm Diabase, and disappears below the Huronian cover, reappearing south of Northwoods Camp. Further, an aeromagnetic map (Dept. Mines Tech. Surv. #505G) shows a large positive anomaly west of Lake Timagami, on strike with this band of iron formation, suggesting the probable continuity of the band under the Huronian rocks and under the diabase sill. Northwest of the Vogt Granite iron formation recurs, and with allowance for dilation related to the diabase intrusion, this may be correlated with the thick band to the west. Several thin bands of iron formation are present near the base of the metavolcanic section in Vogt township.

The iron formation is a black and grey, aphanitic to fine-grained, banded rock with quartz, magnetite and actinolite as the main constituents. The last two are dominant in some bands, quartz in others. The bands are about 1-10 mm. in width. Jasper was only found at the eastern extremity of the main band south of Austin Bay, but quartz veins are common. The rock was highly susceptible to minor deformation, and minor folds are approximately concordant with the major anticlinal structure.

Pre-Algoman Quartz Diorite and Gabbro

Quartz diorite and associated gabbro occur north and east of the Vogt Granite and are overlain by sediments of the Gowganda Formation. These rocks are considered "pre-Algoman" because they are intruded by the "Algoman" Vogt Granite (see p. 33), as seen about one mile south of the outlet of Lake Timagami, where the easterly trending contact truncates the foliation of the quartz diorite. That the quartz diorite and gabbro intrude the Keewatin-type rocks is implied by the outcrop pattern and the site of the body high in the anticlinal structure, but the actual contact was not found.

The quartz diorite is similar in age and general petrology to "Granite 1" of Johnston (1954) in the adjacent area to the northwest. This "Granite 1" he considered to extend into the Grenville province and to show an increase in grade of metamorphism from the Superior to the Grenville province.

The quartz diorite is a grey, fine- to medium-grained rock, commonly with a faint vertical foliation striking N60°W. The plagioclase often forms stumpy greenish-grey phenocrysts, the biotite and amphibole tend to be aggregated and the quartz appears as interstitial grains and aggregates of grains which are megascopically bluish in color. The rock typically consists of 15-30% quartz, 40-55% plagioclase, trace to 8% microcline microperthite, 3-10% greenish-brown biotite, 2-20% actinolitic hornblende and minor amounts of chlorite, sericite, epidote, sphene, zircon, apatite and opaques. The plagioclase (oligoclase to low andesine) is saussuritized, locally very considerably so; embayment by microcline is common, especially near Lone Arm. The amphibole is closer to true hornblende than that found in the Keewatin-type rocks, having $\gamma \wedge c \geq 19^\circ$, but is still termed actinolitic hornblende. It shows marked variation in color within one grain, and a spindle-like intergrowth is common due to twinning on (100). The amphibole is intergrown with biotite flakes in a manner suggesting replacement by the latter. The biotite itself may be intergrown with chlorite, and this may also be due to alteration. The "epidote" here is epidote except probably in the saussurite. Sphene occurs as rims on titaniferous magnetite or ilmenite and also as tiny granules in biotite and chlorite.

Immediately south of Outlet Bay and to a lesser extent north of Lone Arm, a gabbroic phase is found. This is a grey-black, fine- to coarse-grained, inequigranular rock with even more markedly saussuritized plagioclase than has the quartz diorite. It has a mineralogy similar to that of the quartz diorite, typically consisting of about 55% oligoclase, 20% actinolitic hornblende, 15% epidote and 5% quartz, with sericite, biotite, sphene, apatite and magnetite. One quarter of a mile south of the outlet of Lake Timagami the gabbro grades into a massive rock consisting of magnetite, epidote, chlorite, sericite and pyrite, which is responsible for a high magnetic anomaly there. (Dept. Mines Tech. Surv. Map #505G.)

In the vicinity of Contact Cliff (1/8 of a mile north of the north-eastern corner of the Vogt Granite) a pale pink, fine- to medium-grained, faintly foliated, allotriomorphic and leucocratic phase of the quartz diorite occurs. Due to its leucocratic nature it superficially resembles a phase of the Vogt Granite, however, it has the foliation, texture and dioritic composition of the pre-Algoman rock. Moreover, it is cut by a granophyre dike at Contact Cliff, the dike being probably one of the many apophyses of the Vogt Granite. This phase of the quartz diorite generally consists of about 40% quartz, 45% albite, 5% microcline and less than 5% each of white mica and biotite with minor chlorite, epidote, sphene, zircon, apatite and opaques.

Evidence of metamorphism of these pre-Algoman rocks is limited to saussuritization of plagioclase, the alteration of amphibole to biotite and of biotite to chlorite, and the development of sphene rimming opaques. Any recrystallization was insufficient to obliterate the igneous texture and, in particular, the spindle texture of the amphibole has not been annealed.

Algoman Granitic Rocks

Leucocratic albite granite forms a stock, here called the Vogt Granite, centered in southeastern Vogt township. Similar granites appear in the vicinity of the Grenville Front, notably the Sinton Lake

Granite, and in the terrane to the south: these are correlated on the basis of lithology with the Vogt Granite. However, this is not an unequivocal criterion and more than one age of "granite" may be involved. The term "Algoman" was coined by Lawson (1913) in the Rainy Lake area of western Ontario to denote granitic intrusives similar to the post-Keewatin, pre-Seine "Laurentian", but of post-Seine (and therefore, according to Lawson, post-Huronian) age (1913, p. 82). However, the term has come to be used in eastern Ontario for pre-Huronian, post-Keewatin (or post-Timiskaming if present) granitic intrusives (e.g. Todd, 1928, p. 14-15; Moorhouse, 1946, p. 5). It is in keeping with this usage that the term is used here. These Algoman granites are similar in age and lithology to "Granite 2" of Johnston (1954) in the adjacent area to the northeast. In this section only the Vogt Granite and the Sinton Lake Granite will be considered. Both the granites wholly within the Grenville subprovince and the problem of correlation will be considered later.

The Vogt Granite is a stock roughly three miles by two, elongate in a northeasterly direction, and intruding the Keewatin-type rocks and the quartz diorite. The main body was not found in contact with the Huronian rocks, but is considered older than these on the bases of (a) the truncation of a granophyre dike, considered to be one of the apophyses of the Vogt Granite, by the unconformity at the base of the Gowganda Formation at Contact Cliff, (b) the similarity to the Vogt Granite of many clasts found in the Gowganda Formation, and (c) corroboration from Johnston's work to the northeast where (1954, p. 1054) the

Gowganda Formation overlies his "Granite 2".

The stock is fairly homogeneous: typically it is a pink, massive, medium- to coarse-grained, leucocratic albite granite to quartz monzonite. The texture is allotriomorphic granular, and the potassium feldspar may form phenocrysts. Cataclasis is commonly evident in the undulatory extinction of quartz and fracture of feldspar. Quartz may fill these fractures and diffuse veinlets of white mica with epidote may be present.

The rock consists of 20-30% quartz, 40-55% microcline microperthite, 15-35% albite, less than 5% (combined) biotite, white mica and chlorite, with minor epidote, sphene, zircon, apatite and opaques. The plagioclase shows minor sericitization and very slight epidotization. Microcline has embayed the plagioclase, but no myrmekite is found. The biotite is brownish green and commonly intergrown with chlorite. The biotite, chlorite, white mica and the minor minerals tend to cluster together.

In the northernmost part of the stock is a grey, fine- to medium-grained, massive quartz monzonite with phenocrysts (3-4 mm.) of quartz albite, and microcline microperthite in a fine-grained allotriomorphic groundmass of the same minerals. Minor amounts of biotite, white mica, chlorite, sphene, apatite and opaques are present, and anhedral grains of fluorite occur locally.

In the central part of the stock, oval xenoliths 2-8 cm. in length are to be found. The rock is a hornfels with the assemblage quartz-microcline-albite-biotite-epidote-carbonate-sphene, microcline occuring in part as megacrysts, quartz in part as nests of grains with or without sphene. No trace of the pre-metamorphic texture remains.

The Vogt Granite is locally intruded by dikes less than two feet in width, similar in composition to the host but of finer grain size and even more leucocratic. Pegmatites are conspicuous by their absence. There are many apophyses from the Granite into the surrounding rocks. The granophyre dike at Contact Cliff, as already mentioned, is considered to be one of these. It is a fine- to medium-grained albite granophyre with less than 2% mafic minerals. The dike is about one foot wide; it intrudes the pale pink, fine-grained variety of the pre-Algoman quartz diorite and is truncated by the unconformity at the base of the Gowganda.

The Sinton Lake Granite lies athwart the Front, southwest of the Vogt Granite, and is similar in composition to the latter. This pluton, about four miles long by one-third of a mile wide, elongate slightly north of east, is centered on the south end of Sinton Lake. It is intrusive into the metagreywacke and is itself intruded by diabase similar to the "Nipissing" diabase (see p. 52) near Front Lake. It is not in contact with the Huronian System.

Typically this is a pink, medium-grained, massive or very slightly foliated, leucocratic albite granite to quartz monzonite. The texture is allotriomorphic, granular and fairly equigranular. Cataclasis is occasionally obvious. It is composed of 30% quartz, 25-50% microcline, 20-40% albite, 0-5% biotite, with minor white mica, chlorite, epidote, sphene, apatite, zircon and opaques. The plagioclase shows slight saussuritization and the microcline shows little development of perthite. The biotite is partially chloritized and this and the other accessory minerals tend to be aggregated.

Contact metamorphism of the metagreywacke is inconspicuous although the contact is locally well exposed and xenoliths of the metagreywacke (schist) are present at the margin of the body one-half mile southwest of Sinton Lake. Increased sericitization of the plagioclase of the schist may be attributable to the emplacement of the Granite, but no new phases are found and the texture of the schist is unchanged.

Granitic lenses, dikes and veins are common in the surrounding metagreywacke (phyllite or schist). These may be concordant or discordant with respect to the schistosity of the host rock, concordance being more common to the south of the pluton, where the veining may yield lit-par-lit gneiss. The larger lenses and dikes especially are similar to the Sinton Lake Granite in lithology and on this basis can be correlated with it (only rarely is it possible to trace the "apophyses" back to the main body). Some of the smaller dikes are granite pegmatite with conspicuous white mica: such pegmatite also appears within the pluton itself. One pegmatitic dike, composed of quartz, albite and white mica and intruding the schist south of Bass Lake, is unusual in that it contains a trace of unaltered garnet. The small dikes or veinlets, from a few millimeters to a few centimeters in width, range from granite similar to that of the main body to grey or grey-pink, fine-grained, equigranular rock of quartz dioritic composition, with less than 10% biotite and white mica. These may be discordant and massive, or concordant and foliated parallel to the foliation of the host rock. The latter situation is most common south of the pluton, where lit-par-lit gneiss may be formed. It is possible that the quartz dioritic veining predates the granitic (Plate 4) but it is well nigh impossible to distinguish two separate events. Especially where the veining is concordant and similar in composition to the schist, the origin of the veining is indeterminate.

Immediate contact effects of the two granites on the surrounding rocks are inconspicuous, although the contact with the metagreywacke is well exposed, and xenoliths of metagreywacke (schist) occur half a mile south of Sinton Lake. The development of sericite, especially as shimmer aggregates after andalusite, in the metagreywacke may be attributable to the emplacement of granite, but no new phases are found and the texture of the rock is unchanged. This apparent lack of contact effects is involved in the problem of the pre-Huronian metamorphism of the Keewatin-type rocks, and this will be discussed in the chapter on metamorphism.

Huronian System

Mississagi Formation

Radioactive quartz-pebble conglomerate and quartzite occur two miles southwest of Austin Bay, dipping 20-30° west and lying athwart the Keewatin-type rocks with profound angular unconformity. They are overlain without angular unconformity by the Gowganda Formation. The outcrop extends only two and one-fourth miles along strike, the beds pinching out so that the Gowganda comes to rest directly on the Keewatin-type rocks. The conglomerate and quartzite are lithologically similar to the Mississagi Formation in the Blind River area, especially

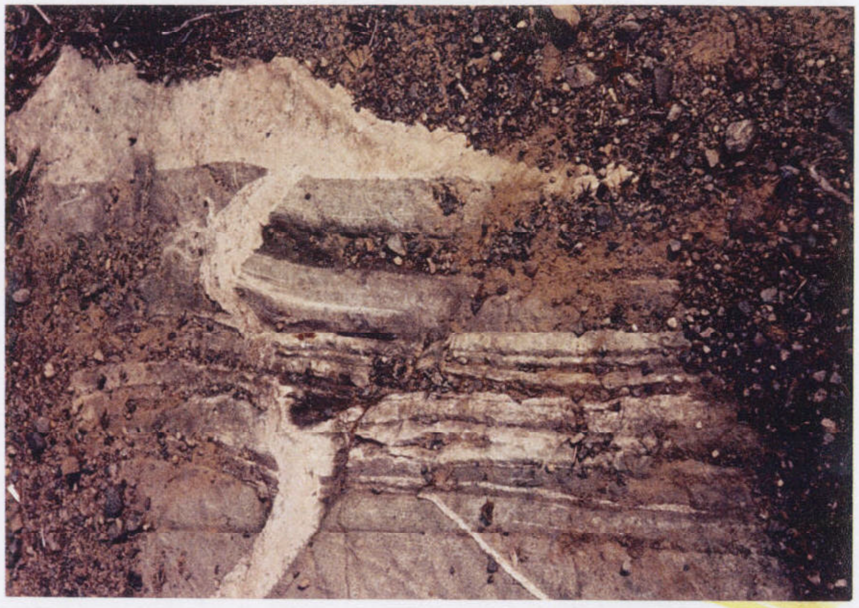


Plate 4. Concordant and discordant granitic veins in biotite-quartz-plagioclase schist. SE shore of Front Lake.

to the Lower Mississagi (e.g. Thomson, 1962, p. 82), and while there may be doubt as to the exact correlation of these strata within the Mississagi Formation (or Mississagi and Elliot Formations, see Roscoe, 1957, Fig. 1), there seems to be no doubt as to the general correlation.

The unit is up to about 100 feet in true thickness, the conglomerate occurring mainly at the base where it is about 20 feet thick. However, conglomerate lenses occur within the overlying quartzite, locally up to 10 feet in thickness.

The conglomerate typically consists of well-rounded quartz pebbles, 1 cm. to 5 cm. in diameter and rare clasts of metavolcanics in an impure quartzite matrix, the pebbles being partly coated with pyrite. The matrix consists of angular to subrounded quartz grains, 0.5 mm. in diameter, with interstitial fine-grained sericite and quartz. In some lenses or layers this interstitial argillitic material is dominant over the large quartz grains. The rock has a fissility best seen in these lenses.

According to Card (1959) as reported by Thomson (1960, p. 15), the radioactivity is largely due to uraninite associated with the pyrite and also in the matrix.

Brown biotite appears in clots associated with the sandy matrix usually surrounded by the interstitial sericitic material with which they have quite sharp boundaries. The clots are about 0.3 mm. across with a decussate texture, the individual grains being about 0.05 mm. The association with the sandy matrix, the sharp boundaries and the texture and the ready source of such biotite clots in the "intermediate" metavolcanic rocks suggest that these are indeed clastic. However, tiny biotite flecks appear in the sericitic material and it is possible that this is not clastic, but metamorphic biotite.

The "quartzite" is a pinkish-grey, medium-grained, massive arkose, consisting of about 85% detrital grains (0.5 mm.) and 15% matrix. One thin section shows 70% quartz, 12% microcline and less than 1% each of biotite, white mica, chlorite and opaques, the biotite appearing in part as clots similar to those described above. The sericitic matrix (15%) yields the only definite evidence of recrystallization.

Folding, metamorphism and uplift of the Keewatin-type rocks must have preceeded deposition of the Lower Huronian sediments. This follows from presence of an angular unconformity between the metamorphosed Keewatin-type rocks and the virtually unmetamorphosed Huronian. Further, since no microcline is found in the Keewatin-type rocks and since it is very minor in the quartz diorite, one may conclude that granitic rocks must have been exposed, probably though not necessarily equivalent to the Algoman granites.

Nevertheless, the matrix of the Lower Huronian sedimentary rocks here is recrystallized and these rocks therefore are not entirely unmetamorphosed. Metamorphism resulted at least in the formation of sericite and possibly biotite.

Gowganda Formation

The Gowganda Formation underlies most of Vogt township, except in the south-central and southeastern parts, and continues into western Torrington, forming a segment of the southern margin of the Cobalt Plain (Fig. 1). Here, conglomerate, greywacke, quartzite and argillite of the

Gowganda Formation lie with marked unconformity on the Keewatin-type rocks, the pre-Algoman and Algoman intrusives and, without angular discordance, on the Mississagi Formation. No Lorrain sediments (which are the Upper Cobalt Series, typically arkose) were found here. The Gowganda is cut by the so-called Nipissing diabase.

The unconformity is exceptionally well exposed in west-central Torrington, and here the writer's assistant, P. E. Schenk, found critical evidence supporting a glacial (or fluvio-glacial) origin for the Gowganda Formation. At the base of Contact Cliff the unconformity between the quartz diorite and conglomeratic greywacke of the Gowganda Formation is exposed almost continuously for about 400 feet. The surface on which the Gowganda was deposited shows the polish, grooves and striae characteristic of a glacial pavement (Plates 5 and 6).

The quartz diorite here shows a faint vertical foliation striking about north 60° west, and is cut by the narrow granophyre dike (mentioned above, p.35): both are truncated against Gowganda sediments, dipping about 30° northeast. There is no regolith. However, at the base of the Gowganda the matrix of the conglomeratic greywacke unit is laminated and the laminations have opened and weathered: at first glance this resembles a thin regolith. The glacial grooves are about 15 cm. to 30 cm. in wavelength and about 10 cm. in amplitude. These parallel the striae and have an average trend of north 28° east and a plunge here of 30° northeast. The striae and grooves definitely continue under the Gowganda and are therefore not due to Pleistocene glaciation. However, the possibility existed that the pavement was a

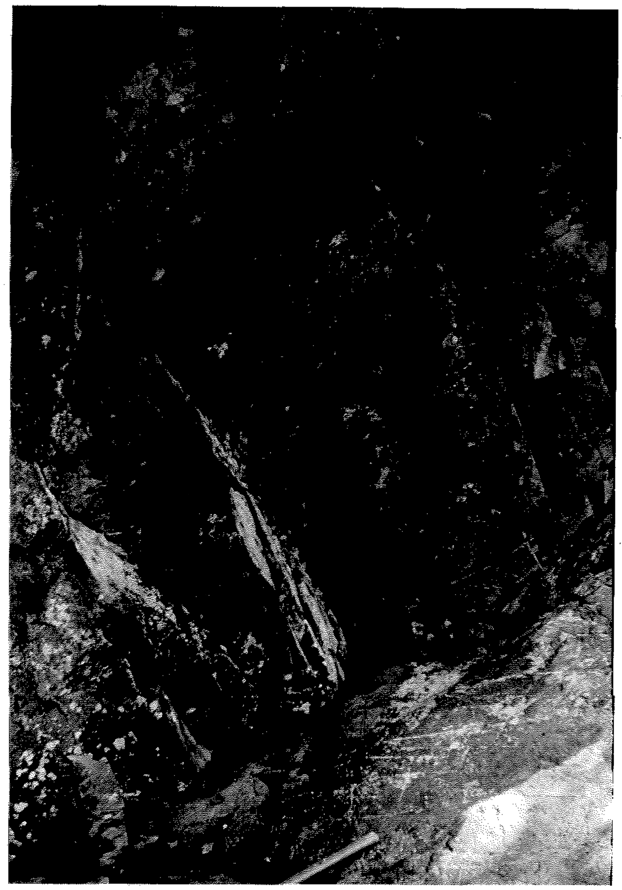


Plate 5. Glacial pavement on Pre-Algoman quartz diorite, overlain by Gowganda conglomeratic greywacke. Contact Cliff.

fault surface. In order to test this, a survey was made of structural features in the vicinity of Contact Cliff (Fig. 2). Only two out of 36 measured s-planes lie within the spectrum of attitudes of the pavement and none of the other lineations coincide in attitude with striae or grooves.

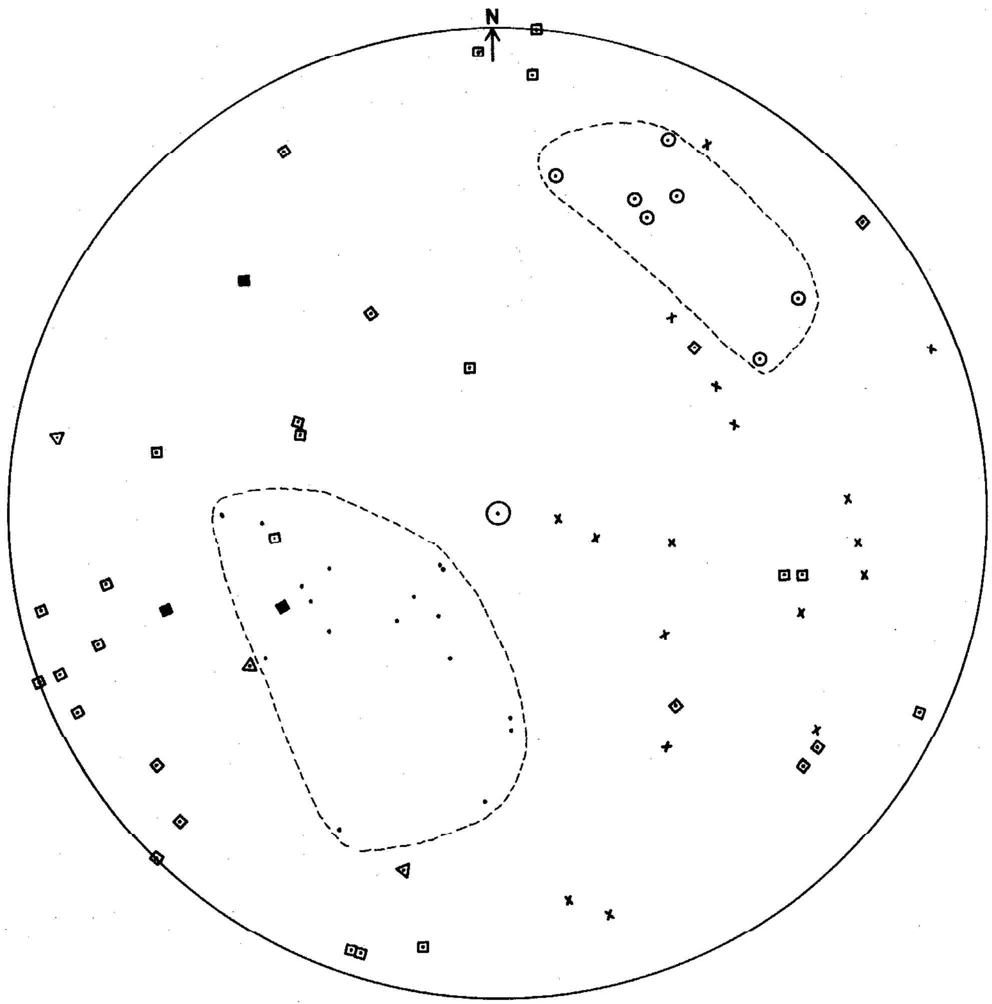
The unconformity is also well though intermittently exposed on the east side of Southwest Arm, southeast of Northwoods Camp, where Gowganda conglomerate overlies both Keewatin-type metavolcanic rocks and metagreywacke without a regolith. One and one-half miles south of Northwoods Camp a ridge and a groove occur in Keewatin-type metagreywacke, the groove being filled by Gowganda conglomerate and trending north 25° east, approximately parallel to the striae and grooves in Torrington (Plate 7).

The Gowganda sediments are warped into broad folds plunging gently slightly east of north; bedding usually dips northerly, between 10° and 30°. However, bewildering changes in attitude occur locally without disruption of the overall continuity of units. These are ascribed to soft-rock deformation of which there is abundant evidence. In the vicinity of Cross Lake only is faulting probably the major cause of disruption.

At the base of the sequence in Vogt there may be 1,000 feet of interbedded conglomeratic greywacke, greywacke with pebbles, argillite and quartzite. Rapid lateral and vertical changes in facies are common, but generally the lower part of this unit is dominated by greywacke, the upper by argillite and quartzite. The conglomeratic greywacke is

Fig. 2. Structural Features at Contact Cliff.

(Equal area projection, lower hemisphere.)



· Bedding in Gowganda Formation.

⊙ Groove or stria on pavement.

⊡ Joint. ▽ Shear plane. ■ Cleavage.

X Slicken or other lineation not on pavement.

Plate 6. Detail of pavement shown in Plate 5. Note polish, grooves and striae. Contact Cliff.

Plate 7. Groove in Keewatin-type metagreywacke filled by Gowganda conglomerate. 1.5 miles south of Northwoods Camp.

best developed at or near the base of the unit.

Above this lie about 1,000 to 2,000 feet of massive greywacke with scattered pebbles, virtually devoid of bedding. This is the basal unit exposed in eastern Vogt and Torrington. It is overlain in turn by 500 to 1,500 feet of interbedded argillite and quartzite and 1,500 to 3,000 feet of greywacke with pebbles. About 300 feet of argillite and quartzite separated this last unit from more greywacke with pebbles in northern Vogt.

The conglomeratic greywacke consists of angular pebbles of pink, rarely white, granite in a feldspathic greywacke matrix. Fragments of other rocks, some attributable to the Gowganda itself, are to be found. The pebbles tend to be not more than 2 cm. in maximum dimension and the ratio of pebbles to matrix is about 1:1. This type of conglomerate occurs as thin interbeds or lenses with greywacke, quartzite and argillite, rather than as thick massive units.

The greywacke is a grey-black, fine to aphanitic, unsorted, generally massive rock with abundant "black" quartz eyes. Pebbles, cobbles and boulders are scattered through it yielding so-called "greywacke with pebbles", and in the basal unit there is a transition from this to the conglomeratic greywacke. In the "greywacke with pebbles" angular to sub-angular clasts up to two meters in diameter occur; clasts 15-30 cm. are common, and pebbles abundant, these larger clasts constituting roughly 5% of the rock. Pink granite is the dominant clast, but grey granite, biotite granite-gneiss and Keewatin-type and Gowganda rocks also occur as clasts. The greywacke itself consists of angular grains

(0.1 - 0.5 mm.) of quartz, plagioclase and microcline with chlorite, biotite, sphene, epidote, opaques and composite grains in a very fine-grained matrix (< 0.01 mm.) of quartz, feldspar, clinozoisite, chlorite and sericite.

Interbedded argillite and quartzite occur as distinct units; the latter occurring as layers 5-15 cm. thick between argillite layers up to 1 meter thick. Less commonly, as on the east side of the peninsula 1.5 miles south of Northwoods Camp, quartzite is the dominant member. Commonly boulders or pebbles are found in these sediments, suggesting ice rafting (see below, p. 49). The argillite is usually laminated. Ripple marks, load casts and cross bedding are found in the more siliceous beds, and rarely grain gradation is seen in the argillite. The laminations of the argillite may represent varves (see below, p. 49). The interbedded argillite and quartzite was particularly susceptible to soft-rock deformation, the more competent siliceous sediments forming pods round which the less competent mud flowed. Slumping of these beds leads to highly anomalous attitudes.

The argillite is a grey-black, aphanitic rock with lamination visible on weathered or wet surfaces. The grain size is quite uniform, 0.01 - 0.05 mm., and the rock is composed of anhedral grains of quartz and feldspar with sericite, chlorite, clinozoisite and opaques. Epidote and carbonate occur very rarely as discrete grains and in veinlets, and quartz-carbonate veins are common as in all the Gowganda rocks. The interbedded light grey "quartzite", actually arkosic sandstone, differs only in being richer in quartz and feldspar (up to 70%).

The Gowganda Formation is not completely unmetamorphosed. By comparison with the underlying Keewatin-type rocks it is in general poorly recrystallized, but the development of sericite, chlorite and clinozoisite is widespread in the argillite and in the matrix of the greywacke. Recrystallization is more pronounced adjacent to the diabase intrusions, and there a hornfelsic texture may be developed. The assemblages found there are white mica-chlorite-clinozoisite-carbonate (originally ankerite?) or white mica-biotite-epidote-(chlorite?), and the first assemblage appears in a phyllitic argillite at Portage Bay, one-half mile from the nearest diabase outcrop. Biotite, in the form of a diffuse veinlet of poikiloblastic grains, occurs in a specimen of greywacke three-quarters of a mile southwest of Camp Acouchiching and one and one-half miles from the nearest diabase.

There is thus no doubt that low grade metamorphism accompanied the emplacement of the diabase intrusions. However, the assemblage sericite-chlorite-clinozoisite occurs in argillite two and one-fourth miles from the nearest diabase outcrop in the extreme north of the area. Thus, while the original extent of diabase now removed by erosion is of course unknown, it is probable that low grade metamorphism not related to the diabase has affected the Gowganda Formation.

The origin of the Gowganda Formation has been a subject of controversy since Coleman (1907) suggested that it is of glacial origin. Recently the problem has devolved to whether or not such deposits, characterized by heterogeneous unsorted pebbly mudstone, are due to gravite flow of unconsolidated material or to glacial deposition. In particular a recent paper by Dott (1961) discusses this problem. As he points out (1961, p. 1290),

> "The most important alternatives are subaqueous and subaerial gravity sliding and flow of masses of sediment soon after deposition. Churning may destroy stratification and produce a heterogeneous, unsorted till-like pebbly mudstone (Crowell, 1957). Turbidity currents, hydrodynamically distinct from but closely related to mass flow, can deposit repetitious graded sand or silt layers which resemble closely seasonal Pleistocene glacial varves."

In the present area the following evidences indicate that the Gowganda sediments are indeed glacial or fluvioglacial in origin.

(a) The presence of a grooved, striated and polished pavement overlain by poorly sorted pebbly greywacke.

(b) Low relief of the pre-Gowganda surface. This is suggested by the broad overlap of successive basal units onto the basement, by the Mississagi association of mature quartz-pebble conglomerate and quartzite and supported by the lack of great relief in the basal contact where visible.

(c) The virtually complete dominance of poorly sorted greywacke with pebbles over sorted conglomerate or conglomeratic greywacke.

(d) The abundance of isolated boulders and pebbles in the argillite.

(e) The fine scale of "varves" in the Gowganda argillite as compared with graded beds from turbidites. (Dott, 1961, Plate 4.)

(f) The lack of extensive zones of contortion. (Soft-rock deformation is common in the interbedded argillite and quartzite units, but only locally.)

"Nipissing" Diabase

Diabase intrusions of known or apparent post-Huronian age occur both north and south of the Front. On the map the several diabasic bodies are grouped as "Keewenawan". This assignment was made because no definite evidence was found that alteration of the diabase north of the Front was due to the Grenville metamorphism rather than to autometamorphic processes, and diabase south of the Front cross-cuts the migmatitic terrane with a chilled margin and is thus later than the postulated Grenville metamorphism. Thus it was possible that these diabase intrusions were all of post-Grenville age. This now apparently requires revision. The diabase which intrudes the Gowganda sediments is similar to the so-called "Nipissing" diabase throughout the region from Blind River to western Quebec in the Superior province. Dating of "this" diabase indicates a probable age of at least 2 b.y. (see p. 12). Further, as will be shown later (see p. 116), Grenville metamorphism has been proven in the migmatitic terrane. Therefore there are probably two ages of diabase intrusion in this area.

In this section the older "Nipissing" diabase will be discussed, and discussion of the younger diabase will be deferred to a later section (see p. 68).

"Nipissing" diabase appears chiefly as a dike about half a mile wide, trending northeast through the Keewatin-type rocks in Vogt and northern Hobbs townships. This body continues westwards on the surface as a sill cutting Gowganda rocks close to the major unconformity, and extends to the west beyond the map area for about ten miles (see Thomson, 1960, Chart A). Here it is referred to as the Southwest Arm Diabase.

The Southwest Arm Diabase varies in composition from quartz norite to quartz diabase or gabbro. The typical rock is a grey-black, massive, medium-grained rock whose texture is normally ophitic but locally gabbroic. It consits of about 50% plagioclase (An_{35}-An_{55}), 40% pyroxene and amphibole and not more than 10% quartz and accessory biotite and opaques. Epidote, sphene, apatite, chlorite and sericite may also be present.

In one locality, one-half mile west of Camp Whitebear, quartz biotite diorite appears as a marginal phase of the quartz diabase into which it grades. It is a grey, fine- to medium-grained, massive rock with an interlocking allotriomorphic texture. It is notably rich in epidote (10%).

The diabase sills in the northeast corner of the map area are similar to the Southwest Arm Diabase and ranges in composition from quartz norite to quartz diabase.

The diabase, as opposed to the norite, typically has an amphibole as the dominant mafic mineral. The pleochroism is variable within a single grain, but is commonly from α-colorless to pale brown, β-green to γ-bluish green, $\gamma \wedge c \geq 18°$, 2V(-) about 80°. This is actinolitic hornblende. It commonly consists of intergrowths of "fibers" of differing orientations and in some cases this is due to twinning on (100). In the norite, replacement of complex pyroxene grains by the amphibole is found. These pyroxene grains are hypersthene with augite lamellae and replacement of this intergrowth by amphibole carried to completion would duplicate the texture seen in the diabase. It may be noted that there is a tendency for preferential replacement of the orthopyroxene.

The norites carry smaller discrete grains of augite as well as the hypersthene. No relic pigeonite was found, but in one sample relic twinning on (100) indicates inversion of pigeonite to hypersthene (Hess, 1960). The epidote is secondary, associated with the alteration of pyroxene to amphibole and epidotization of plagioclase.

From Blind River to western Quebec, "Nipissing" diabase is commonly quite unaltered. However, in the Sudbury area (Grant, et al., 1962, p. 7), in the vicinity of Crerar, 25 miles to the northeast of Sudbury (Thomson and Card, 1963, p. 7) and in the present area, alteration of pyroxene to actinolitic amphibole is notably greater than to the north. Of course such alteration may be due to autometamorphism, but the restriction of widespread uralitization to the neighborhood of the Front suggests that it may be related to the metamorphism by which the Front is defined.

The "Nipissing" Diabase in the present area does not show definite evidence of increasing metamorphic grade southwards. Specimens from the diabase at Aileen Lake show almost the same spectrum of degree of alteration as do those from the Southwest Arm Diabase. The most altered samples found come from one-half mile west of the Front near Front Lake. Here the plagioclase is almost obliterated by saussuritization, and the amphibole is partially bleached and variegated in color. However, the igneous texture has not been destroyed.

South of the Front, at the southeast end of Front Lake, narrow dikes of diabase are found, generally sheared. A thin section from this locality shows considerable recrystallization, with the assemblage (not in equilibrium): quartz-plagioclase-actinolitic hornblende-biotite-epidote-chlorite-carbonate. Apart from the minor chlorite and carbonate, this assemblage is the same as that found in adjacent amphibole-bearing schist.

The rather meager evidence thus favors the conclusion that the "Nipissing" diabase here was affected by late metamorphism. In the main bodies, both north of the Front, this resulted in the development of actinolitic hornblende and the saussuritization of plagioclase, the extent of these alterations varying from place to place. The greatest alteration is found in the southernmost samples studied. Diabase not directly traceable into the Southwest Arm intrusion appears one-half mile south of the Front. This rock has an assemblage referable to the amphibolite facies and compatible with the adjacent schists, but did not reach, or does not now show, complete equilibrium.

The Grenville Metamorphic Terrane

The southern third of the map area is essentially a migmatitic complex which, in grade of metamorphism and in structure, corresponds to the characteristics of the northwestern margin of the Grenville province (see Table 1). The designation "migmatitic complex", however, obscures the major interest in this area. The rocks of the Superior province can be traced southwards into the migmatitic complex, in particular this is true of the Keewatin-type metagreywacke and the Algoman granite. This is at once implied by the mapped relations (Plate 1) of the metagreywacke and equivalent schist and the Sinton Lake Granite to the Front south of Sinton Lake.

The Front as depicted on the map is "defined" in terms of the transition in the metagreywacke from phyllite to schist. It must be emphasized at once that the definition of such a line is arbitrary. It is a convenience used to separate rocks considered characteristic of the Superior province from those considered characteristic of the Grenville province. It also serves to emphasize the abrupt transition between the two provinces. In this area the following criteria have been used to determine the line with respect to the Keewatin-type metagreywacke:

(1) The transition from phyllite to biotite-quartz-plagioclase schist.

(2) Disappearance of the sericitic knots, pseudomorphous after andalusite, due to recrystallization.

(3) Marked increase in the contortion of the rocks, with the appearance of flowage folding and the development of a lineation plunging to the southeast.

(4) The development of granitic permeation, yielding migmatite and lit-par-lit gneiss where well advanced.

Despite its obvious defects, this line can be defined to within plus or minus 1,000 feet, given such good exposures as are found along lumber roads southwest of Sinton Lake.

In mapping, the term "migmatite" was used to designate rock obviously or probably of mixed origin. This may or may not be true in hand specimen, but is true as far as a practical mapping unit is concerned (see p. 65). It is typically a grey-pink granitic augen gneiss with lenses, pods and schlieren of various compositions due to segregation or differing protoliths or both. Apparently the major protoliths for the migmatite were biotite-quartz-plagioclase schist, granite and metadiorite. Where the dominant protolith of the metamorphic terrane was the schist, it has been mapped separately, although the schist is rarely free of granitic stringers for more than a few feet and there is complete transition into migmatite (compare Plates 8, 9 and 10). Homogeneous areas of granite or granite gneiss were also distinguished: these contain only minor schlieren or xenoliths. Metadiorite was not found as a separable map unit but is a major component of the migmatite, at least in north-central Hobbs, where metadiorite is intimately intruded and veined by granite, and this variety of migmatite has been mapped separately. Locally amphibolite and amphibole schist occur in the Grenville terrane, and have been mapped as such where possible. "Amphibolitic migmatite" has been distinguished from the general migmatite: this variety, containing abundant amphibolitic schlieren, is common only in western Torrington.

In the following pages the petrography of these rocks and of the late olivine diabase will be described. Discussion of the problems of metamorphism will be deferred to a later section.

Biotite-quartz-plagioclase Schist

The Keewatin-type metagreywacke increases in grade to the south or southeast, becoming a phyllite near the Vogt-Hobbs township line (see p. 21). The increase in degree of metamorphism continues southwards and the phyllite grades into a biotite-quartz-plagioclase schist. Granitic permeation varies in intensity and the schist is rarely free of such permeation in a single outcrop (see below). The schist tends to form low ground, and is thus commonly found only on the sides of hills composed of granite or granitic migmatite. There are, however, extensive areas of the schist immediately south of the Front and northeast of Hobbs Lake.

Where lacking granitic stringers, the typical schist is a grey, fine- to medium-grained, equigranular rock, with biotite forming folia in a granoblastic matrix of quartz and plagioclase. Bedding can still be discerned locally, and the foliation is usually parallel to it. The schist consists mainly of 20-35% quartz, 30-45% plagioclase and 20-30% biotite. Amphibole is a major constituent in some samples, and locally garnet and staurolite occur. Common accessory minerals are epidote, sphene, apatite, zircon and opaques.

Both quartz and plagioclase grains tend to be slightly elongate in the foliation plane. The plagioclase varies in composition from An_{19}-An_{37}, and shows minor to negligible alteration. The biotite is brown with $\gamma = 1.627 \pm 0.01$. This index is lower in the north (1.618 - 1.628) than in the south (1.626 - 1.637) corresponding to a higher Mg/Mg + Fe + Mn + Ti in the north (see p. 22). Chloritization of biotite is very minor and no primary chlorite is found. The amphibole is pleochroic from α-pale yellow-green, β-green to γ-bluish green, $\gamma \wedge c \geq$ 18-20°, 2V(-) 80°. It is actinolitic hornblende (see p. 23). The epidote has a negative 2V of 75-85° and birefringence of 0.02 - 0.03. Cores of metamict allanite occur rarely. Sphene occurs commonly as discrete grains, but in the north tiny granules appear in the biotite, and

Plate 8. Biotite-quartz-plagioclase schist showing relic bedding and granitic lenses. 0.13 miles SE of Front Lake.

Plate 9. Biotite-quartz-plagioclase schist permeated by granitic material and transitional to migmatite. 0.6 miles NE of the east end of Hobbs Lake.

sphene occasionally occurs as mantles on what is probably titaniferous magnetite.

White mica occurs as minor sericite in plagioclase. Only next to the Front does it appear in discrete grains away from granitic material, apparently as the last trace of the knots so common to the north of the Front. Tourmaline is found only in one sample, at Front Lake. Micro-cline is restricted to samples adjacent to granitic lenses and even there is very minor.

The granitic lenses are commonly parallel to the schistosity, rarely cross-cutting (Plates 4 and 8). In texture they are similar to the schist but of medium grain size. They vary in composition from that of a quartz biotite diorite to that of a biotite granite. The appearance of microcline or white mica in the lits may be accompanied by minor amounts of these minerals in the immediately adjacent schist.

In the vicinity of Front Lake some of the lits are readily related to the Sinton Lake Granite by virtue of similar lithologies. However, normally the origin is indeterminate, especially when the mineralogy of the lit is identical to that of the normal schist.

The critical assemblages found in the schist where not permeated by granitic material, and considered to be equilibrium assemblages are:

(a) quartz-plagioclase-biotite-epidote-actinolitic hornblende,

(b) quartz-plagioclase-biotite-epidote-white mica,

(c) quartz-plagioclase-biotite-garnet-actinolitic hornblende,

(d) quartz-plagioclase-biotite-garnet-staurolite.

Assemblages (a) and (b) (with clinozoisite rather than epidote) occur north of the Front (see p. 25). Assemblage (c) occurs locally south of the Front in the vicinity of Hobbs Lake and of Surveyor Lake. Assemblage (d) has only been found north of Hobbs Lake. These are all possible assemblages of the amphibolite facies.

Granitic Rocks

Granitic rocks similar in composition to the Algoman granitic rocks are found as generally concordant homogeneous bodies within the migmatitic terrane. In fact one pluton, the Sinton Lake Granite, lies athwart the Front. Correlation between the plutons on either side of the Front, and between the several plutons south of the Front is based on their similar, and unfortunately commonplace, lithologies. The main differences across the Front are in texture and structure.

The Vogt Granite is markedly discordant, with few and generally cross-cutting apophyses. The Sinton Lake Granite is in part discordant, in part concordant, and apophyses are abundant and quite commonly concordant. The granite plutons to the south are largely concordant, concordant granitic veining in schist is common, and granite is a major component of the migmatite.

These granitic rocks are foliated and, although the foliation varies in intensity, it is concordant with that of the surrounding terrane and the characteristic southeasterly lineation is present inside as well as outside the plutons. Therefore the granites are either syntectonic or pretectonic. That the granites are pretectonic is suggested by the presence in them of basic dikes which are themselves metamorphosed to amphibolite, and have the characteristic southeasterly lineation of the Grenville terrane. Such a dike occurs in west-central

McCallum, for example.

On their margins, the granite bodies are in general concordant with the surrounding rocks, but in detail they present a variety of relationships, from cross-cutting relationships with schist, through lit-par-lit gneiss to subtle transition into migmatite. Lenses of schist (xenoliths?) are to be found within the granite bodies, and lits and patches of granite are ubiquitous in schist and migmatite. The marginal relationships of these bodies are obscured by distributed movement.

This "distributed movement" has profoundly affected the textures of the granites, wherein lie the main differences from the plutons to the north. From an equigranular, fairly massive, allotriomorphic interlocking texture such as that of the Sinton Lake Granite, cataclasis results in a texture where augen of feldspar are set in in "streams" of quartz which may be ribbon-like or granular depending upon the degree of recrystallization. Where shearing was extreme a phyllonite may be produced. But in general the movement was, in fact, distributed and on the scale of individual folia: the result is a granoblastic, foliated, augen granite passing into schist or migmatite via an augen granite gneiss.

The typical granite is a pink or grey-pink, fine- to medium-grained, granoblastic, foliated, augen granite to quartz monzonite. It consists of 20-30% quartz, 25-50% microcline microperthite, 20-35% plagioclase, less than 5% biotite and accessory white mica, chlorite, epidote, sphene, zircon, apatite and opaques. The plagioclase is oligoclase except north of Centre Lake, where it is commonly sericitized albite and rarely oligoclase. Saussuritization is more common in the north than in the south, and the epidote and white mica tend to be well crystallized. The brown biotite locally shows minor chloritization, and forms folia in association with the other accessory minerals. The pluton in southwest Hobbs is an unusually coarse-grained foliated augen granite.

The critical assemblage in the granitic rocks is: quartz-oligoclase-microcline-biotite-white mica-epidote, and this is compatible with the assemblages from the adjacent schist contrary to the conclusions of Johnston (1954, p. 1069) from the area to the northeast, which are not based on convincing evidence. The assemblage is referable to the amphibolite facies.

Metadiorite

Metadiorite is common as a constituent, or a possible constituent, in migmatite, but was not found as a separate mappable unit. It is most recognizable and widespread in the "metadiorite-granite complex" which has its greatest extent northeast of Centre Lake.

The most southerly exposure of pre-Algoman quartz diorite in the Superior province (on Lone Arm) is in fact a slightly foliated, allotriomorphic, biotite-amphibole granodiorite veined by granite. The plagioclase is highly saussuritized, the biotite is light brown, contains tiny granules of sphene and is partly intergrown with the amphibole in a manner suggesting replacement of the latter.

Within the metadiorite-granite complex a very similar rock occurs. As in the pre-Algoman pluton, the composition of the "metadiorite" in the complex varies from gabbroic to granodioritic. The typical rock is grey, medium-grained, massive to foliated, usually with a relic igneous texture in evidence. The rock consists of 6-20% quartz, 30-60% plagioclase, 1-8% microcline microperthite, 0-15% biotite, 0-60% amphibole and minor sericite, chlorite, epidote, sphene, apatite, zircon, carbonate and opaques.

The plagioclase is oligoclase (An_{11}-An_{25}), with the products of saussuritization (epidote and minor white mica) usually well recrystallized. Fine-grained saussuritization is largely associated with cataclasis and in some cases two generations can be seen. The greenish brown biotite is still light in color and contains granules of sphene and rarely rutile. These inclusions seem related to (a) alteration of biotite to chlorite or (b) lightening of the color of the biotite. The biotite may be intergrown with amphibole in more sharply bounded, larger grains than to the north, and here the two are apparently in equilibrium. The amphibole is pleochroic from α-pale brown, β-green to γ - bluish green, $\gamma \wedge c \doteq 18$-$23^\circ$, 2V(-) about 80°. Even within the metadiorite-granite complex, plagioclase augen locally dominate the texture, and there is a slight tendency for epidote to be concentrated not in the core of plagioclase but towards the margins or outside the feldspar. There is also a tendency for the amphibole to be deeper in color.

With increase in the degree of recrystallization the igneous origin of the rock becomes less evident, and locally north of the fault zone and generally south of it, it becomes difficult or impossible to distinguish "metadiorite" from a possible paragneiss. However, it may be noted that fine-grained biotite-quartz-plagioclase schist derived from metagreywacke is ubiquitous if not abundant throughout the metamorphic terrane, and is quite different in texture from the probable metadiorite. The probable metadiorite in the south is a quartz-plagioclase-biotite-epidote augen gneiss, with or without amphibole, microcline or white mica. Minor constituents are sphene, apatite, zircon and opaques, locally with chlorite and in one case with fluorite. Locally the biotite and amphibole are deeper in color than to the north, and the epidote tends to lie largely outside the plagioclase.

The assemblages found in the metadiorite are:

(a) quartz-plagioclase-microcline-biotite-epidote-amphibole,

(b) quartz-plagioclase-microcline-biotite-epidote-white mica.

In no case were amphibole and white mica other than that in plagioclase found in the same section. Both chlorite and carbonate are found locally. The former is obviously retrograde after biotite, the latter appears in conjunction with cataclasis and is not considered to be a member of the equilibrium assemblages.

Amphibolite

Amphibolite is rarely found as a mappable unit here, although it is a major unit in the Grenville province in the Sudbury region. Some bodies resemble the metagabbro noted in the previous section, some are interbanded with the schist and may represent the metavolcanic rocks of the Superior province and, as mentioned above, fine-grained amphibolite dikes and sills are found in both granite and migmatite.

The probable metagabbro is found west and southwest of Hobbs Lake and in western McCallum, where similar patches are common in migmatite. It is a grey, medium- to coarse-grained, rather massive rock, whose texture is that of a metagabbro. It consists dominantly of plagioclase and amphibole with minor epidote and opaques. Quartz, biotite, sphene, apatite, sericite, chlorite and carbonate may be present in variable though minor quantities, and in two samples relic clino-pyroxene was found. As in some of the metadiorites the plagioclase is slightly zoned; the grains are epidotized, the epidote being well formed usually. Rarely the plagioclase is altered in part to sericite or carbonate. As in the metadiorite, the biotite is brown, with tiny inclusions of sphene, and intergrown with the amphibole, but apparently in equilibrium with the latter. The amphibole is similar to that found in the metadiorite, with considerable variation in the depth of color and γ^C $\geqslant 20^\circ$.

Amphibolite and amphibolite schist appear locally as boudins in the migmatite and as bands in the biotite-quartz-plagioclase schist. These rocks may be equivalent to the metavolcanic rocks found north of the Front, adjacent to, or interbanded with the metagreywacke. They are grey-black, fine-grained, amphibole-biotite-epidote-quartz-plagioclase schists in which the amphibole usually defines a lineation plunging southeast. These rocks are commonly banded. The mineralogy is similar to that of the probable metagabbro, but no trace of pyroxene is found, and the texture is wholly metamorphic. A chemical analysis of one such schist (193) is similar to an analysis of interbedded tuff and metasediment (G135) from north of Lone Arm (Table 3), except in that G135 is low in alkalis, corresponding to an unusually low feldspar content.

Amphibolite dikes and sills are found locally in granite or migmatite. These are not banded, but have the characteristic southeasterly lineation. They are grey-black, fine-grained rocks composed dominantly of plagioclase and amphibole with epidote and biotite in a granular mosaic as seen transverse to the lineation.

The critical assemblage in these amphibolites is: quartz-plagioclase (oligoclase to andesine)-biotite-amphibole-epidote. None of the minerals chlorite, sericite, carbonate or clinopyroxene which are locally present appear to be part of the equilibrium assemblage.

Migmatite

The area south of the Front is a migmatitic terrane, the bulk of the exposed rock being of apparently mixed origin. This may or may not be true in hand specimen, but in the area mapped as migmatite it is true as far as a practical mapping unit is concerned. This is illustrated by the islet in Timagami River 2.25 miles upstream from Red Cedar Lake where one finds an augen granite, grading into biotite-quartz-oligoclase augen gneiss (possibly metadiorite, see above p. 63), which in turn grades into schist of similar composition (probably metagreywacke). Although the three rock types can be distinguished readily in hand specimen, the tiny islet on which they are intermixed is classed as migmatite. However, the bulk of the migmatite is a more intimate mixture than this.

The typical migmatite (Plate 10) is a grey-pink, augen gneiss of quartz dioritic to quartz monzonitic composition in which the layering varies from indistinct biotite-rich schlieren to biotite-rich bands a

Plate 10. Typical migmatite of the Grenville terrane. Note schlieren of schist and characteristic augen texture. 1.5 miles NE of Hobbs Lake.

few inches in width separated by more quartzo-feldspathic rock. The feldspars form the augen and are set in quartz-rich matrix with variable amounts (rarely > 20%) of brown to green-brown biotite and minor white mica, epidote, sphene, chlorite, apatite, zircon and opaques. The composition of the plagioclase is An_{20}-An_{35}. Locally the migmatite may be granitic, as is the case three-quarters of a mile southwest of Cross Lake Dam, but lacks the homogeneity of the granites described above as a separate unit.

Two varieties of migmatite have been distinguished from the general map unit. One is the "metadiorite-granite complex" mentioned above. The granite intimately intrudes the metadiorite and both intrude the biotite-quartz-plagioclase schist. This sequence and the lithologic similarities allow one to correlate these rocks confidently with the Algoman granitic rocks and the pre-Algoman quartz diorite and gabbro of the terrane to the north. This may be the protolith of a considerable portion of the general migmatite to the south and west. However, it should be emphasized that this metadiorite-granite complex apparently owes its nature to the anastomosing intrusion of the granite rather than to the overprint of metamorphism which gives it a structure characteristic of that of the Grenville province. Locally within the main complex north of Sinton Creek and generally in the remainder of the Grenville terrane, the metamorphism obscures the pre-metamorphic relationships.

The second variety is found in the eastern part of the area. Here some of the migmatite contains sufficient amphibolitic material to warrant the term "amphibolitic migmatite". The amphibolitic component ranges from schlieren in a dominantly granodioritic migmatite to a biotite-amphibole-quartz-plagioclase gneiss. It is possible that this represents the pre-Algoman gabbro, or the metavolcanic rocks, or both, but this is no more than speculation.

No additional assemblages have been found in the migmatites. Those represented are (a) quartz-plagioclase-microcline-biotite-epidote-white mica and (b) quartz-plagioclase-microcline-biotite-epidote-amphibole.

Keweenawan Olivine Diabase

In southwestern Hobbs township an olivine diabase dike intrudes the migmatitic terrane. Its width is about 150 feet, its trend northwest. It is similar to the "Keweenawan" olivine diabase dikes found in the Superior province in this region (see, for example, Grant, et al., 1962, Map #2017). However, few have been found in the Grenville province.

It is typically a brown-weathering, grey, massive, medium-grained diabase with sharp fine-grained margins against the country rocks. Augite (50%) and plagioclase (An_{50}, 40%) are the main constituents and show an ophitic texture. Relics of olivine appear within serpentinous alteration products, and trace amounts of interstitial micrographic quartz and plagioclase are found. Apatite and magnetite are the other accessory minerals. Locally one finds slight uralitization of the pyroxene and coronas of Fe-zoisite (?), brown biotite and green amphibole around magnetite.

This rock post-dates the major metamorphism in this area. It has fine-grained contacts, cross-cuts the structure of the country rock and has a mineralogy incompatible with the assemblages in the country rock. Although Johnston (1954, p. 1064) states that olivine diabase in his area has been locally converted to amphibolite, this dike shows no alteration that may not be readily ascribed to late stage autometamorphic processes.

Chapter 3

STRUCTURAL GEOLOGY

The structural geology is markedly different in the three main subdivisions of the area - the northern Huronian terrane, the central Keewatin-type terrane and the southern Grenville terrane. These structural features are summarized in Fig. 3 . The Huronian rocks form a nearly flat-lying blanket which unconformably overlies the Keewatin-type rocks and is gently folded about a series of north-trending axes. The Keewatin-type terrane is underlain by easterly trending, nearly vertical rocks, which to the east swing abruptly southeastward. This bend is truncated on the southeast by a fault system which there forms the boundary between the Superior and Grenville provinces. As shown on Fig. 3, the system includes northeast trending reverse faults and north northeast trending high angle faults, which are apparently related. The Grenville terrane is underlain by rocks whose foliations suggest a series of southeasterly plunging, overlapping, synform shingles.

Folds

Huronian Terrane

The Huronian sedimentary rocks lie with marked angular unconformity on the Keewatin-type rocks. The strip of Mississagi conglomerate and quartzite shows no angular discordance with the overlying Gowganda Formation, which appears in a series of broad folds with dips generally

Fig. 3

Structural Cartoon of the Lake Timagami Area.

Nipissing diabase.

Huronian sedimentary rocks.

Vogt and Sinton Lake Granites.

Pre-Algoman quartz diorite.

Folds in the Huronian rocks.

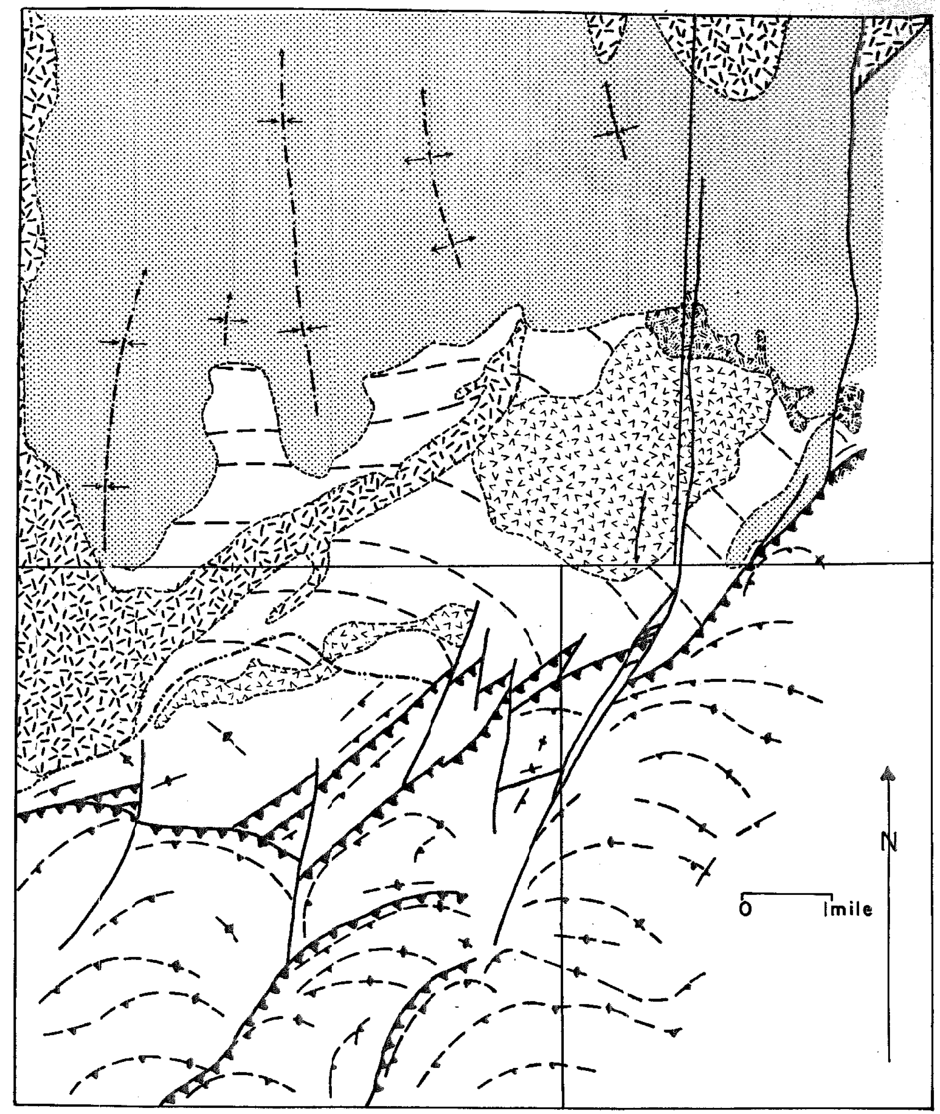
Trend lines of bedding in Keewatin-type rocks.

Trend lines of foliation in Grenville terrane, with approximate dip (◆ 70°-90°, ▼ < 70°).

Reverse fault.

Strike-slip fault, or steep fault with unknown displacement.

Grenville Front.



about 10-20°. However, locally highly variable attitudes are to be found and, except in the vicinity of Timagami River, these appear to be mainly due to soft-rock deformation. Grain gradation and current bedding yield ample data on the direction of tops and indicate that the beds are right side up. Bedding plane data are shown in equal-area projection in Fig. 4.

The bedding plane data, not from one fold but from the Gowganda throughout the area, show broad maxima which approximately define (Fig. 4) an axial plane striking N5°E, dip 85-90°E and an axis plunging 10°N. Cleavage is poorly developed in general. However, in the north-east around Aileen Lake it has a similar strike but steeper dip in the same direction as bedding. In the vicinity of Lone Arm and Cross Lake, cleavage is apparently related to the fault systems.

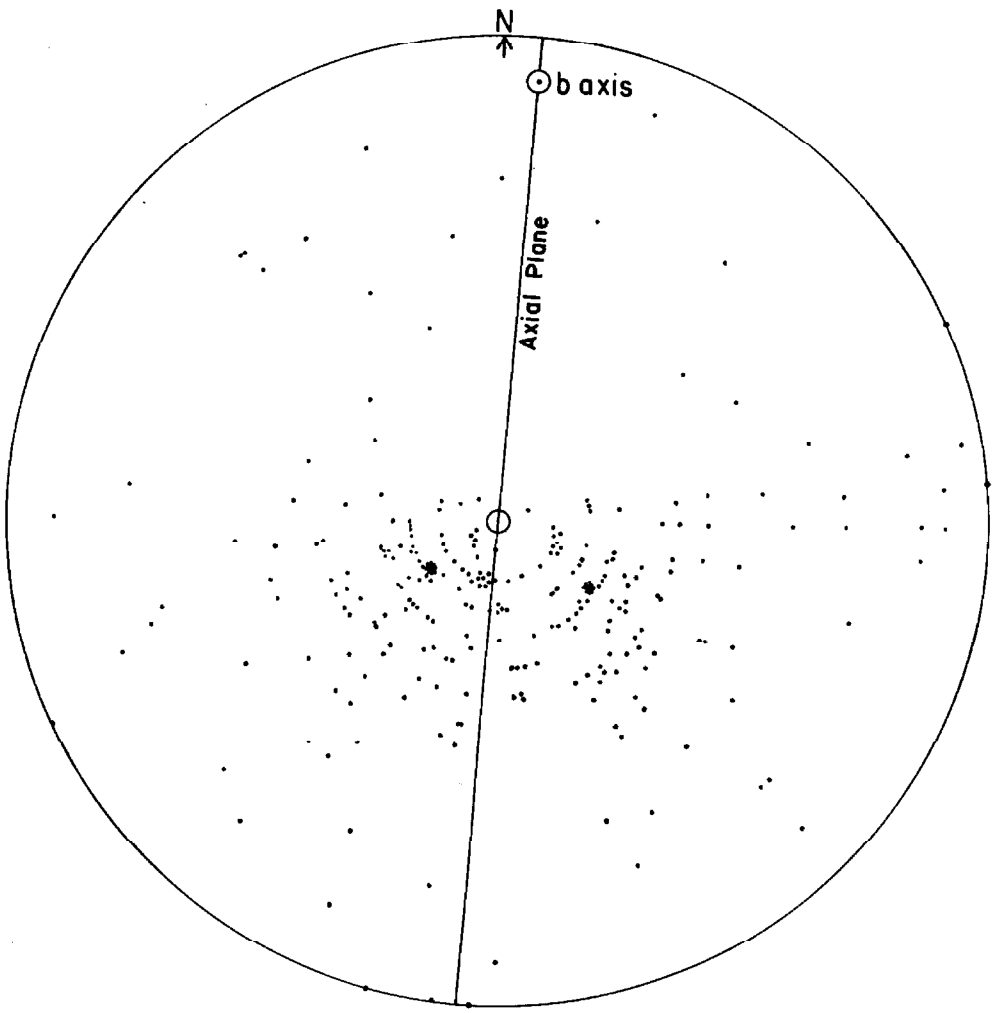
This folding is not discernable in that of the basement rocks and, although this may be due to the gentle nature of the folding, it is possible that it is due to compaction over the pre-existing topography of the basement.

Keewatin-type Terrane

The bend or partial fold in the Keewatin-type rocks is implied by the disposition of the major units therein, and by bedding attitudes within these. The disposition of the major units - metagreywacke, metavolcanics and iron formation is shown on Plate 1. A high magnetic anomaly to the west of the map area (see p. 29) suggests that the easterly trend continues westward below the Huronian blanket and the Southwest Arm Diabase. Bedding in the Keewatin-type rocks strikes

Fig. 4. Bedding-plane Attitudes in Gowganda Rocks.

(Equal area projection, lower hemisphere.)



• Bedding-plane.

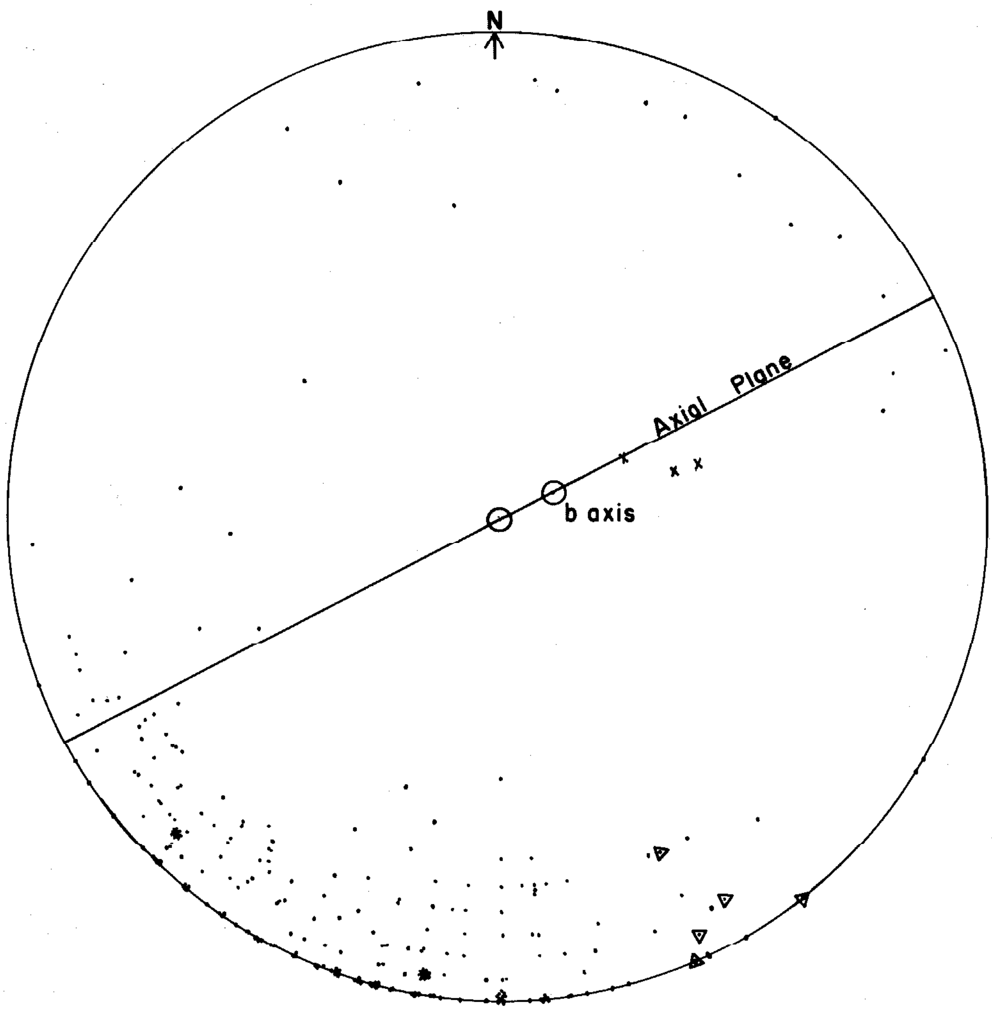
* Bedding-plane maxima (approximate).

easterly in the western part of the area, and dips vertically or steeply to the north. In the eastern part, the strike swings southeastward and the dip is vertical or steep to the northeast. Grain gradation in the metagreywacke indicates tops to the north, and the one top determination from pillow lava agrees with this. Thus the metavolcanics and iron formation apparently lie conformably and stratigraphically above the metagreywacke, and the fold or bend is anticlinal. However, no trace of a complimentary limb has been found.

With only a few local exceptions, schistosity in the Keewatin-type rocks is parallel to bedding. Transverse cleavage and minor folds are unfortunately rare. There is no evidence at all of small scale folding other than the minor folds and absolutely no evidence of isoclinal folding. The pre-Algoman rocks have a southeasterly trending steep to vertical foliation roughly parallel to the attitudes in the adjacent metavolcanics. The Algoman granites are in general massive, and foliation is rarely discernible. The Vogt Granite cross-cuts the foliation of the pre-Algoman quartz diorite and the bedding of the Keewatin-type rocks. From the discordance of the Vogt and Sinton Lake Granites with respect to the bend in the Keewatin-type rocks, it is possible that the emplacement of granite post-dates the bending. Certainly the anticlinal bend is pre-Huronian, as evidenced by the unconformable relations between the Keewatin-type and the Huronian rocks. The attitudes of bedding in the Keewatin-type rocks, along with the few determinations of minor folds and transverse cleavage, are shown on an equal-area projection in Fig. 5. Bedding plane maxima are poorly defined, but allow one to define the axis of the bend

Fig. 5. Structural Features in Keewatin-type Rocks.

(Equal area projection, lower hemisphere.)



· Bedding-plane.

✳ Bedding-plane maxima (approximate).

▽ Transverse cleavage.

X Axes of minor folds.

approximately. The axis so defined plunges about 80°ENE (Fig. 5). The average of four observations of minor folds yields a plunge of 65° ± 10°, bearing N65-75°E. The average of five observations of transverse cleavage yields a strike of N60-65°E and a dip of 85°N. These data are approximately compatible with those from bedding plane attitudes, and suggest that the axial plane of the "fold" strikes ENE, and is approximately vertical, the plunge of the axis being about 80° ENE.

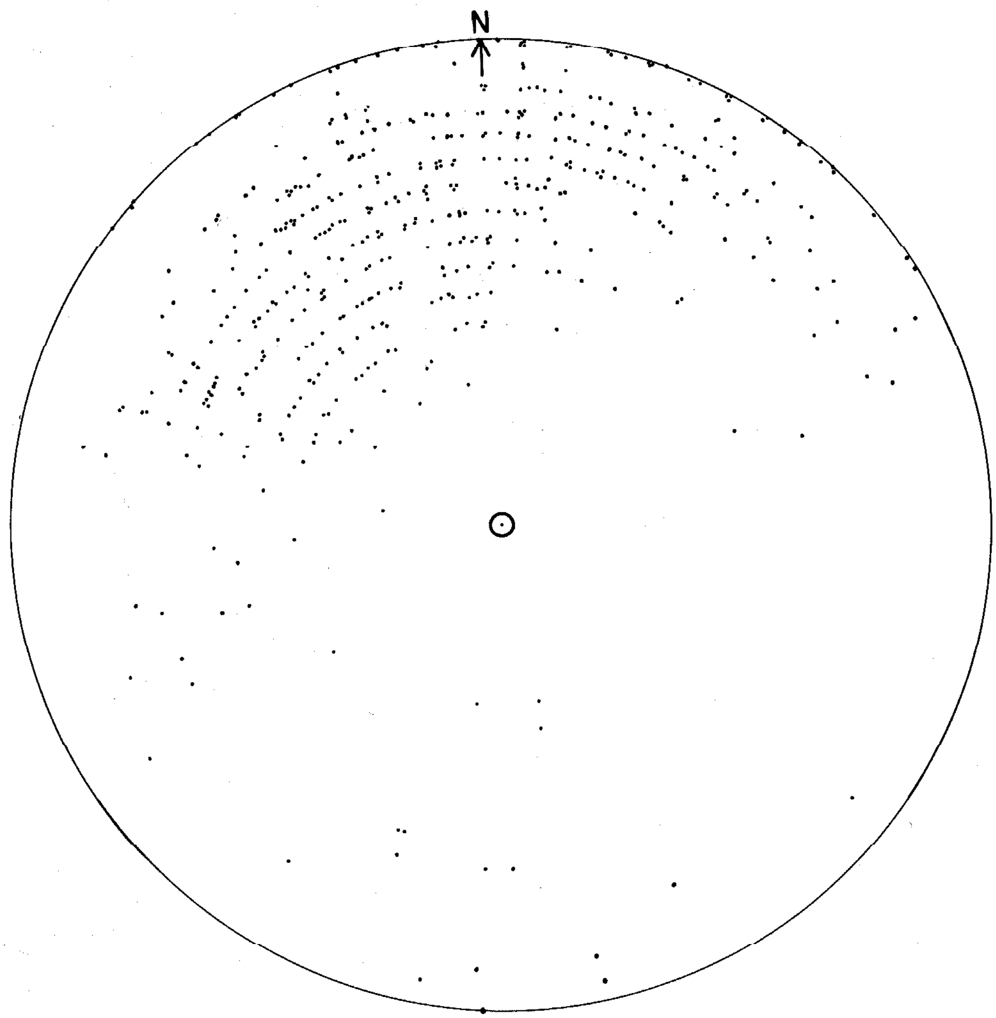
The "fold" is truncated on the SSE by the system of faults which there defines the boundary between the two provinces.

Grenville Terrane

Foliation in the rocks of the Grenville terrane appears in plan as discontinuous arcs concave to the SSE. This is apparent on Fig. 3 , on which foliation attitudes from Plate 1 have been generalized into trend lines. The dip of the foliation is steep to vertical on the east to southeast trending "limbs" and moderate on the northeast trending "keels". The dips are towards the centers of the arcs. Discontinuities in foliation trends are common in the field: generally a steep or vertical foliation trending ESE abuts against foliation trending NE and dipping about 60°SE. This may be seen, for example, in several localities in the vicinity of Hobbs and Shallowpan Lakes. The pattern is interpreted as a series of synform shingles overlapping one another to the southeast. This is a reflection of the "distributed movement" which characterizes the terrane and resulted in the widespread formation of augen gneiss. The foliation attitudes are plotted in equal-area projection in Fig. 6 , and one finds a broad maximum of attitudes in the

Fig. 6. Foliation in Grenville Province.

(Equal area projection, lower hemisphere.)



· Foliation.

northwest quadrant. This dies out gradually into the northeast quadrant, but terminates rather abruptly in the opposite direction. These features reflect the marked dominance of the southeasterly trending limbs over the short or absent southerly (?) trending limbs, rather than the presence of complete isoclinal folds. Antiform foliation is almost entirely lacking, due to the crests being sheared out during movement, giving rise to the lateral margins of the plates.

In Fig. 7 , the axes of minor folds (which are not abundant) and the lineations due to mineral elongation are plotted. Acknowledging the spread in the attitudes, the axes and the lineations coincide and plunge southeast at a moderate angle. The maximum corresponds to a bearing of 130° and a plunge of 45°. Coincident with these lineations are the dip of the keels of the shingles, lineations on the northeasterly trending fault planes (see below), and the long axes of the rare amphibolite boudins. The dip of the northeasterly foliation and the plunge of the lineations tend to decrease southeastward.

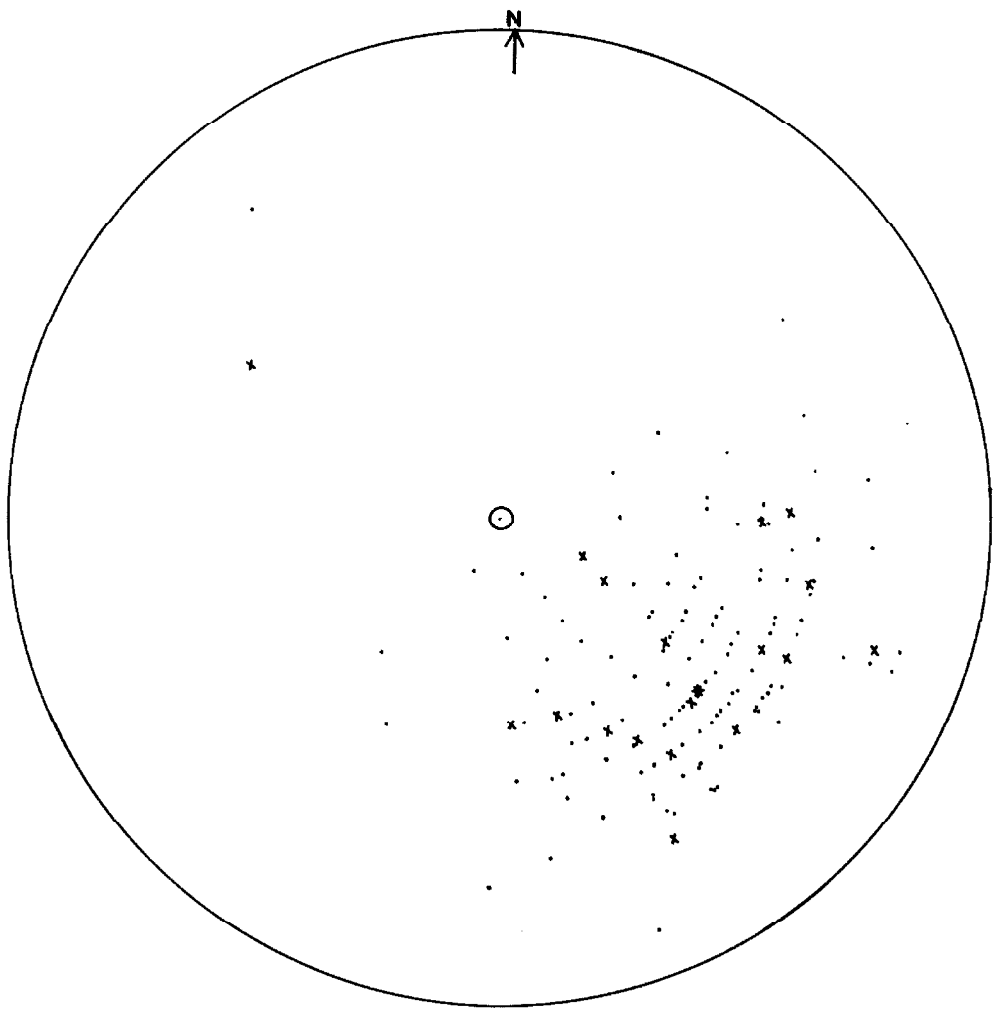
Folding in the southern and central sectors was not sufficiently intense to yield evidence of refolded folds. Rather one finds that especially adjacent to the main fault zone a southeasterly plunging lineation or a northeasterly trending schistosity or both were imposed on the rocks of the central sector. This is best seen northeast of Lone Arm.

Faults

Faults have been proven only within the Grenville terrane, adjacent to its northwestern boundary and in the vicinity of Timagami River. The

Fig. 7. Lineations in Grenville Province.

(Equal area projection, lower hemisphere.)



· Lineation due to mineral elongation.

x Minor fold axes.

* Average lineation (approximate).

major fault zone extends from west-central Hobbs through Centre Lake to Lone Arm, and its width is at least half a mile. Cataclasis is most marked within this zone, but is widespread throughout the Grenville terrane, commonly yielding augen gneiss. As noted above, distributed movement on the foliation planes is indicated, and certainly movement was not restricted to the few discrete planes shown on the map (Plate 1). Two fault sets may be distinguished.

The major fault set is approximately parallel to the foliation on the "keels" of the synform shingles and in general the strike is about N45°E, the dip 60°SE. Obviously the interpretation of these shingles as discussed above requires that the individual shingles be fault bounded, but it is not practicable to depict all these breaks. The NE faults shown at Hobbs Lake, Shallowpan Lake and along Sinton Creek northeast of Centre Lake are, in fact, composite fault zones. The NE faults which form the northwest side of the main fault zone are better defined in general, and commonly show development of phyllonite with a down-dip lineation. Although it has not been possible to correlate structures or find marker horizons on each side of the faults, the lineations, the attitude of the fault planes and the generally higher metamorphic grade of the rocks to the southeast suggest that the movement was south side up, and that the NE faults are reverse faults. This is in agreement with the overturning of Gowganda rocks to the northwest as found in the area northeast of here (Johnston, 1954). Yet these faults as seen at the contact of the two provinces are not colinear, but in en-echelon arrangement. This pattern, coupled with meager evidence from southeast Vogt and adjacent McCallum and Torrington, suggests that these NE reverse faults have been offset by apparent right-lateral movement on steeply dipping faults trending slightly east of north.

This NNE fault set is largely inferred from the offset of the NE reverse faults: for the most part they are inconveniently concealed by drift. Nevertheless an estimate of their attitude is obtained from the attitude of shearing on Cross Lake and also 1.5 miles east of Sinton Lake. The inferred trend is NNE, the dip vertical to 80°E. Although most of the NNE faults offset the NE reverse faults at the northern boundary of the Grenville, they may be themselves truncated by other NE reverse faults within the province. This suggests that the two sets were penecontemporaneous, as will be discussed below.

Joints

Three prominent joint sets are found in the area: trending northwest, slightly east of north and northeast, while a minor set trends east. These are steeply dipping to vertical. Quartz with or without carbonate, especially in the Gowganda, may appear in any of the joint sets. These trends are obvious in strong lineaments visible on aerial photographs, but except as noted above, evidence of movement is lacking.

Discussion

The anticlinal structure in the Keewatin-type rocks is well defined and apparently simple. However, it seems very difficult to obtain such a structure from a single event, i.e. to transform originally flat lying beds into an anticline with steep or vertical limbs with an axis plunging about 80°. It is apparently necessary to envisage two events: (a) an event in which the beds were rotated into a northerly dipping monocline (possibly a limb of a fold with an approximately horizontal axis) and (b) an event in which this fold was refolded into the steeply plunging anticlinal structure now seen here. There is, in fact, some slight evidence for the two events. The schistosity generally present in the Keewatin-type rocks is parallel to the bedding. The formation of this structure may be correlated with the first event. Transverse to the schistosity is a very faint cleavage marked by the recrystallization of micas. This is apparently parallel to the axial plane of the main fold (more correctly it is compatible with the other structural data from the fold (Fig. 5) and is itself used in defining the geometry of the anticline). The development of this transverse cleavage may be correlated with the second event.

The original folding may have been comparable to that found north of the Larder Lake break near Kirkland Lake (Fig. 1) in Keewatin-type volcanic rocks (Thomson, 1950, Fig. 2), to the syncline west of Timagami in Keewatin-type volcanic rocks and iron formation (Moorhouse, 1946, p. 21), or to the early monocline inferred by Henderson (1936, p. 14) in the Kipawa area. Steeply plunging folds are locally found in the Superior province. For example, in the area northeast of Lake Chibougamau, Gilbert (1958, p. 27) reports that Keewatin-type rocks "have been compressed into tight synclinal and anticlinal folds striking N60°E and plunging northeastward at a steep angle". At the Front east of Val d'Or, Norman (1947) and Tiphane and Dawson (1947) describe a situation similar to that in the Timagami area, where Keewatin- and Timiskaming-type rocks forming an easterly trending belt swing abruptly southeastward to abut against northeasterly trending gneisses. The most feasible explanation of this anticlinal "bend" requires the postulation of a strike slip fault trending ENE, on which this bend would have been a "minor" fold suggesting right-lateral movement. Speculation from this hypothesis leads one to note (a) the virtually identical situation at the Front east of Val d'Or, as described above, (b) the evidence of right-lateral movement on steeply dipping faults trending east to northeast in the vicinity of Sudbury (Yates, 1948, p. 607) including the Worthington Fault which continues NE as the Wanapetei Fault forming the boundary between the Superior and Grenville provinces east of Sudbury, and (c) the linearity of the Grenville Front as depicted on Fig. 1. Norman (1936, p. 120) postulated that the Front is due to faulting, but considered this faulting to thrust movement from the southeast. This is not the postulate here. Rather it seems within the bounds of possibility that a pre-Huronian, (pre-Algoman?), steeply dipping ENE trending fault zone with right-lateral movement existed in the vicinity of what is now the Grenville Front. If so then this fault zone has been largely obliterated by later events, and indeed may have controlled the later formation of the structural discontinuity which in part marks the Front. It may be noted, however, that in several areas along the Front it has been possible to tentatively correlate units across the Front, and that in several neighboring areas these units are markedly different (e.g. Sudbury, the present area and that to the northeast). This may place a maximum limit on the possible displacement on the speculative fault zone on the order of 25 miles.

The anticlinal bend is truncated on the south by the structures of the migmatitic terrane. Within this terrane the structure is dominated by shearing rather than folding, and is interpreted as a series of overlapping "thrust" plates (shingles). The "thrust" planes especially well defined at the northern margin of the terrane are not classical low angle fault planes, but reverse faults dipping at about 45-70° southeast. These reverse faults are offset to yield the en-echelon pattern obvious on the map, apparently due to NNE trending steeply dipping faults with apparent right-lateral offset.

These NNE faults are not classical tear faults in that they extend below the lowermost reverse fault and do not have the same sense of movement as the blocks lying within the obtuse angle formed by the NNE fault and the adjacent reverse fault. Nor do these faults appear to be later than the reverse faulting: at least some of them appear to be over-ridden by shingles (e.g. in the vicinity of Sinton Creek, northeast of Centre Lake, and at Lone Arm). Therefore it is considered that these NNE faults were penecontemporaneous with the reverse faulting.

Another problem here is the synform nature of the "shingles". The congruence of these structures with the minor structures of the terrane (lineations and minor folds), and with the reverse faults (to which they are considered analogous), demands a simultaneous explanation of all these features. It is considered that this can serve also to rationalize the NNE faults. The "explanation" requires compression in a northeasterly direction during the development of the reverse faults.

To the northeast, the en-echelon structure extends for at least 30 miles (Johnston, 1954) and its limit is unknown. However, this structure does not appear in the vicinity of the Front westward for more than about seven miles. There the Front apparently swings sharply southward for about five miles (see Thomson, 1960, Chart A) round (?) an anorthosite-metagabbro body more than six miles across (the total extent of the body is not known). This body may have acted as a buttress during the development of the structures under consideration.

Two important conclusions as to the nature of the Grenville Front are evident from the foregoing discussion. First, the easterly trending structures of the Keewatin-type rocks of the Superior province are destroyed and replaced by the complex dominantly northeasterly trending structures of the northwestern Grenville province. Secondly, structural features close to the Front in the Superior province are incompatible with the typical structures of either the Superior or the Grenville province. These features may be logically explained by the presence in the vicinity of the Front of a pre-Huronian regional strike-slip fault zone.

Chapter 4

POLYMETAMORPHISM

The major complication in defining the Grenville Front in terms of the Grenville metamorphism is due to polymetamorphism. Within the Superior province there is evidence of several metamorphic events in pre-Grenville time, the dominant event being pre-2 b.y. in age (e.g. Wilson, 1956; Snelling, 1962; Fairbairn, Hurley and Pinson, 1961). Grenville metamorphism at approximately 1 b.y. is presumably superimposed on earlier metamorphism in the vicinity of the Grenville Front, but this often postulated superposition has not been demonstrated in any of the several detailed studies of the Front (Quirke and Collins, 1930; Johnson, 1954; Deland, 1956; Grant, et al., 1962). Commonly the transition into the Grenville province is based on the appearance of "Grenville-type" rocks (e.g. Deland, 1956). To some extent the rocks of the northwestern part of the Grenville province are indeed distinctive (see Table 1), appearing as schist, gneiss and migmatite of the amphibolite facies. Yet the presence of such rocks does not axiomatically imply Grenville metamorphism. Similar rocks occur locally within the Superior province: granite gneiss, lit-par-lit gneiss, biotite paragneiss with or without staurolite or garnet, hornblende schist, amphibolite, etc., and these are generally spatially related to pre-Huronian granitic intrusions (e.g. Dawson, 1954; Freeman, 1957; Chagnon, 1961; and Thomson, 1961). Thus the appearance of a metamorphic transition in the vicinity of the Front into rocks of "Grenville-type" is insufficient evidence on which to define the Grenville Front. In areas where "Proterozoic" sedimentary rocks or some other unit of age intermediate between the two major events is present, it may be possible to distinguish events older and younger than this unit, but even then it remains to be proved that a given transition is, in fact, of Grenville age and in general this is impossible without the aid of isotopic age determinations.

In the Lake Timagami area there is a transition from greenschist facies in the Superior province into "Grenville-type" rocks of the amphibolite facies in the Grenville province. Moreover, due to the presence of Huronian rocks, it can be proved that there was indeed pre-Huronian metamorphism, and that the observed transition is superimposed on the earlier metamorphism and is probably of post-Huronian age. That the transition is of Grenville age will be demonstrated later by means of a Rb-Sr isochron study across the Front.

In this area the best evidence for polymetamorphism, apart from the isochron study, comes from structural and textural relations. These will be considered before a detailed discussion of the mineral assemblages is given.

Structural and Textural Relations

Pre-Huronian metamorphism is proved by the occurrence of completely or almost completely recrystallized Keewatin-type rocks overlain with profound angular unconformity by very incompletely recrystallized Huronian sedimentary rocks. In the Keewatin-type rocks bedding-plane cleavage is ubiquitous, especially evident in the recrystallization of micas in the metagreywacke, and transverse cleavage and minor folds occur locally. Relic textures and structures are restricted to locally occurring relic trachytic and diabasic textures, bedding in pyroclastic strata, and rare pillow structures in the metavolcanic rocks and to relic bedding structures (including graded bedding) in the metagreywacke. In contrast to this, it is simpler to state the metamorphic rather than the relic features of the Huronian rocks. In general these are restricted to partial recrystallization of the finest-grained material: argillite may be considerably recrystallized but in the conglomerate, greywacke and quartzite only the fine matrix material is recrystallized. Schistosity is in general absent or extremely faint. Thus there is no doubt that metamorphism preceeded the deposition of the Huronian sediments, and the question arises as to the relationship of this metamorphism to the pre-Huronian intrusive rocks.

The pre-Algoman quartz diorite and gabbro have been very little recrystallized, but slight foliation in the body north of the Vogt Granite is approximately parallel to the bedding plane schistosity in the adjacent Keewatin-type rocks. This suggests that the pre-Algoman rocks were emplaced late in the pre-Huronian metamorphism.

The Vogt and Sinton Lake (Algoman) Granites are massive, discordant plutons suggesting that the pre-Huronian metamorphism predated the emplacement of these bodies. However, the two events may be related, for (a) apophyses from the Sinton Lake Granite in particular may be concordant or discordant (Plate 4), (b) contact effects on the immediately adjacent rocks are minimal, dominantly the development of white mica in the adjacent metagreywacke, (c) pseudomorphs after andalusite and possibly cordierite (discussed in detail below, p.100) are widespread in the metagreywacke and grossly related to the plutons, and (d) the metagreywacke is a semi-schist or schistose hornfels rather than a true schist.

Thus there is definite evidence of a pre-Huronian metamorphism which also predated, but was probably related to, the emplacement of the Algoman granite.

Later metamorphism is superimposed on the pre-Huronian rocks, increasing in grade southwards. In the field it cannot be proved that this metamorphism affected the Huronian and Nipissing rocks, but that these rocks were indeed affected is suggested by their mineral assemblages, which will be considered below. Moreover, Rb-Sr studies prove that this metamorphism was of Grenville age (see p.116).

In the field the later metamorphism of the pre-Huronian rocks is evidenced by:

(a) The transition to schist from the imperfectly schistose metagreywacke (see p. 55),

(b) Recrystallization of the sericitic pseudomorphs after andalusite to larger and fewer plates of white mica, no relic knots being found more than 0.2 miles south of the mapped Front,

(c) The obliteration of igneous textures in the probable equivalents of the Algoman and pre-Algoman rocks and the development of equivalent gneisses (see p. 60-62),

(d) The development of structures typical in orientation and character of the northwestern part of the Grenville province and markedly different from those found north of the Front (see p. 78).

In defining the Front in the field, the appearance of granitic permeation in the schist and the development of migmatite, i.e. the appearance of "Grenville-type" rocks was also considered diagnostic. However, it is entirely possible that the development of the migmatitic "Grenville" terrane was at least initiated during the pre-Huronian event. This possibility is suggested by the metadiorite-granite complex north of Sinton Creek, which apparently originated as an intrusive complex during the emplacement of the Algoman granite, but now shows the typical northeasterly trending, southeasterly dipping foliation and the downdip lineation characterisitc of the Grenville terrane.

The question arises as to how far north the effects of the Grenville metamorphism can be traced, for the Front as defined is an arbitrary boundary (see p. 54). The Huronian rocks provide the best chance of answering this question because of the difficulty of distinguishing later low grade metamorphism from the earlier metamorphism and retrogression of the Keewatin-type rocks or from autometamorphism in the granitic rocks and "Nipissing" diabase north of the Front. Contact metamorphism of the Huronian rocks by the "Nipissing" diabase resulted in the formation of hornfels close to the diabase, but in the Huronian rocks away from diabase there is little macroscopic evidence of metamorphism. Thus the macroscopic effects of Grenville metamorphism are not discernible more than about a quarter of a mile north of the Front (or the fault zone in the eastern part of the area) and then only definitely in the pre-Huronian rocks. This is hardly surprising because the Front was defined in terms of field evidence of the later metamorphism, and cannot be defined to within less than a quarter of a mile.

The conclusions from the preceeding evidence are that two major metamorphic events have occurred in the Lake Timagami area.

(a) Pre-Huronian metamorphism, predating, but possibly associated with, the emplacement of the Algoman granite.

(b) Later (Grenville) metamorphism of at least the Algoman and older rocks.

Mineral Assemblages

Additional evidence of the nature and extent of the Grenville metamorphism may be obtained from an analysis of the mineral assemblages found throughout the area. The detailed assemblages of the Grenville terrane will be discussed first because in this terrane the late metamorphism has obliterated virtually all trace of the previous metamorphism. The sequence of assemblages will be traced into the area north of the Front and finally into the Huronian rocks.

In the south of the area the critical assemblages are, with quartz and plagioclase (oligoclase-andesine):

biotite-microcline-epidote-amphibole (metadiorite and migmatite),

biotite-microcline-epidote-white mica (metadiorite, granite and migmatite),

biotite-garnet-amphibole (schist),

biotite-garnet-staurolite (schist).

Assemblages similar to the first two, but lacking one or more phases (other than biotite) are common in the schist and amphibolite. Other minor constituents are sphene, apatite, zircon and magnetite.

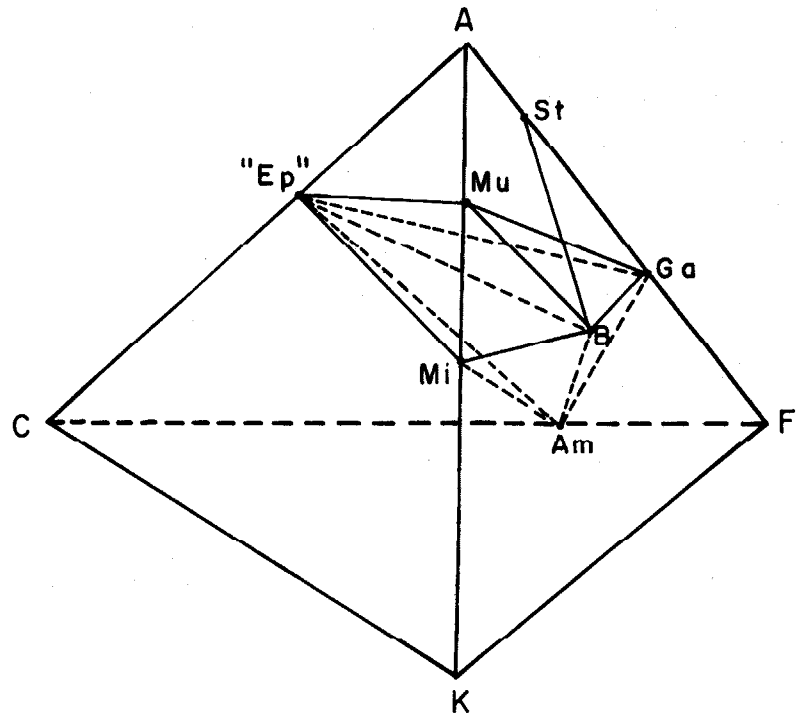
Carbonate occurs rarely along grain boundaries and as partial alteration of plagioclase in amphibolitic rocks. Sericite and associated epidote occur as minor alteration of plagioclase. Rarely chlorite occurs intergrown with biotite and very rarely enclosing remnants of garnet. These minerals are considered secondary here and are omitted from the following discussion.

Omitting those major components which appear as major constituents only in one phase, omitting SiO_2 because of the excess quartz present, and considering H_2O as a mobile component (Thomson, 1957), one is left with five components: K_2O, CaO, Al_2O_3, FeO and MgO. For the purposes of representing the above assemblages on a diagram it is convenient to consider FeO and MgO as a single component as a first approximation. The remaining components (K, Al, Ca and Fm) form the vertices of the tetrahedron of Fig. 8 , on which the above assemblages are plotted. All the observed assemblages are compatible with one another and are typical of the amphibolite facies. However, several comments are necessary over and above this statement.

In no case have amphibole and white mica been observed together (discounting sericitic alteration of plagioclase), and the variations in the common assemblages of the schist depend upon slight perturbations in composition above or below the biotite-epidote "line", close to the biotite "point". The staurolite-bearing assemblage, found in only one sample, consists of 20% biotite, 2% garnet and a trace of staurolite. This also represents only a slight perturbation about the biotite "point".

It is notable that no stable five-phase assemblage has been found

Fig. 8. ACFK Diagram for Mineral Assemblages of the Amphibolite Facies (Grenville Province).



The vertices of the tetrahedron are aluminum (A), calcium (C), ferrous iron and magnesium (F) and potassium (K). The minerals shown are epidote (Ep), muscovite (Mu), staurolite (St), garnet (Ga), biotite (B), microcline (Mi) and actinolitic hornblende (Am).

here to correspond to the five components. Although the two observed four-phase assemblages do occur widely they are uncommon in the schist and amphibolite; moreover, garnet and staurolite are rare in the schist. The common assemblages in the schist and amphibolite are (in addition to quartz and plagioclase) biotite, biotite-epidote and biotite-epidote-amphibole. The possibility of considerable compositional ranges within one or more of the phases means that the corresponding point, line, and plane in the diagram are all actually volumes. This, plus the fact that the bulk composition of the schist must be close to biotite in this diagram, for biotite is by far the most abundant phase other than quartz or plagioclase, accounts for the widespread appearance of less than the theoretical maximum number of phases (five).

Approaching the Front from the south, the only mineralogical changes noted are within the topology of the diagram (Fig. 8). These are (a) the occurrence of albite-oligoclase rather than oligoclase-andesine in the metadiorite-granite complex and (b) a tendency for biotite to be lighter in color, with inclusions of sphene or rutile, and for a decrease in the refractive index γ , corresponding to an increase in Mg/Mg + Fe + Mn + Ti (see p. 56) from about 0.45 to 0.6.

Chlorite and white mica appear as widespread but minor constituents of the schist within a quarter of a mile of the Front near Bass Lake, averaging 5-10% of the rock. In part the chlorite and biotite are intergrown in folia, but chlorite porphyroblasts truncating biotite and, more commonly, biotite porphyroblasts truncating chlorite are found. White mica occurs dominantly as porphyroblasts within the fine-grained white mica knots, pseudomorphous after andalusite, but also occurs in folia with biotite and in cross-cutting prophyroblasts. These relations are not explained by chloritization of biotite for the most common relationship is biotite truncating chloritic folia, suggesting that the biotite is indeed prograde. That the biotite formed from chlorite and white mica is indicated by the occurrence of biotite dominantly around the white mica knots with chlorite dominant in the remainder of the matrix. The development of the biotite, chlorite and white mica porphyroblasts in adjacent but discrete grains, however, implies that the three were in equilibrium here. Thus there is an anomaly in that both relic and prograde chlorite and white mica occur in the same rock. The two generations of white mica are represented by the fine-grained aggregates of the relic knots and the large porphyroblasts which appear both inside and outside the knots. The two generations of chlorite are represented by that intergrown with biotite in folia and that in the discrete porphyroblasts. No optical distinction has been found between the postulated two chlorites, but if the formation of biotite was indeed largely from white mica and chlorite, then an aluminous chlorite could be a biproduct of the reaction, and it is not possible to estimate the Al-content of chlorite by optical means (Albee, 1962). As a complicating factor some of the chlorite may in addition be secondary after biotite. In any case it seems clear that in the immediate vicinity of the Front biotite, white mica and chlorite form a stable prograde assemblage of the later (Grenville) metamorphism.

In the vicinity of the Front, the critical assemblages found in rocks in which the effects of late metamorphism can be discerned are (with quartz and plagioclase):

biotite-white mica-chlorite-epidote (metagreywacke)

biotite-amphibole-epidote-chlorite (metagreywacke, metavolcanics and metadiabase)

microcline-biotite-white mica-epidote (granite)

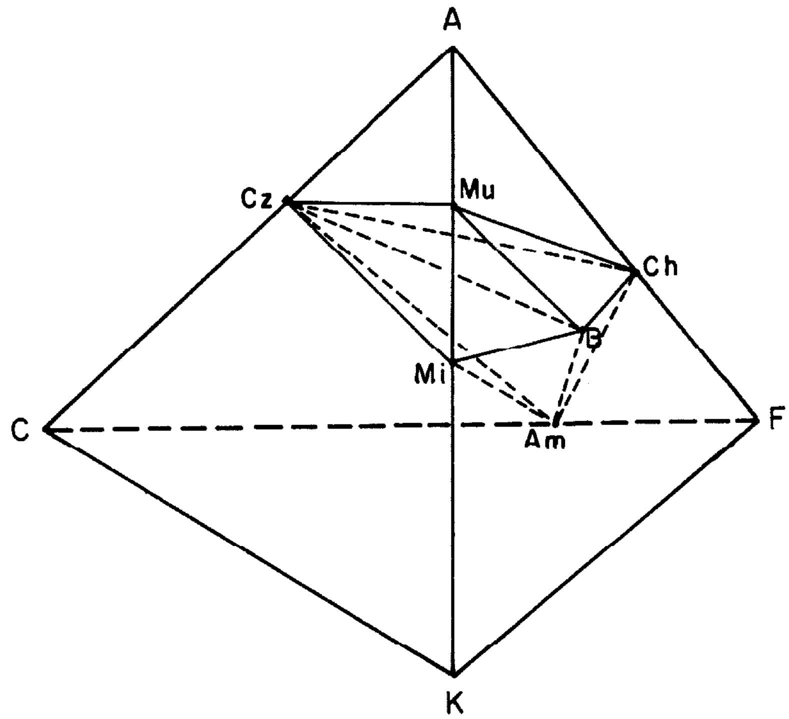
microcline-biotite-amphibole-epidote (quartz diorite)

Within the metagreywacke the plagioclase is oligoclase: the sieve-like grains (see p. 22) suggest incomplete recrystallization and thus they are probably relic from the early metamorphism. Similarly the saussuritized plagioclase in the quartz diorite is oligoclase, and obviously did not attain equilibrium during the metamorphism. In the granite and in the metavolcanics at Lone Arm the plagioclase is albite, but the significance of this is uncertain, because albite is the common composition of plagioclase in the granite and metavolcanics in general north of the Front. The epidote in most samples of the metagreywacke and metavolcanics is strictly clinozoisite rather than more Fe-rich epidote.

Retrograde chlorite appears in several of these rocks and secondary (?) carbonate appears in the metadiabase: these and the products of saussuritization of plagioclase have been omitted from the above assemblages. Accessory minerals are the same as those found to the south, with the addition of tourmaline in the metagreywacke. No garnet or staurolite have been found north of the Front.

The above assemblages are plotted in Fig. 9 . They are compatible

Fig. 9. ACFK Diagram for Mineral Assemblages of the Greenschist Facies (Superior Province).



The vertices of the tetrahedron are aluminum (A), calcium (C), ferrous iron and magnesium (F) and potassium (K). The minerals shown are clinozoisite (Cz), muscovite (Mu), chlorite (Ch), biotite (B), microcline (Mi) and actinolitic hornblende (Am).

with one another and the assemblages biotite-chlorite-white mica-clinozoisite and biotite-chlorite-amphibole-clinozoisite are typical of the greenschist facies. There is very little change in topology from the diagram of Fig. 8. The major changes are that the place of garnet has been taken by chlorite, clinozoisite occurs rather than more Fe-rich epidote, and staurolite and garnet are no longer present. The presence of chlorite rather than garnet in these rocks does not necessarily imply a direct substitution, rather the disappearance of prograde chlorite to the south is apparently due to its incorporation (with white mica) into biotite. This requires either a change of the biotite and chlorite fields or a change in the composition of the schist in the direction of the biotite field. Since the Mg/Fe ratio in both chlorite and biotite is not greatly different from unity (see p. 22), the requisite compositional change southwards would probably be towards lower alumina. That this is indeed a possibility will be shown below.

Northwards into the central sector, evidence of the later metamorphism is in general lacking. The assemblages now found in the metagreywacks and metavolcanic rocks are the same as those described above, but it is not possible to decide whether or not they are due to the later metamorphism. If they are, then the recrystallization was mimetic with respect to the earlier formed textures. Within the intrusive rocks in the north of the central sector, i.e. the Southwest Arm Diabase, the Vogt Granite and the pre-Algoman quartz diorite and gabbro (except for that found northeast of Lone Arm, which has the characteristic "Grenville" foliation, and was included in the above discussion), it is not possible to distinguish the effects of the later metamorphism from possible autometamorphic effects. In any event, late metamorphism was insufficient to anneal the spindle texture found in the amphibole of the pre-Algoman rocks, to destroy the pyroxene locally found in the Southwest Arm Diabase, or to radically alter the igneous textures in these rocks or in the Vogt Granite. This is true despite the fact that the Vogt Granite was sufficiently metamorphosed in Grenville times to attain almost complete strontium isotopic equilibration (see p. 120).

The Huronian rocks, although macroscopically unmetamorphosed, show widespread development of sericite-chlorite-clinozoisite in the argillite and in the fine-grained matrix of the coarser sediments. In addition, the assemblage biotite-sericite is present in the matrix of the Mississagi rocks (see p. 39). These assemblages are found in rocks far removed from known diabase, the first assemblage being present in argillite in the extreme north of the area, 2.25 miles from known diabase. The assemblages are compatible with those found to the south in the vicinity of the Front (Fig. 8), and suggest that Grenville metamorphism did, in fact, affect the Huronian. At the very least, these assemblages place an upper limit of low greenschist facies on the grade of post-Huronian metamorphism in the north of this area.

The foregoing discussion does not emphasize the striking increase in migmatization coincident with the metamorphic transition. At the Front only a few granitic pods and veins occur in the schist, but within half a mile to the south these may constitute over 30% of the rock. This coincidence suggests that the migmatization is related to the metamorphic transition. However, pre-Huronian migmatization is evident at least in the anastomasing intrusion of Algoman granite into pre-Algoman quartz diorite northeast of Centre Lake, on which is superimposed structures and textures typical of the northwest Grenville province (see p. 67).

The transition in mineral assemblages is not spectacular due to the compositions of the rocks involved. Were the metasedimentary rocks of pelitic composition, one might have found an abrupt transition from the chlorite zone into migmatitic rocks of the kyanite zone similar to that found at Sudbury (Grant, *et al.*, 1963).

Pre-Huronian Metamorphism

The overprint of later (Grenville) metamorphism largely obscures the nature of the earlier (pre-Huronian) metamorphism, but nevertheless, reconstruction of the effects of this metamorphism may now be attempted.

The postulated relationship between the pre-Huronian metamorphism and the Algoman granite depends largely upon the appearance of relic knots in the metagreywacke (see p. 23), and their distribution with respect to the granite. The chlorite-white mica knots, which on the basis of composition may be pseudomorphous after cordierite (or possibly staurolite or may have been simply micaceous knots), occur in the northwestern part of the metagreywacke belt. The most southerly occurrence is 0.75 miles northeast of Sinton Lake. South and east of here the knots are dominantly of white mica and, between Sinton Lake and Bass Lake, have the form of andalusite. The appearance of andalusite and probable andalusite was thus restricted to the area adjacent to and between the Vogt and Sinton Lake Granites, the possible cordierite-bearing assemblages being restricted to the area to the northwest.

The two kinds of knots have not been found in the same rock. This could be due to compositional differences in the metagreywacke, but this does not seem plausible considering the range of composition found in the metagreywacke (see below). It is more probable that the transition from chlorite-white mica knots to those retrograde after andalusite represents a metamorphic transition from assemblages bearing cordierite to andalusite-bearing assemblages such as is commonly found in contact metamorphic areas.

Reconstruction of the other phases present involves considerable speculation, but probably quartz, biotite, plagioclase and clinozoisite were stable in both assemblages. The plagioclase at least in the inner zone was oligoclase, which now appears as relic partially recrystallized grains. Due to later retrogression it is not possible to determine to what extent white mica and chlorite were stable in the early assemblages. However, in the metavolcanic rocks the assemblage quartz-plagioclase (albite, rarely oligoclase)-biotite-amphibole-chlorite-clinozoisite was apparently stable during both the pre-Huronian and the Grenville metamorphisms.

Noting the development of white mica in the metagreywacke adjacent to the Granites, it is probable that the retrogression of andalusite to white mica and the possible retrogression of cordierite, were also related to the emplacement of the Granites.

It must be emphasized that (a) the gross zonal relationship of andalusite and possible cordierite-bearing assemblages is not spatially related to either Granite, (b) the Keewatin-type rocks are not hornfelsic in texture, but semi-schists or schistose hornfelses and (c) the Granites are discordant with respect to the poor schistosity of the Keewatin-type rocks.

Therefore the pre-Huronian metamorphism was probably related to, but preceeded, the emplacement of the Algoman granite and resulted in the formation of andalusite and possibly cordierite-bearing schistose hornfels from the Keewatin-type greywacke. This metamorphism was thus not strictly contact metamorphism, but rather of the "regional contact" or Buchan type (Read, 1952; Miyashiro, 1958; Sugi, 1930).

Chemical Composition of the Metagreywacke and Schist

Field, structural and petrographic evidence indicate that there is a textural and mineralogical difference, but no pronounced difference in chemical composition between the Keewatin-type metagreywacke and its equivalent schist in the Grenville province. However, it has been suggested that the Grenville Front is the locus of an abrupt compositional change, and hence it is necessary to test the validity of the above conclusions analytically. To this end, the variation in bulk composition of the metasedimentary unit within each province has been determined. This also provides a means of testing whether the correlation of metagreywacke and schist is permissible and whether the mineralogical changes found are due to differences in chemical composition rather than to differences in grade of metamorphism.

The greywacke is an apparently monotonous unit, and it is not possible to recognize and carry an individual thin stratigraphic unit across the Front. For this reason it is necessary to establish both the average and range of composition of the greywacke for comparison with its apparent equivalent south of the Front. The metagreywacke north of the Front was sampled extensively during the field work, hence a composite sample (44 specimens) provides a means of establishing a valid average. The range of chemical composition was established by analysing those samples which petrographic examination indicated represent the extremes of the range of mineralogical variation.

It is not economically reasonable to obtain the necessary data by conventional wet chemical techniques alone. Therefore the bulk of the data has been obtained by X-ray fluroescence techniques, using three conventionally analysed samples of the metagreywacke and schist as standards (Analyst, D. Maynes) supplimented by other standards already available. Analyses for SiO_2, Al_2O_3, TiO , total Fe as Fe_2O_3, MnO, CaO and K_2O, were obtained using a borax-La_2O_3-fusion technique similar to that described by Rose, Adler and Flanagan (1963). These analyses were carried out by the writer except where otherwise noted. Na_2O and MgO could not be determined satisfactorily with the available equipment, and were determined by A. K. Baird, using the "soft" X-ray apparatus developed at Pomona and described by Henke (1963) and Baird, McIntyre and Welday (1963).

In addition, determinations of ferric and ferrous iron were made by wet chemical means (Analyst, D. Maynes) in four of the samples otherwise analysed by X-ray fluorescence to permit the recalculation of modes according to the observed mineralogy.

The three wet chemical total rock analyses are reported in Table 2. Fourteen partial X-ray fluorescence analyses, with the additional data on ferric and ferrous iron are given in Table 3, along with data from the three standards, for convenience. In this table recalculated or estimated modes are given for each sample, and the ratios Na_2O/K_2O (wt. percent) and $Mg/Mg + Fe^{++}$ (cation percent) are tabulated. Estimates for each oxide of the analytical error in the X-ray fluorescence analyses are also given. These are generally low, except for the light elements Si and Al and for those present in amounts less than 1% (MnO and TiO_2). The locations of the samples are given in the appendix.

Table 2. Wet Chemical Analyses of Metagreywacke

	X 4	X 16	G 14
SiO_2	62.05	58.10	66.92
TiO_2	0.69	0.67	0.59
Al_2O_3	16.43	13.21	14.94
Fe_2O_3	0.99	1.97	0.55
FeO	5.59	4.92	4.91
MnO	0.07	0.13	0.07
CaO	2.21	7.60	2.46
MgO	3.64	6.85	2.87
Na_2O	3.52	2.29	2.92
K_2O	2.69	1.62	2.27
H_2O^+	1.78	1.83	1.07
H_2O^-	0.06	0.16	0.05
P_2O_5	0.18	0.39	0.14
Total Fe as Fe_2O_3	7.20	7.44	6.01
S	0.11	0.01	0.15
Correction O for S	-.05	---	-.07
Total	99.96	99.75	99.84

Analyst: A. D. Maynes

Table 3. Partial Chemical Analyses and Modal Analyses of Metagreywacke and Schist.

SUPERIOR PROVINCE

	X3	X4**	X6	X12	G135	X5*	121*	Ave. gw.⊖
SiO_2	63.8	62.1	62.9	58.3	57.0	59.0	58.2	63.5
TiO_2	0.65	0.69	0.58	0.90	1.15	0.66	0.70	0.70
Al_2O_3	13.2	16.4	16.5	17.0	14.2	18.5	19.0	17.8
**Fe_2O_3	1.0	0.99	0.73	ND	3.27	ND	ND	ND
**FeO	4.68	5.59	5.44	ND	9.46	ND	ND	ND
Total Fe as Fe_2O_3	6.20	7.20	6.77	9.19	13.78	7.90	8.26	7.40
MnO	0.06	0.07	0.03	0.13	0.41	0.08	0.08	0.07
CaO	3.00	2.21	2.38	1.89	7.39	1.00	1.37	2.31
Φ MgO	3.63	3.64	3.22	4.18	2.40	ND	ND	3.85
Φ Na_2O	3.28	3.52	3.80	2.55	0.76	ND	ND	2.74
K_2O	1.90	2.69	2.22	2.60	2.60	4.37	4.31	2.80
Na_2O/K_2O	1.7	1.3	1.7	1.0	0.3			1.0
$Mg/Fe''+Mg$	0.58	0.54	0.51		0.31			
Quartz	29 c	25 c	26 c	35 e	30 c	25 e	25 e	
Plagioclase	45	44	47	35	8.5	25	20	
Biotite	17.4	23	21.4	8	24	21	15	
White mica		2.8	T	5		18	15	
Chlorite	1.2	4.4	4.2	8		8	25	
Amphibole	5				7.5			
Epidote	T	T	T	1	25		T	
Magnetite	2.4	T	T	2	2.8	T	T	
Sphene	T		T	T	0.9	T	T	
Apatite	T	T		T		T	T	
Zircon	T	T	T			T		
Tourmaline	T	T		T		T	T	
Garnet								
Staurolite								
Microcline								
An% (Plag)	28	26	26		18	25	28	

GRENVILLE PROVINCE

	X16**	X18	116	157	X20	X23	G14**	193	223	Est.✝ Error
SiO_2	58.1	54.4	55.2	64.0	63.2	61.2	66.9	52.1	63.8	± 1.2
TiO_2	0.67	0.86	0.66	0.61	0.68	0.74	0.59	0.95	0.58	± 0.07
Al_2O_3	13.2	17.7	17.1	15.7	16.8	16.4	14.9	12.7	16.4	± 0.7
**Fe_2O_3	1.97	ND	ND	ND	ND	2.15	0.55	ND	ND	
**FeO	4.92	ND	ND	ND	ND	4.14	4.91	ND	ND	
Total Fe as Fe_2O_3	7.44	10.39	7.73	4.43	6.48	6.75	6.01	11.74	5.65	± 0.1
MnO	0.13	0.17	0.09	0.02	0.04	0.07	0.07	0.31	0.06	± 0.03
CaO	7.60	1.53	1.32	2.40	2.91	4.09	2.46	9.68	2.26	± 0.04
Φ MgO	6.85	4.62	3.87	2.94	3.17	2.90	2.87	3.07	2.75	± 0.1
Φ Na_2O	2.29	3.48	2.43	3.68	3.68	3.27	2.92	3.35	3.75	± 0.1
K_2O	1.62	5.26	4.79	2.13	3.04	3.16	2.27	1.38	2.95	± 0.1
Na_2O/K_2O	1.4	0.7	0.5	1.7	1.2	1.0	1.3	2.4	1.3	
$Mg/Fe''+Mg$	0.72					0.56	0.51			
Quartz	16 c	25 e	30 e	29 e	20 e	26 c	35 c	15 e	40 e	
Plagioclase	34	35	27	38	44	40	39	25	32	
Biotite	15	35	30	25	34	24	22	13	25	
White mica		1	12						1	
Chlorite		T								
Amphibole	27							40		
Epidote	4.7	T		1	1	6.5		7	T	
Magnetite	T	T	T	1	T		T	T	T	
Sphene	1.5	T		T		1.5		T	T	
Apatite	T	T	T	T	T		T	T	T	
Zircon		T	T		T		T		T	
Tourmaline										
Garnet							2			
Staurolite							1			
Microcline				6						
An% (Plag)	38	26	20	29	29	25	31	31	22	

All samples analysed by X-ray fluorescence by J. A. Grant, except:

** Wet chemical analyses (Analyst A. D. Maynes)

* X-ray fluorescence analyses (Analyst A. A. Chodos)

Φ X-ray fluorescence analyses (Analyst A. K. Baird) except for X4, X16, G14

✝ Estimated analytical error (%) for X-ray fluorescence analyses.

⊖ Composite of 44 samples.

ND Not determined.

c Calculated modes supplimented by observed mineralogy.

e Estimated modes.

Sample locations are given in the appendix.

In Fig. 10 the analyses of samples from north and south of the Front are compared. In each diagram metagreywacke from the Superior province is in the left hand column and the schist from the Grenville province in the right hand column. For convenience, the data for the composite sample from the metagreywacke north of the Front are represented by a cross in each diagram to the left of the left hand column.

There are no significant differences in the compositional ranges of the metagreywacke from the Superior province and the schist from the Grenville province. This implies that there is no major change in chemical composition across the Front in the metasedimentary unit, and supports the correlation of metagreywacke and schist. It also suggests that the metamorphism was indeed isochemical.

In the case of each oxide except Al_2O_3, the analysis of the composite sample falls well within the ranges both north and south of the Front. This, of course, may reflect incomplete sampling south of the Front, but this is not apparent with respect to the other oxides. It is possible that the apparently lower content of Al_2O_3 in the schist is real and reflected in the relatively rare occurrence of white mica in the schist south of the Front compared with the metagreywacke north of the Front, in the disappearance of chlorite south of the Front and the slight increase in the abundance of biotite south of the Front (see p. 98).

The Na_2O/K_2O ratios from the metagreywacke and schist are compared in Fig. 11a with data from paragneisses from the Grenville province outside the Lake Timagami area (after Engel, 1956, p. 85). The spectrum

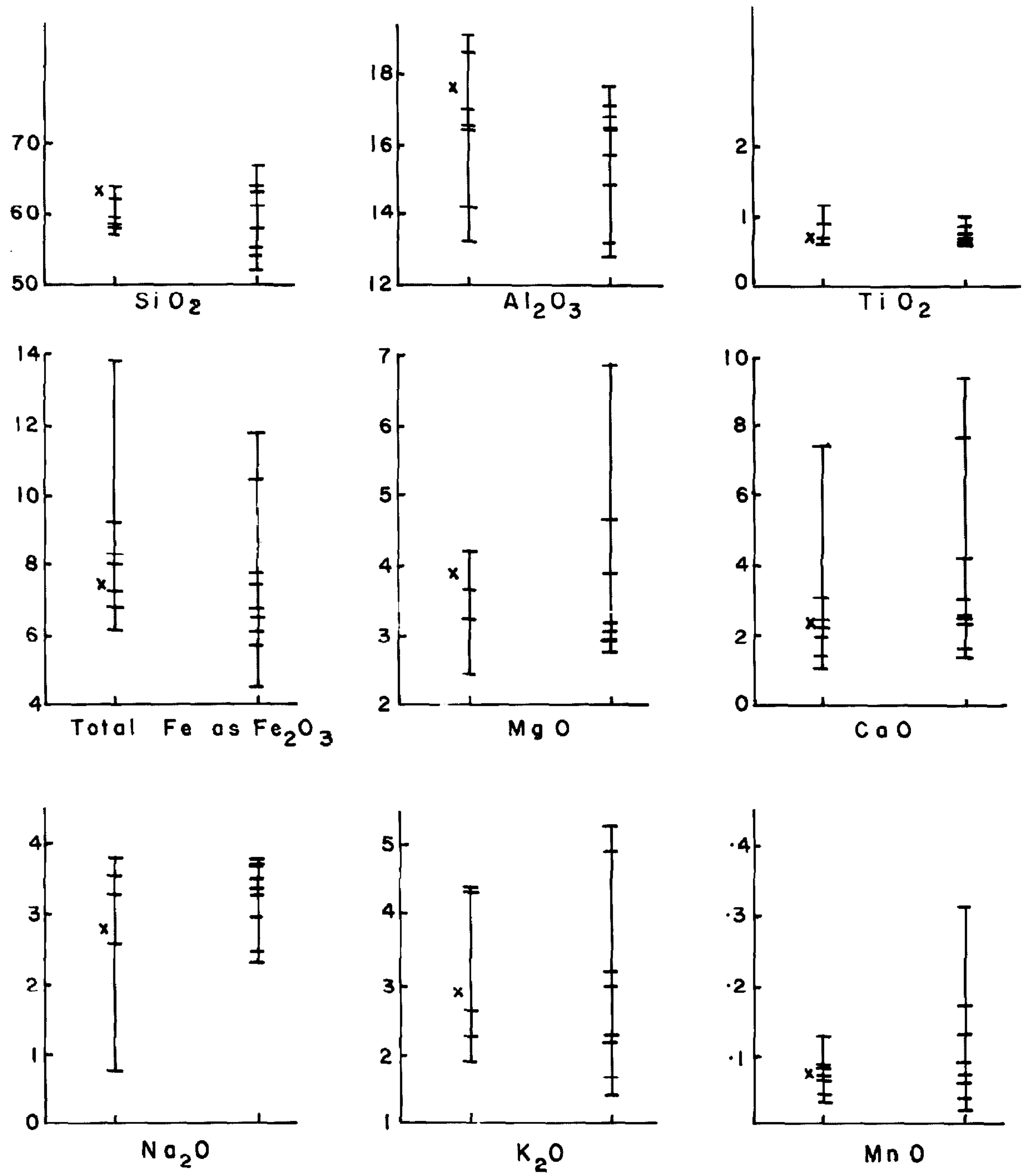


Fig. 10. Comparison of the chemical composition of metagreywacke from the Superior province (left hand column) with that of schist from the Grenville province (right hand column).

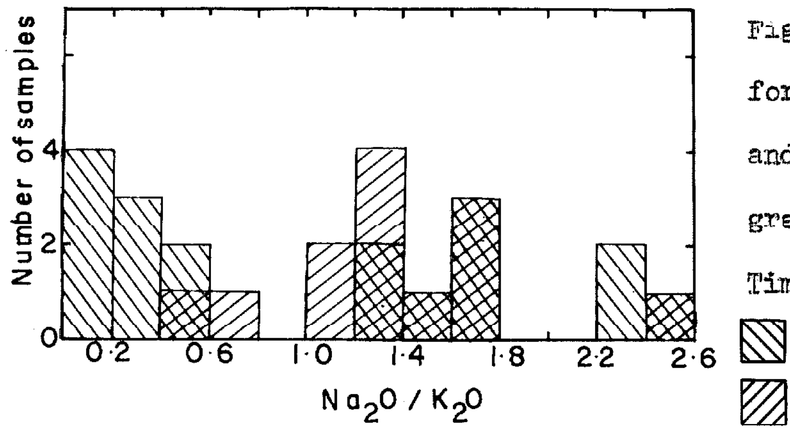


Fig. 11a. Na_2O/K_2O ratios for Grenville paragneiss and for schist and meta-greywacke from the Lake Timagami area.

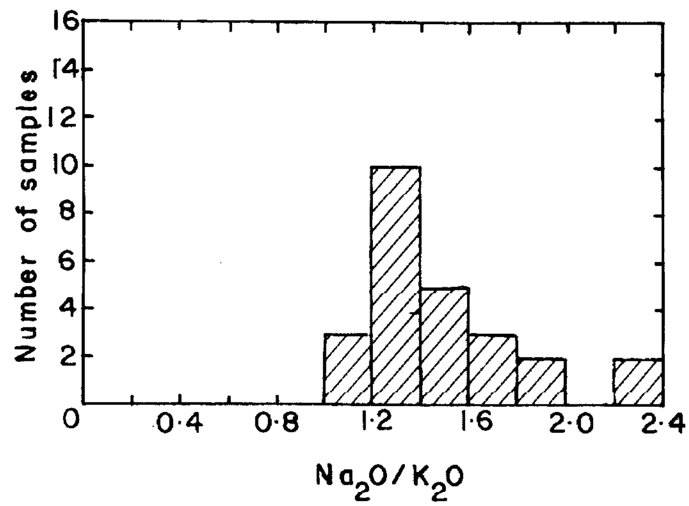


Fig. 11b. Na_2O/K_2O ratios for 25 Precambrian greywackes.

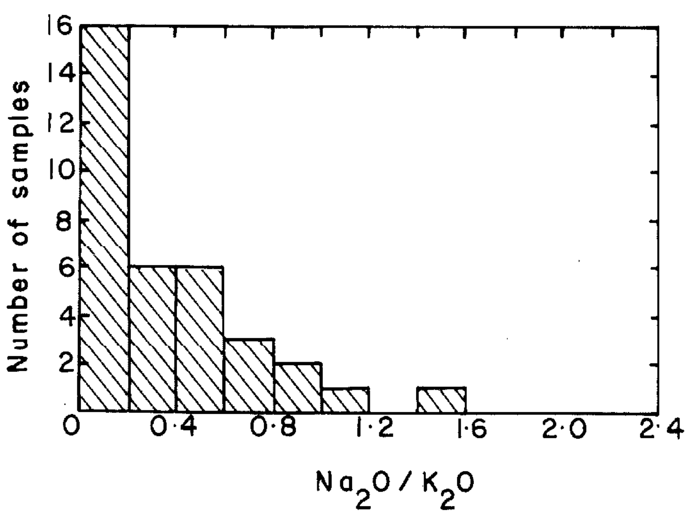


Fig. 11c. Na_2O/K_2O ratios for 35 Precambrian slates.

of Na_2O/K_2O ratios is similar to that in the Grenville paragneisses, except that a markedly lesser proportion of the samples from the present area have values less than unity. These data may also be compared with Na_2O/K_2O ratios for Precambrian greywackes (Fig. 11b, Engel, 1956, p. 84) and slates (Fig. 11c, Nanz, 1953, p. 53-55). The majority of the samples from the Lake Timagami area have ratios similar to those common in Precambrian greywackes rather than in Precambrian slates, as would be predicted from the field observation that these rocks are indeed metagreywacke.

These data show that there is no major difference in the chemical composition of the metasedimentary rocks on either side of the Front in this area, and that the correlation of metagreywacke of the Superior province and schist of the Grenville province is permissible. However, the lack of a major difference in chemical composition does not prove the correlation across the Front. To prove this it is necessary to apply the more rigorous test of a Rb-Sr isochron study.

Chapter 5

Rb-Sr ISOCHRON STUDY

It has been shown in the preceeding chapters that later metamorphism is superimposed on pre-Huronian metamorphism, resulting in the development of a migmatitic terrane with lithologies, grade and structures typical of the northwestern portion of the Grenville province. Apparently Keewatin-type metagreywacke, pre-Algoman quartz diorite and Algoman granite of the Superior province were the major protoliths of this terrane, which is tentatively referred to the Grenville province. In particular, it is implied that within the Grenville province there are granitic plutons which might well be considered to be primary Grenville granites, but which are, in fact, older than this age by a factor of two.

However, the correlations are based on factors such as lithology which do not yield unequivocal evidence, and the assignment of the later metamorphism to the Grenville is not axiomatic. Such problems of polymetamorphism may be amenable to Rb-Sr whole rock and mineral isochron studies. This has been suggested by the work of Compston and Jeffrey (1959), in western Australia, and Fairbairn, Hurley and Pinson (1961) at Sudbury, Ontario. The possibilities of this approach have been studied in detail by Lanphere, Wasserburg, Albee and Tilton (1963) working in the Panamint Range, California. They show that from whole rock studies it may be possible to determine the age of the initial strontium isotopic equilibration of a suite of co-genetic rocks, and from mineral isochron data, the age of the last equilibration.

The theory and assumptions underlying the interpretation of Rb-Sr isotopic relationships have been discussed in detail by Lanphere, et al. (1963) using the Sr-evolution diagram of Nicolaysen (1961).

For a system closed to Rb and Sr one may write the age equation in the form

$$(Sr^{87}/Sr^{86})_t = (Sr^{87}/Sr^{86})_o + (Rb^{87}/Sr^{86}) \quad (e^{\lambda t} - 1).$$

All such co-eval systems, be they whole rocks or minerals, with the same $(Sr^{87}/Sr^{86})_o$ and differing (Rb^{87}/Sr^{86}) will define on a strontium evolution diagram a straight line (isochron) whose slope is a function of the time since the initial isotopic equilibration of strontium throughout the systems.

If, during subsequent metamorphism(s) of a rock, equilibration is attained and subsequent to the last equilibration the minerals have remained closed, then the mineral isochron will define the time of this last equilibration. If, in addition, the whole rock has remained closed throughout and its original $(Sr^{87}/Sr^{86})_o$ is known then the age since the original equilibration may be determined.

In order to test the tentative correlations in the Lake Timagami area and assignment of a Grenville age to the later metamorphism, four granites from north of the Front (Y1), just south of the Front (Y13, Y14), and in the extreme south of the area (Y15), and a schist adjacent to the southernmost granite (X23) have been submitted to a Rb-Sr isochron study. (The locations of these samples are shown on Plate 1.) If the correlation of the granites is correct and they satisfied the assumptions of closure and original homogeneous strontium isotopic composition, they should define a whole rock isochron whose slope defines the age of the original equilibration at a value of $(Sr^{87}/Sr^{86})_o$ given by the intercept at $Rb^{87}/Sr^{86} = 0$. If the assignment of a Grenville age to the last metamorphism is correct and the requisite assumptions satisfied, mineral isochrons from the schist and southernmost granite should be parallel, both defining a Grenville age of the last equilibration. The mineral isochron from the northernmost granite may lie anywhere between the whole rock isochron and the "Grenville" isochron depending on to what extent it was affected by the Grenville or preceeding metamorphisms.

Results

The analytical results are given in Table 4. All strontium data are normalized to (Sr^{86}/Sr^{88})normal = 0.1194. Other constants used are (Sr^{84}/Sr^{88})normal = 0.0067476, (Rb^{85}/Rb^{87})normal = 2.591. The value of 0.139×10^{-10} years^{-1} is taken as the decay constant of Rb^{87}. Errors in Sr^{87}/Sr^{86} from composition runs is less than $\pm 0.2\%$, the errors in the same ratio calculated from concentration runs is less than $\pm 0.3\%$. The error in Rb^{87}/Sr^{86} is larger due to the unknown discrimination in rubidium runs and in the calibration of the Rb^{87} spike, but less than $\pm 1\%$. An important source of error not included in the above estimates is in the splitting of a sample. In mineral isochron studies where the isochron is a well defined line this may not be vitally important. However, in whole rock isochron work where the whole rock isochron does not coincide with the mineral isochrons, it is imperative to obtain

Table 4. Rb-Sr Analytical Data

	Sr^{87} ($x10^{-6}$ moles/gm)	Rb^{87} ($x10^{-6}$ moles/gm)	$\frac{Sr^{87}}{Sr^{86}}$(comp)*	$\frac{Sr^{87}}{Sr^{86}}$(calc)**	$\frac{Rb^{87}}{Sr^{86}}$
Y1W1	0.066680	0.8621		1.1828	15.293
Y1W2	0.067148	0.8760		1.1850	15.460
Y13W1	0.12681	0.8865		0.9263	6.4754
Y13W2	0.13407	0.9002		0.9218	6.1897
Y14W	0.29370	0.5157	0.7456	0.7453	1.3087
Y15W1	0.63711	0.5360	0.7208	0.7219	0.6064
Y15W2	0.59090	0.4590	0.7207	0.7195	0.5598
Y1A	0.16014	0.01786	0.7805	0.7814	0.0872
Y1P	0.033985	0.09928		0.9748	2.8476
Y1Mi	0.074111	2.235		1.7696	53.362
Y1B	0.11430	5.142		6.2763	282.34
Y15A	0.48594	0.002822	0.7138	0.7141	0.0041
Y15P	0.52764	0.09574	0.7130	0.7150	0.1294
Y15Mi	0.73027	0.9032	0.7260	0.7272	0.8994
Y15Mu	0.29028	1.186		0.7541	3.0811
Y15B	0.72847	2.735	1.3824	1.3789	51.899
X23W	0.42998	0.4355		0.7284	0.7378
X23E	1.2817	0.008001	0.7146	0.7158	0.0045
X23P	0.50033	0.02549		0.7202	0.3669
X23B	0.028555	1.498		2.3278	122.13

* From unspiked aliquot
** From spiked aliquot

good splits of a representative sample, and to check the quality of splitting three samples were run in duplicate.

The whole rock data for the four granites are shown in Fig. 12. These data approximately define an isochron, and are considered proof that the granites conformed closely to the postulates that at one time they had the same strontium isotopic composition, and that since then they have remained as closed systems. A least squares analysis of the four sets of data yield an age of 2,220 m.y. and an initial Sr^{87}/Sr^{86} value of 0.709. However, this requires further comment. The data for Y1, Y14 and Y15 all lie on a straight line isochron within experimental error, but the data for Y13 deviate from this line. Both Y13 and Y14 come from the Sinton Lake Granite, and are therefore considered comagmatic. However, the apparent initial Sr^{87}/Sr^{86} derived from these two samples is 0.698 ± 0.003, which is similar to values obtained for achondrites by Gast (1962) and Hedge and Walthall (1963). This strongly suggests that either (a) Y13 and Y14 did not have the same initial (Sr^{87}/Sr^{86}) or (b) Y13 or Y14 did not remain closed to Sr and Rb subsequent to their formation or (c) Y13 or Y14 is not a representative sample. Because (a) Y13 and Y14 are both from the same pluton, (b) Y13 comes from the margin of the pluton and (c) Y14 lies on the Y1-Y15 join, it is considered that Y13 is indeed the deviate, possibly because it did not satisfy the requirement of closure.

The isochron from the three granites, Y1, Y14 and Y15, yields an age of 2,220 m.y. ± 70 m.y. (the same as that derived from the least squares analysis of all four granites) and an initial Sr^{87}/Sr^{86} of

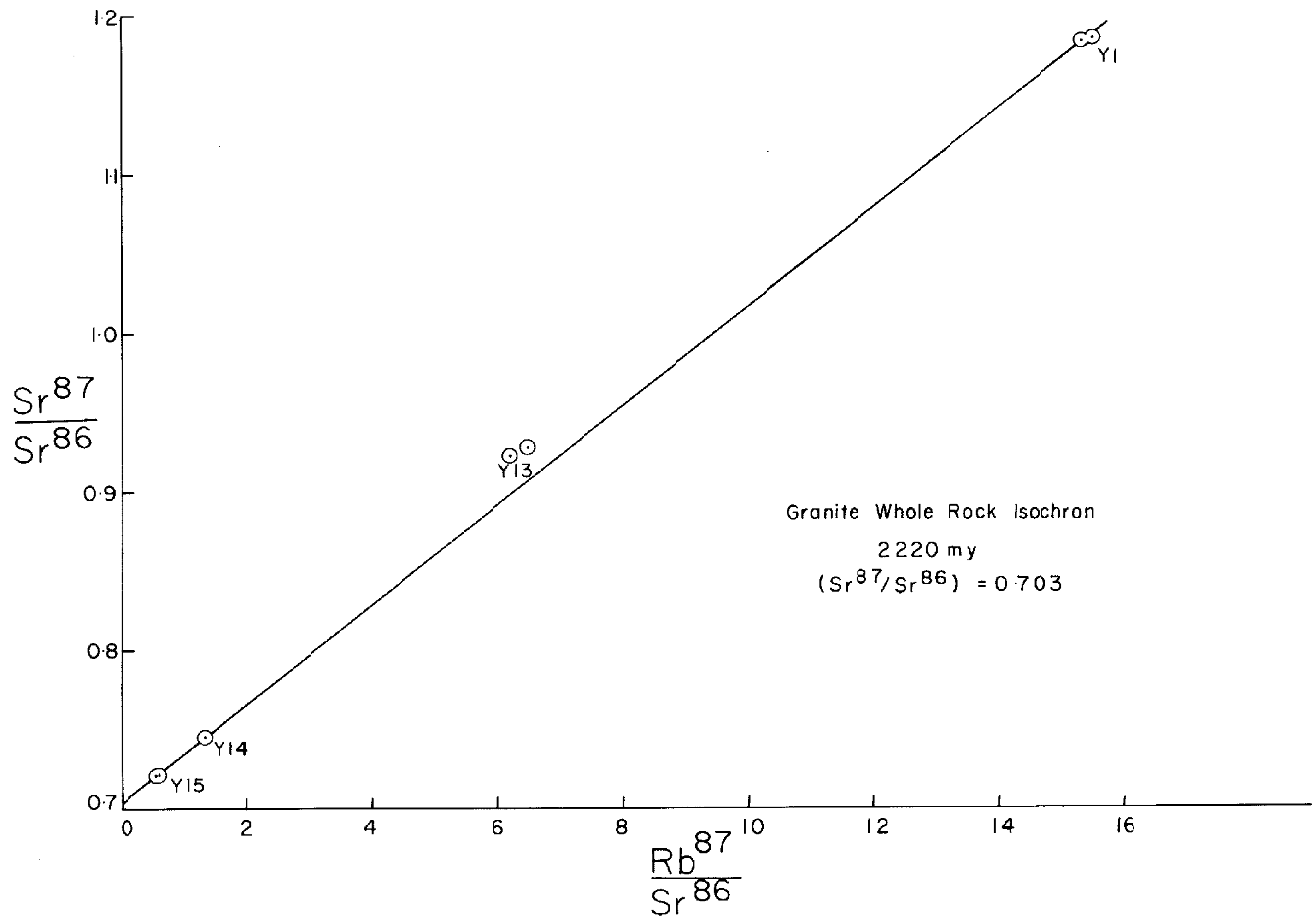


Fig. 12. Strontium Evolution Diagram for Granite Whole Rock Samples.

0.703 ± 0.001.

The interpretation of these data is that the three granites from north and south of the Front were comagmatic intrusions with an age of 2,220 m.y. ± 70 m.y., and an initial ratio Sr^{87}/Sr^{86} of 0.703 ± 0.001, proving the tentative correlation of the granites.

The mineral isochron from the southernmost granite (Y15) is shown in Fig. 13. Five minerals, apatite, plagioclase, microcline, white mica and biotite have been analysed and the corresponding five points and the two whole rock points all lie within analytical error on an isochron. The slope of this isochron yields an age of 920 m.y., and an intercept at $Rb^{87}/Sr^{86} = 0$ of $(Sr^{87}/Sr^{86})_o = 0.713$.

Epidote, plagioclase and biotite from the schist (X23) adjacent to Y15 were analysed as well as a whole rock split. These results are also shown in Fig. 13. Plagioclase and epidote lie respectively above and below the whole rock - biotite isochron close to $Rb^{87}/Sr^{86} = 0$, the departure of the epidote being well outside experimental error, suggesting incomplete equilibration. However, the biotite - whole rock isochron yields an age of 940 m.y., in close agreement with the value of 920 m.y. obtained from Y15.

These results confirm virtually complete equilibration of strontium within the granite (Y15) and approximate equilibration within the schist (X23) at 920-940 m.y., that is, during Grenville metamorphism. The intercept of the biotite - whole rock isochron for the schist is $(Sr^{87}/Sr^{86})_o = 0.719$ and this is different from the value of 0.713 obtained from the granite (Y15). From this it may be inferred that while the

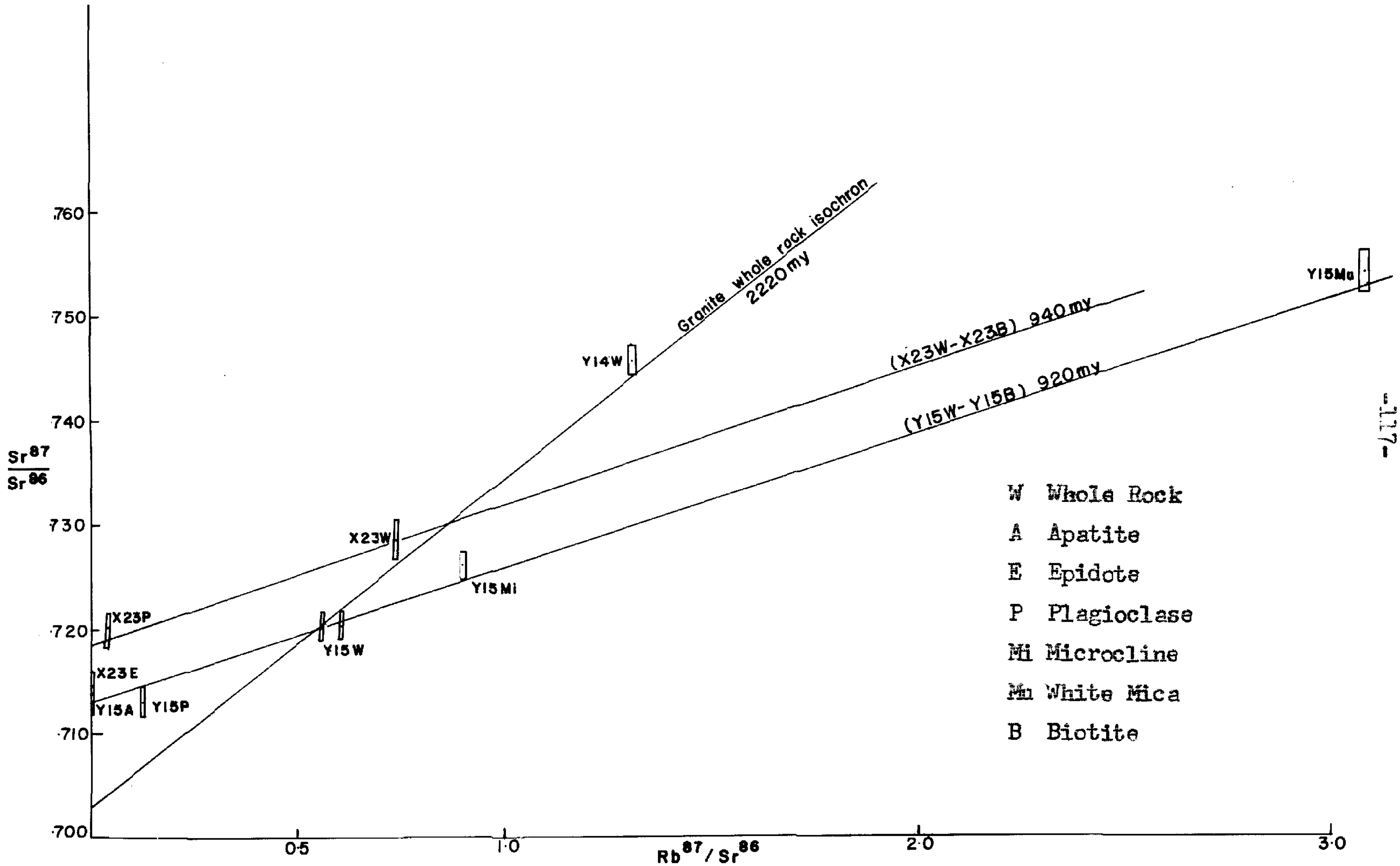


Fig. 13. Strontium Evolution Diagram for Granite (Y15) and Schist (X23) from Grenville Province.

schist and granite individually came to almost complete equilibration of strontium at the same time, this equilibration did not extend over the half mile that separates the two samples, despite the fact that the metamorphism here was to the amphibolite facies.

The determination of an age of the schist requires that (a) the corresponding $(Sr^{87}/Sr^{86})_o$ is known and (b) the whole rock sample has subsequently remained closed to rubidium and strontium. It is not possible to obtain $(Sr^{87}/Sr^{86})_o$ or to prove closure from the single sample analysed. Assuming the requirement of closure, however, one can bracket the age of deposition of the original sediment. A reasonable minimum for the original $(Sr^{87}/Sr^{86})_o$ in this sediment is 0.700. This yields a maximum age of 2.7 b.y. From geological evidence, the schist is older than the granite and therefore has a minimum age of 2220 m.y. ±70 m.y. Thus the deposition of the sediment (and any pre-Algoman metamorphism) probably occurred in the period from 2.7 to 2.2 b.y.

The granite Y1, at the upper extremity of the whole rock isochron, is also the northernmost granite studied. Apatite, plagioclase, microcline and biotite from this rock were analysed and the results are shown in Fig. 14. The minerals do not form as precise an isochron as those of Y15, plagioclase lying above the biotite - whole rock join, apatite and microcline below. The age derived from the biotite - whole rock join is 1360 m.y., those from the plagioclase - whole rock join and the microcline - whole rock join are 1206 m.y. and 1100 m.y. respectively. The average of these apparent ages is 1222 m.y., the average intercept at $Rb^{87}/Sr^{86} = 0$ is $(Sr^{87}/Sr^{86})_o = 0.92 \pm .03$.

These data suggest that granite Y1 suffered approximate

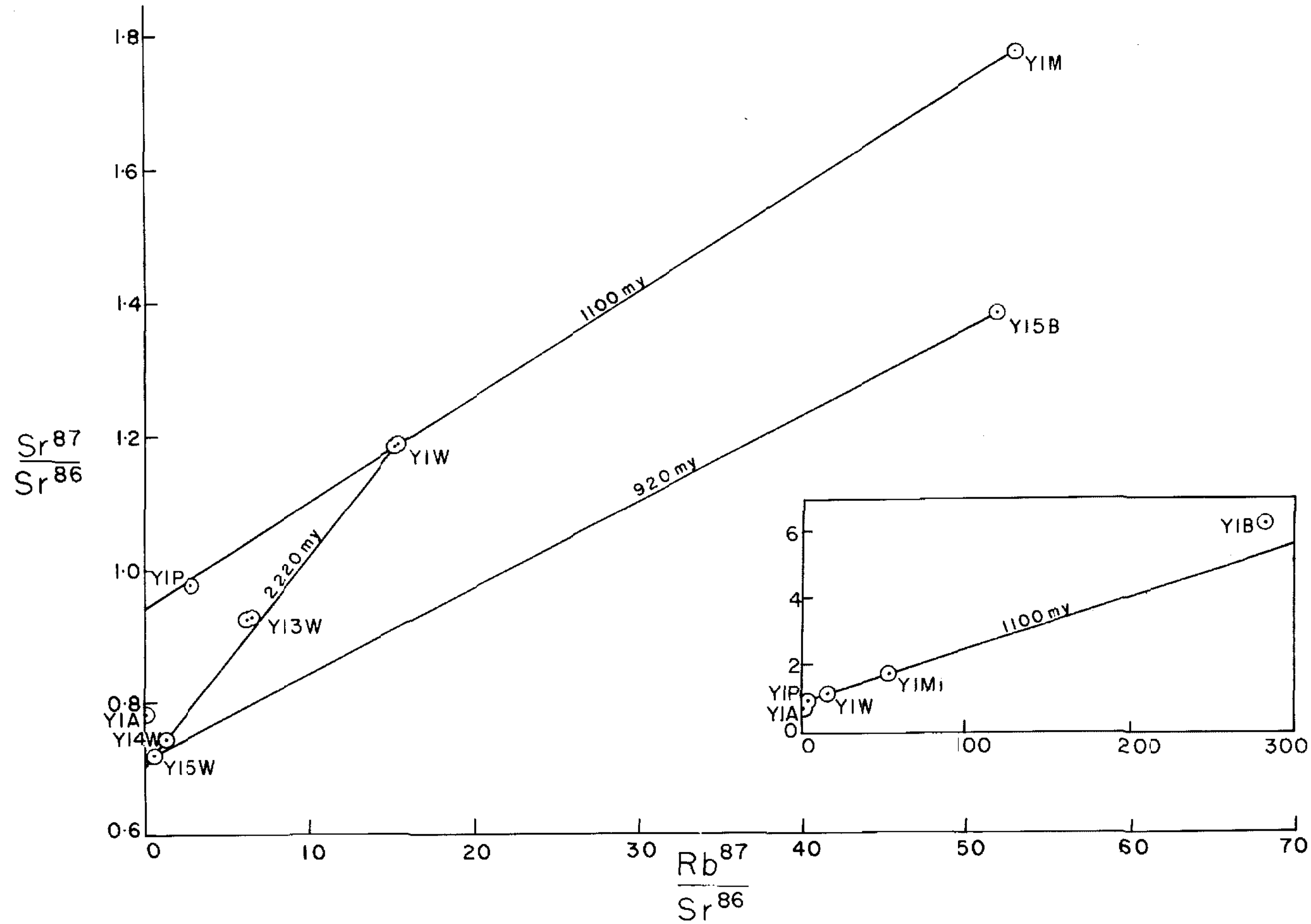


Fig. 14. Summary Strontium Evolution Diagram for Granites, Inset shows complete mineral data for the Vogt Granite (Y1).

re-equilibration of strontium at about 1222 m.y., which is within the age limits of Grenville metamorphism. However, it is useful to examine the "isochron" more closely. The spread of the mineral points around the whole rock point may be due to some or all of the minerals having been open to some extent during the evolution of the rock after the last equilibration. From the whole rock diagram the inference was that the rock itself remained essentially closed and there is no evidence to support the hypothesis of partial opening of the minerals since Grenville times. No such opening is indicated by the isochron of Y15. It is much more plausible, and indeed to be expected, that Y1 did not attain complete re-equilibration during this last (Grenville) episode, for the granite and the surrounding rocks show comparatively little evidence of the late metamorphism. If this is the case then at the time of the approximate equilibration, minerals to the left of the whole rock (plagioclase and apatite) and those to the right (microcline and biotite) would approach the new zero isochron from below and above respectively. If the system were "quenched" prior to complete equilibration and if the equilibration paths did not cross the "zero isochron" or the whole rock isochron, then all mineral - whole rock "isochrons" would give ages higher than the true age. Thus the minimum age of 1100 m.y., derived from the microcline - whole rock join of Y1, is probably a maximum for the true age of this last event. The inference then is that this granite approached closely to strontium isotopic equilibration at $(Sr^{87}/Sr^{86}) \geq 0.947$ during Grenville metamorphism, at a time less than 1100 m.y. ago.

Comparing these results with those of other workers one can immediately say that the results for "Grenville metamorphism", 920-1100 m.y. are in agreement with a host of data from several independent methods (see discussion in Lepp, Goldich and Kistler, 1963, p. 703-706). The value of 920 m.y. is considered to be well defined. The figure of 1100 m.y. is intermediate between 920 m.y. and 2220 m.y. and suggests incomplete resetting of the Rb-Sr clock during Grenville metamorphism. Of course, it is possible that the mineral isochron of Y1 represents a true age, that of an early cessation of Grenville metamorphism (as it affected Rb and Sr) north of the Front. These two possibilities are also noted by Snelling (1962), Lepp, et al. (1963) and Quirke, Goldich and Krueger (1960). Snelling, using the K-Ar technique on micas in the Val d'Or area, also found an intermediate apparent age (1695 m.y.) between samples north and south of the Front yielding 2205 m.y. and 950 m.y. respectively. Lepp, et al. (1963) discuss a traverse across the Grenville subprovince south of the Labrador Trough. They report K-Ar ages of 860-990 m.y. and Rb-Sr ages (on micas and feldspar) from 860 m.y. to 1140 m.y., all within the Grenville subprovince. In addition Quirke, et al. (1960) report K-Ar ages from the Grenville subprovince, from the Mt. Reed and Mistassini areas, of 890-1000 m.y. and Rb-Sr ages of 860-1060 m.y. They also report a K-Ar age of 1610 m.y. and Rb-Sr age of 1670 m.y. from the Takwa complex north of the Front.

The 1600-1700 m.y. ages in the Val d'Or and Mistassini areas may reflect a metamorphism of that age, comparable to that reported from Sudbury (Fairbairn, et al., 1961), Blind River (Van Schmus, et al., 1963), Lake Superior (Goldich, et al., 1961) or from the eastern Labrador Trough (e.g. Lowdon, Stockwell, Tipper and Wanless, 1963). Stockwell (in Lowdon, et al., 1963) discusses several intermediate K-Ar biotite ages found in the vicinity of the Front by the Geological Survey of Canada, but attributes them to migration of argon, because where coexisting muscovite has been analysed it yields normal Grenville ages. Moreover, neither in the work of Lepp, et al. (1963), nor in the present Rb-Sr study, is there any evidence of a 1600-1700 m.y. orogeny, nor does Snelling (1962, p. 16) favor the possibility in the Val d'Or area. Indeed, in any area affected by a later re-equilibration such as the Grenville, one would not expect an earlier re-equilibration to be demonstrable.

The age derived from the granite-whole rock isochron is 2220 m.y. ± 70 m.y. This is similar to the K-Ar date of 2205 m.y. (Snelling, 1962) for biotite from quartz syenite less than five miles to the north of Grenville gneisses. Both values are within, but at the lower end of, the spectrum of K-Ar dates on micas reported from the Timiskaming subprovince by Lowdon, et al. (1963). The significance of this with respect to earlier events is not yet clear. In the area studied by Snelling (1962), the Precambrian rocks occur in three easterly trending belts: to the north lies a group of volcanic rocks (Abitibi) metamorphosed to the albite-epidote-amphibolite facies, to the south lie interbedded mica schist and volcanic rocks of somewhat higher grade (Pontiac Group), and between these and overlying them unconformably there is a synclinorium of conglomerate and greywacke (Timiskaming). The Pontiac Group is intruded by granite which is a major component of the belt of banded gneiss and granite separating the Pontiac Group from the Grenville province. Snelling's work (1962) indicates a minimum age of 2635 m.y. for the Preissac-Lacorne batholith and for the metamorphism of the Abitibi Group which it intrudes. He states (1962, p. 13) that "the apparent ages indicate that regional metamorphism of the Pontiac schist (GSC 59-77) occurred 2460 million years ago and intrusion of granitic rocks (GSC 59-78) about 2285 million years ago." As he notes, however, these dates are from only two determinations by the same method (K-Ar), and therefore, the two events cannot be considered well defined. The age of granitic emplacement in the Lake Timagami area is in agreement with the values of 2205-2285 m.y. determined by Snelling, and the time limits on the age of deposition of the Keewatin-type rocks in the Lake Timagami area (2.7 - 2.2 b.y., see p. 118) are compatible with his evidence of the metamorphism of the Keewatin-type Abitibi and Pontiac Groups.

The age of 2220 m.y. obtained for the Vogt granite (Y1) is important with respect to the maximum age of the Huronian System. From the evidence in this area (Grant, 1964) and in the area to the northeast (Johnston, 1954), the granites are pre-Gowganda in age. The Gowganda Formation is intruded by Nipissing diabase. A biotite K-Ar determination for similar diabase at Cobalt is 2095 m.y. (Lowdon, et al., 1963, p. 92) and an Rb-Sr study of similar diabase in the Blind River area (Van Schmus, et al., 1963) yield a minimum age of 1755 m.y. ± 100 m.y. and a probable age of 2170 m.y. ± 200 m.y. These results suggest that deposition of the Gowganda must have taken place between 2220 m.y. ± 70 m.y. and 1755 m.y. ± 100 m.y., probable between 2300 m.y. and 2100 m.y.

Conclusions

(a) Three granite plutons (north of the Front, just south of the Front and four miles south of the Front) were tentatively correlated as Algoman granite, although the southernmost granite has the characteristic structure and texture of the northwestern part of the Grenville province. Three samples, one from each of the plutons, define a whole rock isochron within experimental error and this is considered to confirm that these rocks have conformed to the postulates of strontium isotopic equilibration and subsequent closure. An additional sample from the margin of the second (Sinton Lake) pluton, lies slightly to the left of this isochron and is anomalous probably because it did not meet the requirement of closure after equilibration. The age calculated from the whole rock isochron is 2220 m.y. ± 70 m.y. and the initial value of $(Sr^{87}/Sr^{86})_o = 0.703 \pm 0.001$. This age is not altered by inclusion of the supposedly anomalous sample. This is considered to confirm the correlation of these granites as co-magmatic intrusions, and the determination on the northernmost granite in particular (Vogt Granite) provides a new maximum limit (approximately 2300 m.y.) to the time of deposition of the Gowganda Formation.

(b) The mineral isochron of the southernmost granite shows complete strontium isotopic equilibration of the several minerals within experimental error at $(Sr^{87}/Sr^{86})_o = 0.703 \pm 0.001$. The age of this equilibration is 920 m.y. An adjacent schist shows almost complete equilibration of its constituent minerals at $(Sr^{87}/Sr^{86})_o = 0.719 \pm 0.002$. The corresponding age of equilibration is 940 m.y. The minerals of the northernmost granite (Vogt Granite) show incomplete equilibration. The biotite-, plagioclase-, and microcline-whole rock joins yield apparent ages of 1360 m.y., 1200 m.y. and 1100 m.y. respectively. These are all within the broad limits of Grenville metamorphism, but it is probable that the youngest apparent age (1100 m.y.) represents a maximum age for the partial equilibration and the corresponding value of $(Sr^{87}/Sr^{86})_o$ is 0.947.

(c) These data are considered to confirm that rocks of the Superior province, with primary ages of over 2 b.y. have been cannibalized by the Grenville metamorphism at approximately 1 b.y. In particular, this is proved beyond all reasonable doubt by the whole rock and mineral analyses of the Vogt Granite by virtue of its high values of (Sr^{87}/Sr^{86}) and (Rb^{87}/Sr^{86}), which minimize the effects of uncertainties in the initial $(Sr^{87}/Sr^{86})_o$.

The value of 2220 m.y. ± 70 m.y. is the oldest primary age yet obtained for rocks proved to have suffered Grenville metamorphism by almost a factor of two.

(d) This study provides strong support for the hypothesis that strontium isotopic equilibration is not a local phenomenon but a widespread accompaniment of metamorphism and provides a most sensitive approach to problems of polymetamorphism.

Chapter 6

CONCLUSIONS

The major conclusion from field, petrographic and chemical studies is that rocks of the Superior province were subjected to the Grenville orogeny, and can be traced into the Grenville province. Pre-Huronian "Buchan" metamorphism of Keewatin-type rocks pre-dated, but was probably associated with, the emplacement of Algoman granite. Later metamorphism affected the Algoman and older rocks and probably the Huronian sediments and Nipissing diabase. In the south of the Lake Timagami area this metamorphism gave rise to lithologies, metamorphic grade, and structures typical of the northwestern part of the Grenville province, and for these reasons the late metamorphism was considered to be of Grenville age.

The tentative correlations from the Superior province into the Grenville province, and the Grenville age of the later metamorphism cannot be conclusively proved by classical methods. However, a Rb-Sr whole rock and mineral isochron study provides convincing evidence that these tentative conclusions are correct. The conclusions from this study are as follows:

(a) Granites from north of the Front, just south of the Front and four miles south of the Front, forming a suite from granite "typical" of the Superior province to granite "typical" of the Grenville province, define a whole rock isochron, convincing evidence that those were indeed comagmatic granites and that the correlation of these granites across the Front is correct. The age derived from this isochron is 2200 m.y. ± 70 m.y. (The constants used in the age calculations are given on p.112, and uncertainties in these are not included in the estimated possible errors.)

(b) Mineral isochrons from the southernmost granite (Y15 - see Plate 1 for locations of samples) and an adjacent schist (X23) show almost complete strontium isotopic equilibration within the individual samples and are virtually parallel, yielding an age of 930 m.y. ± 15 m.y. for the equilibration. Analyses of the minerals from the northernmost granite (Y1) show partial equilibration, with a probable maximum age of 1100 m.y. for the event.

These data prove virtually complete strontium isotopic equilibration in individual samples south of the Front and partial equilibration north of the Front between 0.9 b.y. and 1.1 b.y. This is considered proof that the late metamorphism was indeed of Grenville age.

(c) The combined data from the whole rock and mineral isochron studies prove beyond all reasonable doubt that granite of the Superior province, with a primary age of 2220 m.y. ± 70 m.y., was subjected to the Grenville orogeny at approximately 1 b.y.

(d) The whole rock isochron and, in particular, the analyses of Y1, place a new maximum limit on the time of deposition of the Upper Huronian sediments. The whole rock isochron is considered proof that Y1 satisfied the requirement of closure since equilibration. If the value of $(Sr^{87}/Sr^{86})_o$ and the data for Y1 are adjusted within the limits of experimental error to give a maximum age for Y1, this limiting age is 2264 m.y.

(e) This study supports the hypothesis that strontium isotopic equilibration is not a local, but a widespread accompaniment of metamorphism and provides a most sensitive mode of attack on problems of polymetamorphism.

This work has implications affecting several regional problems of the southeastern Canadian Shield. Some of these are specific, some in the realm of speculation.

There is evidence of metamorphism of intermediate age (1700 m.y. ± 150 m.y.) in the Sudbury area (Fairbairn, Hurley and Pinson, 1961) and at the southern end of the Labrador Trough (Lowden, *et al.*, 1963). Ages within this range have been found locally in the vicinity of the Front between these two regions (see p. 121). However, none of the workers in this intervening zone attribute the intermediate ages to a definite metamorphic event of that age, but consider them to represent incomplete resetting of the "clocks" during Grenville metamorphism. Nor is there any evidence for such a middle-age spread in the Lake Timagami area. While it is certainly possible that metamorphism of intermediate age did occur in the vicinity of the Front, it would be most difficult to resolve this event in any area where later (Grenville) metamorphism was superimposed upon it. To prove the presence of metamorphism of intermediate age in such an area, there would have to be present rocks with real or apparent primary ages corresponding to this event. No such rocks are known in the 800 miles between the Sudbury area and the Labrador Trough.

The time of deposition of the Upper Huronian is limited by the maximum of 2264 m.y. from this study. The lower limit is less well defined. The Rb-Sr study of post-Huronian Nipissing diabase by Van Schmus, et al. (1963) places a possible lower limit to the time of deposition of the Huronian at 1755 m.y. ± 100 m.y., i.e. 1655 m.y. Their "probable" age for this diabase is 2170 m.y. ± 200 m.y. This is in agreement with a K-Ar determination of 2095 m.y. on biotite from similar diabase (Lowdon, et al., 1963, p. 92).

These data suggest that the deposition of the Upper Huronian, and probably of the Huronian Group as a whole, took place between 2.3 b.y. and 1.6. b.y., probably between 2.3 b.y. and 2.1 b.y. Allowing time for unroofing of the Vogt Granite (Y1), it is possible that the deposition took place between 2.25 b.y. and 2.1 b.y. Although this may seem to constrict the Huronian unduly, it is evident from the Phanerozoic record that 150 m.y. is by no means too short a time for deposition of a sedimentary sequence similar to the Huronian.

North of the Front, the relative and even the absolute ages of the major geological units are well established. In contrast to this, the primary age of the bulk of the metasedimentary rocks within the Grenville province, especially the Grenville Series, has not been established. The isotopic age determinations known to the author within the Grenville province date only the Grenville metamorphism and associated intrusions and do not pertain to the primary age of the Grenville Series. K-Ar determinations show only evidence of the metamorphism and intrusion. U-Pb analyses on zircon could yield limiting values for the age of deposition of the Grenville Series, but such analyses have been made only on the intrusive rocks rather than on the metasedimentary rocks. Nor have Rb-Sr whole rock analyses been made on rocks of the Grenville Series, although these analyses might well provide the required definitive evidence. Rb-Sr analyses of minerals from metasedimentary rocks have been make on micas and on one feldspar, and yield only evidence of Grenville metamorphism (see Lepp, et al., 1963). Such analyses do not preclude the possibility of an older age for the parent rock, as is illustrated by the schist (X23, see p. 116-118) in the present study. The primary age of this schist is pre-2.2 b.y., yet biotite from this rock yields a maximum apparent age of 0.95 b.y. (using 0.700 as the minimum probable value of $(Sr^{87}/Sr^{86})_0$).

Thus the problem of the primary age of the Grenville Series remains an open question, and several possible relationships of this Series to the superficial rocks of the Superior province may be entertained:

(a) The Grenville Series may be equivalent to the Keewatin-type rocks of the Superior province, in which case there must be a sedimentary facies change between the area immediately adjacent to the Front and the limits of the typical Grenville Series (see Fig. 1).

(b) The Grenville Series may be equivalent to the Huronian Series (or similar "Proterozoic" sedimentary rocks), in which case there must be an unconformity, within the Grenville province equivalent to that found north of the Front below the Huronian.

(c) The Grenville Series may be younger than the Huronian rocks, in which case one or two unconformities are possible within the Grenville province.

In the latter two possibilities, the Grenville Series would be underlain by Archean rocks, which could be exposed within the Grenville province in anticlines or in mantled gneiss domes. However, the available evidence at present favors the first possibility. Osborne and Morin (1962, p. 135) suggest on very tenuous geological arguments that Keewatin-type rocks and the Grenville Series may be equivalent in age of deposition, and in the present area it has been proved that rocks of the Superior province including Keewatin-type metasedimentary rocks have been cannibalized during the Grenville orogeny.

How far did this cannibalism extend? The Rb-Sr study proves that partial strontium isotopic equilibration extended at least one mile north of the Front and petrographic evidence suggests that the effects of Grenville metamorphism may extend at least six miles north of the Front. In tracing this metamorphism northward using the sensitive Rb-Sr technique, one may predict that mineral isochrons from cogenetic rocks such as the Algoman granites, in a traverse northward from the Front, would show successive regression from the 0.9 b.y. isochron to the undisturbed 2.2 b.y. isochron. Even within the Lake Timagami area the differences between the mineral data for Y15 and Y1 suggest that this regression has started one mile north of the Front.

To the southeast of the Lake Timagami area this question is of prime importance. In this direction, no primary ages significantly older than Grenville age have been found. However, the only detailed study of this particular problem is that of Krogh (1964) in the vicinity of the Hastings Basin, some 180 miles to the southeast. He studied only granitic rocks, and found no evidence of primary ages significantly older than Grenville. If the surrounding metasedimentary rocks were deposited only a short time before the intrusion of these granites, an unconformity separating them from the Archean rocks must exist between the Hastings Basin and the Lake Timagami area, and this would represent the margin of the old Superior craton. However, on the basis of present evidence, it is entirely possible that the metasedimentary rocks in the Hastings region were deposited contemporaneously with the Keewatin-type rocks north of the Front.

Thus the Grenville Front does not represent the juxtaposition of rocks of differing primary ages, compositions, and lithologies. The Front does represent the superposition of metamorphism and structures of Grenville age on the rocks of the Superior province. The coincidence of these metamorphic and structural transitions in a narrow and linear zone over 800 miles in length suggests the existence of some fundamental control. Norman (1936) suggested that this was a regional fault zone, his Huron-Mistassini Fault, which he attributed to thrusting associated with the Grenville orogeny. It is now apparent, however, that the Grenville Front is dominantly a metamorphic and structural transition, only locally complicated by faulting associated with the Grenville orogeny. Nevertheless the possibility is entertained here that control by a regional fault zone in the vicinity of the Front may indeed be a valid hypothesis. The meager evidence (see p. 83) suggests that this was a regional strike-slip fault zone with dominantly right lateral movement, originating in pre-Huronian time, and exercising profound control over the later development of the Grenville Front.

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APPENDIX

Locations of chemically analysed samples (see Table 3).

X 3 : Grey, fine-grained, schistose metagreywacke, 0.75 miles NE of Sinton Lake.

X 4 : Grey-black, knotted, phyllitic metagreywacke, chlorite-white mica knots comprise about 15% of the rock, 0.75 miles NE of Sinton Lake.

X 5 : Grey, fine- to medium-grained, knotted, schistose metagreywacke, knots of white mica comprise about 30% of the rock, and have the form of andalusite, 0.25 miles north of the Bass Lake - Sinton Lake portage.

X 6 : Grey, fine-grained, schistose metagreywacke, the complimentary arenaceous portion of the bed from which came X 5.

X 12 : Grey-black, aphanitic, laminated metagreywacke, 1.51 miles NW of Sinton Lake.

121 : Grey, fine-grained, phyllitic metagreywacke, with about 25% white mica-rich knots, 2.5 miles E of the south end of Sinton Lake.

G 135: Grey, fine-grained to aphanitic, laminated metagreywacke and tuff, adjacent to Vogt Granite, 0.75 miles NW of Lone Arm.

X 16 : Grey, fine- to medium-grained schist, with amphibole-rich folia and rare granitic lenses (not present in the analysed sample), from the SE shore of Front Lake.

X 18 : Black, medium-grained schist, SE shore of Front Lake.

146 : Grey, fine- to medium-grained, crenulated schist, 0.06 miles N of the Sinton Lake Granite, 0.35 miles E of the SW corner of Bass Lake.

223 : Grey, fine-grained, crenulated schist, xenolith in the Sinton Lake Granite, 0.5 miles SSW of Sinton Lake.

157 : Grey, fine-grained schist, with medium-grained quartzo-feldspathic lenses (not present in the analysed sample) from the metadiorite-granite complex, 1.5 miles SSE of Sinton Lake.

X 20: Grey, medium-grained schist, adjacent to granite, 0.25 miles SE of the south end of Centre Lake.

X 23: Grey, medium-grained schist, 0.25 miles E of the east end of Hobbs Lake.

G 14: Grey, medium-grained schist, 0.3 miles north of the NW corner of Hobbs Lake.

193 : Black, medium-grained, amphibolitic schist, a band in the normal biotite-quartz-plagioclase schist, 0.5 miles NE of the east end of Hobbs Lake.

Description of Samples Used in Rb-Sr Study

Y1: Pink, medium-grained, fairly equigranular, massive, leucocratic, quartz monzonite. The rock consists dominantly of quartz (30%), slightly saussuritized plagioclase (albite) (25%) and microcline microperthite (40%) in an allotriomorphic granular texture with evidence of cataclasis. There is $<$ 1% of brown biotite, in part intergrown with chlorite. Trace amounts of white mica, epidote, apatite, sphene, zircon and opaques are present. This is from the southern side of the Vogt Granite, intruding Keewatin-type rocks and considered pre-Huronian in age.

Y13: Pink, medium-grained, very slightly foliated, equigranular, leucogranite. The rock consists dominantly of quartz (35%), slightly saussuritized plagioclase (albite) (17%), and microcline microperthite (45%) in an allotriomorphic granular texture. There is 2% brown biotite with which chlorite is intergrown. There are traces of white mica, epidote, sphene, apatite, zircon, and opaques. (See below, Y14.)

Y14: Pink, medium-grained, very slightly foliated, equigranular quartz monzonite, consisting of quartz (25%), saussuritized plagioclase (albite) (40%), with slight development of myrmekite, microcline microperthite (25%), brown biotite (5%) with slight chloritization and $<$ 1% of white mica, epidote, sphene, apatite, zircon and opaques.

Both Y13 and Y14 are from the Sinton Lake Granite which intrudes Keewatin-type metagreywackes. The two samples are from south of the Grenville Front as defined in the metagreywacke.

Y15: Grey-pink, slightly foliated, medium- to coarse-grained, inequigranular quartz monzonite. The rock consists of quartz (10%), oligoclase (35%) and microcline (45%), brown biotite (4%) with very minor chloritization, and trace amounts of white mica, epidote, apatite, zircon and opaques. There is segregation of dominantly microcline-rich and dominantly plagioclase-rich regions in the rock, grading into one another. The texture consists of large grains of quartz and feldspar with fine-grained interstitial quartz and feldspar in which there is considerable development of myrmekite. The texture suggests granulation accompanied or followed by recrystallization.

This is from a particularly homogeneous mass one-half mile in diameter within the migmatite. There are occasional inclusions of biotite-quartz-plagioclase schist, but these have conformable contacts. The quartz monzonite was tentatively correlated on lithology with the pre-Huronian "granites" to the north, but is generally conformable with adjacent schist or migmatite referred to the Grenville metamorphism.

X23: Grey, medium-grained epidote-biotite-quartz-plagioclase schist. The rock consists of quartz (30%), oligoclase (45%), brown biotite (20%) and epidote (4%) with traces of sericite, sphene, apatite and opaques. This is a "least-altered" schist from one-half mile north of Y15, tentatively correlated with Keewatin-type metagreywacke, metamorphosed to the amphibolite facies.

Procedure Used in Rb-Sr Analyses

Rocks were pulverized to -35 mesh using approximately 35 kg. of sample (except for the schist, X23, where only 2 kg. were available). Splits of about 5 kg. were used for whole rock analyses, portions of the remainders being used for standard mineral separation. The whole rock split was treated in platinum with HF and perchloric acid, evaporated to dryness, and taken into solution in triple-distilled H_2O. The solution was made up to 2000 ml. and stirred for more than eight hours. Aliquots of this solution were used in the analyses.

The concentrations of Rb^{87} and Sr^{87} were determined by standard techniques of isotope dilution, essentially according to the procedure outlined by Zartman (1963). Two major differences are (a) the use of teflon-ware rather than glassware to eliminate possible leaching effects during evaporations (Wasserburg, Wen and Aronson, 1964) and (b) the use of an 83% Sr^{84} spike which permits discrimination and hence strontium isotopic compositions to be calculated accurately from spiked runs.

ONTARIO
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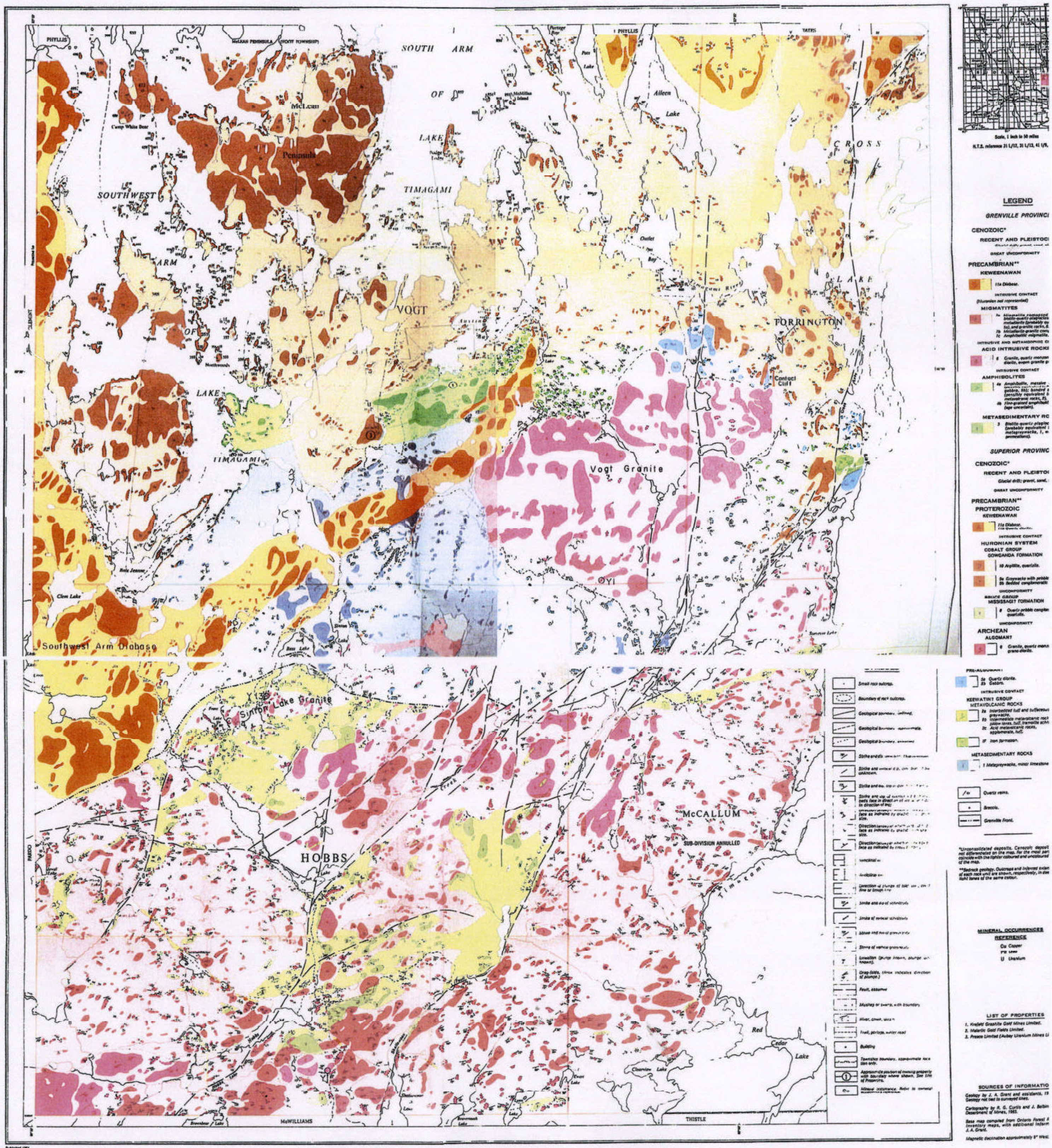
D. P. Douglass, Deputy Minister   M. E. Hurst, Director, Geological Branch

Map 2048
Vogt-Hobbs Area



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Map 2048
VOGT-HOBBS AREA
NIPISSING DISTRICT

Scale 1:31,680 or 1 Inch to ½ Mile