THE PRECAMBRIAN GEOLOGY AND GEOCHRONOLOGY OF MINNESOTA

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The Precambrian Geology and Geochronology of Minnesota

BY

SAMUEL S. GOLDICH, ALFRED O. NIER, HALFDAN BAADSGAARD, JOHN H. HOFFMAN, AND HAROLD W. KRUEGER

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FOREWORD

This bulletin is an outstanding example of the cooperation of several scientists and scientific organizations. Without the cooperation of all concerned, such a comprehensive correlation of age determinations and regional geology would have been impossible short of many years of work. The results are a particularly important demonstration of cooperation among geologists, chemists, and physicists.

The grants from the National Science Foundation were a major source of funds and made the project possible. In addition the Minnesota Geological Survey supported the project, particularly the field work and the entire cost of publication. The Graduate School of the University of Minnesota also made notable contributions of funds at critical points during the course of the project.

As the authors point out in several places, geochronology is a relatively new development and much is still to be learned. The present work is, in effect, a pioneering effort and points the way to more work in Minnesota and elsewhere.

As Director of the Minnesota Geological Survey, I wish to express my sincere appreciation of their devoted work to all concerned, especially to Dr. Samuel S. Goldich who initiated the project and furnished the extra energy to push it to a conclusion.

George M. Schwartz

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ABSTRACT

Radioactivity dating of a large number of igneous and metamorphic rocks by the potassium-argon and the rubidium-strontium methods is the basis for revision of the classification of the Precambrian rocks of Minnesota. The major divisions of the three-fold classification are made at time boundaries of 2.5 and 1.7 billion years (b.y.), corresponding to the time of two major orogenies, the Algoman and the Penokean, respectively.

The eras are referred to as Early, Middle, and Late Precambrian in preference to the older terminology of Earlier, Medial, and Later Precambrian. The division between the Early and Middle Precambrian is placed at the time of the Algoman rather than of the older Laurentian orogeny. The division between the Middle and Late Precambrian is made on the basis of the Penokean orogeny which resulted in a mountain chain that extended from central Minnesota through Wisconsin into Michigan. The Penokean Mountains formerly were assigned erroneously to late Keweenawan time.

The Early Precambrian rocks are divided into the Ontarian and the Timiskamian systems. The Ontarian rocks include the Keewatin group of Minnesota and the Coutchiching metasediments which underlie the Keewatin greenstones in Ontario. Some of the gneisses in the Giants Range and the Vermilion granite regions of Minnesota probably were derived by metamorphism of ancient sediments that were deposited prior to the great outpouring of basalt flows assigned to the Ely greenstone of the Keewatin group.

The Laurentian orogeny, although not closely dated, occurred 2.6 billion or more years ago. Folding was accompanied by intrusion of numerous dikes and plutons of tonalitic to granodioritic composition, the largest of which is the Saganaga granite mass on the Minnesota-Ontario boundary. The Ontarian rocks and the Laurentian intrusives are overlain unconformably by the Knife Lake group which is correlated with the Seine of Ontario. These metasediments are assigned to the Timiskamian. The sedimentary cycle was ended by the Algoman orogeny or mountain building.

The Giants Range and the Vermilion batholiths, better called granitic complexes, were formed during the Algoman orogeny. Radioactivity ages for these rocks range from 2.6 to 2.5 b.y. Similar ages were found for the Morton gneiss in the Minnesota River Valley. Postkinematic granite plutons, emplaced in the folded Coutchiching metasediments in the Rainy Lake area, Ontario, were mapped by Lawson as Algoman. They are dated at 2.4 b.y. Postkinematic granites in the Minnesota River Valley, notably the Sacred Heart granite, give a similar age.

The unconformity at the base of the Middle Precambrian Animikie group of the Mesabi district represents a hiatus of several hundred million years. The Animikie formations, the Pokegama quartzite, the Biwabik iron-formation, and the Virginia argillite were deposited on a relatively stable craton of the Early Precambrian granitic rocks. The strata were tilted and warped in the Penokean and subsequent folding but were not highly deformed. To the south, however, the iron formations and related sediments in the Cuyuna district and the Thomson formation in east-central Minnesota were tightly folded. Farther south, the McGrath gneiss, dated at 1.7 b.y., is a deeper-seated synkinematic phase of the Penokean orogeny. The St. Cloud Red granite and similar intrusives in Wisconsin and in Michigan, dated at 1.65 b.y., are postkinematic and were intruded following the main period of Penokean folding. Tonalites and granodiorite in the St. Cloud area, dated at 1.8 b.y., may represent an early phase of the Penokean cycle.

Similar relationships are found in the Minnesota River Valley where the Montevideo granite gneiss was intruded or folded at approximately 1.8 b.y. This event was followed by the intrusion of a system of basaltic dikes and then by emplacement of a small granite pluton, dated at 1.7 b.y.

The Late Precambrian rocks include the Puckwunge formation, the North Shore volcanic group, the late Keweenawan Fond du Lac and Hinckley sandstones, the Duluth complex, and similar intrusive rocks of the North Shore region. A hiatus of several hundred million years is represented in the unconformity at the base of the Puckwunge formation in the Duluth area. The Duluth complex, formed by a number of successive intrusions, was emplaced at approximately 1.1 b.y. In the southwestern part of the state, the Sioux formation of Late Precambrian age was folded at about 1.2 b.y.

Ages determined by the potassium-argon and by the rubidium-strontium methods generally are in good agreement; however, the apparent age obtained by either method may reflect metamorphism subsequent to the original crystallization. The study of the possible loss or gain of parent and daughter nuclides in the minerals and also in the whole rock under diverse geologic conditions is an important area for future investigations.

The geologic names formerly used in Minnesota and in the Lake Superior region have been retained. It is recognized that some of these terms no longer possess their original usefulness; nevertheless, the rejection of the old terms, as well as the introduction of new names, is inadvisable for the present.

The major structural disturbances recorded in the Precambrian rocks of Minnesota and adjacent areas can be correlated tentatively with orogenic cycles in other parts of the world. It is not likely that the world-wide occurrence of radioactivity ages in the ranges: 2.6–2.5 b.y.; 1.8–1.6 b.y.; and 1.1–0.9 b.y. is due to chance. The geosynclinal accumulation of sediments and the mountain building that follows cannot be explained

through any agency or force acting entirely within the crust of the earth. Deeper-seated or subcrustal phenomena are involved, and with such hypotheses the case for world-wide orogenies is improved. Equally improved are the prospects that eventually a world-wide time scale for the Precambrian rocks will be evolved.

THE PRECAMBRIAN GEOLOGY AND GEOCHRONOLOGY OF MINNESOTA

I. INTRODUCTION

The State of Minnesota, situated on the southern edge of the Canadian Shield (Fig. 1), is in large part underlain by rocks of Precambrian age. In the northern counties the Precambrian rocks are exposed at the surface or are encountered at relatively shallow depths beneath the cover of the glacial deposits. They contain the iron ore deposits of the Mesabi and Vermilion districts. A large part of the east-central counties also is underlain by Precambrian metamorphic and igneous rocks. Locally, granites of a variety of color and texture are quarried, and St. Cloud is the center of the stone fabrication industry of the state. In the southern counties the Precambrian basement is overlain by sedimentary formations of early Paleozoic and Cretaceous age. These strata have been penetrated by many water wells which are bottomed in the Precambrian basement. There are numerous small exposures of the Precambrian rocks in the southwestern part of the state, particularly in the Minnesota River Valley where outcrops of granite and gneiss are the sites of numerous quarries.

Because of their extent, varied character, and economic significance, the Precambrian rocks of Minnesota have been the subject of geologic investigations for many years. Organized geologic work commenced in 1872 with the appointment of N. H. Winchell as State Geologist in charge of the Minnesota Geological and Natural History Survey. Twenty-four annual reports and six large volumes of the final report were published under his direction. Volume 6, a geologic atlas with synoptical descriptions, was published in 1901, and from that date to approximately 1911, the Minnesota Survey was relatively inactive. Fortunately, during that period geologists of the United States Geological Survey, coming into the state with a broad and varied experience in the Precambrian of other areas, carried on extensive field investigations which led to the publication of three important monographs (Clements, 1903; Leith, 1903; Van Hise and Leith, 1911).

In 1911 W. H. Emmons became director of the reactivated Minnesota Geological Survey. Vigorous field investigations were renewed, and a number of bulletins were published. Many of the investigations dealt with problems of Precambrian geology and were more or less under the guidance of the late Professor F. F. Grout. This work has been summarized in a paper by Grout, Gruner, Schwartz, and Thiel (1951) that reviews not only the contributions made by the older Minnesota Geological and Natural History Survey and by the present Survey but also the contributions of the United States Geological Survey and the numerous papers by other geologists, many of whom were employed by mining companies. More recent contributions to the Precambrian of Minnesota are compiled in a

FIGURE 1. — Sketch map showing the position of the State of Minnesota on the southern margin of the Canadian Shield. The geologic provinces of the Shield in Canada are after Collins, Farquhar, and Russell (1954, p. 18). The dates indicate the approximate time of a major orogeny in each of the provinces. The Precambrian area in Minnesota, as well as in Wisconsin and Michigan, is the southern extension of the Superior province. As explained in the text, this area has undergone four periods of orogeny, at 1.1, 1.7, 2.5, and 2.6 or more billion years ago.

guidebook, *The Precambrian of Northeastern Minnesota*, edited by G. M. Schwartz (1956a). The contributors to the guidebook summarized different phases of the Precambrian geology of northeastern Minnesota and also added much new information.

THE PROBLEM

As a result of the many investigations briefly outlined above, the Precambrian succession (Table 1) in Minnesota probably is as well known as that of any region of comparable size. The main objective of the present investigation was to date by radioactivity methods as many of the intrusive and metamorphic rock types as possible and to build the framework of a time scale within which the formations and events as interpreted from geologic studies can be fitted. The need for such a study has been anticipated by our colleagues in their review of the Precambrian stratigraphy of Minnesota (Grout *et al.*, 1951, p. 1017), and with regard to the methods of correlation of Precambrian rocks they conclude: "Most valuable are the ages determined by radioactivity, the characters of the zircons in large intrusions, the petrographic peculiarities of the iron-formations, and the sequence of beds." Since this statement was written, considerable advances have been made in radioactivity-dating methods, and the potassium-argon and rubidium-strontium methods have greatly extended the possibilities of determining the ages of Precambrian minerals.

The plan for a program of radioactivity dating in Minnesota was formulated in 1955. Facilities for chemical and mass spectrometric investigations were already available for the most part, and a grant from the National Science Foundation permitted initiation of the project in 1956. The potassium-argon method was selected for the early phase of the study, and most of the results here reported were obtained by this method. A second grant from the National Science Foundation for the years 1958 and 1959 permitted the addition of the rubidium-strontium dating method, and a large number of the samples were also dated by this technique. A third phase of the investigation, involving uranium-lead dating of zircons was originally planned, but circumstances made it necessary to terminate the project.

An important objective of the study is the interpretation of the Precambrian history of Minnesota and adjacent areas. In addition to the collection of samples, geologic studies were carried on in a number of critical areas in northern Minnesota and in Ontario, and for this purpose field camps were maintained during the summer months of 1956, 1957, and 1958. The work in Ontario was particularly necessary because many of the older Precambrian formations were first studied and defined in Ontario. Shorter field studies involved traverses in the Steeprock Lake and the Kashabowie areas, along the highways from Port Arthur to Kenora and International Falls, across the area of the Knife Lake slates in Minnesota to Saganaga Lake and Northern Light Lake in Ontario, in central and southwestern Minnesota, and in Wisconsin and Michigan.

PRESENTATION OF RESULTS

The geologic succession and chronology of the Precambrian of Minnesota are shown in Table 2. Ages have been assigned to many of the rocks, but many uncertainties remain, and areas for further field and laboratory studies are indicated. The three-fold division of Precambrian time (Table 1) is retained, but the terminology of Earlier, Medial and Later for the major subdivisions is replaced by Early, Middle and Late. Precambrian time is divided at 2.5 and 1.7 billion years (10^9 years or b.y.). Major un-

Table 1. Precambrian Column in Minnesota, Chronologic and Stratigraphic Sequence
(After Grout *et al.*, 1951)

	Eras and Rocks	Groups	Formations and Members			Other Names Used in Minnesota
Phanerozoic Eon	Cenozoic Mesozoic Paleozoic	(For detail *see* Minn. Geol. Survey Bull. 29)				
		unconformity, great on Wisconsin boundary and east				
Precambrian (or Cryptozoic Eon)	Later	Keweenawan Group	Upper:	Sandstones and other sediments	Hinckley Fond du lac	Red Clastics*
			Middle:	Intrusives, acidic and basic	Scattered granites* Duluth gabbro Beaver Bay Complex, and Logan intrusives	
				Flows, tuffs and sediments	Keweenaw Point Volcanics	
			Lower:	Conglomerate and sandstones	Puckwunge formation	
		unconformity, may be great on the Cuyuna range				
		? Sioux formation* ?				
		Animikie Group	Virginia slate (minor iron formation?) = Rove = Biwabik iron formation series = Gunflint = Pokegama quartzite			Upper Cuyuna slate* Deerwood*
		unconformity, great on the Mesabi and Gunflint ranges				
	Medial	Algoman batholithic intrusives, orogeny and erosion Central and southwestern Minnesota granites*				
		Knife Lake Group (about 18 members)	slate = Thomson* graywacke iron-bearing beds conglomerate tuffs, lavas and intrusives			(Carlton)* Emily* Agawa* Ogishke*
		unconformity, great west of Saganaga Lake				
	Earlier	Pre-Knife Lake batholithic intrusives, orogeny and erosion				
		Keewatin volcanics, and Soudan iron formation member. (No Coutchiching recognized in Minnesota)				Ely greenstone

* Means uncertain as to place.

TABLE 2. STRATIGRAPHIC SUCCESSION AND GEOCHRONOLOGY OF THE PRECAMBRIAN OF MINNESOTA
(Compare with Table 1)

Era (10^9 Years)	Period-System	Major Sequence	Formation	Orogeny	Intrusive Rocks
Paleozoic	Cambrian				
			...Unconformity...		
(0.6 b.y.)					
			Hinckley sandstone		
			Fond du Lac sandstone		
			...Unconformity...		
(1.1 b.y.) Late Precambrian	Keweenawan	North Shore volcanic group	Undivided	Grenville	Duluth complex, sills at Duluth, Beaver Bay complex, Logan intrusives
			Puckwunge		
			...Unconformity...		Granite: St. Cloud Red, Rockville (?) granite at Granite Falls, Bellingham (?)
			Sioux quartzite (?)		
			...Unconformity...	Penokean	Gneiss: McGrath, Montevideo (?)
(1.7 b.y.)			Virginia argillite = Rove = Thomson		Tonalites: St. Cloud Gray, Warman, Hillman, Freedhem, Montevideo
		Animikie group	Biwabik iron-formation = Gunflint		
Middle Precambrian	Huronian		Pokegama quartzite		
					Granite: Gold Island, Giants Range, Sacred Heart, Fort Ridgely (?)
			...Unconformity...	Algoman	
(2.5 b.y.)					Gneiss: Giants Range, Vermilion, Morton
	Timiskamian	Knife Lake group	Undivided		
(? b.y.)			...Unconformity...	Laurentian	Saganaga granite, Grassy Island tonalite (?)
			Soudan iron-formation		
Early Precambrian		Keewatin group			
	Ontarian		Ely greenstone		
		Coutchiching (?)	Undivided		
			Older rocks		

conformities are indicated at these dates in Table 2, but it is not implied that these unconformities were formed precisely at these times.

The major change from the earlier classification of the Minnesota Geological Survey arises from the recognition of the Penokean orogeny which followed deposition of the Animikie group. The expression *Penokean orogeny* apparently was first used by Blackwelder (1914) for a period of folding and mountain building which he assigned to post-Keweenawan, that is, at the close of Precambrian time. The Penokean Mountains, as will be explained in a later section of this report (pp. 118–20), extended from Minnesota through Wisconsin to Michigan, and possibly connected by way of the Mistassini district with a mountain range which formerly existed in the site of the Labrador trough (Fig. 1). Failure to recognize a post-Huronian orogeny has made many correlation problems that have been the subject of papers, as for example, one by Cooke (1926) with the interesting title, "Between the Archean and the Keweenawan is the Huronian." Cooke used the name Keweenawan Mountain range for the Penokean Mountains of Blackwelder. The present work shows that the Penokean Mountains actually are much older than had been previously thought. The term is derived from the Penokee Range in northern Wisconsin.

The major orogeny which involved folding of the Knife Lake group and intrusion of the Algoman granites marks the transition from Early to Middle Precambrian time, whereas in earlier classifications (Table 1) the division was made on the basis of the Laurentian orogeny. In the present classification the Laurentian orogeny is subordinated and is placed within Early Precambrian time. Metamorphism at the time of the Algoman orogeny apparently was so severe that the biotite in many of the older rocks was recrystallized, and the ages determined for biotites from pre-Algoman rocks are essentially the same as those for the Algoman, 2.5–2.6 b.y. Further discussion of the results is deferred to later sections of this report.

The analytical methods used in this investigation are presented in Chapter 2. These methods are largely based on procedures developed in other laboratories, and some of the important contributions of these laboratories are reviewed. It is hoped that the detailed descriptions of the methods will give geologists a better understanding of some of the technical problems and also will be useful to others engaged in similar studies. Chapter 2 also includes a comparison of the results by the potassium-argon and rubidium-strontium methods and a discussion of some of the problems in evaluating radioactivity ages.

The project, as first formulated and as carried out, is fundamentally a geologic one. The principal Precambrian rock units described in earlier geologic investigations are reviewed, new field and laboratory observations are presented, and the geologic history is interpreted with the aid of the K-A and Rb-Sr ages. The geologic results are presented in three chapters on a geographic basis that is more or less dictated by the distribution of outcrops in Minnesota. Chapter 3 deals with the data from northern Minnesota and from Canada. Chapter 4 discusses the results for east-central Minnesota and the data from Wisconsin and Michigan. Chapter 5 gives the results for southwestern Minnesota, obtained chiefly for the rocks of the Minnesota River Valley.

The general problems of correlation and development of a quantitative time scale are considered in Chapter 6.

The locations and brief descriptions of the dated samples, for the most part material not contained in the text, are included in the Appendix. The counties of Minnesota are shown in Figure 37 as an aid to reading and locating samples. In the Appendix and throughout the text, references to public-land divisions in Minnesota for purposes of location are abbreviated, as, for example, "Sec. 22, T. 65 N., R. 5 W." to Sec. 22:65–5. Descriptions with an east range in Minnesota and those outside of the state are given in the full form.

2. METHODS

GENERAL STATEMENT

Several naturally occurring radioactive nuclides are useful in determining geologic time. Under different geologic environments an age determined from the decay of one radioactive nuclide may be more significant than that from another, but in general the following requirements must be met:

1. The rate of decay of the radioactive nuclide must be accurately known. The half-lives of many naturally occurring radioactive isotopes are of the order of billions of years, and the energy released by the decay of the nuclides is very small, making the determination of the rates of decay difficult.
2. With the occasional exception of the uranium-lead methods, the techniques assume that the mineral or rock is a closed system with respect to both the parent and the daughter nuclides.
3. Appreciable amounts of the daughter nuclide must not be present at the time of formation of the mineral or material to be dated.
4. The isotopic composition of the parent element must have been the same throughout the upper lithosphere.

If these requirements are fulfilled, the computed age should correspond with the time elapsed since the sample was last an open system with respect to both the parent and daughter nuclides. The age is obtained from the fundamental relationship:

$$\text{Age} = \frac{\text{Total amount of decay product}}{\text{Average rate of production of decay product}}.$$

POTASSIUM-ARGON METHOD

Development

At the turn of the century, Thomson (1905) first observed that normal potassium emits weak radiation in the form of β-particles. In addition to this activity, Köhlhorster (1930) detected γ-emission from potassium. The source of this radioactivity was suggested to be the presence of a radioactive potassium isotope of mass 40 (Klemperer, 1935 and Newman and Walke, 1935). The presence of K^{40} in natural potassium was verified by Nier (1935, 1936). In view of the dual activity of K^{40} and the high abundance of A^{40} in the atmosphere, Weizsäcker (1937) suggested that K^{40} decays to A^{40} as well as to Ca^{40} and that old potassium minerals should contain radiogenic A^{40}. Thompson and Rowlands (1943) subsequently proved that the radioactive decay of K^{40} involved the production of A^{40}, and

Aldrich and Nier (1948a) found old potassium minerals to contain appreciable quantities of radiogenic argon.

Aldrich and Wetherill (1958) have reviewed the radioactivity-dating methods which are useful in determining geologic time and have summarized the determinations by various investigators of the specific gamma and beta activities of natural potassium. From the values accepted by Aldrich and Wetherill (1958, p. 264–265) and the value of 0.0118 atom per cent for the relative abundance of K^{40}, the computed decay constants used in the present investigation follow:

$$\lambda_\beta = 4.76 \times 10^{-10} / \text{yr.}$$
$$\lambda_\epsilon = 0.589 \times 10^{-10} / \text{yr.}$$

The equation used to calculate the A^{40} / K^{40} age of a rock or mineral is

$$t = \frac{1}{\lambda_\epsilon + \lambda_\beta} \ln \left[\frac{A^{40}}{K^{40}} \left(\frac{\lambda_\epsilon + \lambda_\beta}{\lambda_\epsilon} \right) + 1 \right].$$

Converting to the common logarithm and using the constants given above, the equation becomes

$$t = 4.31 \times 10^{9} \log \left[\frac{A^{40}}{K^{40}} (9.08) + 1 \right].$$

Where duplicate determinations are reported in the tables, the A^{40} / K^{40} values have been averaged and the age computed.

Sample Preparation

Rocks containing fresh, unaltered micas furnish the best material for K-A dating. If the grain size of the potassium mineral is larger than 200 mesh, a separation is usually made. The rock sample is crushed to less than 40 mesh, and usually the 40–60 mesh fraction supplies adequate material. Most of the biotite separations are made by passing the fraction repeatedly through a Franz Isodynamic separator until a clean separate is obtained. If the biotite is still contaminated by relatively large amounts of hornblende and pyroxene, the impure material is crushed under a heavy machined steel roller to break up the more brittle hornblende and pyroxene. The biotite is much less disaggregated by this process and is concentrated by sieving. Repeated treatment effectively removes all but small amounts of the brittle impurities.

Bromoform and alcohol mixtures of adjusted specific gravity are used to separate potassium feldspar from the nonmagnetic fraction of the sample.

In the preparation of very fine-grained material for which mineral separations are not practicable, the rock sample is crushed and screened, and the 40–60 mesh fraction is taken for analysis. The mineral samples are generally left as coarse as possible to minimize argon loss during the argon extraction procedure, although it has been shown (Goldich, Baadsgaard, and Nier, 1957) that the fine-grained slates of the Thomson formation in Minnesota show little argon loss compared to coarse mica in the same formation.

Portions of the sample to be used for analysis are taken by coning and quartering only after the entire sample has been thoroughly mixed by rolling on hard-surfaced paper.

Determination of Potassium

Experience has shown that the accurate determination of potassium is not the simple matter often supposed. Potassium may be determined by a number of methods such as isotope dilution, X-ray fluorescence, flame photometry and several wet chemical methods. In this work a combination of flame spectrophotometric and wet chemical methods was used.

J. Lawrence Smith Method. Fusion of a 0.5 gm. sample of a finely ground potassium mineral or rock with pure, low-alkali calcium carbonate and A.R. ammonium chloride is carried out in standard-form J. Lawrence Smith crucibles. After cooling, the sintered mass is slaked with water, washed into a beaker, boiled with water and carefully filtered by decanting the supernatant liquid. The boiling leach is repeated three or more times after which the residue is transferred to the filter and thoroughly washed with hot water. The hot filtrate is treated with aqueous ammonia and ammonium carbonate to precipitate calcium, and the calcium carbonate filtered off. If the sample contains more than 5 per cent K_2O, the residue and the precipitated calcium carbonate are dried, mixed with 0.5 gm. of ammonium chloride, and the entire fusion and leaching process repeated. The combined filtrates are evaporated to dryness in a large fused-silica dish, and the ammonium salts removed by careful heating. The residue is dissolved in water, treated with a few drops of aqueous ammonia and ammonium carbonate, filtered into a platinum dish through a small filter, and the dish and filter washed with hot water. After evaporation of the filtrate to dryness and removal of the ammonium salts, this step is repeated using a weighed platinum dish.

When constant weight of the alkali chlorides has been attained through careful heating, a conventional chloroplatinate separation for potassium is made. The separated potassium (plus Rb and Cs) and the sodium (plus most of the Li) fractions are treated with ammonium formate to reduce the chloroplatinates, evaporated to dryness, leached with water and filtered. The filtrate is evaporated to dryness, treated with a little sulfuric acid, evaporated and ignited. The alkali sulfate fractions are taken up in water, diluted to 50 ml., and flame spectrophotometric determinations of the K in the sodium fraction and of the Rb, Cs and Na in the potassium fraction are carried out.

Blank. Available A. R. "low-alkali" grades of calcium carbonate generally yield a blank of from 0.01 to 0.10 per cent K_2O on a half-gram sample basis. Careful blanks are run periodically exactly as the analyses, except that a pair of purified alkali chloride blanks are combined and are analyzed with a flame spectrophotometer. With carefully purified calcium carbonate it is possible to reduce the blank somewhat, but rarely to the point where it may be neglected. Thus it is desirable to obtain the best grade of calcium carbonate available. The blank in the present work ranged from 0.01 to 0.06 per cent K_2O (to be subtracted from the determined K_2O). After taking into account the blank and correction data, the K_2O content of the sample is calculated.

Rapid Flame Method. A rapid flame spectrophotometric procedure is used with materials containing less than 3 per cent K_2O. A 0.1 to 0.5 gm. sample is decomposed in a platinum dish with hydrofluoric acid and a few drops of sulfuric acid. A solution of magnesium chloride containing the equivalent of one-half the sample weight of MgO is added either before or after the hydrofluoric acid decomposition. After evaporating and fuming off the excess sulfuric acid, the dish is washed down, and the residue is broken up with a stout platinum wire. A few drops of sulfuric acid are added, and the evaporating and fuming operation is repeated. The second evaporation is necessary to ensure complete removal of chloride.

Following the expulsion of the excess sulfuric acid, the platinum dish is heated carefully, first over a Tirrill, and then over a Meker burner for 3 to 5 minutes. The alkali sulfates are leached with water and filtered into a volumetric flask which is made up to the mark. Potassium is determined with a flame spectrophotometer, using standards containing 500 ppm. of MgO. Some comparative results are given in Table 3.

Precision and Accuracy. The J. Lawrence Smith method, the basic procedure in the determination of K_2O for most of the samples, is an extraction method. A consideration of the various steps suggests that if a bias exists that cannot be detected by replicate determinations, the results are somewhat low rather than high. High results might be caused by the introduction of potassium from the reagents which is not properly corrected by the blank or by failure to remove all the NH_4Cl prior to the conversion to the chloroplatinates. Low results would be caused by failure to extract all the potassium from the mineral and from the calcium carbonate precipitates and by loss of potassium through volatilization during the ignition and in subsequent heating steps to obtain the purified alkali chlorides. Skill and experience are important factors.

Replicate determinations made in the Minnesota Rock Analysis Laboratory over a number of years and throughout the present project rarely differ by more than one per cent relative of the K_2O content in the range of 1 to 14 per cent K_2O. The variation in the potassium values obtained by different analysts and between replicate determinations by the same analyst is of the same order of magnitude (Table 4). The accuracy of the potassium determinations may be partially assessed by the determinations made on the standard granite, G-1.

TABLE 3. COMPARISON OF RESULTS FOR K_2O BY RAPID FLAME SPECTROPHOTOMETRIC AND GRAVIMETRIC METHODS
(C. O. Ingamells, analyst)

	Weight Per Cent	
Sample No.	Flame	Gravimetric
KA-238	7.10	7.13
KA-277	5.23	5.32
KA-278	6.85	6.68
KA-39	5.06	5.16
KA-40	4.56	4.56
R-2339	3.44	3.46

TABLE 4. REPLICATE DETERMINATIONS OF K_2O ON GRANITE G-1

Source or Analyst	Weight Per Cent
Average for 24 laboratories (Fairbairn *et al.*, 1951, p. 37)	5.51
Average recomputed by Fairbairn (1953, p. 146)	5.42
Eileen H. Oslund, Rock Analysis Laboratory (Goldich and Oslund, 1956, p. 813)	5.49
S. S. Goldich	5.54
S. S. Goldich and Eileen H. Oslund	5.52
R. A. Burwash (average of 4)	5.54
Eileen H. Oslund & Halfdan Baadsgaard	5.52
Average for Rock Analysis Laboratory	5.52
P. L. D. Elmore, U.S. Geological Survey *	5.51
W. W. Brannock, U.S. Geological Survey *	5.54

* Personal communication from W. T. Pecora, May 1959.

TABLE 5. REPLICATE DETERMINATIONS OF K_2O, Rb_2O, AND Cs_2O ON LEPIDOLITES

	Weight Per Cent		
Locality and Analysts	K_2O	Rb_2O	Cs_2O
Bikita, Southern Rhodesia			
Halfdan Baadsgaard & S. S. Goldich	8.79	3.67	0.25
C. O. Ingamells & Eileen H. Oslund	8.78	3.75	0.29
Portland, Connecticut			
Halfdan Baadsgaard & S. S. Goldich	10.58	0.79	0.32
C. O. Ingamells & Eileen H. Oslund	10.48	0.80	0.32

In certain samples, such as lepidolites which contain relatively large amounts of all the alkali metals, flame spectrophotometric determinations must be carried out with greater than usual care. The combined gravimetric and flame spectrophotometric method gives good precision for potassium in lepidolites (Table 5). With such complex samples, and with most micas, it has been found necessary to employ a double fusion to ensure complete recovery of the potassium. With samples containing 10 to 14 per cent K_2O, 1 to 2 per cent of the K_2O content may be retained in the calcium carbonate precipitate and residue unless extremely efficient fusion and extra leachings are employed.

Determination of Argon

Extraction. The argon extraction system employed in this project is a flux fusion system essentially the same as that described by Wasserburg (1954) and by Wetherill, Tilton, Davis and Aldrich (1956). During the course of the project several modifications were made (Fig. 2A and Fig. 2B). The major change consisted in relocating the magnesium perchlorate and copper oxide traps in the fusion train to remove hydrogen and water as fast as they are generated. The cold trap and tungsten filament were eliminated and titanium sponge metal replaced pyrophoric uranium as the chemical getter. In addition, a standard-taper glass joint was introduced just below the sample suspension to eliminate glass blowing. The seal proved to be tight and trouble-free. Mercury cutoffs separate the system into three parts: the pumping system, the fusion train, and the purification train.

The pumping system consists of a standard mechanical forepump in series with a two-stage mercury diffusion pump. This system permits reasonably rapid evacuation to the point where normal argon contamination is low and the outgassing of the sample, flux, and purification reagents is thorough. Blank runs on the train yield $1\text{–}2 \times 10^{-7}$ cc. STP of A^{40} and less than 10^{-9} cc. STP of A^{36} and A^{38}. This blank is obtained without a sample, however, and it is usual for the argon contamination from the sample to contribute more than this amount of air argon. For old rocks and minerals, a blank of 10^{-6} cc. STP of A^{40} is usually still small; a correction is applied through the A^{36} measurement in any case. To follow outgassing of the system, as well as subsequent gas transfer and purification, thermocouple pressure gauges are situated between the forepump and the diffusion pump and on the purification train.

The fusion train consists of a nickel crucible, a sample-mounting device, an A^{38} spike, a magnesium perchlorate trap, and a copper oxide trap. The sample to be analyzed is suspended from a steel rod about one foot above the 1×12 inch nickel crucible (Figs. 2A and 2B). The crucible is normally charged with 30 grams of sodium hydroxide pellets (low in carbonate) and may be heated to 750° C. by means of a removable resistance furnace. The A^{38} spike is a break-seal tube previously filled with a known amount of A^{38}, usually $2\text{-}5 \times 10^{-5}$ cc. STP. The magnesium perchlorate serves to take up water from the fusion and is outgassed at 220° C. but is used at room temperature. The copper oxide trap oxidizes hydrogen to water and is outgassed and operated at approximately 450° C.

The purification train contains a titanium-sponge getter and an activated charcoal trap in a break-seal tube. The titanium sponge metal is contained in a stainless steel tube with a Kovar-to-glass seal and is outgassed and operated at approximately 1000° C., but may be opened to air when cold. The activated charcoal trap is outgassed at 400° C. and is used to collect the purified argon at liquid nitrogen temperature.

The argon extraction, purification, and collection are carried out as fol-

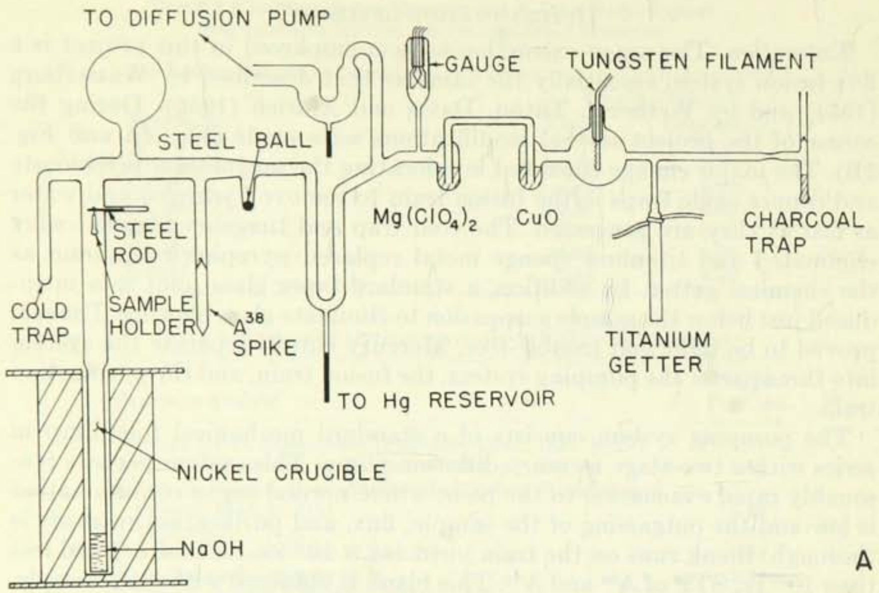

FIGURE 2A. — Early argon extraction system with which a pyrophoric uranium getter also was used in place of the titanium getter shown.

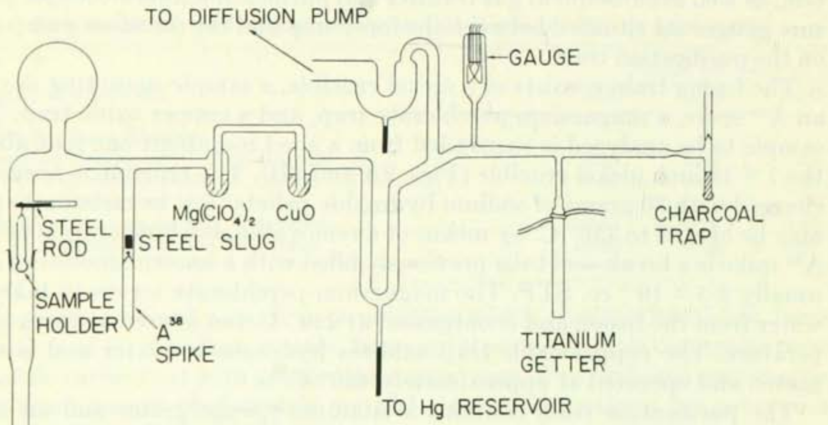

FIGURE 2B. — Later, modified argon extraction system.

lows: a weighed sample (1–3 gm.) in a thin glass ampule is suspended from the steel rod extended above the crucible, and an A^{38} spike, a charcoal break-seal trap and a clean nickel crucible containing fresh sodium hydroxide flux are attached to the system. The system is evacuated, leak tested, and all the heaters and furnaces except that for the titanium getter are turned on to their outgassing temperatures. The system is allowed to outgas for at least twelve hours, usually overnight.

When the outgassing is completed, the flux is allowed to cool, the mercury cut-off to the fusion train is raised, and the sample is dropped onto the solidified flux by withdrawing the steel rod with a magnet. The magnesium perchlorate is allowed to cool, and the fusion is started by slowly heating the flux to its melting temperature, about 320° C. If the fusion proceeds satisfactorily, the A^{38} spike is introduced by shattering the break-seal tip with a steel ball or slug. The furnace for the titanium getter is turned on, and the outgassing of the purification train is continued. After a fusion of four hours at 750° C., the sample and glass ampule have been completely dissolved in the flux and most of the water and hydrogen eliminated.

On completion of the fusion, the titanium getter is cooled, and the purification train is sealed off from the pumps by raising the second mercury seal. The first mercury seal between the fusion and purification trains is then dropped to begin the final clean-up of the gas. If the pressure indicated by the thermocouple gauge is about 10^{-2} mm. Hg or less, the titanium getter is heated to 1000° C., operated until a constant pressure is attained, and allowed to cool slowly. The heater is now removed from the charcoal trap, and the argon trapped for 20 minutes using liquid nitrogen. The sample is finally sealed off from the system and is ready for mass spectrometric analysis.

A^{38} Spikes. The A^{38} spikes are prepared in sets of approximately 36 break-seal tubes. The volumes of the individual tubes are determined, and they are filled with spike A^{38} on a manifold similar to that described by Wasserburg and Hayden (1955). The A^{38} was obtained from the Oak Ridge National Laboratories and contains some A^{40} and A^{36} which were determined for nearly all of the spike sets. An average of 15 determinations gave the following argon isotope ratios: $A^{40}/A^{38} = 0.238 \pm .003$ and $A^{36}/A^{38} = 0.00122 \pm .00001$. The spikes are calibrated by two methods. In the capillary pipette method (Wasserburg and Hayden, 1955), the spike argon is mixed with a measured amount of normal air argon. The A^{36}/A^{38} ratio is used to calculate the amount of A^{38} present. Two or more spikes of each set are calibrated by this method.

The second method of spike calibration employs the multiple expansion of atmospheric argon through a system of known volumes. The apparatus is shown schematically in Figure 3. Valves A and C are double valves and have standard volumes between the seats. Volume A is filled with argon from the tank argon bulb to a pressure which may be measured on the

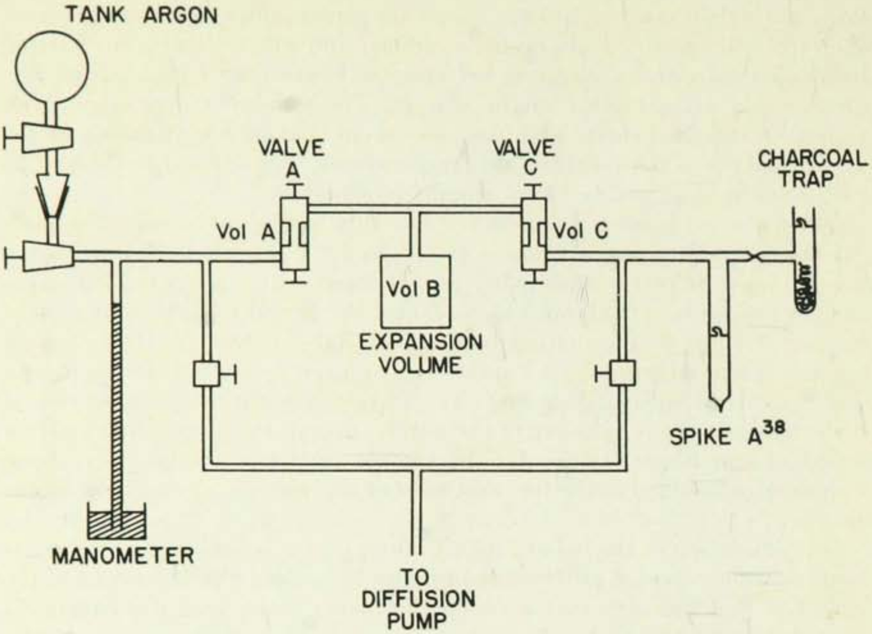

FIGURE 3. — Manifold for calibrating A^{38} spikes. Volumes A and C are 0.504 and 1.002 cc., respectively. Expansion volume B is 17.30 cc.

mercury manometer. The gas in volume A is then expanded into volumes B and C. The amount of gas in volume C is further expanded into the right-hand side of the system. The break-seal on the spike is broken, and all the argon in this part of the system is trapped on the charcoal using liquid nitrogen. The quantity of argon delivered by the system is 1.048×10^{-2} P/T_r cc. STP where P is the pressure measured on the Hg manometer in cm. Hg and T_r is the room temperature. P is adjusted so that when making the isotopic determination the intensities of the A^{36}, A^{38} and A^{40} peaks all fall in the measuring range of the mass spectrometer. Thus a calibration of A^{38} can be made simultaneously against A^{40} and A^{36} of the atmospheric argon. The agreement between the A^{36} and A^{40} calibrations is always within 1 per cent. The agreement between two determinations on each spike set is about 1 per cent and between the capillary pipette method and the expansion volume method, about 2 per cent. An average difference of 1.2 per cent between eight spike sets was found.

Isotopic Measurements. Most of the argon analyses were made with a 60° Nier-type (Nier, 1947) mass spectrometer. The manifolding system used with the instrument is adapted so that samples can be run either by the conventional dynamic technique or by a recirculating technique (Aldrich and Nier, 1948b). A schematic diagram of the mass spectrometer and associated equipment is shown in Figure 4.

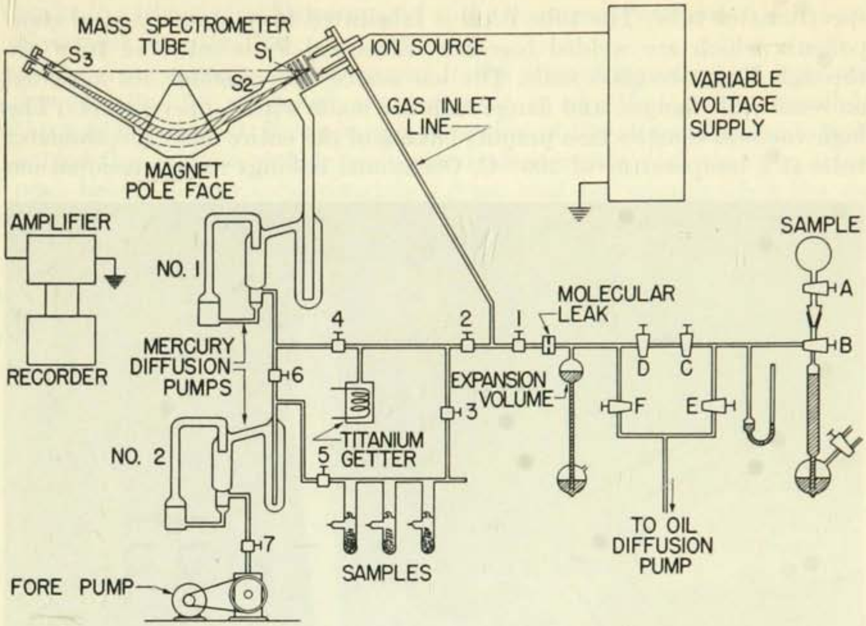

FIGURE 4. — Schematic diagram of argon mass spectrometer tube and gas-handling manifold. Radius of curvature of central ion beam in magnetic field, 6 inches; defining slits S_1, S_2, and S_3 have widths of 0.01, 0.02, and 0.05 inches, respectively. Ion accelerating voltage approximately 1800 volts. Ionizing electron beam of approximately 125 microamperes collimated by magnetic field of approximately 200 gauss perpendicular to diagram in source region.

In the dynamic method the gas to be analyzed flows continuously into the mass spectrometer tube through the molecular leak and gas-inlet line at the rate of approximately 10^{-6} cc. STP/sec. It is pumped away continuously by the two mercury diffusion pumps in series with the mechanical forepump. The pressure in the ion source is such that the argon current for A^{40}, using atmospheric argon, is of the order of magnitude of 10^{-10} amperes. After passing through slit S_3, the resolved ion currents impinge on the ion collector and are measured by the inverse feedback electrometer tube amplifier. Focusing electrodes in the ion source are adjusted so that in the mass range under consideration the ion current is independent of ion accelerating voltage. Mass spectra are obtained by varying the ion accelerating voltage with a motor-driven potentiometer in the power supply furnishing this voltage, and observing the output voltage of the electrometer tube amplifier with a strip-chart recording potentiometer.

Figure 5 is a photograph of the mass spectrometer tube and magnet. The ion source is near the bottom center. The gas manifold is behind and around the box housing the valves toward the right of the photograph. The magnet is mounted on a carriage and can be easily withdrawn from the mass spectrometer tube. A box furnace can be lowered over the entire all-metal mass spectrometer tube. The tube itself is fabricated from stainless steel components which are welded together. Electrical leads into the tube are through Kovar-to-glass seals. The ion source and collector are mounted on removable flanges, and flange seals are made with copper gaskets. The high vacuum construction permits baking of the entire mass spectrometer tube at a temperature of 300° C. Occasional bakings reduce residual ion

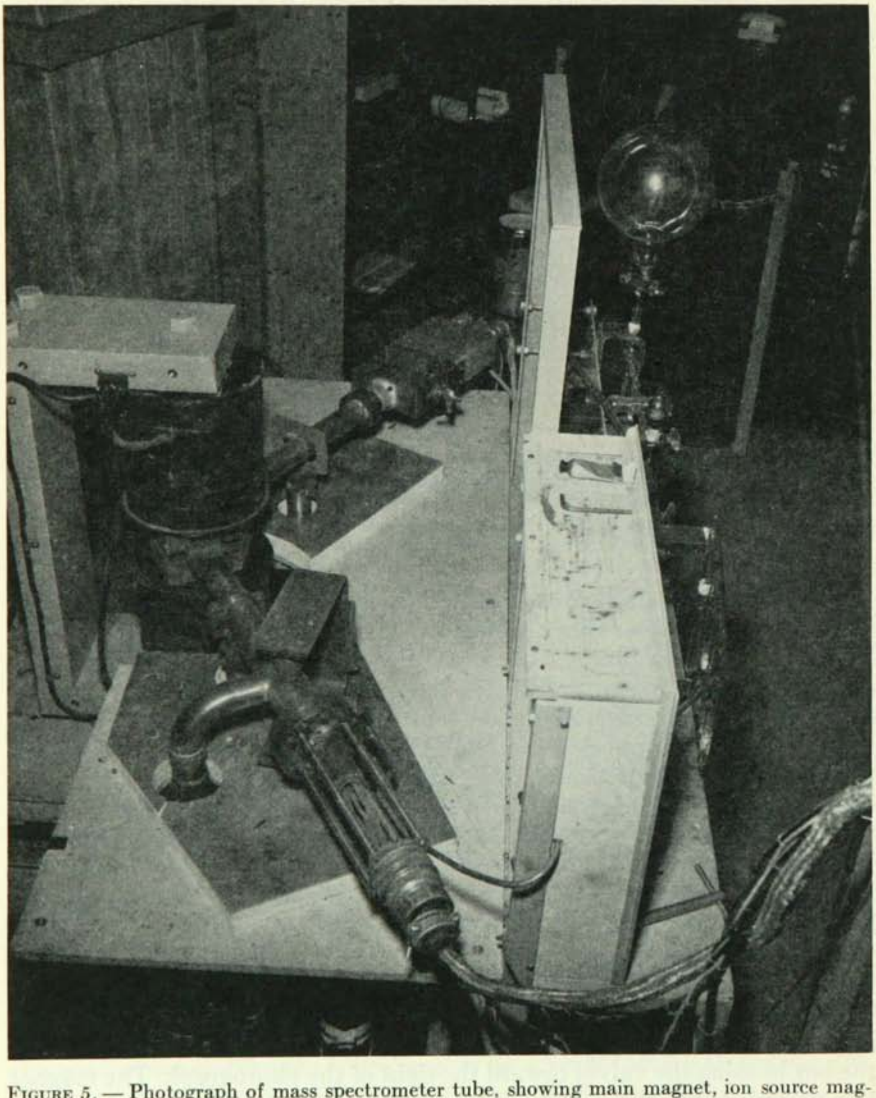

FIGURE 5. — Photograph of mass spectrometer tube, showing main magnet, ion source magnet, ion source and collector assemblies, and gas manifold. Diffusion pumps and traps are below table top.

peaks to a level negligible compared with the currents associated with samples under investigation.

The great majority of the samples in the present investigation were run dynamically. An extracted argon sample is admitted to the manifold through stopcock B. By appropriate setting of the stopcocks, the sample is bled through the pinhole molecular leak at a rate such that the argon peak height decays approximately 1.5 per cent per minute when the expansion volume is 500 cc. Experience has shown that a scan of ten peaks is sufficient to give an accuracy of 1 per cent in the A^{40} / A^{38} ratio. During a run, the ion peaks decay about 10 per cent. Figure 6 shows a typical mass spectrum obtained when the argon extracted from a Precambrian biotite, spiked with A^{38}, is run dynamically.

Samples are generally analyzed in groups of six or more. The perform-

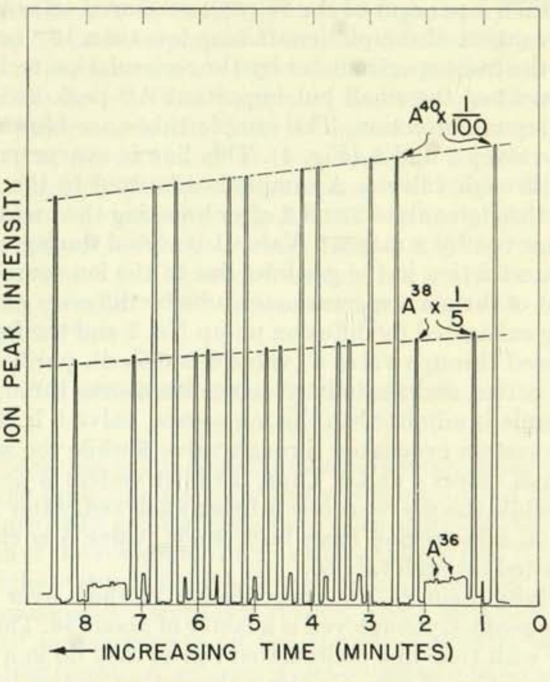

FIGURE 6. — Strip chart of argon from sample KA-24 which had been spiked with A^{38} tracer. Sample was run by the dynamic method, and 10 successive scans of the 40 to 36 region are shown. Ion currents at mass 40, 38, and 36 positions are approximately 8×10^{-11}, 2.5×10^{-12}, and 5×10^{-15} amperes, respectively. Approximately one half of the A^{36} in this sample is due to A^{36} impurity in the spike itself, the remainder to atmospheric argon contamination arising in the gas extraction and handling process. The atmospheric argon contamination generally does not contribute more than one per cent to the A^{40} peak, and correction is made as needed. The peak observed at the mass 39 position comes from the spike and presumably is due to A^{39}, as it appears with the same abundance in all spike samples and cannot be removed by purification of the gas. Slanting lines show decay of the A^{40} and A^{38}. As drawn, the lines fall slightly below the tops of peaks, because a correction has been made for amplifier zero readings.

ance of the instrument is checked with atmospheric argon before and after each group of from three to five samples. A typical afternoon's work might thus consist of running six samples interspersed between three atmospheric argon runs. Such a sequence of runs requires approximately 2½ hours.

The standard atmospheric argon runs (also called discrimination runs) are made primarily to check the mass discrimination characteristics of the mass spectrometer. If the A^{40}/A^{36} ratio measured for atmospheric argon deviates from 295.5 (Nier, 1950), a mass discrimination correction is applied to the data. In practice the A^{40}/A^{36} measured for atmospheric argon seldom differed by more than 2 per cent from the accepted value.

Before and after each run a scan is made of the spectrum over the mass 36 to 40 region. Residual peaks in the instrument are generally so small that no 36 peak is detected, and the correction at the 38 position was invariably less than 1 per cent of the 38 peak measured on samples.

The argon content of samples containing less than 10^{-4} cc. STP A^{40} are measured on the mass spectrometer by the recirculation technique to permit measurement of the small but important A^{36} peak necessary for the atmospheric argon correction. The sample tubes are blown onto a glass line between valves 3 and 5 (Fig. 4). This line is evacuated by diffusion pump No. 2 through valve 5. A sample is admitted to the mass spectrometer source through valves 3 and 2 after breaking the break-seal tip with an iron slug moved by a magnet. Valve 1 is closed during this operation. There is no constriction in the gas inlet line to the ion source, and the gas is pumped out of the mass spectrometer tube by diffusion pump No. 1. Instead of being exhausted by diffusion pump No. 2 and the forepump, however, it is passed through valve 4 (valve 6 is closed), purified by the titanium-sponge getter, and readmitted to the ion source through valve 2.

After a sample is admitted to the ion source, valve 3 is closed, and the sample input system evacuated through valve 5 while the sample is recirculated through valves 4 and 2. Thus, the inlet system is prepared for the next sample while the previous one is being analyzed. After 10 to 20 scans of the 40 to 36 mass region have been made, valve 5 is closed, and the sample exhausted through valve 6.

The sensitivity gain of the recirculation method over the dynamic method in the geometry employed is a factor of about 50. The peak heights do not decay with time in a recirculated run as they do in a dynamic run, because the quantity of argon in the recirculating system is not changing with time. A residual blank is obtained in the same manner as the recirculated run, since the method is sensitive enough to detect desorption of very small amounts of argon from the walls of the mass spectrometer tube. This "memory" effect is measured before each recirculating run and an appropriate correction made. Even for young (Cretaceous) samples the residual correction for A^{38} and A^{40} is less than 1 per cent, unless too short a pumping time is allowed between runs. The mass discrimination factor for recirculated runs is determined in the same manner as for dynamic runs.

Analytical Errors. The probable error in the determination of the A^{38} contents of a typical spike set was found to be 1.3 per cent. The error in the potassium determination is estimated to be 1–2 per cent and that for the isotope ratio measurement approximately 1 per cent. The probable total error based only on consideration of the estimated errors for single measurements is approximately ±5 per cent. Variations such as those arising from incomplete recovery of argon from the sample, losses during outgassing, isotope fractionation in gas transfer procedures, and desorption of residual impurities during mass spectrometric analyses have gradually been minimized by improvements and tests over a period of time, but may appear in individual runs to give erratic results.

During the course of the investigation two or more determinations of the argon contents of approximately 90 samples were made, and the average difference in the A^{40} / K^{40} ratios is about 3.5 per cent. The average age difference is less. Two or more argon determinations for 54, or slightly more than one-third of the samples, are listed in Tables 14, 21, and 28. Fifty per cent of these differ by less than 3 per cent, and 80 per cent by less than 5 per cent. The difference in the A^{40} / K^{40} ratios for nine of the samples ranges from 5 to 10 per cent, and for two samples it is greater than 10 per cent. Of the latter, KA-94 (Table 14) is a sample of biotite for which three argon extractions were made, giving A^{40} / K^{40} ratios of 0.292, 0.302, and 0.332. The age computed for the average ratio is 2.50 b.y., and for the extremes, 2.42 and 2.60 b.y. The second sample is a graphitic slate (KA-35, Table 21) which gave A^{40} / K^{40} ratios of 0.140 and 0.166, corresponding to ages of 1.54 and 1.72 b.y.

RUBIDIUM-STRONTIUM METHOD

DEVELOPMENT

Rankama (1954) has summarized the development of the Rb-Sr dating method from the beginning made by Hahn, Strassman and Walling (1937) up to 1953. Since 1953 great strides have been made in the development and application of the rubidium chronometer. Aldrich and Wetherill (1958) have reviewed the status of the Rb-Sr method and the work done in evaluating the decay constant. Since this review, Flynn and Glendenin (1959) have completed measurements on the specific β-activity of Rb^{87} using liquid scintillation counting techniques and obtained a value of $47 \pm 1 \times 10^{9}$ years for the half-life. This value yields $\lambda_\beta = 1.47 \times 10^{-11} / yr.$

The equation for the calculation of the Rb-Sr age,

$$t = \frac{1}{\lambda_\beta} \ln \left[\frac{Sr^{87}}{Rb^{87}} + 1 \right]$$

or

$$t\,(years) = 1.56 \times 10^{11} \log \left[\frac{Sr^{87}}{Rb^{87}} + 1 \right]$$

was used to calculate the Rb-Sr ages found in this report. Comparison ages taken from the literature have been recalculated using the Flynn and Glendenin value for λ_β. In the analytical computation the value of 27.85 atom per cent was used for the relative abundance of Rb^{87}.

Sample Preparation

In general the mica samples prepared for the K-A determination were used; however, a small portion of the original sample was further purified, mainly by the crushing and sieving technique previously described. The potassium feldspar samples were ground to less than 200 mesh and centrifuged in heavy liquids to minimize the amount of plagioclase. The sericite, KA-328, from Gold Island, Saganaga Lake, was also centrifuged.

Analytical Procedures

Reagents and Apparatus. The water is double distilled, the hydrochloric acid redistilled as constant-boiling acid, and the oxalic acid solution purified by passing through a large ion exchange column. These three reagents are stored in polyethylene containers. The A.R. grades of hydrofluoric, perchloric, and sulfuric acids are used without further treatment. All glassware is cleaned with hot nitric acid prior to use.

The cation exchange column employed contains 200-400 mesh, medium porosity Dowex 50 W $\times$ 8 styrene-type cation exchange resin. After precleaning with nitric acid and hydrochloric acid, the resin is slowly settled in a pyrex tube, 70 cm. in length and 1 cm. in diameter. The tube is fitted with a fritted-glass disc and tapered at the bottom so that liquid cannot collect in greater than drop-size quantity before entering the collection vessel.

Decomposition. A sample sufficiently large to give about about 250 μ g. Rb is decomposed in a platinum dish with a mixture of hydrofluoric, perchloric and hydrochloric acids. An amount of Sr^{86} spike solution is added to make the abundances of Sr^{86} and of Sr^{87} in the sample solution of the same order of magnitude. The solution is evaporated to dryness, treated with additional perchloric and hydrofluoric acids and again evaporated to dryness. Biotite is easily decomposed by this procedure, but muscovite is more resistant, and care must be taken to ensure that complete decomposition has been achieved. The residue is dissolved in 6 N hydrochloric acid and made up to 50 ml. in a volumetric flask.

Rubidium. With the exception of a few unusual samples, a 5 ml. aliquot of the sample solution is transferred to a platinum dish, and an amount of rubidium spike is added which makes the relative abundance of Rb^{87} about twice that of Rb^{85}. A few drops of sulfuric acid are added, the solution is evaporated to dryness, the sulfuric acid fumed off and the residue ignited over a Meker burner. The ignited residue is leached with double-distilled water, decanted or filtered off, and the solution evaporated to dryness for isotope analysis on the mass spectrometer.

Strontium. The remainder of the original sample solution is evaporated to about 10 ml. and enough of the radioactive Sr^{85} isotope added so that strontium may be traced with a scintillation counter in subsequent steps. A little perchloric acid is added and the solution is chilled in an ice bath to precipitate as much of the potassium and rubidium as possible. After filtering or centrifuging, oxalic acid is poured into the ion exchange column, and the filtrate or supernate added. Enough oxalic acid is passed through the column to elute the iron in the sample quantitatively, and 2.5 N hydrochloric acid is passed through the column to elute the Sr. That portion of the eluate (about 20 ml.) containing the greatest part of the Sr, as determined by testing the collected portions of the eluate with a scintillation counter, is treated with 1–2 drops of perchloric acid and evaporated to dryness preparatory to isotopic analysis on the mass spectrometer.

Spike Solutions. Strontium carbonate enriched in Sr^{86} and rubidium chloride enriched in Rb^{87} were obtained from the Oak Ridge National Laboratories. The salts were dried, weighed and dissolved in double-distilled water to make the primary spike solutions. The solutions are kept in airtight polyethylene bottles to minimize evaporation and change in concentration.*

The absolute concentrations of the spike solutions were calibrated by isotope dilution using normal rubidium and strontium salts (Davis and Aldrich, 1953). Purified normal rubidium and strontium salts were used to make up standard solutions, and the isotope ratios were checked on the mass spectrometer. Aliquots of the respective normal salt standard were mixed with the spike solution, and the determination of the isotopic ratios on the mass spectrometer enabled the calculation of the concentration of the spike solution. The values obtained were checked against the gravimetric values.

Several calibrations were made, and the relative abundance of the Sr isotopes in the spike solution was found to be as follows: Sr^{84}, 0.0197; Sr^{86}, 83.44; Sr^{87}, 2.028; and Sr^{88}, 14.52 atom per cent. The Sr^{86} spike solution contained Sr^{86}, 3.712; Sr^{87}, 0.0913; and Sr^{88}, 0.6609 μg./ml. The relative abundance of the Rb isotopes in the enriched Rb^{87} spike solution was determined to be Rb^{85}, 4.81; and Rb^{87}, 95.18 atom per cent, and the solution contained Rb^{85}, 0.127 and Rb^{87}, 3.002 μg./ml.

Isotopic Measurements. The rubidium and strontium isotope ratio measurements are made on a six-inch, 60° Nier-type mass spectrometer. The usual shield and electron beam apparatus are replaced by a shield milled from a solid block of stainless steel with an opening on the side into which interchangeable stainless steel filament blocks can be slipped. Approximately 1×30 mil tantalum filaments are spot welded onto Kovar pins which fit into the filament blocks in such a way that the filaments are aligned 1½ mm. behind the first slit of the ion source. Conventional J

* There is some evidence suggesting polyethylene bottles are not wholly satisfactory and that solutions should be checked at 3-6 months intervals.

plates and collimating slits are used. The grounded collimating slits are 0.005 and 0.010 inches wide, respectively. A 0.025-inch collector slit and conventional feedback electrometer amplifier (10^{11} ohm resistor) follows the magnetic analyzer. Since ions are formed on the tantalum filament by surface ionization, a source magnet is not used. Strontium ions appear and produce a steady ion beam of the order of 10^{-12} amperes at about 2.3 amperes filament current. Rubidium ion beams of about 10^{-11} amperes are obtained at about 1 ampere filament current.

One or two drops of the extracted strontium perchlorate are placed on a clean filament and loaded into the spectrometer. It was found that the most stable ion currents are obtained after outgassing the filament (with sample) overnight at 1.5 amperes filament current. Any rubidium present is thus baked off the filament. By slowly bringing the filament current to more than 2 amperes over a period of several hours, strontium peaks appear and can be stabilized at a convenient intensity. Twenty to thirty scans of the 86, 87, and 88 mass regions are sufficient to calculate the isotope ratios with a 1 to 2 per cent error. Constant checking of the mass-85 position during a run will indicate rubidium contamination. Whenever an 85 peak appears, the ion source is cooled for an hour or more before the run can be continued, as rubidium could be emitted from hot source parts other than the filament.

After the strontium run is completed, the same filament is used for the rubidium determination. One drop of the spiked rubidium sample solution is placed on the filament and loaded into the mass spectrometer. Steady ion beams are obtained after half an hour of outgassing. In order to ensure that there is no cross-contamination between the samples, the ion source parts are cleaned in nitric acid between each run. In addition, separate shield blocks and slits are used specifically for rubidium or strontium determinations. This ensures the appearance of only normal rubidium (as measured at mass 85) in strontium runs, enabling a correction to the mass 87 peak to be made in the case of contamination.

Analytical Errors. An important unavoidable contribution to the error in the calculated Rb-Sr age lies in the determination of, and correction for, the amounts of normal strontium present in mineral samples. This amount of strontium is usually small, less than 20 ppm., but often it is relatively large compared with the amount of radiogenic Sr^{87} present, especially in young or Rb-deficient minerals. Gast (1955) has shown that the variations in the isotopic composition of normal strontium are small, so that a good correction may be made for normal strontium most of the time. If the amount of normal strontium is very large compared to the radiogenic Sr^{87}, the error in the isotopic abundance of Sr^{87} in normal strontium will affect the calculated Rb-Sr age.

In the corrections for normal strontium the ratios $Sr^{87}/Sr^{88} = 0.0841$ and $Sr^{87}/Sr^{86} = 0.713$ were used. These values based on the measurements of White and Cameron (1948) are essentially the ratios recommended by

Gast (personal communication, 1959). Gast has treated the subject of analytical errors in Rb-Sr dating more completely and calculated probable errors in the Sr^{87} / Rb^{87} ratios of from 2 to 3.4 per cent for old Precambrian micas. In the present work the mass spectrometric measurements are considered to be accurate to about 2 per cent, and the probable error in the Sr^{87} / Rb^{87} ratios is approximately ± 5 per cent. Duplicate determinations on nine samples showed a maximum difference of 6 per cent and an average difference of 2.5 per cent.

EVALUATION OF RADIOACTIVITY AGES

The evaluation of radioactivity ages is a complicated matter, because many factors are involved some of which are poorly understood. The present discussion touches briefly on analytical problems, decay constants, and some of the geologic problems.

Analytical Problems

The precision or reproducibility of the methods used to determine the relative abundance of parent and daughter nuclides for the calculation of an age usually can be estimated, but the accuracy is much more difficult to appraise. Efforts to determine probable accuracy include comparison of the basic analytical determinations by different methods and by different laboratories and also comparison of the age found for a rock or geologic formation by different dating techniques.

A number of samples has been available through the courtesy of the geochronology groups of the Carnegie Institution of Washington, the Massachusetts Institute of Technology, the Lamont Geological Observatory, and others. In an earlier paper (Baadsgaard, Goldich, Nier, and Hoffman, 1957) a comparison of the A^{40} / K^{40} determinations on the same minerals made by a number of groups suggested that the reproducibility among these laboratories was of the order of five per cent.

Analytical data for some of the interlaboratory check samples have been recently published by Aldrich, Wetherill, Davis, and Tilton (1958), and in the discussion that follows some comparative data from the Carnegie Institution of Washington and from the University of Minnesota are given (Table 6). The basic analytical data are in parts per million by weight; K^{40} has been computed on the basis of $K^{40} = 1.21 \times 10^{-4}$ gm./gm. K; and the ages are computed with the constants used in this report and given in billions (10^9) of years.

Bikita Quarry Lepidolite. The A^{40} / K^{40} and Sr^{87} / Rb^{87} ratios for lepidolite from the Bikita quarry in Southern Rhodesia, calculated from the data given by Aldrich, Wetherill, Davis, and Tilton (1958), are in good agreement with the results obtained at Minnesota. Although the ratios and the ages from the two laboratories differ by less than 1 per cent, the analytical determinations made at Minnesota are consistently lower by 2–3 per

TABLE 6. ANALYTICAL DATA FOR LEPIDOLITE, MUSCOVITE, AND BIOTITE FROM INTERLABORATORY CHECK SAMPLES

Lab.	A^{40} ppm.	K^{40} ppm.	A^{40}/K^{40}	Age b.y.	Sr^{87} ppm.	Rb^{87} ppm.	Sr^{87}/Rb^{87}	Age b.y.
			Lepidolite (Southern Rhodesia)					
Carnegie Inst.	2.46	9.05	0.272	2.33	356	9370	0.0380	2.53
Univ. of Minnesota	2.38	8.81	0.270	2.32	348	9110	0.0382	2.54
			Muscovite (North Carolina)					
Carnegie Inst.	0.232	10.78	0.0215	0.330	1.43	270	0.00529	0.360
					1.50	275	0.00545	0.370
Univ. of Minnesota	0.217	10.18	0.0213	0.330				
			Biotite (Texas)					
Carnegie Inst. (granite)	0.370	4.44	0.0832	1.05	1.77	115	0.0154	1.04
Univ. of Minnesota (pegmatite)	0.685	8.19	0.0835	1.06	9.88	634	0.0156	1.05

cent. A possible explanation is that the samples were slightly different, but compensating errors cannot be ruled out.

Chestnut Flat Mine Muscovite. Comparative analytical data for muscovite from the Chestnut Flat mine, Spruce Pine district, North Carolina, show considerably larger variations than were found for the Bikita lepidolite. Although the basic analytical data differ by 6 per cent, the resulting A^{40}/K^{40} ratios differ by 1 per cent, and the agreement must be the result of differences in the samples or of compensating errors. Duplicate Rb-Sr determinations in the Carnegie Institution laboratory differ by 3 per cent.

Petrick Quarry Biotites. The samples of biotite analyzed in the Carnegie Institution and at the University of Minnesota are not the same and cannot be considered interlaboratory check samples, but the agreement in ages from the two laboratories is noteworthy. The granite and pegmatite of the Petrick quarry in Llano County, Texas, have been described by Goldich (1941) and by Barnes, Dawson, and Parkinson (1947). Biotite dated by the Carnegie Institution group is from the granite, but the biotite dated at Minnesota is from a pegmatite in the granite; hence the analytical data are not comparable.

COMPARISON OF K-A AND Rb-Sr AGES

The analytical data and the Rb-Sr ages for 35 samples are given in Table 7. Four of these samples were analyzed by P. W. Gast in the Lamont Geological Observatory and one by George Edwards in the Shell Development Company laboratory in Houston, Texas. The K-A ages, all determined at Minnesota, for 32 samples of mica are included in Table 7, and the analytical data for these samples are given in tables that follow. Age determinations for miscellaneous samples are presented in Table 8. Figure 7 is a plot of the K-A versus Rb-Sr ages for the 32 samples (Table 7) but also includes five additional samples which will be reported in papers now in press or in preparation. The scattering of the points in Figure 7 may be attributed in part to analytical errors; each point represents a pair of ages for which four analytical determinations are required. The scatter may also reflect the different behavior of the micas with regard to the retention of argon and of strontium during metamorphism.

The arithmetic mean of the ratio, Rb-Sr age/K-A age, for the 37 samples is 0.99, with a range of 0.90 to 1.10. The difference between the two ages is less than 5 per cent for 30, or 80 per cent, of the samples and between 5 and 10 per cent for the remainder. Aldrich, Wetherill, Davis, and Tilton (1958) give comparative K-A and Rb-Sr ages for micas from 37 localities. Three of these localities are duplicated in the Minnesota samples, but the others are widely distributed in North America and include six

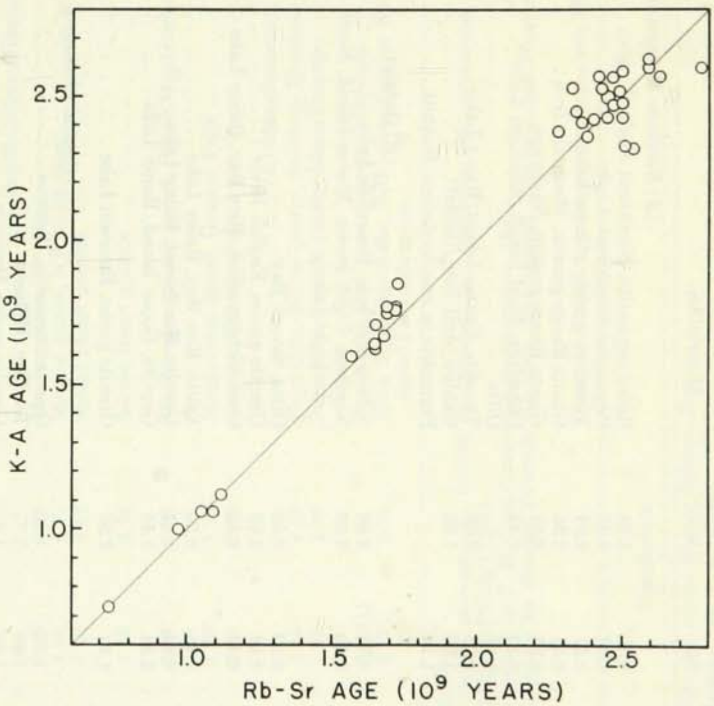

FIGURE 7. — Plot of K-A versus Rb-Sr ages. Grouping of the samples reflects the major periods of orogeny; Algoman, ~2.5 b.y., Penokean, ~1.7 b.y., Grenville, ~1.0 b.y. Data in Table 7.

TABLE 7. Sr^{87}/Rb^{87} AGE DETERMINATIONS
(Data in parts per million by weight)

KA No.	Rb-Sr Age b.y.	K-A Age b.y.	Description	Total Rb	Rb^{87}	$*Sr^{87}$	Normal Sr	Sr^{87}/Rb^{87}
			(A) Northern Minnesota					
17M[a]	2.50[b]	2.48	Rader pegmatite, Northwest Angle	4730	1340	50.4	2.0	0.0376
88B	2.47	2.47	Pegmatite, Northwest Angle	1200	340	12.6	56.3	0.0371
239B	2.47	2.57	Vermilion granite, Crane Lake	593	168	6.25	9.2	0.0372
48B	2.51	2.33	Giants Range granite, Mountain Iron	727	206	7.79	10.4	0.0378
237B	2.33	2.53	Giants Range granite, Nashwauk	364	103	3.61	7.9	0.0350
328S	2.50	2.43	Pegmatite, Gold Island, Saganaga Lake	274	77.6	2.92	34.3	0.0376
328F	2.49		Ditto	470	133	4.98	45.1	0.0374
307B	2.28	2.38	Tonalite, Grassy Island, Rainy Lake	470	133	4.55	33.4	0.0342
65B	1.09	1.06	Gabbro, drill hole, Babbitt	470	133	2.17	18.9	0.0163
296B	1.12		Pegmatite in iron formation, Babbitt	1890	535	8.89	12.2	0.0166
			(B) Ontario					
112B	2.77 (?)	2.60	Schist, drill hole, Briarcliffe Lake	306	86.6	3.61	11.1	0.0417
76B	2.50	2.59	Northern Light gneiss. Moose Island, Northern Light Lake	250	70.9	2.63	26.3	0.0371
				253	71.7	2.73	18.5	0.0381
77B	2.59	2.60	Ditto, Savage Bay	339	95.9	3.74	20.4	0.0390
262B	2.59	2.63	Granite gneiss, English River	487	138	5.38	8.2	0.0390
191B	2.49	2.52	Coutchiching schist, Rice Bay, Rainy Lake ..	262	74.3	2.86	3.8	0.0385
				276	78.2	2.83	15.2	0.0362
320B	2.45	2.50	Aplite, Rice Bay, Rainy Lake	530	150	5.51	27.5	0.0368
222B	2.36	2.41	Granite, Ben Island, Rainy Lake	678	192	6.81	37.3	0.0355
224B	2.34	2.45	Granite, Goose Island, Rainy Lake	434	123	4.26	13.7	0.0346
				424	120	4.25	10.5	0.0354
272B	2.38	2.36	Granite gneiss, Emerson Lake	625	177	6.33	7.1	0.0358
			(C) Central Minnesota					
1B	1.72	1.76	Quartz monzonite, Warman	427	121	3.11	17.0	0.0257
64B	1.69	1.77	Tonalite, Hillman	484	137	3.45	17.3	0.0252
41B	1.68	1.67	Granite gneiss, Denham	420	119	2.96	48.2	0.0249
				406	115	2.90	5.2	0.0252
58B	1.65	1.64	St. Cloud Red Granite	886	251	6.17	8.5	0.0246
164B	1.65	1.71	McGrath gneiss, McGrath	515	146	3.61	10.5	0.0247

TABLE 7 — *Continued*

KA No.	Rb-Sr Age b.y.	K-A Age b.y.	Description	Total Rb	Rb^{87}	$*Sr^{87}$	Normal Sr	Sr^{87}/Rb^{87}
			(D) Southwestern Minnesota					
14B	2.43[c]	2.53	Morton gneiss, Morton	748	212	7.74	32.2	0.0365
107B	2.42	2.57	Morton gneiss, NW of Morton	547	155	5.64	10.6	0.0363
13B	2.45	2.43	Sacred Heart granite	692	196	7.21	13.4	0.0368
				696	197	7.22	17.3	0.0366
9B	2.40	2.42	Sacred Heart granite	745	211	7.52	36.4	0.0356
				798	226	8.22	3.9	0.0364
27B	1.73[c]	1.85	Montevideo granite gneiss, SE of Montevideo	957	271	7.03	25.4	0.0259
	1.75			953	270	7.07	30.3	0.0262
54B	1.69[c]	1.75	Montevideo gneiss, Granite Falls	477	135	3.42	13.1	0.0253
29B	1.65	1.63	Granite, Granite Falls	431	122	3.01	30.3	0.0247
			(E) Miscellaneous					
OSD(L)	2.54	2.32	Pegmatite, Bikita quarry, Southern Rhodesia.	32170	9110	348	22.6	0.0382
128B	1.05	1.06	Pegmatite, Petrick quarry, Llano County, Texas	2240	634	9.88	11.5	0.0156
OSA(F)	1.62		Pegmatite, Dickinson County, Michigan	1020	289	6.98	9.2	0.0242
190	0.73[d]	0.74	Illite, Siyeh limestone, Belt series, Glacier National Park, Montana	235	66.6	0.72		0.0108

* Radiogenic Sr^{87}.
[a] Letter denotes mineral: (B), biotite; (F), feldspar; (L), lepidolite; (M), muscovite; (S), sericite.
[b] Gast, Kulp, and Long (1958).
[c] Determination by P. W. Gast (personal communication, 1959).
[d] Determination by George Edwards (Goldich, Baadsgaard, Edwards, and Weaver, 1959).

TABLE 8. A^{40}/K^{40} AGE DETERMINATIONS FOR MISCELLANEOUS SAMPLES

KA No.	Description	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}	K-A age b.y.	Rb-Sr age b.y.
11B	Granite gneiss, Rio de Janeiro, Brazil	8.57	8.59	0.271	0.0316	0.47	
11F	Ditto	13.69	13.72	0.340	0.0248		
128B	Pegmatite, Petrick quarry, Llano County, Texas	8.17	8.19	0.685	0.0835	1.06	1.05
190	Illite, Siyeh limestone, Belt series, Glacier National Park, Montana	10.38	10.40	0.558	0.0537	0.74	0.73
OSD (L)	Pegmatite, Bikita quarry, Southern Rhodesia	8.79	8.81	2.38	0.270	2.32	2.54
OSH (M)	Pegmatite, Chestnut Flat mine, Spruce Pine, North Carolina	10.16	10.18	0.217	0.0213	0.33	

African localities in addition to the Bikita quarry which is common to both sets of data. The Rb-Sr ages (Carnegie Institution) have been recomputed ($\lambda_\beta = 1.47 \times 10^{-11}$/yr.) for comparison, and the ratio, Rb-Sr age/K-A age, ranges from 0.95 to 1.35 with a mean of 1.04. If two samples with ratios of 1.25 and 1.35 are excluded, the mean is 1.03. The variance for the Minnesota data is 0.17 and for the Carnegie Institution laboratory data, 0.35. The Minnesota samples are a more selective group, areally, and probably also geologically, but the agreement between the two laboratories is nonetheless noteworthy.

The Carnegie Institution data are of special interest, because they include a good representation of different micas. The arithmetic mean of the ratio, Rb-Sr age/K-A age, for 16 samples of biotite is 1.01; for 9 of muscovite, 1.03; and for 11 of lepidolite, 1.04. The age ratio for 31 samples of biotite analyzed at Minnesota is 0.99.

Decay Constants

One of the assumptions tacitly implied in the discussion above is that the decay constants for K^{40} and Rb^{87} are known well enough to warrant comparison of K-A and Rb-Sr ages. In the early phases of the development of the potassium-argon method a specific gamma activity of 3.24 ± 0.15 gammas per second per gram of natural potassium was calculated by Wetherill, Wasserburg, Aldrich, Tilton, and Hayden (1956) by comparing the A^{40} / K^{40} ratios of micas with the concordant uranium-lead ages of cogenetic uraninite. Wetherill (1957) later found a specific gamma activity of 3.39 ± 0.12/sec./gm., and the latter value was used to calculate $\lambda_\epsilon = 0.589 \times 10^{-10}$/yr. used in this report. Wetherill (1957, p. 548) calculated that the 11 mica samples, which were used in the earlier investigation (Wetherill *et al.*, 1956) to obtain λ_ϵ, retained from 80 to 99 per cent of their radiogenic argon, the mean being 91 per cent.

The half-life of Rb^{87} was also determined by Aldrich, Wetherill, Tilton, and Davis (1956) by comparing Sr^{87}/Rb^{87} ratios of six mica samples with concordant uranium-lead ages. Their computed value of 50×10^9 years for the half-life falls within the limits of laboratory experiments which give a range of from 41 to 61×10^9 years. In this report the laboratory-determined half-life of 47×10^9 years found by Flynn and Glendenin (1959) has been accepted and used in preference to the geologically determined half-life. Comparative ages for the three localities, Bikita quarry, Chestnut Flat mine, and Petrick quarry, serve to illustrate some of the problems (Table 9).

The ages determined by the various methods for the Petrick quarry locality are in good agreement; however, the K-A ages for the Bikita quarry lepidolite and for the Chestnut Flat mine muscovite are notably lower than the Rb-Sr ages, and these in turn are lower than the U-Pb ages. If a half-life of 50 billion years (Aldrich *et al.*, 1956) is used for Rb^{87}, the Rb-Sr ages given above are increased by 6 per cent and are brought into good

TABLE 9. COMPARATIVE AGES OBTAINED BY DIFFERENT DATING METHODS
(Aldrich, Wetherill, Davis, and Tilton, 1958)

Mineral	K-A	Rb-Sr	U^{238}-Pb^{206}	U^{235}-Pb^{207}	Pb^{207}-Pb^{206}	Th^{232}-Pb^{208}
		Bikita Quarry				
Lepidolite	2.33	2.53				
Monazite			2.64	2.67	2.70	2.64
		Chestnut Flat Mine				
Muscovite	0.330	0.360				
K-feldspar		0.360				
Uraninite			0.385	0.390	0.400±.050	
Uraninite			0.370	0.375	0.420±.050	
		Petrick Quarry				
Biotite	1.05	1.04				
Zircon			0.950	0.990	1.07	0.890

agreement with the U-Pb ages. Using 50 rather than 47 billion years for the half-life of Rb^{87} in the comparison of Rb-Sr versus K-A ages, the ratio, Rb-Sr age/K-A age, for the samples analyzed in the Carnegie Institution becomes 1.10, and with the exception of one sample, the Rb-Sr ages are consistently greater than the K-A ages. This difference between Rb-Sr and K-A ages, then, might be attributed to loss of argon. It is well known that K-feldspars commonly are appreciably deficient in argon compared to the associated micas, and therefore some loss of argon from the micas might also be expected.

The K-A ages of micas may be appreciably reduced by metamorphism as has been demonstrated in a number of areas and will be further discussed in the following section. The Rb-Sr age, however, may be similarly considerably reduced by metamorphism. In view of the geologic problems it is obviously desirable to derive the decay constants from laboratory determinations of the specific activities of the parent nuclides. Corroboration or further refinement of the constants for Rb^{87} and for K^{40} will be particularly useful.

GEOLOGIC PROBLEMS

Quite apart from the analytical errors and the uncertainties of the decay constants, alteration by weathering or by metamorphism, or by combinations of processes may be an important factor in evaluating radioactivity ages. Geologic processes acting on minerals subsequent to their formation may affect not only the K-A and Rb-Sr but also the U-Pb ages, and the problem is one of determining whether or not the mineral has been a closed system with respect to both parent and daughter nuclides. The complexity of this aspect of age evaluation or interpretation should not be minimized, and a great deal of study will be necessary to solve some of the problems.

The loss of argon from potassium-bearing minerals is perhaps the chief non-analytical factor which affects A^{40} / K^{40} ages. The apparent deficiency in argon of K-feldspars relative to associated micas was shown by Wetherill, Aldrich, and Davis (1955), Wasserburg, Hayden, and Jensen (1956), and Folinsbee, Lipson, and Reynolds (1956). The A^{40}/K^{40} ratios for 20 mica-feldspar pairs are plotted in Figure 8. A large number of the points fall close to the line indicating an argon deficiency of 35 per cent for the K-feldspar. Some of the scattering of samples may be the result of analytical errors, but duplicate determinations on some of the samples indicate that other factors must be involved to explain the behavior of the mica-feldspar pairs such as those representing the granites from Snowbank Lake and Babbitt in Minnesota and from Mellen, Wisconsin.

At Babbitt the Giants Range granite has been affected by intrusion of gabbro related to the Duluth complex, and a similar relationship is highly

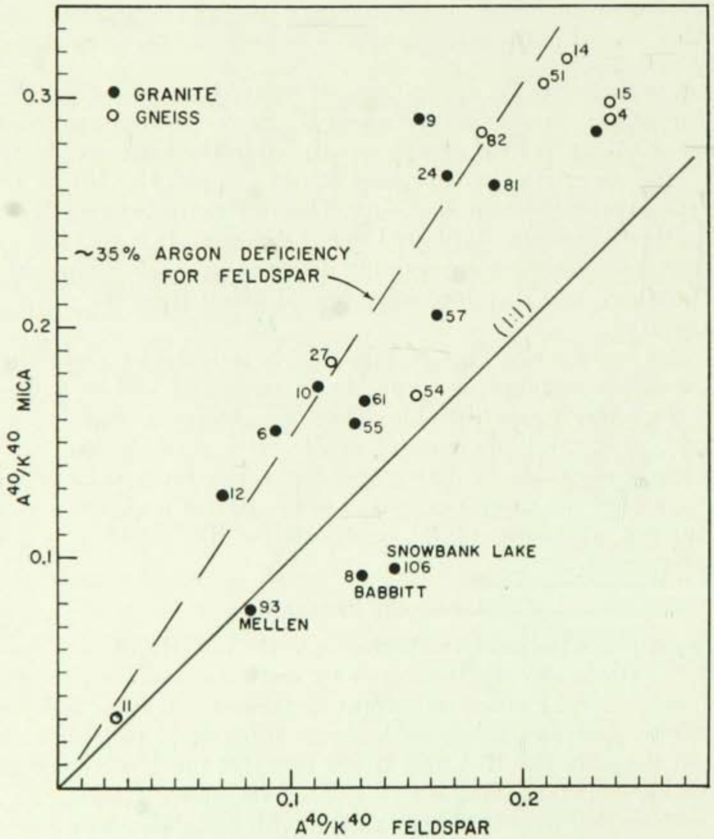

FIGURE 8.—Plot of A^{40}/K^{40} ratios for mica-feldspar pairs. Numbers refer to KA-sample numbers. No. 4 is a mica-feldspar pair from the pegmatite near Kinmount; all others represent granites or granitic gneisses. Data are given in tables in text.

probable at Snowbank Lake. The K-A ages for biotite samples from Babbitt and from Snowbank Lake are 1.1 and 1.2 b.y., respectively, and similar ages are found for the gabbro at Duluth and for related intrusives (Table 14). The Biwabik iron-formation in the vicinity of Babbitt has been thoroughly recrystallized, and biotite from a pegmatite in the iron formation is dated at 1.1 b.y. (Rb-Sr). The apparent K-A ages for K-feldspar from the granites at Babbitt and at Snowbank Lake are 1.5 and 1.6 b.y., and the inference is that the feldspars were less affected by the metamorphic action of the gabbro than was the biotite.

A plot of the A^{40}/K^{40} determinations for the mica-feldspar pairs compiled from the literature suggests that the argon loss from the feldspars may be time dependent, but the problem of the variable effects of metamorphism together with the unknown precision of the data from the many different laboratories makes it impossible to treat the rate of loss quantitatively. Very young feldspars, less than 100 million years old, apparently may lose little or no measurable argon compared to the associated micas.

Because of their variable argon deficiency K-feldspars from Precambrian rocks are unreliable for K-A age determinations. Although the A^{40}/K^{40} ratios for a number of feldspars are included in the tables for comparison with the associated micas, ages are not calculated for the feldspar determinations.

The possibility of gain or loss of potassium without simultaneous loss of argon cannot be completely dismissed. The biotites from many granites and gneisses used in the present project were partially chloritized; however, no correlation could be found between the degree of alteration and the apparent age for different samples from a single geologic unit. Aldrich and Nier (1948b) showed that beryl crystals may contain large amounts of argon, and Damon and Kulp (1958) demonstrated that all beryl crystals contain excess argon and that cordierite and tourmaline also may contain A^{40} in excess of that which can be accounted for from radioactive decay. Damon and Kulp conclude that the argon is trapped at the time of formation of the minerals. Whether or not A^{40} is occluded in feldspars and in micas at the time of crystallization cannot be easily demonstrated. The general concordancy of the K-A and Rb-Sr ages for many micas suggests that large quantities of argon probably are not occluded at the time of crystallization.

The greater stability of K-feldspar compared to mica under conditions of regional metamorphism is suggested by the recent work of the Carnegie Institution of Washington laboratories (Tilton, Wetherill, Davis, and Hopson, 1958; Davis, Tilton, Aldrich, and Wetherill, 1958) on rocks in the Baltimore, Maryland–Washington, D.C. area. Isotopic U-Pb analyses of zircons from the Baltimore gneiss give an age of approximately 1100 million years. Two samples of microcline from the gneiss in the Baltimore area give similar Rb-Sr ages, but the biotite fractions from the gneiss give a much lower age of approximately 300 million years. Tilton, Wetherill, Davis, and Hopson (1958, p. 1473) considered the possibility of the Baltimore gneiss being a clastic sediment that was metamorphosed during the Appalachian orogeny, 300–350 million years ago, but they favor an origin at the time of the Grenville orogeny (1.1 b.y.) which affected the eastern part of the continent. This interpretation is supported by the U-Pb ages of approximately 1100 million years obtained for zircons from the Canada Hill gneiss and the Storm King granite, Bear Mountain, New York, and from gneiss of Mary's Rock Tunnel in the Shenandoah National Park, Virginia.

A plot of the K-A versus Rb-Sr ages for biotites from the Appalachian rocks analyzed by the Carnegie Institution group is shown in Figure 9. It would appear from these samples that if the degree of discordancy between the U-Pb ages for zircon and the Rb-Sr age for mica is indicative of the

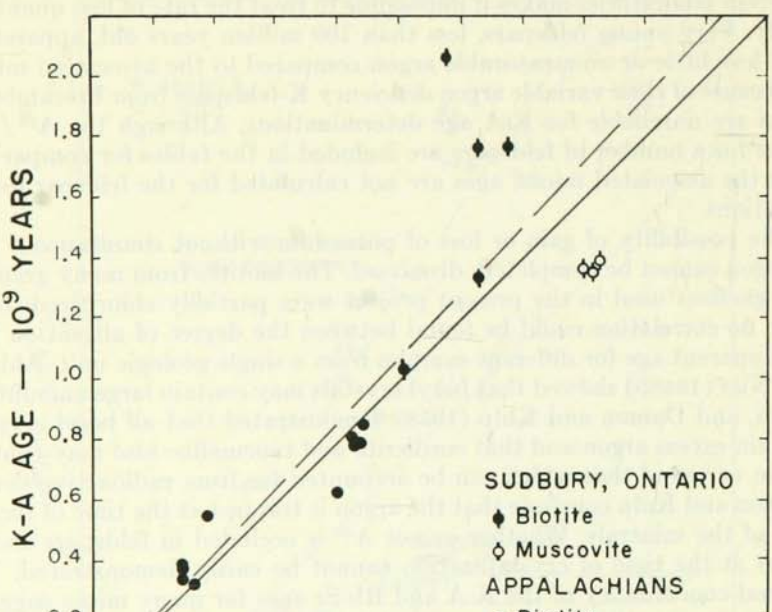

FIGURE 9. — Plot of K-A versus Rb-Sr ages for micas from rocks of the Appalachian Mountains and the Sudbury, Ontario regions. Data from Tilton, Wetherill, Davis, and Hopson (1958); Davis, Tilton, Aldrich, and Wetherill (1958); and Aldrich and Wetherill (1958). The Rb-Sr ages were recomputed on the basis of a half-life of 47×10^9 yr. ($\lambda_\beta = 1.47 \times 10^{-11}$/yr.). The dashed line shows position the samples would have with reference to the 1:1 line if the half-life were taken as 50×10^9 yr. ($\lambda_\beta = 1.39 \times 10^{-11}$/yr.).

degree of metamorphism, severe metamorphism may result in Rb-Sr ages that are lower than the corresponding K-A ages for the biotite samples. Long, Kulp, and Eckelmann (1959), in their study of the major metamorphic events in southeastern United States, obtained similar results.

Marked discordance between the Rb-Sr and K-A ages has also been found for the Sudbury, Ontario region (Aldrich, and Wetherill, 1958, p. 272). The plot of K-A versus Rb-Sr ages (Fig. 9) for eight samples shows a marked difference in the behavior of muscovite and biotite. The Rb-Sr ages for three samples of muscovite are greater than the K-A ages for these samples, and the ratio, Rb-Sr age/K-A age, is approximately 1.2. Three samples of biotite show a reverse relationship with a range in the ratio of from 0.56 to 0.76. The ratios for the other two biotite samples are approximately 1.0.

The data from the Appalachians and from the Sudbury region illustrate the complexity of the behavior of micas under conditions of metamorphism and together with observations from the work in Minnesota and adjacent areas provide ample reason for a cautious approach to the interpretation of K-A and Rb-Sr ages. Further discussion of the problems will be undertaken in the presentation of the results in later sections of this report.

3. NORTHERN MINNESOTA

INTRODUCTORY STATEMENT

Early Precambrian rocks similar to those which occur in northern Minnesota were first defined in Ontario. The Keewatin was named by Lawson (1885) for exposures around Lake of the Woods in the Keewatin district of Ontario. Later, in a study of the Rainy Lake region, Lawson (1888) found a sequence of sedimentary rocks beneath the Keewatin, and to this unit he gave the name Coutchiching for outcrops of schist and gneiss at Coutchiching Rapids at the head of Rainy River at the west end of Rainy Lake.

Rainy Lake was one of a number of areas in the Lake Superior region visited by a committee of Canadian and American geologists appointed by the Geological Survey of Canada and the United States Geological Survey to consider some of the problems and nomenclature which concerned both groups. The report of the Special Committee (Adams, Bell, Lane, Leith, Miller, and Van Hise, 1905) discredited the designation of Coutchiching in the vicinity of Shoal Lake, Ontario, and Rat Root Bay, Minnesota. At Shoal Lake, schists mapped by Lawson as Coutchiching were found to overlie a conglomerate which in turn rests on the Bad Vermilion granite and on Keewatin greenschists. The conglomerate contains boulders of granite, greenschist, and greenstone which were locally derived. Similar relationships were found on the American side. The succession and nomenclature recommended by the Committee are given in Table 10.

TABLE 10. PRECAMBRIAN SUCCESSION AND NOMENCLATURE RECOMMENDED BY SPECIAL COMMITTEE (Adams *et al.*, 1905)

Cambrian: Upper sandstones, etc., of Lake Superior
unconformity
Precambrian
Keweenawan (Nipigon)
unconformity
Huronian { Upper (Animikie)
Huronian {   unconformity
Huronian { Middle
Huronian {   unconformity
Huronian { Lower
unconformity
Laurentian
Intrusive contact
Keewatin

In 1911 the Canadian Geological Survey returned Lawson to the Rainy Lake area for additional work which led to the preparation of a detailed map. Lawson (1913a, p. 24) was frank to admit that his earlier work was in error, in that the conglomerate and schists in the Shoal Lake area are younger than the Keewatin. He redefined the rocks and named them the Seine series for outcrops along the Seine River east of Shoal Lake. He reaffirmed, however, his earlier view concerning the existence of a sedimentary series below the Keewatin greenstone for which he retained the name Coutchiching (Fig. 10). Unfortunately, the two areas which best support Lawson's interpretation, Rice Bay and Bear Passage, were not seen by the Special Committee.

Both in the Lake of the Woods and in the Rainy Lake areas Lawson (1885, p. 100; 1888, p. 142) recognized granite and gneiss, intruding the Keewatin, to which he applied the name Laurentian. Lawson's long-range correlation of the granite and gneiss in Ontario with the Laurentian of Quebec (Logan and Hunt, 1855) was never questioned, apparently because geologists at that time felt that the oldest geologic unit would have to be some type of "Fundamental gneiss." Lawson also recognized that younger granites intrude the Laurentian granite, and although these were differentiated on the geologic maps, no separate name was given to them.

In his re-study of the Rainy Lake area, Lawson (1913a) distinguished two periods of granitic intrusion. He retained the name Laurentian for the older period, as for example the Bad Vermilion granite at Shoal Lake

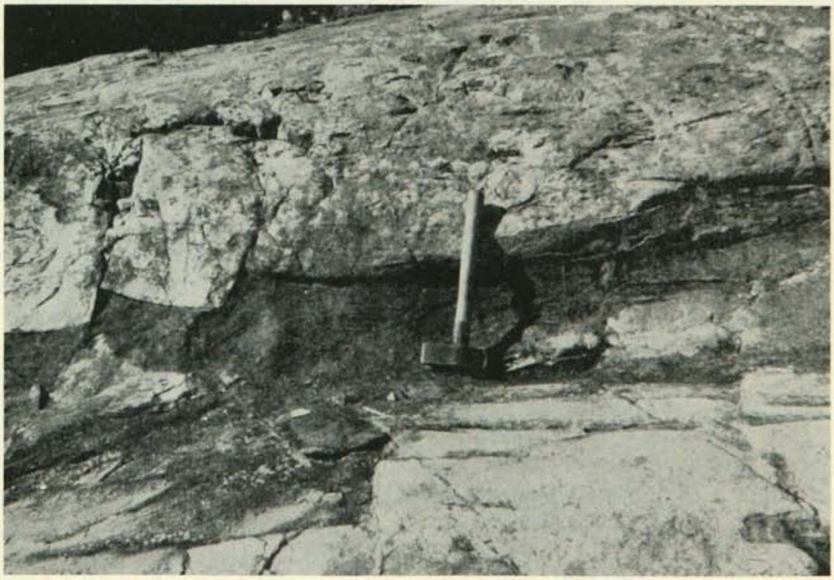

FIGURE 10. — Schist and paragneiss, Coutchiching, north side of Lichen Island, Rainy Lake, Ontario.

(Pl. 3), which is post-Keewatin and pre-Seine. The usage of Laurentian for granite with these relationships has been accepted, probably in large part because of the recognition given it by the Special Committee in their report of 1905. For the younger period of granitic intrusion, Lawson (1913a, p. 4) proposed the name Algoman, "from the old district of Algoma." He interpreted the Algoman granites to be younger and intrusive into the Seine series. The geologic succession and nomenclature proposed by Lawson (1913a, p. 109) is essentially the one given in Table 11 which was presented as "A Standard Scale for the Pre-Cambrian Rocks of North America" (Lawson, 1913b) at the International Geological Congress in Ottawa in 1913.

Following the publication of Memoir 40 (Lawson, 1913a) the geology of Rice Bay, Bear Passage, and the Rainy Lake area as a whole, was reviewed by a number of geologists. Bruce (1925) and Tanton (1927) concluded that the Coutchiching was a valid formation underlying the Keewatin; Grout (1925a) and Merritt (1934) advanced negative views. Grout admitted that Lawson's arguments for a sedimentary series below the greenstone are good in the Rice Bay area, but he argued that quantitatively these rocks are insignificant and do not deserve a formational name. The Coutchiching-Seine (Knife Lake) controversy was not confined to the Rainy Lake area, and the problem has been ably reviewed by Pettijohn (1937).

In connection with the present investigation geologic studies were carried on for two summers in the Rainy Lake area. The detailed results of these investigations will be presented in a later paper; however, the main

TABLE 11. SEQUENCE AND CLASSIFICATION OF THE PRECAMBRIAN ROCKS OF THE LAKE SUPERIOR REGION
(Lawson, 1913b)

	Upper Cambrian (Potsdam)		
	unconformity		
	Algonkian	Keweenawan (Nipigon)	
		unconformity	
		Animikie	
	Eparchean Interval		
Archean	Algoman (granite-gneiss, batholithic in Huronian)		
	Intrusive contact		
	Huronian	Upper	
		unconformity	
		Lower	
	unconformity		
	Laurentian (granite-gneiss, batholithic in Ontarian)		
	Intrusive contact		
	Ontarian	Keewatin	
		Coutchiching	

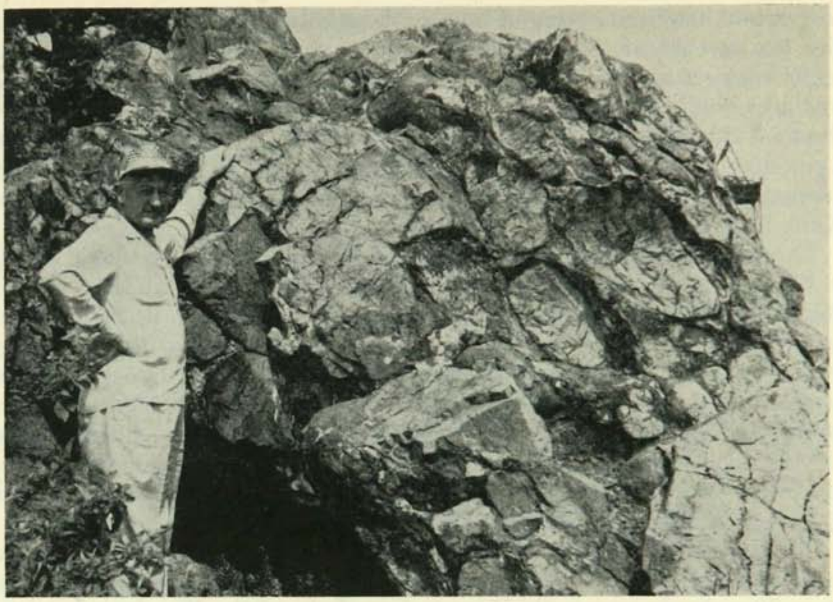

FIGURE 11. — Ely greenstone, showing ellipsoids or pillow structure. Headframe of the Zenith mine in the background, Ely.

conclusions (Yardley, Goldich, Peterman, and Frye, 1959) are pertinent to the present discussion. (1) The central part of Rice Bay, originally mapped by Lawson as Laurentian granite, consists of paragneisses formed by high-grade metamorphism. (2) The sedimentary rocks to which Lawson applied the name Coutchiching have an aggregate thickness of thousands of feet, and consequently the Coutchiching cannot be invalidated on the basis of insignificant thickness. (3) The structure of the Bear Passage area was reviewed, and the conclusions of Lawson and of Bruce were substantiated in that the structure is that of a large anticline, although this had been questioned by Grout and by Merritt. Thus the main problem resolves itself to the question of whether or not the greenstone in the Rice Bay dome and in the Bear Passage anticline is Keewatin or whether it represents a younger group of volcanics.

Pettijohn (1937, p. 156) has pointed out that all the greenstones mapped as Keewatin may not be of the same age, and he has suggested that greenstones in southern Ontario may be of at least two different periods. Lawson (1888) correlated the Keewatin greenstone in the Rainy Lake area with that at the type locality of Lake of the Woods and traced the rocks from Lake of the Woods to Rainy Lake. The Ely greenstone (Fig. 11) of the Vermilion district, Minnesota, was named by Van Hise and Clements (1901) and was correlated with the Keewatin of Lake of the Woods. This correlation has been accepted by the Minnesota Geological Survey. From Ely, the greenstone, commonly ellipsoidal, can be traced in a belt of Keewatin rocks extending northeast to Saganaga Lake where the greenstone was intruded by the Saganaga granite during the Laurentian orogeny. On the west side of the Saganaga granite, particularly in the Cache Bay area, a conglomerate, containing boulders of the Saganaga granite as well as of greenstone and various other aphanite porphyries, lies at the base of the Knife Lake group.

The sequence of geologic units and the interpretation of geologic events in the Cache Bay area are so similar to those for the Shoal Lake area in the Rainy Lake district to the north that there seems to be little reason to question the correlation of the respective rock units. The Saganaga granite and the Bad Vermilion granite are intrusive into greenstone. On erosion surfaces cutting both granite and greenstone, conglomerates, which contain locally derived boulders, are found in both areas. Locally these are the basal conglomerates of the Knife Lake group in Minnesota and of the Seine series in Ontario. If the greenstone in the Minnesota area is Keewatin, surely that at Shoal Lake is also Keewatin.

The greenstone that underlies the Seine conglomerate at Shoal Lake can be traced westward without apparent interruption to the Bear Passage area. Thus by Lawson's direct route from Lake of the Woods and a more circuitous route, via Ely, Minnesota, a correlation is made of the greenstone in the Rice Bay and Bear Passage areas with that of the type locality of the Keewatin. This rather lengthy discussion is pertinent to the problems of the Early Precambrian rocks of Minnesota, because the Coutchiching was not recognized within the State (Table 1).

In the discussion that follows, northern Minnesota is divided into four regions: Vermilion district, Vermilion granite region, Mesabi district, and the North Shore region. The geologic work in these regions, on which the established Precambrian classification (Table 1) is based, is reviewed, and the origin of the principal rock units, particularly the granitic gneisses, is reinterpreted.

VERMILION DISTRICT

General Statement

The Vermilion district, or Vermilion range, is a narrow strip of Keewatin, Knife Lake, and Laurentian rocks, 12–15 miles wide, extending from a point west of Vermilion Lake northeast to Saganaga and Gunflint lakes on the Minnesota-Ontario boundary, a distance of approximately 100 miles. Geologically, the Vermilion district is bounded on the north by the Vermilion and the Saganaga granites and on the south principally by the Giants Range granite and by the Duluth gabbro (Pl. 1). The relief is not great, but the country is quite rugged and reflects the bedrock structure which in general trends east-northeast.

Monograph 45 (Clements, 1903) is the earliest comprehensive work on

TABLE 12. STRATIGRAPHIC SUCCESSION IN THE VERMILION DISTRICT
(Clements, 1903, p. 33)

Pleistocene	Drift
Keweenawan	Duluth gabbro and Logan sills
unconformity	
Upper Huronian (Animikie series)	Rove slate Gunflint formation (iron-bearing)
unconformity	
Lower Huronian	Intrusives. Granite, granite-porphyries, dolerites, and lamprophyres Knife Lake slates Agawa formation (iron-bearing) Ogishke conglomerate
unconformity	
Archean	Intrusive granites, granite-porphyries, and some greenstones Soudan formation (the iron-bearing formation) (Minor unconformity) Ely greenstone, and ellipsoidally parted basic igneous and largely volcanic rock

the district. Clements' description of the rock types (Table 12) and of localities remains a source of much valuable information. According to Clements (1903, p. 29) the discovery of iron-bearing rocks in this district should be credited to J. G. Norwood. The Soudan mine, first to be opened in Minnesota, shipped ore in 1884 and has been in continuous operation since then. Large deposits of hematite were also discovered in the vicinity of Ely, and some of these have been completely mined out. At the present time two mines are still in operation in Ely.

KEEWATIN GROUP

Ely Greenstone. The Keewatin rocks were divided by Van Hise and Clements (1901) into two formations, the Ely greenstone and the Soudan iron-formation. The Ely greenstone, the lower but by far the greater part of the Keewatin, consists largely of basaltic lavas and clastic materials that are usually interpreted as pyroclastic or tuffaceous deposits. Metamorphism has altered the rocks to schists so that the original character is appreciably obscured. The ellipsoidal structure of the greenstone at the type locality in Ely is shown in Figure 11. Although it is difficult to determine structure within the greenstone because of its massive character, the formation has been involved in tight folding as is indicated by the associated rocks. The thickness of the Ely greenstone is unknown. The upper contact can be seen in a number of places described by Grout and coauthors (1951). The lower contact has been interpreted as an intrusive one formed by the various granites and the Duluth gabbro.

Klinger (1956) found that the Ely greenstone in the Soudan mine and in the vicinity of Soudan and Tower contains a very large amount of clastic materials, tuffaceous and sedimentary, which may exceed 40 per cent of the formation. A well-developed schistosity strikes E.-W. to N. 80° E. and dips at high angles to the north. In describing the sedimentary rocks that flank the belt of greenstone at Soudan, Klinger (1956, p. 130–131) notes that there is a distinct difference in lithology between the sequence on the north side of the greenstone and that on the south side. On the north, the Knife Lake conglomerate, which was originally called the Ogishke conglomerate by Clements, is typically developed along the south shore of Lake Vermilion; however, on the south the greenstone is bounded by interbedded slates and graywacke without conglomerate. In one of these outcrops Klinger found excellent graded bedding with the tops of the beds clearly toward the greenstone, so that the slates and graywacke, if projected to the north, lie beneath the Keewatin and may be an older formation at the base of the Ely greenstone. Klinger also reports well-rounded granitic pebbles in some of the greenstone, and these suggest the presence of an older granite which has not been recognized in the district.

Soudan Iron-Formation. The thickness of the Soudan formation is not known, but it probably does not exceed a few hundred feet, and Klinger (1956, p. 126) states that in the vicinity of the Soudan mine "thicknesses greater than 100 feet are unusual, except in folded masses." Clements (1903) thought that the Soudan formation could be divided into lower and upper parts. The lower part consists largely of clastic material, and the upper part of iron formation. He described the rocks and the exceedingly complex structure of the formation in detail and explained the discontinuous *en echelon* pattern of the outcrops (Pl. 1) as being the result of the complex crossfolding which the district has undergone. According to Clements' interpretation, the Soudan formation represents remnants infolded within the Ely greenstone. A more recent interpretation (Schwartz, 1956b) is that the Soudan formation should be considered an iron-bearing member within and near the top of the Ely formation; however, the fact that the iron formation can be mapped locally, in spite of the complex structural relations, suggests that it warrants formational rank.

In the Soudan area (Klinger, 1956) the iron formation is composed chiefly of quartz, hematite, and martite or magnetite. There is considerable ferruginous carbonate, some chlorite and sulfides, of which pyrite is the most common, but chalcopyrite is also present. The iron formation is very fine-grained and distinctly banded. Bands may be straight or complexly folded as shown in Figure 12.

Klinger distinguished three types of iron formation which he was able

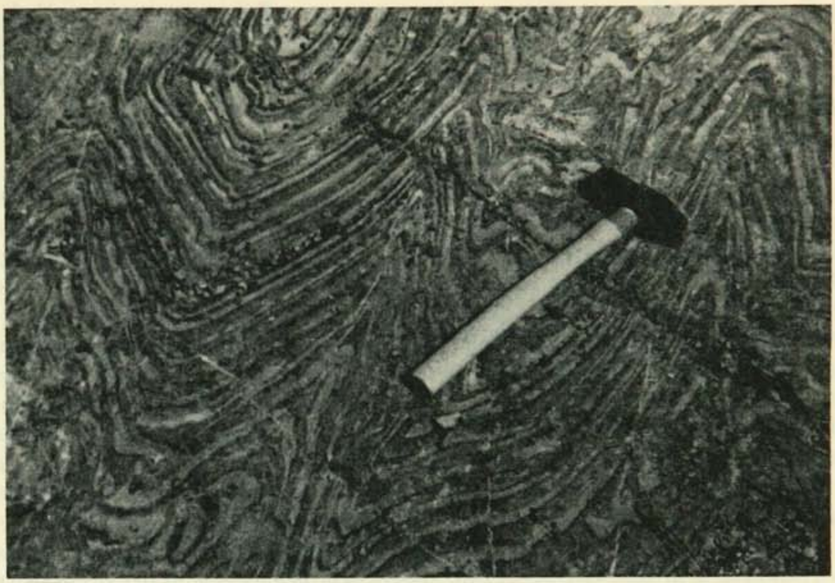

FIGURE 12. — Tight folds in the Soudan iron-formation, crest of Soudan Hill, south of large pit and just east of road to Stuntz Bay, Soudan.

to map in the Soudan mine. These are (1) greenish-white chert, (2) lean jasper and (3) jaspilite. The greenish-white chert, composed principally of quartz, contains minor amounts of chlorite and pyrite. The iron content is low, and Klinger gives the average composition as 93.2 per cent of SiO_2 and 1.82 per cent of total Fe. The lean jasper consists of quartz, hematite and martite. The iron content is much higher but is generally less than 20 per cent by weight. The jaspilite is a banded rock of quartz, jasper, and hematite or martite, averaging 34 per cent of total iron as Fe.

The orebodies in the Soudan mine, according to Klinger, are replacements localized by the iron formation. Small amounts of hematite replace chlorite and sericite schists, but these are not of commercial size. The orebodies are commonly associated with the jaspilite type of iron formation. An origin by hydrothermal replacement of the siliceous iron formation is generally accepted (Schwartz and Reid, 1955). This replacement involved removal of silica and introduction of iron, both ferrous and ferric. According to Klinger, the iron probably was largely derived from the original iron formation itself and concentrated rather than introduced from outside sources.

The orebodies at Ely are fragmental hematite which in places is cemented by secondary hematite (Reid, 1956b). Graphitic and sericitic schists associated with the iron ore may represent lenses of clastic sediments within the formation. A sample of black slate from the station at the 825-foot level of the old Savoy shaft in Ely, analyzed in the Rock Analysis Laboratory, contains 0.87 per cent of CO_2 and 0.25 per cent of carbon.

Laurentian Intrusives

Granitic intrusives that are Laurentian, as defined by the Special Committee (Adams *et al.*, 1905), in Minnesota, are post-Keewatin and pre-Knife Lake. The best example is the Saganaga granite on the Minnesota-Ontario boundary (Pl. 1; Fig. 13). In the vicinity of Saganaga Lake, in Minnesota, the granite was intruded into greenstone and tuff of the Keewatin group; however, east of Saganaga Lake in the vicinity of Northern Light Lake, in Ontario, the granite was emplaced in an older gneiss (Fig. 13). Although the Northern Light gneiss is not known to crop out in Minnesota, it is included in this discussion because of its relationship to the Saganaga granite and because of its bearing on the Coutchiching problem.

Many smaller intrusive masses, including mafic and silicic rock types, have been called Laurentian.

Dikes. Among the numerous dikes in the Vermilion district microgranite porphyry is a prominent type, but andesitic and basaltic types are locally important. The dikes in the Tower and Ely areas have been described by Clements (1903) and assigned to the Laurentian, because pebbles and cobbles of these rocks are abundant in the conglomerate at the base of the Knife Lake metasediments. These conglomerates are well exposed at Vermilion Lake, particularly at Stuntz Bay. Similar porphyritic dike rocks are described by Gruner (1941, p. 1589) in the area of the Knife Lake slates. The dikes are rarely more than 100 feet wide and strike parallel to the greenstone belts. They have not been found intrusive into the Knife Lake and therefore are assigned to the Laurentian.

Diabase dikes occur throughout the Vermilion district, and a number of gabbroic intrusives have been encountered in mining operations. Some of these undoubtedly are of Early Precambrian age, but as some were intruded into Knife Lake conglomerate, age assignments are uncertain.

Northern Light Gneiss. There are excellent outcrops of the Northern Light gneiss in the vicinity of the old ranger cabin on the north shore of the North Channel of Northern Light Lake (Fig. 13). The fine-grained, leucocratic gneiss contains 5 to 10 per cent of aligned biotite which gives the rock a distinct foliation. Good outcrops of the gneiss can be seen along the shores and on the many islands in Northern Light Lake. On Moose Island (KA-76), in the southeastern part of the lake, the gneiss is compositionally banded. The fine-grained, light-gray layers contain coarser lenses of quartz and feldspar. Mutually sutured aggregates of quartz grains form "eye-like" structures similar to those that characterize the Saganaga granite.

Fine-grained, compositionally banded gneiss was sampled on a small

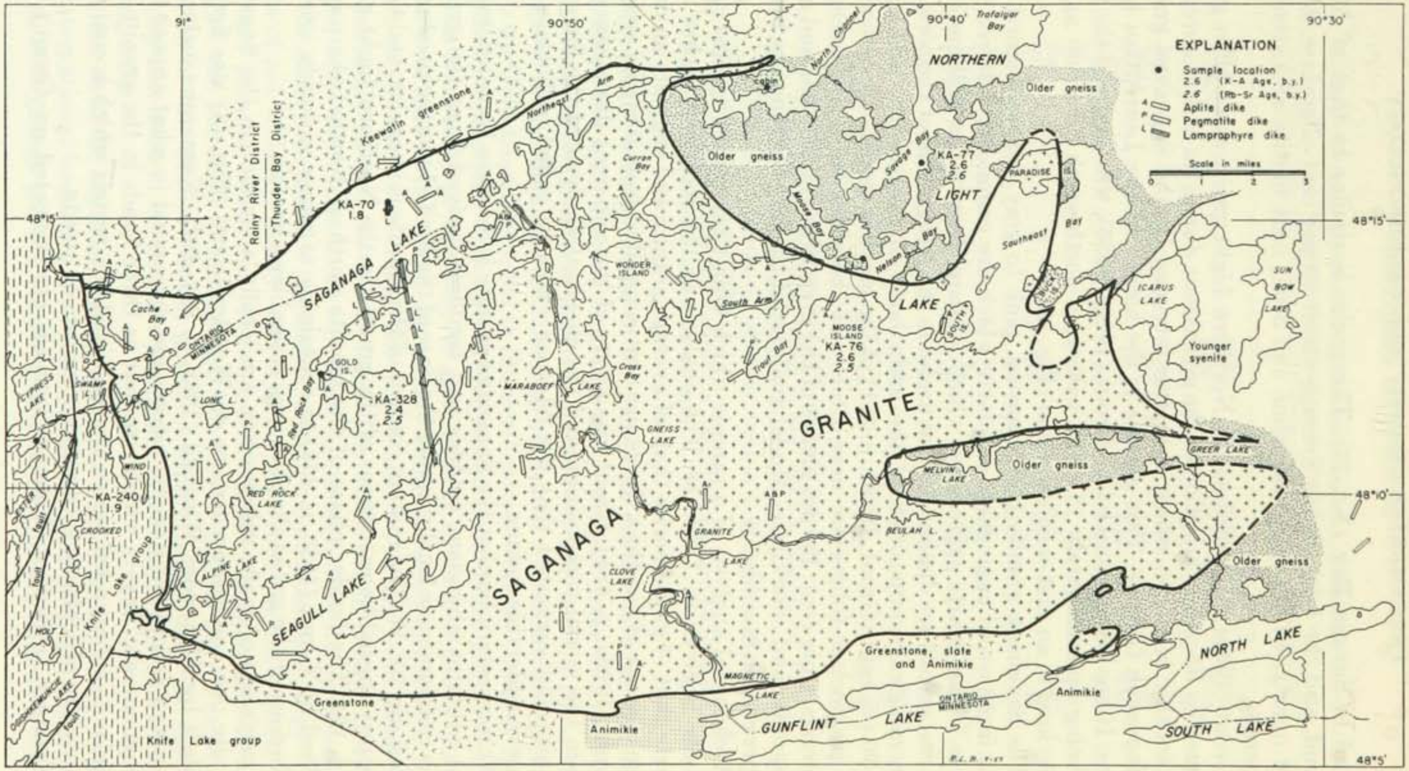

FIGURE 13. — Map of the Saganaga batholith, Minnesota-Ontario, after Grout (1936).

island in Savage Bay (KA-77). The gneiss is similar to that of Moose Island, and the felsic layers average about 60 per cent oligoclase, 25 per cent quartz, 10 per cent microcline and 5 per cent biotite and accessory minerals.

Grout (1929a, b) described the Northern Light gneiss as an older gneiss formed by *lit-par-lit* injection of the greenstone during an early Laurentian batholithic intrusion which was later intruded by the Saganaga granite.

Saganaga Granite. This granite is the largest of the Laurentian intrusives. It has been described by Grout (1929a, 1936), who mapped the mass as being approximately 15 miles wide in a north-south direction and 25 miles long in an east-west direction (Fig. 13).

The Saganaga granite is an unusual, pink to gray, coarse-grained rock with large ovoid aggregates of quartz which are commonly referred to as "eyes." The quartz aggregates, which measure from a few millimeters to 1.5 cm. across, are distinctive and useful in the recognition of the rock. The mineralogical composition of the main body of the granite, making up 85–90 per cent (Grout, 1929a, p. 581) of the mass, is quartz, 26; orthoclase, 22; plagioclase (oligoclase near albite), 45; hornblende, 6; and accessory minerals, 1 per cent. Border phases of the granite are more mafic and grade to syenite and shonkinite. Modal analyses of these rocks range as high as 65 per cent in hornblende.

A chemical analysis of a sample which Grout considered typical of the granite is given in Table 13. The analysis of the rock approaches more nearly that of granodiorite than of average granite and suggests an orthoclase content of less than the 22 per cent computed from 9 modal analyses (Grout, 1929a, p. 581). Grout was aware of the apparent discrepancy between the modal composition and the chemical analysis of the Saganaga granite and suggested that the feldspar which he called orthoclase contains considerable sodium.

At its western border, the Saganaga granite is overlain by conglomerate that contains abundant cobbles and boulders derived from the granite. This conglomerate locally marks the base of the Knife Lake metasediments which dip 70° W. The eastern contact of the granite is irregular, and Grout mapped finger-like extensions of the granite in the Northern Light gneiss (Fig. 13). The border phase of the granite north of North Lake was described by Grout (1936, p. 258) as containing so many variously oriented inclusions of the gneiss that the rock resembles a breccia.

Inclusions of mafic composition are locally abundant in the Saganaga granite. An unusual occurrence on Wonder Island (Fig. 13) was first described by Alexander Winchell (1888, p. 217–222). Numerous inclusions, mainly of amphibolite or greenstone, are segregated in what appear to be "conglomerate" layers which crop out as three bands in the granite. The angular to subrounded pieces are contained in a matrix which is composed principally of feldspar with minor amounts of quartz.

Younger Intrusives. Younger syenites are indicated on Grout's map

TABLE 13. CHEMICAL ANALYSES OF SAGANAGA GRANITE, NORTHERN LIGHT GNEISS, AND GNEISS FROM RICE BAY

	1	2	3
SiO_2	68.81	73.01	71.64
Al_2O_3	16.34*	15.05	16.69
Fe_2O_3	1.95	tr.	.39
FeO	.75	.99	.70
MgO	.91	1.62	.67
CaO	2.19	3.44	2.61
Na_2O	4.97	4.20	5.26
K_2O	2.29	.88	1.10
BaO	.10	n.d.	.07
TiO_2	.22	n.d.	.21
P_2O_5	.07	n.d.	.17
MnO	.02	n.d.	.02
H_2O+	1.38	.64	.49
H_2O-	.12	.12	.06
CO_2	.30	.06	.02
S	.03	n.d.	.01
Total	100.45	100.01	100.11

* Includes 0.02 Cr_2O_3 and 0.02 ZrO_2 originally reported.

1. Saganaga granite from island in Sec. 22:65-5, Minnesota. F. F. Grout and A. J. Bauernschmidt, analysts (Grout, 1929a).

2. Older gneiss, Northern Light Lake, Ontario. F. F. Grout and George Ward, analysts (Grout, 1929a).

3. Gray gneiss, "probably Laurentian," upper Rice Bay of Rainy Lake, Ontario. T. Kameda, analyst (Grout, 1938).

(Fig. 13) on the eastern border of the Saganaga granite. Within the mass itself, there are a number of localities which suggest later intrusions. A fluorite-bearing red granite of medium-grained texture, lacking the quartz aggregates of the Saganaga granite, may represent a later intrusion which makes up Gold Island, situated in the northeastern entrance to Red Rock Bay, the southwestern extremity of Saganaga Lake. Gold Island derives its name from early prospecting for gold. A large outcrop of milky quartz on the west side of the island apparently attracted prospectors who sank a shaft on the northwest side of the island, about 100 feet from shore and approximately 20 feet above lake level. The shaft, which is now caved in and partially filled, is 15 to 20 feet deep. Material on the dump indicates that the shaft penetrated a pegmatite, and there are abundant large fragments of red feldspar, smoky, amethystine, and rock crystal quartz, fluorite and granular masses of yellowish sericite. The feldspar and sericite supplied the materials of sample KA-328. Grout (1929a) gave a brief description of the fluorite-bearing granite and concluded that the fluorite probably was introduced from the pegmatite, replacing in part the feldspar of the granite.

On islands of the northernmost group in the United States around which the international boundary line makes a sharp bend (Fig. 13), inclusions of typical Saganaga granite are abundant in a medium-grained syenite or granite in which quartz is not readily visible in hand specimens. The coarse-grained inclusions contain the quartz aggregates of the Saganaga granite, and as the pieces appear to be differently oriented, there seems to be little doubt that two periods of intrusion are represented.

The Saganaga granite was blasted in the construction of the paved road leading to the parking area and the boat landing on Gull Lake which is used as an entry to Saganaga Lake. The pink, coarse-grained granite contains the usual quartz aggregates, but it is veined with fresh red orthoclase, which is obviously related to fractures, indicating later introduction of K-feldspar.

Numerous aplites, pegmatites and dikes of granite, of diabase and of lamprophyre occur throughout the Saganaga mass, and many of these have been mapped by Grout (Fig. 13). The longest of the lamprophyre dikes was traced by Grout from a point northeast of Gull Lake northward for about 4 miles where it crops out on an island just south of the international boundary. The same dike was found during the present investigation on an island in Canada so that the over-all known length of the dike is about 5 miles. The dike is approximately 30 feet wide, very dark to black in color, and hence stands out by contrast with the light-colored Saganaga granite. The coarse-grained lamprophyre was sampled for biotite on the Canadian island (KA-70).

Sequence of Intrusions. Grout concluded that the Northern Light gneiss is an early Laurentian batholithic intrusion in the Keewatin greenstone and tuff and that the Saganaga granite is a late Laurentian intrusion. The lamprophyre dikes in the Saganaga granite were thought by Grout (1936, p. 262) to have been developed at a late magmatic stage, because at one locality on the Northeast Arm a pegmatite crosses a lamprophyre, and at a second locality a thin dike is faulted and offset repeatedly. Grout attributed the fragmentation to late movements in the emplacement of the granite and therefore suggested that the lamprophyres were intruded prior to final consolidation. At Cache Bay, however, Grout found a dark dike rock, resembling the lamprophyres, which intruded the Knife Lake metasediments, and for this clearly younger dike he suggested a possible Algoman age.

From his structural studies, Grout developed some interesting ideas in which he postulated that the Saganaga granite originally was a vertical intrusion which was tilted in the later Algoman orogeny. The western end of the mass, in Cache Bay, represents the upper surface of the eroded batholith overlain by the Knife Lake conglomerate, whereas the eastern end represents the finger-like extensions in the older gneiss which may have been the feeders at the base. Grout's interpretations were based on the assumption that the structures which he observed and plotted are primary and are not the result of metamorphism. A consideration of the geologic history of the region in a later section indicates that this assumption is open to question.

Knife Lake Group

History of the Name. In the Sixteenth Annual Report of the Geological and Natural History Survey of Minnesota there are a number of references to the slates in the Knife Lake area, and Alexander Winchell (1888, p. 253) speaks of the Knife Lake slates. In the early report on the Vermilion district, Van Hise and Clements (1901) divided the rocks, which are now included in the Knife Lake group, into the Ogishke conglomerate and the Knife slates. In the later monograph, Clements (1903, p. 33) formally used the Knife Lake slates for one of three formations of the "lower Huronian." From oldest to youngest these are the Ogishke conglomerate, the Agawa iron-formation, and the Knife Lake slates (Table 12). As Clements (1903 p. 335) noted, the slates are aptly named for Knife Lake which was called Lac des Coteaux by the fur traders who traversed it as part of the canoe route along the international boundary. The sharp knife edges of the slates apparently were very hard on canoes and on moccasins.

The detailed stratigraphic and structural study of the Knife Lake area, made by Gruner (1941) with the assistance of C. E. Dutton (unpublished Ph.D. thesis. Univ. Minn., 1931), G. R. Gibson (unpublished Ph.D. thesis, 1934), and Grout, is an outstanding contribution to the Precambrian geology of Minnesota. Gruner concluded that the Ogishke and the Agawa formations are not mappable units and are not deserving of formational rank. He called the sequence the Knife Lake series; however, in the review paper (Grout *et al.*, 1951, p. 1031), group rather than series is used. On the basis of lithologic characters, Gruner (1941, Pl. 1) differentiated 19 members on his geologic map of the Knife Lake area.

Ogishke Conglomerate. The Ogishke conglomerate was considered by Clements (1903, p. 297) to be the basal formation of the Knife Lake, resting on an erosion surface of Keewatin and Laurentian rocks. At the type locality, Ogishkemuncie Lake, the conglomerate consists of pebbles and boulders of many rock types. Prominent among these are rounded pieces of Saganaga granite. There are also pebbles of a variety of porphyries, of greenstone and of sedimentary rocks including slate, graywacke, chert, and jasper. Gruner (1941), however, found that in many places slates and graywackes lie directly on the greenstone without intervening conglomerate. He also noted that the conglomerate at Ogishkemuncie Lake grades into finer sediments and disappears along the strike within 3 or 4 miles to the southwest and within 4 or 5 miles to the northeast. The conglomerate, however, is more than 4000 feet thick north of the center of the lake.

Agawa Iron-Formation. The iron-bearing beds within the Knife Lake sedimentary sequence were originally assigned to the Agawa formation by Clements, but they are particularly troublesome because they are local and discontinuous. Gruner concludes that throughout the time of deposition of the Knife Lake sequence, iron carbonate was being precipitated locally, but extensive deposits were not formed in any one place. An additional difficulty with the Agawa iron-formation is that some of the iron-bearing rocks formerly assigned to this formation are replacements along shear zones and faults, as for example on the east shore of Ogishkemuncie Lake where Gruner (1941, p. 1616) found a lens of supposed Agawa formation more than 1500 feet long and several hundred feet wide which is a replacement along a shear zone.

Principal Rock Types. The principal lithologic units include slates, graywackes, arkosites, tuffs conglomerates, and agglomerates. The agglomerates (probably better called volcanic breccia) grade to conglomerates and to finer tuffaceous materials. The graywackes grade to rocks which Gruner called arkosites, although he indicates the difficulty in attempting to distinguish them in the field.

The breccias are difficult to distinguish from andesite porphyry which may represent either intrusives or flows. Nowhere in the area did Gruner find ellipsoidal greenstone within the Knife Lake group. For details of the various lithologic types, the reader is referred to the original paper (Gruner, 1941).

Structure and Thickness. Detailed mapping in the Knife Lake area revealed the presence of major longitudinal faults which previously had not been known. Physiographic features, such as the strike of Knife Lake, and local shear zones are suggestive of faults, but their general pattern and significance did not become apparent until Gruner plotted the regional geology. The longitudinal faults in the western part of the area, in the vicinity of Snowbank Lake (Fig. 14), trend nearly east-west, but in the eastern part, the faults swing sharply to the north and trend east of Saganaga Lake (Fig. 13). The faults displaced highly folded rocks, and therefore it is difficult, if not impossible, to estimate their throw. As Gruner points out, the horizontal displacement must be very large. The structure is further complicated locally by later intrusives, such as the large batholiths of the Basswood Lake area and the smaller Kekekabic and Snowbank stocks.

On the basis of the longitudinal faults, Gruner divided the Knife Lake area into a number of segments, or structural units. One of the largest of these was named the Knife Lake synclinorium segment, bounded by faults which parallel the arms of Knife Lake. Gruner describes this segment as a synclinorium, the axis of which curves from a strike of N. 80° E. on the west to N. 20° E. at the eastern end, carrying the folds west of the Saganaga granite mass. The folds of the western and main part of the synclinorium pitch to the northeast, but in the northern part, the pitch is to the southwest. The general configuration supports Gruner's contention that the Saganaga granite, in the Seagull and Saganaga lakes area east of the Knife Lake folds, acted as a positive area or buttress during the time of the Knife Lake folding.

Because the complicated structure makes it impossible to correlate stratigraphic units from one segment to another, a reliable estimate of thickness can not be made; however, Gruner (1941, p. 1624) estimated a probable thickness of 15,000 feet of sediments in the Knife Lake synclinorium segment. The minimum total thickness is 11,000 feet, and a probable maximum is 22,000 feet. Most of this accumulation consists of slates, graywackes, and tuffs.

Ages for the Vermilion District

Radioactivity ages for rocks from northern Minnesota are given in Table 14, and ages for the Vermilion district in Sections A-D, inclusive. Locations of samples are shown on Plate 1 and on Figures 13 and 14, and descriptions are given in the Appendix.

Soudan Area. A sample of slate (KA-147) from the outcrop south of the Soudan mine that shows graded bedding, indicating that the slate may be stratigraphically below the Ely greenstone, is dated at 2.54 b.y. The age, however, is interpreted to indicate the last period of major folding in the district, the Algoman orogeny. A sericite sample (KA-97) from the mine gives a similar age, but a second sample (KA-18) is much younger, 1.6 b.y.

In the Soudan mine, a light-yellow sericitic schist is closely associated with the ore (Schwartz and Reid, 1955, p. 299) and is related to wall rock alteration and mineralization. Chemical analyses of the greenstone, the wall rock and the sericitic schist are given in Table 15. Reid (1956a, p. 119) concludes that the main period of ore formation in the Vermilion district must have been later than the main period of diastrophism, because the ore appears to be related to the present structure and shows no development of a micaceous texture. Reid assigns this period of diastrophism to the Algoman, and the 2.5 b.y. date obtained for the slate and for sericite sample KA-97 gives the approximate time of the folding.

Klinger (1956, p. 132) notes that some deformation has taken place since ore deposition in the Soudan deposit, where the ore is cut by faults and is locally brecciated. He found that at least one of these post-ore faults is mineralized with pyrite, and possibly the age of 1.6 b.y. obtained for the second sericite sample (KA-18) dates this later faulting and mineralization. The younger sericite, compared to the older sample and the sericitic schist of the mine, is much purer, with a K_2O content of 9.4 per cent (Table 15).

Knife Lake Area. Six samples of the Knife Lake slates, collected along the canoe route from Moose Lake to Saganaga Lake, were dated by the K-A method (Table 14, Sec. B) and give a wide range, 0.8 to 2.6 b.y. Two samples from Knife Lake give ages of 2.5–2.6 b.y., essentially the time of folding in the Soudan-Ely area and very likely the time of the Algoman orogeny. Sample KA-200 comes from a small island near the west end of Knife Lake. In his field notes, Grout refers to this island as a "type locality" for the Knife Lake slate. Interbedded dark-gray slates and fine-grained graywacke are well exposed and dip 67° S. Sample KA-228 comes from the south shore of the South Arm of Knife Lake, approximately 0.6 miles west of the portage to Eddy Lake.

TABLE 14. AGES FOR ROCKS FROM NORTHERN MINNESOTA
(Including data from Ontario)

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
	(A) Soudan-Ely Area						
147	Knife Lake slate, Soudan.	2.54		2.73	2.74	0.869	0.317
97S	Sericite, Soudan Mine....	2.53		6.04	6.05	1.91	.316
18S	Sericite, Soudan Mine....	1.59		9.41	9.43	1.37	.146
						1.39	.148
	(B) Knife Lake Area (slates)						
200	West end, Knife Lake....	2.6		2.82	2.83	0.960	0.339
228	East end, Knife Lake.....	2.5		.91	.91	.275	.302
244	Eddy Lake	2.2		2.28	2.28	.551	.242
243	Portage, Jean-Eddy lakes.	1.9		2.58	2.59	.521	.201
242	Portage, Ogishkemuncie-Annie lakes	0.8		2.42	2.42	.136	.056
240	Cypress Lake	1.9		2.14	2.14	.427	.200
						.421	.197
	(C) Snowbank Lake Area						
106B	Syenite	1.16		8.39	8.41	0.802	0.095
106F	Syenite			8.98	9.00	1.29	.144
323B	Conglomerate	1.67		7.89	7.91	1.25	.158
229B	Microgranite porphyry ..	2.34		2.37	2.37	.652	.275
	(D) Saganaga Lake Area						
328S	Pegmatite, Gold Island...	2.43	2.50	5.30	5.31	1.56	0.294
328F	Pegmatite, Gold Island...		2.49				
	(E) Ontario						
76B	Northern Light gneiss, Moose Island	2.59	2.50	7.02	7.03	2.31	0.329
77B	Northern Light gneiss, Savage Bay	2.60	2.59	6.55	6.56	2.11	.322
						2.24	.342
262B	Granite gneiss, English River	2.63	2.59	8.85	8.87	3.01	.339
112B	Schist, Briarcliffe Lake ...	2.60	2.77(?)	8.49	8.51	2.83	.332
111M	Pegmatite cutting 112 ...	2.54		9.84	9.86	3.14	.319
Average	....	*2.59*					
258B	Granite, Kashabowie Lake	2.55		6.02	6.03	1.93	0.320
298B	Granite Steeprock Lake ..	2.56		5.32	5.33	1.72	.323
21B	Lamprophyre, Kashabowie	2.50		5.63	5.64	1.75	.310
191B	Coutchiching, Rice Bay ..	2.52	2.49	9.15	9.17	2.94	.321
						2.81	.307
191M	Coutchiching, Rice Bay ..	2.60		9.36	9.38	3.10	.331
178B	Paragneiss, Rocky Islet Bay	2.55		8.63	8.65	2.79	.322
						2.76	.319
320BM	Aplite, upper Rice Bay ...	2.50	2.45	8.72	8.74	2.70	.309
Average	....	*2.54*					
222B	Granite, Ben Island	2.41	2.36	7.51	7.53	2.18	0.289
224B	Granite, south of Goose Island	2.45	2.34	8.53	8.55	2.54	.297
						2.54	.297
272B	Granite gneiss, Emerson Lake	2.36	2.38	9.08	9.10	2.54	.279
Average	....	*2.41*	*2.36*				
70B	Lamprophyre, Saganaga Lake	1.75		2.39	2.40	0.41	0.171

TABLE 14 — *Continued*

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
	(F) Vermilion Granite Region						
47B	Granite, Burntside Lake..	2.62		4.57	4.58	1.54	0.337
46B	Granite, Echo Trail	2.59		3.96	3.97	1.29	.325
						1.33	.334
239B	Granite, near Echo Lake..	2.56	2.47	9.19	9.21	2.98	.324
249B	Gneiss, north of Cusson ..	2.48		9.33	9.35	2.86	.305
250B	Gneiss, Highways 73-53 ..	2.50		8.14	8.16	2.52	.309
Average	....	*2.55*					
94B	Pegmatite, Nett Lake	2.50		7.93	7.95	2.32	0.292
						2.40	.302
						2.65	3.32
4B	Pegmatite, Kinmount	2.39		7.73	7.75	2.19	.283
						2.28	.294
						2.15	.277
4F	Pegmatite, Kinmount			12.74	12.76	2.85	.223
						3.02	.237
						2.97	.233
83B	Graywacke gneiss, International Falls	2.50		6.48	6.49	2.00	.308
82B	Gneiss, Birchdale	2.39		7.89	7.91	2.26	.285
82F	Gneiss, Birchdale			13.50	13.53	2.47	.182
307B	Tonalite, Grassy Island ..	2.38	2.28	8.80	8.82	2.50	0.283
	(G) Northwest Angle						
17M	Pegmatite	2.48	2.50	10.28	10.30	3.13	0.304
88B	Pegmatite	2.48	2.47	8.40	8.42	2.56	.304
	(H) Giants Range Region						
236B	Granite, Grand Rapids ...	2.50		6.43	6.44	2.03	0.315
						1.96	.304
237B	Granite, Nashwauk	2.53	2.33	4.75		1.48	.311
				4.75	4.76	1.54	.323
48B	Granite, Mountain Iron ..	2.33	2.51	3.50	3.51	.948	.270
						.967	.276
105B	Granite gneiss, Virginia ..	2.63		5.81	5.82	2.02	.347
						1.93	.332
317B	Gneiss, north of Virginia..	2.61		8.72	8.74	2.92	.334
316B	Gneiss, Idington	2.55		8.17	8.19	2.62	.320
81B	Granite, Ely	2.28		2.76	2.77	.728	.262
81F	Granite, Ely			7.18	7.19	1.34	.187
8B	Granite, Babbitt	1.13		4.26	4.27	.398	.0932
						.385	.0902
137	Virginia argillite, Virginia.	1.5		4.10	4.11	.539	.131
212	Virginia argillite, West Mesabi	1.2		4.07	4.08	.396	.097
	(I) Duluth Complex and Related Intrusives						
295B	Pyroxenite, Duluth	1.09		7.14	7.15	0.624	0.0873
92B	Diabase, Beaver Bay	1.00		7.51	7.53	.584	.0776
176B	Diorite, Aurora, drill core.	1.20		6.73	6.74	.669	.0993
65B	Gabbro, Babbitt	1.06	1.09	7.24	7.25	.605	.0835
296B	Granitic pegmatite, Babbitt		1.12	8.21			
	(J) Contact Rocks Related to the Duluth Gabbro						
232	Thomson formation, Duluth	1.22		4.28	4.29	0.433	0.101

TABLE 14 — *Continued*

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
233	Thomson formation, Duluth	1.17		4.02	4.04	.387	.0958
131	Rove formation, Gunflint Trail	1.06		4.89	4.90	.410	.084
177B	Contact rock, Aurora, drill core	1.04		8.70	8.72	.709	.0813
8B	Granite, Babbitt	1.13		4.26	4.27	.398	.0932
						.385	.0902
8F	Granite, Babbitt			5.02	5.03	.653	.130
106B	Syenite, Snowbank Lake	1.16		8.39	8.41	.802	.095
106F	Syenite, Snowbank Lake			8.98	9.00	1.29	.144
93B	Granite, Mellen, Wis.	.99		5.79	5.80	.455	.0785
						.435	.0750
93F	Granite, Mellen, Wis.			12.77	12.80	1.06	.0824
						1.03	.0808
	(K) Duluth Area Granophyres						
101	Dike, 8th St. at 3rd Ave.	0.9		5.40	5.41	0.301	0.0556
						.293	.0542
102	Quarry on Woodland Ave.	1.2		4.34	4.35	.345	.0793
103	Quarry on Kenwood Ave.	1.0		3.21	3.22	.259	.0805
104	Intrusive, 27th Ave. at 12th St.	0.9		3.05	3.06	.196	.064

Three samples collected along the canoe route from Knife Lake to Ogishkemuncie Lake show progressively younger ages: KA-244, north of Eddy Lake, 2.2 b.y.; KA-243, north of Jean Lake, 1.9 b.y.; and KA-242, between Annie and Ogishkemuncie lakes, 0.8 b.y. The significance of the lower ages is not apparent. Similarly, sample KA-240 from Cypress Lake (Fig. 13), northeast of Knife Lake, gives a low age of 1.9 b.y.

Snowbank Lake Area. The stock at Snowbank Lake (Fig. 14) was studied by Sanders (1929), who showed that it is a composite intrusion of porphyritic augite syenite, syenite, and granite. A chemical analysis of the granite is given in Table 16. The area was remapped by G. R. Gibson (unpublished Ph.D. thesis, Univ. Minn., 1934), and Figure 14 is adapted from the map published by Gruner (1941). Balk and Grout (1934) made a structural study of the Snowbank stock and concluded that a "succession of intrusives made room for themselves by crowding the walls aside and possibly, in part, upthrusting a roof that has long since been eroded." The dynamic period of intrusion must have ended about the time of granite intrusion, because, according to Balk and Grout (1934, p. 635), the granite shows little internal structure, and the aplites and pegmatites which cut it are practically massive. The elongation of the mass was found to be upward to the north at an angle of 10°–30° from vertical. Apparently the intrusives formed an elliptical chimney, pushed aside the walls and deformed the schists for about a mile from the contact. The Snowbank stock is cited by Buddington (1959, p. 707) as an example of "a typical stock emplaced

TABLE 15. CHEMICAL ANALYSES OF ELY GREENSTONE, WALL ROCK ALTERATION, SERICITE SCHIST, AND SERICITE SAMPLES FROM SOUDAN AREA

	1	2	3	KA-97	KA-18
SiO_2	49.72	31.85	59.71		
Al_2O_3	16.76	27.93	16.05		
Fe_2O_3	1.92	2.15	.73		
FeO	7.33	23.38	1.81		
MgO	7.62	1.33	2.78		
CaO	9.35	.04	4.55		
Na_2O	3.14	.43	.51	0.61	0.51
K_2O	.71	3.26	4.18	6.04	9.41
BaO	.06				
TiO_2	.89	.81	.28		
P_2O_5	.09	.08	.16		
MnO	.16	.08	.15		
H_2O+	1.57	8.12	2.07		
H_2O-	.06	.48	.29		
CO_2	.10	.04	6.40		
S	.04				
	99.52	99.98	99.67		
$<O=S$	.01				
Total	99.51	99.98	99.67		

1. Ely greenstone, M4011, from outcrop, Sec. 9:61-14. Eileen H. Oslund, analyst (Schwartz and Reid, 1955, p. 299).

2. Altered wall rock, drill hole on 19th level, Soudan mine. H. Baadsgaard, analyst (*Ibid.*).

3. Sericitic schist, drill hole 708, 175-210 ft., 12th level. Soudan mine (*Ibid.*).

KA-97. Sericite, cross cut north of main drift on 27th level, Soudan mine, Doris Thaemlitz, analyst.

KA-18. Sericite, north wall of Shaft Vein orebody, approximately 25 feet above 27th level, Soudan mine, Eileen H. Oslund, analyst.

in the mesozone." According to Buddington, granites of the mesozone, for the most part, are emplaced at depths ranging from 4 to 10 miles.

K-A ages for three of the rocks of the Snowbank stock are given in Table 14, Section C. If the ages are taken without interpretation, they might be said to indicate intrusions at widely separated times; microgranite porphyry (KA-229) at 2.3 b.y., a second intrusion metamorphosing the Knife Lake conglomerate (KA-323) at 1.7 b.y., and finally a granite (KA-106) at 1.2 b.y. The A^{40}/K^{40} ratio of K-feldspar separated from the granite (KA-106), however, is greater than that of the associated biotite (Fig. 8). This clearly indicates that the biotite has been recrystallized and that the determined age is a survival number and not the time of crystallization of the granite. The contact of the transgressive Duluth gabbro is just south of Round Lake (Fig. 14), approximately 1.5 miles south of sample KA-106. The gabbro was intruded at approximately 1 b.y. and has affected the granite. The biotite, being more sensitive than the feldspar, apparently lost all or the greater part of its argon at the time of intrusion of the gabbro. If the granite is Algoman, as the field data indicate, the feldspar also lost considerable radiogenic argon during this event. The 2.3 b.y. age, ob-

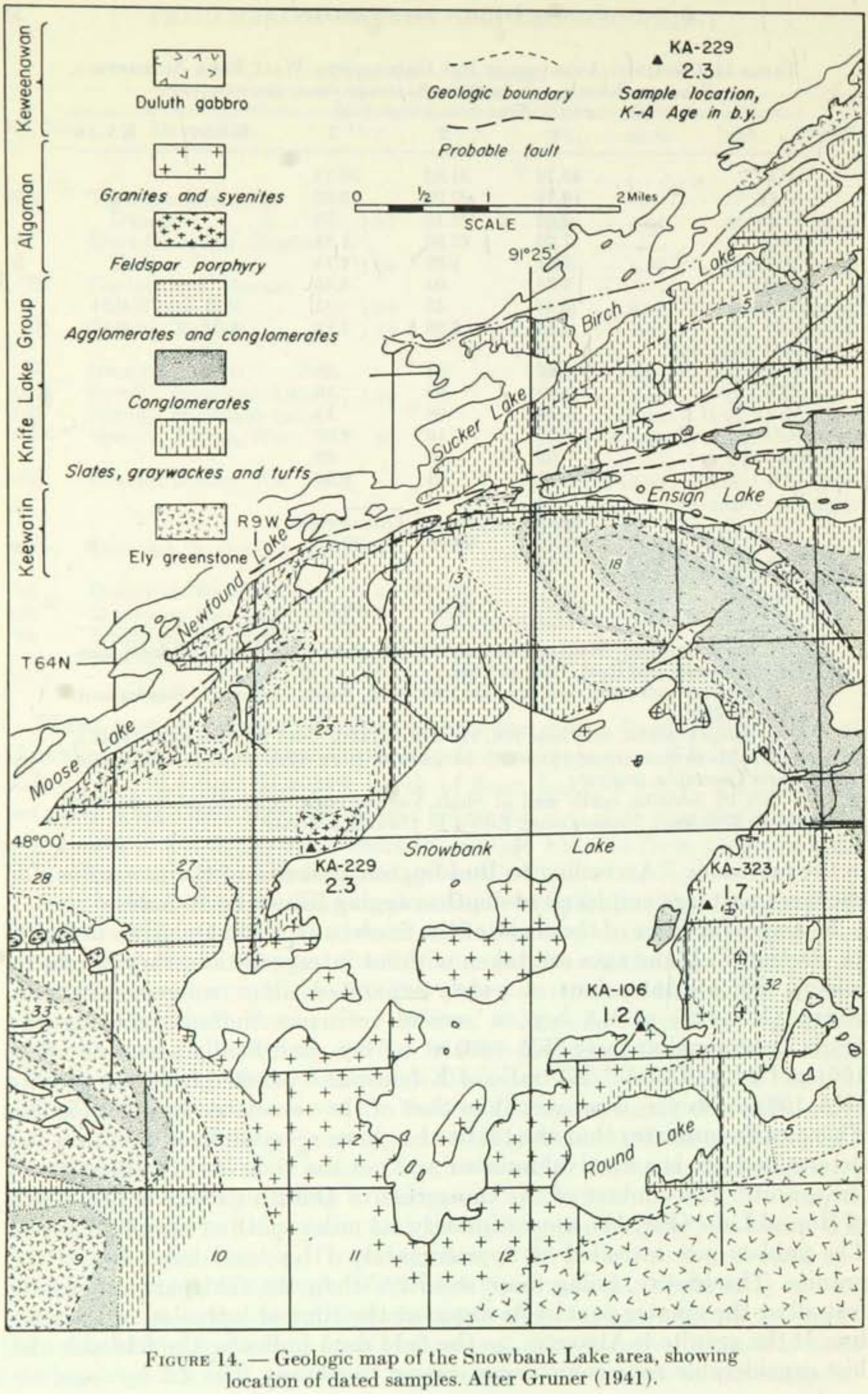

FIGURE 14. — Geologic map of the Snowbank Lake area, showing location of dated samples. After Gruner (1941).

tained for biotite separated from the microgranite (KA-229), supports the geologic assignment of the Snowbank stock to the Algoman, and it seems likely that the ages are low because of subsequent metamorphism, increasing from south to north and northwest.

Saganaga Lake Area. Efforts to separate biotite, suitable for dating, from the Saganaga granite were unsuccessful. Biotite is not abundant and generally is chloritized. Sericite from the pegmatite on Gold Island is dated by the K-A method at 2.43 b.y. and by the Rb-Sr method at 2.50 b.y. Feldspar from the pegmatite gives a similar Rb-Sr age of 2.5 b.y. Two samples from the Northern Light gneiss, collected from Northern Light Lake, east of Saganaga Lake in Ontario (Fig. 13 and Pl. 3) were dated by both K-A and Rb-Sr methods, and the age is 2.6 b.y., although one of the Rb-Sr determinations is somewhat lower, 2.5 b.y. The ages by themselves would suggest that the Saganaga granite is younger than 2.6 and older than 2.5 b.y. However, this interpretation may not be justified, as will be shown later in the discussion of the history of Early Precambrian time.

Biotite from the large lamprophyre dike in the Saganaga granite is dated at 1.8 b.y. (Table 14, Sec. E), and this age indicates activity at a much later time. Whether the age is the time of intrusion of the dike or the time of later alteration is uncertain. It seems possible that the low ages on the samples of the Knife Lake slate may be in some way related; although the age of 0.8 b.y. for the slate west of Ogishkemuncie Lake requires another explanation.

Efforts to date the orthoclase, which makes up the veins in the Saganaga granite at Gull Lake, by the Rb-Sr method were unsuccessful because of the large amount of normal strontium in the feldspar.

VERMILION GRANITE REGION

General Statement

Northwest from the Vermilion district to the Ontario border is a region of high-grade metamorphic and granitic rocks. A coarse-grained, light-pink biotite granite is prominent, and Grout (1923, p. 254) named this rock the Vermilion granite from the good exposures on Vermilion Lake and along the Vermilion River. The Vermilion batholith (Pl. 1) measures 80 miles in an east-west direction and approximately 30–40 miles north-south. This large area, which occupies most of northern St. Louis County and parts of Lake and Koochiching counties, is not very well known. The most detailed paper is that of Grout (1925b), which includes chemical analyses and petrographic descriptions. The Vermilion granite is intrusive into the Ely greenstone and also into mica schists, which have been correlated with the Knife Lake group of the Vermilion district. On this basis, Grout assigned the Vermilion granite to the Algoman, so that the Algoman granites in Minnesota, including the Giants Range and the Vermilion granites, far overshadow the older Laurentian Saganaga granite in areal extent.

TABLE 16. CHEMICAL ANALYSES OF VERMILION, GIANTS RANGE, AND SNOWBANK GRANITES, AND OF GNEISS FROM BURNTSIDE LAKE

	Vermilion		Giants Range		Snowbank	Burntside
	1	2	3	4	5	6
SiO_2	71.73	72.06	66.31	71.45	69.50	68.54
Al_2O_3[a]	14.85	16.05	12.77	13.11	16.86	17.89
Fe_2O_3	.58	.46	1.98	2.44	.50	1.77
FeO	1.35	.72	2.66	1.78	.64	.52
MgO	.62	.97	3.01	.84	1.45	1.22
CaO	1.18	.86	4.77	.65	1.70	4.02
Na_2O	3.58	4.56	5.03	3.03[b]	4.58	5.14
K_2O	4.63	3.54	2.33	4.79[b]	3.94	1.05
BaO	.14	.12	.00	.00	n.d.	n.d.
TiO_2	.53	.12	.49	.13	.53	.20
P_2O_5	.14	.09	.13	.04	n.d.	tr.
MnO	.03	.06	.04	.04	n.d.	n.d.
H_2O+	.64	.39	.75	1.24	.42	.46
H_2O-	.20	.05	.05	.10	.20	.18
CO_2	n.d.	.10	n.d.	n.d.	n.d.	n.d.
FeS_2	.06	.09	tr.	tr.	n.d.	(S).06
Total	100.25	100.24	100.32	99.64	100.32	101.05

[a] Figures for Al_2O_3 include ZrO_2 and Cr_2O_3 reported originally.
[b] Original alkalies reported by Allison (1925) are in error.
1. Vermilion granite from northwest part of Sand Point Lake, Sec. 12:68-17. F. F. Grout (1925b), analyst.
2. Vermilion granite from southeast of Pelican Lake, T. 64N., R. 19 W. (*Ibid.*).
3. Hornblende biotite granite, Sec. 28:59-17. I. S. Allison (1925), analyst.
4. Biotite granite, Sec. 31:59-18. R. J. Leonard, analyst (Allison, 1925).
5. Snowbank granite, C. W. Sanders (1929), analyst.
6. Gneiss, portage from Burntside Lake to Little Long Lake, D. Manuel, analyst (Grout, 1926).

VERMILION GRANITE

According to Grout (1925b, p. 471), the Vermilion granite is fairly uniform, with an average composition of quartz, 25; K-feldspar, 50; oligoclase, 20; biotite, 2 per cent; and the remainder, accessory zircon, allanite, muscovite, and magnetite. Hornblende syenite is a border phase of the Vermilion batholith which is locally extensive at Basswood Lake but is also found in other areas. There are numerous inclusions of country rock throughout the granite, and Grout (1925b, p. 476) described what he considered to be assimilation phases. Two chemical analyses of the typical Vermilion granite are given in Table 16 together with analyses of the Giants Range and the Snowbank granites which are also considered to be of Algoman age.

BURNTSIDE GRANITE GNEISS

On Burntside Lake, Grout (1926, p. 29) distinguished a gneiss older than the Vermilion granite which he called the Burntside granite gneiss. The Burntside Lake area is one of two localities in Minnesota in which the possible occurrence of the Coutchiching has been considered, and Grout

(1926, p. 30) gives a detailed map of this area. The older gneissic rock is described as a sodic granite with nearly 50 per cent of oligoclase, 20 per cent of quartz, and an equal amount of orthoclase. Altered ferromagnesian minerals make up 3 or 4 per cent of the rock. A chemical analysis of this rock (Table 16) is similar to the analysis of the Northern Light gneiss (Table 13). Grout considered the Burntside gneiss to be intrusive into schists which he assigned to the Knife Lake group; therefore, like the Vermilion granite, the Burntside gneiss would be post-Knife Lake and of Algoman age.

South of the schists are outcrops of the Ely greenstone, and in placing the schists stratigraphically above the greenstone, Grout interpreted the structure here to be locally overturned. The outcrops were re-examined during the summer of 1956. Efforts to determine the structure from the tops and bottoms of beds were inconclusive, and the problem must remain open. Nowhere along the contact between the Ely greenstone and the schists on Burntside Lake are there conglomerates, whereas just a short distance to the southwest the conglomerate at the base of the Knife Lake series is prominently developed as shown by Grout (1926, Pl. 1).

Other Gneissic Rocks

A gneissic border phase of the Vermilion batholith, on the shores of Namakan Lake, is described by Grout (1926, p. 35), who concluded that the gneiss is not a distinct formation because all gradations from gneiss to massive granite are found. In the present work, however, numerous localities showing gneissic rocks that cannot be considered border phases were examined. Good outcrops are readily accessible along U.S. Highway 53 and State Highway 73 (Pl. 1). At the intersection of the highways graywacke gneiss is interlayered with a gray granite, whereas a pink granite appears to be younger. North of this intersection there are a number of artificial exposures along Highway 53. Road cuts, approximately 6 miles north of Cusson, are instructive. Intricately folded dikes or veins of light-gray granite, composed almost wholly of quartz and feldspar (Fig. 15), are remarkably developed in the gneiss. The convoluted folds are suggestive of ptygmatic folds; boudin structures are also developed. Garnet is abundant in the gneiss. These rocks are interpreted to be the result of high-grade metamorphism (garnet-amphibolite facies) of geosynclinal sediments in the deeper zone. In the same outcrops, younger, red-colored granite cuts the gneiss and the gray granite. Just south of International Falls, highway cuts show well-bedded schist and graywacke gneiss.

West of International Falls at Birchdale, on State Highway 11, granite gneiss is well exposed (KA-82). The high-grade metamorphic rocks, including schists and gneisses in northern Minnesota, were mapped by Lawson (1913a) as Coutchiching. These same rocks were interpreted by Grout to be Knife Lake, and this difference of opinion constitutes the Coutchiching problem.

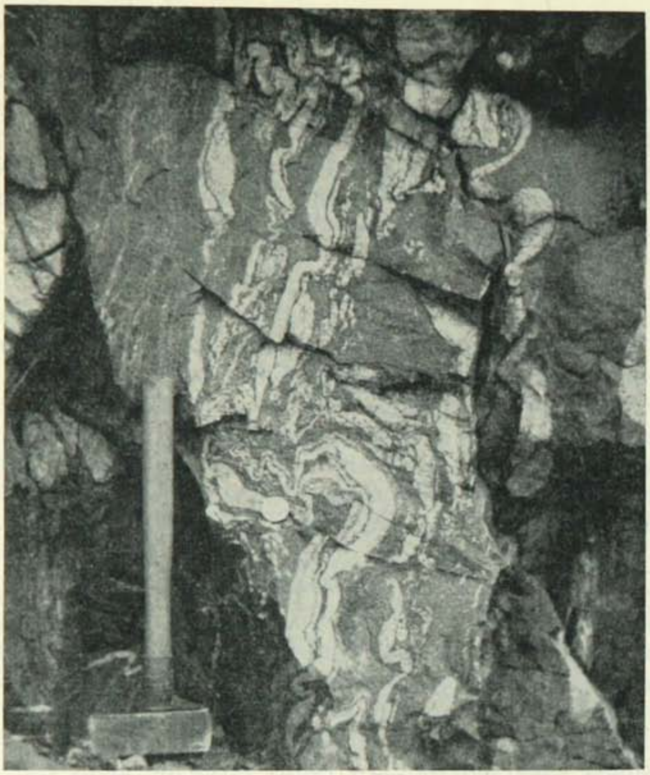

FIGURE 15. — Crenulated folds and boudin structure in migmatitic graywacke gneiss. Cut along Highway 53, 6.6 miles north of Cusson. The K-A age for biotite from this locality is 2.5 b.y.

PEGMATITES

There are numerous dikes and pegmatites cutting the rocks of the Vermilion granite batholith. Many of these contain considerable magnetite, and these have been described by Grout (1923). Pegmatites at Nett Lake (KA-94), near Kinmount (KA-4), and in the Northwest Angle (KA-17, 88) were sampled for dating.

AGES FOR THE VERMILION GRANITE REGION

Vermilion Granite. Two samples (KA-46, 47, Pl. 1) from the eastern part of the Vermilion batholith give similar K-A ages of 2.6 b.y. Sample KA-239 from the Echo Trail southeast of Echo Lake gives a K-A age of 2.6 b.y. and a Rb-Sr age of 2.5 b.y. A sample of gneiss (KA-249) within the batholith, north of Cusson and approximately 25 miles west of KA-239, is dated at 2.5 b.y., and sample KA-250 from gneiss south of the batholith gives a similar age. The average K-A age is 2.55 b.y.

Two pegmatite samples (KA-94 and KA-4) from Nett Lake and from a locality northwest of Kinmount (Pl. 1) give K-A ages of 2.5 and 2.4 b.y., respectively. A sample of graywacke gneiss (KA-83) from International Falls, north of the batholith, is dated at 2.5 b.y., and gneiss from Birchdale, west of International Falls, gives a K-A age of 2.4 b.y. On the map (Pl. 1) this locality is shown as granite. The rock is a gray, medium-grained gneiss with large crystals of pink feldspar. Thin sections show finely granular quartz, 35; oligoclase, 20, in grains larger than the quartz; microcline, 35, in large porphyroblasts; and epidote and biotite, 10 per cent. The rock has been sheared before and, in part, after the development of the microcline. The aggregates of finely granular quartz suggest an original sediment, such as a graywacke, with later introduction of potash to form the microcline porphyroblasts, followed by some mechanical deformation. Biotite and epidote, in about equal amounts, are marginal to the larger grains of microcline and to the quartz aggregates.

Lawson (1913a) mapped granites of both Laurentian and Algoman ages on Grassy Island. The tonalite (KA-307) is similar in composition to the Laurentian tonalite of Shoal Lake, Ontario, and the modal composition is quartz, 23; plagioclase (An_{15}), 58; microcline, 4; biotite, 10; accessory and alteration minerals, 5 per cent. Thin sections indicate that tonalite of this composition supplied the pebbles and cobbles (Fig. 16) of the Seine (Knife Lake) conglomerate on Neil Point, southeast of Grassy Island, and

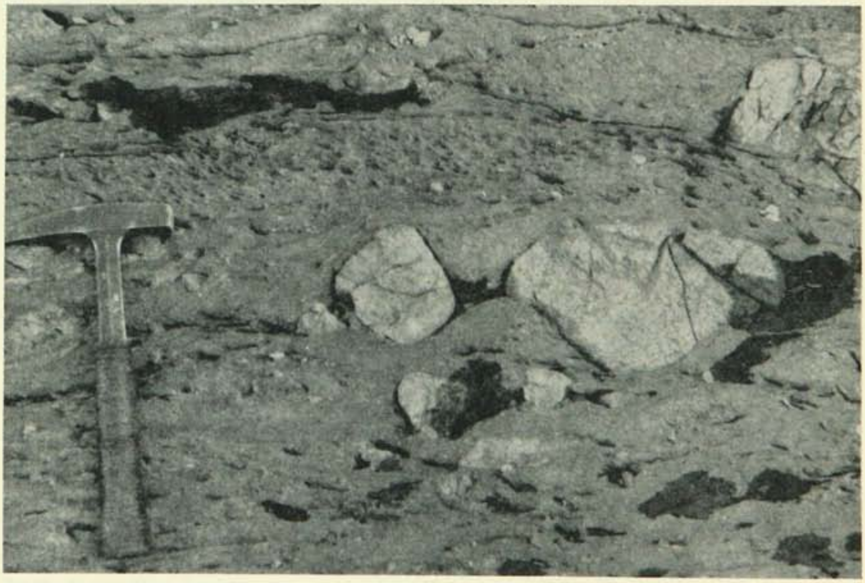

FIGURE 16. — Pebbles and cobbles of Laurentian tonalite in matrix of sericitic and chloritic schist. Seine (Knife Lake) conglomerate on Neil Point, Rainy Lake, Minnesota.

in Rat Root Bay to the west. The tonalite of Grassy Island has been extensively sheared and granulated, and the ages of 2.4 and 2.3 b.y. found by the K-A and Rb-Sr methods, respectively, for sample KA-307 reflect this later deformation.

Mechanical deformation indicated in the sheared tonalite and also in the gneiss (KA-82) at Birchdale suggest that faults, like those mapped by Gruner in the Knife Lake area, may be a factor contributing to the complexity of structural relationships in Rainy Lake.

Northwest Angle Pegmatites. The rocks of the Northwest Angle (Pl. 3) cannot be definitely related to the Vermilion batholith, but as the radioactivity ages (Table 14, Sec. E) are similar, the area is briefly discussed at this time. The geology is poorly known. Grout visited the Northwest Angle, and his field notebook for 1927 gives the principal rock types as ellipsoidal greenstone, breccia, schist, and gneiss. He tentatively assigned these rocks to the Keewatin, but he indicated that some of the schists might be younger. Samples of muscovite from the Rader pegmatite in Sec. 6:167-33 and lepidolite from Falcon Island in Canada were collected by Grout, and Rb-Sr ages reported by Ahrens (1949, 1955) were determined for this material. These results (Grout *et al.*, 1951, p. 1020, 1030, 1074) were obtained with emission spectrographic methods and are not reliable; they need not be further considered.

The Rader pegmatite was once mined for feldspar. Albite, microcline-perthite, quartz, muscovite, and beryl are the principal minerals; garnet and others are minor. Muscovite gives a K-A age of 2.48 b.y. The same mineral was dated by Gast, Kulp, and Long (1958), and their data were recomputed (Table 7) using the decay constant accepted in this report, to give 2.50 b.y., in agreement with the K-A age.

Biotite (KA-88) from a second pegmatite in the Northwest Angle, approximately 4.5 miles west of the Rader pegmatite, near the center of Sec. 32:168–34, gives similar K-A and Rb-Sr ages of 2.48 and 2.47 b.y. This pegmatite consists of microcline-perthite, oligoclase, quartz, and biotite. The country rock of gneiss and schist shows relic structures of folded and crenulated beds.

Pegmatites from just south of the Winnipeg River in southeast Manitoba (Pl. 3), approximately 70 miles north of the Northwest Angle, have been dated by Gast, Kulp, and Long (1958) and by Aldrich, Wetherill, Davis, and Tilton (1958), and the ages obtained for mica by the Rb-Sr method, recomputed for comparative purposes, are similarly 2.5 b.y.

GIANTS RANGE REGION

General Statement

The Giants Range is a ridge of granite which extends from the vicinity of Grand Rapids to a point east of Ely, a distance of approximately 100 miles. The Giants Range granite, which was named by Spurr (1894a), is overlain along its southern flank by the Animikie group, except at the east

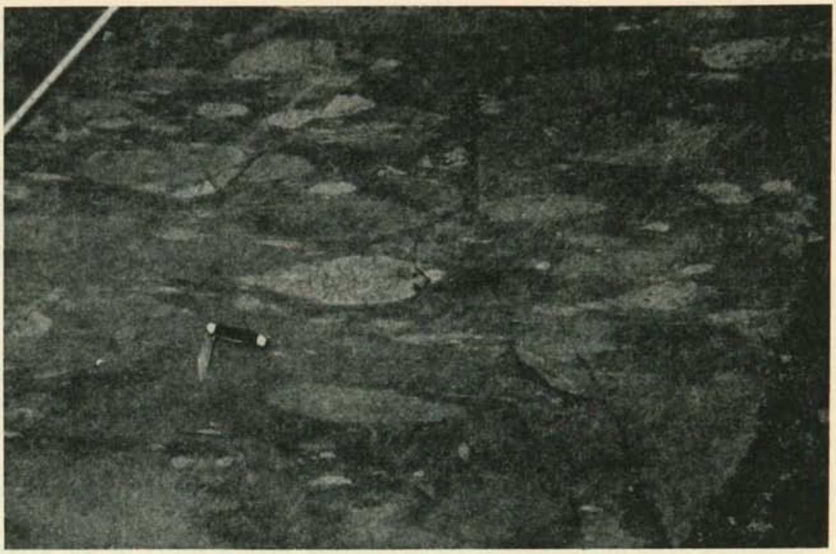

FIGURE 17. — Conglomerate of the Early Precambrian Knife Lake group is well exposed at Midway in the Virginia Horn area, Mesabi district. Note the stretched and sheared pebbles and cobbles. The bedding is essentially vertical and strikes N. 80° E. Nearby, the Knife Lake conglomerate is overlain by conglomerate of the Middle Precambrian Pokegama formation which dips at a low angle to the west and is undeformed.

end where the Duluth gabbro transgresses the formation. The plain northwest of the Giants Range is underlain by the granite, and as mapped by Allison (1925), the batholith is an elongate mass with an average width of 8 miles and a total area of approximately 1000 square miles. Along its northern boundary, the Giants Range granite intrudes the Ely greenstone and the schists and gneisses assigned to the Knife Lake group. In the Virginia Horn area along the southern boundary, similar rocks (Fig. 17) of Early Precambrian age are intruded by the Giants Range granite.

GIANTS RANGE GRANITE

The Giants Range granite is post-Knife Lake and pre-Animikie and hence commonly is cited as an excellent example of Algoman granite. Two principal rock types distinguished by Allison are a hornblende granite, which composes the greater part of the batholith and is well developed in the eastern half, and a younger biotite granite from the western part. Inclusions of the hornblende granite in the biotite granite establish the age relations. The easternmost end of the batholith is recognized as the Embarrass granite, a coarse-grained, red hornblende granite characterized by large and abundant grains of bluish quartz. The Embarrass granite was named by Leith (1903, p. 186) for the exposures at Embarrass Station on the Duluth and Iron Range Railroad, just north of the Mesabi range.

Leith thought that the granite was intrusive into Animikie formations, although he recognized that in the central and western portions of the Mesabi district the Giants Range granite is definitely older than the Animikie group.

Metamorphism of the lower part of the iron formation at Babbitt was ascribed by Leith to the intrusive Embarrass granite, and a similar interpretation was advocated by Richarz (1930) and by Royce (1945). Grout and Broderick (1919), however, showed that the contact between the Giants Range granite and the overlying iron formation in the Babbitt area is a sedimentary one. The granite had been weathered before deposition of the iron formation, and subsequent metamorphism, which Grout and Broderick attributed to the intrusion of the Duluth gabbro, affected both the granite and the iron formation. Small stringers of granite are found in the Animikie rocks in the Babbitt area and to the northeast, as previously described by Leith, but Grout and Broderick attribute these to the younger gabbro complex. At Aurora a sill of red, fine- to medium-grained granite occurs in the iron formation, and reference will be made to this in a later section (see p. 70).

Accessory-Mineral Zonation. In connection with a study of the accessory minerals in the Precambrian rocks of the Lake Superior region, Grout and Thiel (Tyler, Marsden, Grout, and Thiel, 1940) sampled the Giants Range batholith, and on the basis of heavy minerals, were able to zone and distinguish phases of the Giants Range granite in much greater detail than in the original work of Allison. Inclusions of schist and of gneiss in the Giants Range granite are numerous. Larger areas of gneissic rock were distinguished by Grout and Thiel as older gneiss. Later they (Grout *et al.*, 1951, p. 1039) suggested that this gneissic rock may be of Laurentian age but pointed out that the contacts with the hornblende granite, which characterizes most of the eastern part of the Giants Range, are gradational.

The accessory heavy minerals in the Giants Range granite, given by Grout and Thiel, include allanite (?), apatite, carbonates, epidote, fluorite, garnet, hematite and limonite, leucoxene, magnetite and ilmenite, pyrite (and chalcopyrite, pyrrhotite, and galena), rutile, sphene, tourmaline, and zircon. Zircon was found in most of the samples, and according to Grout and Thiel, several kinds of zircon may occur in one sample, but the variation in the zircons within a single facies of the batholith is greater than the variation in different parts of the mass. They state that nearly all the samples show the hyacinth type.

Relative Ages from Zircon Types. Tyler and Marsden (Tyler *et al.*, 1940, p. 1437) found that three age groups of Precambrian igneous rocks can be distinguished on the basis of the type of zircon. The oldest granitic rocks of the Lake Superior region are characterized by hyacinth, a variety of zircon ranging in color from faint pink to deep brownish-purple, purple, and pink. Short prismatic crystals with several pyramidal forms are common, and the apparent roundness of the crystals could easily be confused with rounding due to sedimentary action. Younger granites of pre-Huronian and Huronian age contain malacon, a variety characterized by abnormally weak birefringence and cloudy or dusty appearance. Tyler and Marsden found that hyacinth grains may be included within malacon, and they interpret the nuclei of hyacinth zircon to represent xenocrysts from older rocks. Rocks that have been assigned to the Keweenawan contain normal zircon, characterized by well-developed crystal forms. Refringence is high, birefringence is strong, and inclusions are common. The normal zircon shows a simple habit, generally of prisms and unit dipyramids.

Mixed zircons are common, and the importance of distinguishing the xenocrysts is emphasized by Tyler and Marsden. In the gneisses which are derived by high-grade metamorphism of pre-existing sedimentary rocks intruded by younger granite, it is obvious that mixed zircons can be expected. Thus the presence of hyacinth zircons in the samples of the Giants Range granite is not a basis for correlating the granite with the Saganaga mass in which only hyacinth zircon was found. The zircons from samples of the Pokegama quartzite show similar variety; the hyacinth type is common, but there also are some needle-like crystals with distinct terminal faces.

Allison (1925, p. 495) emphasized the variety of rock types in the Giants Range batholith. Most exposures show more than a single phase, and in some, as many as four successive intrusives are found. The relationships are well shown in the cut along Highway 53 just north of Virginia where the country rock is cut by granite which in turn is intruded by dikes of later age. There are numerous aplite, pegmatite, rhyolite, and granite porphyry dikes, and some small schistose mafic dikes in the Knife Lake slates.

Ages for the Giants Range Region

Eight samples from the Giants Range granitic complex have been dated (Table 14, Sec. H; Pl. 1). The granite at Babbitt has been metamorphosed by the Duluth gabbro and is discussed in a later section. Samples KA-48 and KA-81, from Mountain Iron and Ely give K-A ages of 2.3 b.y., but the other 5 samples range from 2.5 to 2.6 b.y. and are similar in age to dated samples from the Vermilion granitic complex. Two of the samples (KA-48 and KA-237) were also dated by the Rb-Sr method, and the results are puzzling, as the ages seem to be reversed; however, the samples apparently were not confused. No explanation can be given for the discrepancy between the K-A and the Rb-Sr results for the samples.

HISTORY OF EARLY PRECAMBRIAN TIME FOR NORTHERN MINNESOTA

General Statement

All the events formerly assigned to the Earlier and Medial Precambrian eras (Table 1) are here included in the Early Precambrian. The Laurentian orogeny, therefore, is reduced to a secondary status. Although there are geologic reasons that favor this revision, the justification lies chiefly in the results of the radioactivity dating. The term Algoman is here used to designate a major period of folding, metamorphism, and granite intrusion. This was a period of tectonic activity which undoubtedly encompassed a number of lesser periods of folding of which only the Laurentian can be recognized definitely at present. The Algoman in this sense may be regarded as a major orogeny or revolution.

The so-called batholiths of the Precambrian of Minnesota and Ontario, the Giants Range, the Vermilion, and the Saganaga, are granitic complexes whose origins are related to the development and deformation of geosynclinal belts of sediments. The present discussion emphasizes the geosynclinal theory as presented by Knopf (1948).

Geologic Interpretation

The oldest of the Precambrian rocks, the Coutchiching and the Keewatin, were assigned by Lawson (1913a) to the Ontarian system. The term Ontarian is used in this report informally because Dana (1890) suggested Ontarian for rocks now called Silurian in the same year that Lawson (1890) proposed Ontarian as a system to include the pre-Laurentian rocks. For this reason Ontarian was rejected as a geologic name for use by the United States Geological Survey (Wilmarth, 1938, p. 1551) and eventually may be replaced by a more suitable name.

Coutchiching Problem. The presence of a sedimentary formation below the Ely greenstone in Minnesota is difficult to demonstrate, but it is real in Ontario, and therefore the probability of similar occurrences in Minnesota cannot be dismissed. In addition to the Rainy Lake area where recent studies (Yardley, Goldich, Peterman, and Frye, 1959) support Lawson's (1913a) interpretation of the Coutchiching, a further good example is afforded by the Northern Light Lake area (Fig. 13).

The Northern Light gneiss, in the present interpretation, is not a magmatic rock but a paragneiss derived by high-grade metamorphism of a graywacke-shale sequence, similar to the Coutchiching of Rice Bay which it resembles closely in fine-grain size, compositional layering, and in mineralogical and chemical composition. The texture is typically metamorphic, granoblastic to porphyroblastic, and the chemical composition is similar to that of the graywacke gneiss from Rice Bay (Table 13). Plotted on a triangular diagram (Fig. 23) showing the ratio Ca:Na:K, the points representing the gneisses fall quite apart from rocks of magmatic origin.

The position of the Northern Light gneiss, stratigraphically below the Keewatin greenstone in the Northern Light Lake area, can hardly be questioned. Grout explained the gneiss as an early Laurentian intrusion into the Keewatin rocks that was followed later by the intrusion of the Saganaga granite. His studies were directed primarily to the problems of the Saganaga granite, and he did not consider a possible sedimentary parentage for the gneiss.

By analogy with the Northern Light gneiss, the Burntside granite gneiss of the Vermilion granite region may also represent metamorphosed sedimentary beds. Grout (1929b) noted the marked differences in texture, structure, and composition between the Burntside gneiss and the Vermilion granite. He attributed the fine grain of the gneiss to granulation by dynamic metamorphism, but an alternate explanation is that the parent rock was graywacke. Relict structures suggest bedding, and a chemical analysis (Table 16), although obviously not of the best caliber, indicates the similarity of the composition of the Burntside gneiss to the gneisses of Northern Light Lake and Rainy Lake (see Fig. 23). As mentioned earlier in the description of the Burntside gneiss (see pp. 58–59), the structure of the area in the vicinity of Burntside Lake (Pl. 1) is uncertain. Grout concluded that the gneiss is intrusive in Knife Lake metasediments which dip beneath the greenstone as a result of overturning. The alternate suggestion is that the Burntside gneiss is part of the sedimentary sequence beneath the Ely greenstone and that the structural data are inconclusive.

On the basis of the known relationships in Ontario and the less conclusive evidence for the Coutchiching in Minnesota, the deposition of these ancient sediments may be considered a starting point of the history of the Early Precambrian. Clastic materials, ranging from clay to sand, were derived from sources which are unknown and were deposited on an unknown basement. As is apparently common in geosynclinal accumulations of graywacke and shale, large volumes of lava and of pyroclastic materials also were deposited, and these were accompanied by intrusion of gabbroic rocks. These rocks constitute the Keewatin group.

Keewatin Group. The thickness of the basalt flows, the pyroclastic, clastic, and related rocks of the Keewatin is not known, but the opinion of most geologists who have worked with the succession is that thousands of feet of flows were poured out and that locally great thicknesses of pyroclastic materials and of clastic sediments were deposited. Toward the end of the period of volcanic activity, more stable conditions prevailed, and in local favorable areas, the Soudan iron-formation was deposited. Weathering of the flows and pyroclastic rocks, to supply the iron and silica of the iron formation, took place under very different conditions from those which prevailed during the derivation of the clastic materials of the graywacke-shale sequence of the underlying Coutchiching and also of the overlying Knife Lake.

Laurentian Orogeny. It is postulated that by the time of deposition of the Soudan formation the total accumulation of Coutchiching sediments, Keewatin flows, and related rocks had reached a thickness of tens of thousands of feet. The geosynclinal belt became unstable and folding was initiated. The early folds probably were broad rather than tight isoclinal structures. Anticlinal ridges were elevated above the regional base level and were subjected to erosion, adding to the sediments being brought in from the original landmass. Under these conditions there was no widespread break in deposition between the Keewatin and the Knife Lake rocks. The folding, however, probably resulted in a series of more or less parallel ridges and intermontane valleys. Locally, boulders and coarse detritus were deposited contemporaneously with finer-grained sediments in nearby areas, thus conglomerate, such as the Ogishke conglomerate at Ogishkemuncie Lake, occurs as a lens in graywacke and slate.

It is reasoned that subsidence and folding continued during the whole of Timiskamian time and that at Tower, Saganaga Lake, and undoubtedly in a large number of other places, such as Shoal Lake, Ontario, the folding was accompanied by the intrusion of dikes and plutons of tonalitic to granodioritic composition. Metamorphism of the graywacke-shale sequence of the Coutchiching to gneiss and schist was initiated at this time. Continued uplift and erosion finally uncapped the plutons, such as the Saganaga mass, and boulders of the Laurentian intrusives were contributed to the nearby areas. A great thickness of sediments, however, had been accumulated by the time of the unroofing of the Saganaga pluton.

Knife Lake Group. The graywacke-slate sequence of the Knife Lake group is typical of eugeosynclinal deposits. The mode of transport and deposition, whether by turbidity currents or other mechanism, resulted in a sorting of the sediment from very coarse pieces to silt to clay — graded bedding. Chlorite and sericite are characteristic cementing materials. The angularity of grains and the abundance of plagioclase suggest nearby sources, including some igneous rocks of intermediate composition, and rapid removal, transport, and burial. The dark to black color of the slates is caused in part by finely disseminated carbon. Commonly a small amount of pyrite occurs in the slate, and generally some carbonate. Locally in the Knife Lake there are small lenses of iron formation, and siderite is widely distributed throughout, but mechanical rather than chemical sedimentation dominated. Iron formations of possible commercial size within the Knife Lake group are not known in Minnesota, and either stable conditions did not prevail for a long enough time, or the areas of deposition have since been eroded.

The large volumes of pyroclastic rock in the Knife Lake group attest to the accompanying igneous activity. Fine-grained pyroclastic material was incorporated with the graywacke sand and clay, but in addition there were thick accumulations of tuff and volcanic breccia.

The total thickness of sedimentary and volcanic rocks which had accumulated near the end of Timiskamian time must have been on the order of 50,000 feet. Gruner gives a probable maximum of 22,000 feet for the Knife Lake group, and equally large estimates for the thicknesses of the Keewatin group and of the older sediments are not unreasonable.

Algoman Orogeny. It is postulated that near the end of Timiskamian time, approximately 2.5 billion years ago, folding was greatly intensified and a major period of deformation followed. The Knife Lake sediments were tightly folded and elevated in the suprastructure of the Algoman

Mountains. The Keewatin and underlying sediments were downfolded in the infrastructure and depressed to depths of the order of 10 miles where metamorphism produced the gneisses and schists of the garnet-amphibolite facies that characterize the Vermilion granite region of northern Minnesota and southern Ontario. During this metamorphism granitic magma was generated by local melting or partial melting of sediments. Migmatitic gneisses (Fig. 15) were formed in the deeper zone, as were also porphyroblastic gneisses, in part by recrystallization but probably also by potash metasomatism. Granitic magma moved upward, and at higher levels, plutons of more nearly isotropic granite resulted.

Possibly some of the inclusions of schist and of gneiss in the Vermilion granite may represent former Knife Lake sediments which were depressed, but for the greater part, the uplifted suprastructure composed of the Knife Lake in the Vermilion granite region probably was completely removed by erosion. The present area of the Knife Lake slates represents a part of the Algoman Mountains which was downfaulted so that the Knife Lake metasediments have been preserved. This accounts for the low grade of metamorphism (greenschist) of the Knife Lake graywackes and slates, a feature that is very striking as one traverses the country from the high-grade metamorphic rocks of the Vermilion granite and Giants Range regions to Saganaga Lake. Only locally, adjacent to the larger Algoman intrusives, are higher grades of metamorphic schist and gneiss encountered.

The Kekekabic and Snowbank stocks, in the light of the interpretation given above, represent postkinematic, high-level intrusions in the Knife Lake suprastructure of the Algoman Mountains.

Geochronology

The geochronology of the Early Precambrian rocks, as will be seen, is largely resolved to a discussion of the Algoman orogeny. As a check on the ages of the granites in Minnesota that have been assigned to the Algoman, a number of samples of the Early Precambrian rocks of Ontario have been dated. Lawson apparently did not have a specific locality in mind when he introduced the term Algoman. In referring to the extensive development of Algoman granite and gneiss, Lawson (1913a, p. 81) wrote: "It occupies a large portion of the area covered by the Seine River and the Shebandowan sheets, and extends eastward beyond the limits of the latter to Lake Superior."

Data from Ontario. A number of samples collected during the summers of 1957 and 1958 are included in Section E of Table 14 as representative of the Ontario rocks and help to establish the age of the Algoman granite and gneiss. The most northeasterly of the samples are from diamond drilling at Briarcliffe Lake, northwest of Nakina (Pl. 3). Sample KA-112 represents schist cored in exploration for iron formation, and sample KA-111 is a core of pegmatite that cuts the schist. Biotite from the schist is dated at 2.60 b.y. (K-A) and 2.77 b.y. (Rb-Sr); however, the latter value appears to be too high, probably due to analytical error. Muscovite from the pegmatite gives a K-A age of 2.54 b.y. Sample KA-262, representing granite gneiss approximately seven miles east of English River, gives closely agreeing ages of 2.63 b.y. (K-A) and 2.59 b.y. (Rb-Sr).

Granite (KA-258) from Kashabowie Lake gives a K-A age of 2.55 b.y., and a similar age was found for a sample of granite from Steeprock Lake that was kindly supplied by W. J. Huston, Steep Rock Mines Ltd., as typical of the Algoman granite of the area. Biotite from a lamprophyre dike in the ore zone of the Coldstream Copper mine (former Tip Top mine), northwest of Burchell Lake and approximately six miles southwest of Kashabowie, is dated at 2.5 b.y.

Samples from the Rice Bay area in Rainy Lake give ages similar to those for samples from Kashabowie Lake and Steeprock Lake. Biotite and muscovite from Coutchiching schist (KA-191) are dated at 2.52 and 2.60 b.y. (K-A), respectively, and the biotite, at 2.49 b.y. (Rb-Sr). Sample KA-178, dated at 2.55 b.y. (K-A) is from Lawson's unit No. 11, syenite gneiss, from Rocky Islet Bay just south of Rice Bay. Lawson mapped this rock as an Algoman intrusive in the Coutchiching, but the rock is a porphyroblastic paragneiss containing abundant epidote, which is easily visible with a hand lens. The large porphyroblasts are microcline, somewhat sheared to augen. The unit is part of the Coutchiching sequence.

In upper Rice Bay the paragneiss, which Lawson originally mapped as a sheared Laurentian granite, is intruded by numerous dikes and sills. These leucocratic fine-grained rocks were thought by Grout to constitute a large part of the succession, but apparently his locality of detailed measurement was not typical. Some of the aplite intruded prior to, or at the time of, folding was deformed with the Coutchiching sediments, but some of the aplite which crosscuts the bedding is relatively undeformed and is late kinematic. Such an aplite (KA-320) from upper Rice Bay is dated at 2.50 b.y. (K-A) and 2.45 b.y. (Rb-Sr).

East of Rice Bay Lawson mapped large areas of Algoman granite and gneiss. Southwest of Bear Passage there are a number of granite plutons in the Coutchiching. These were designated Algoman by Lawson on the basis of their composition and massive structure; however, Grout assigned the metasediments of the country rock to the Seine or Knife Lake equivalent. The granite commonly is gneissic at the borders but is essentially massive in the central parts of the plutons. It is generally a leucocratic, gray to pink, medium-grained biotite granite. The intrusives are relatively small and were forcibly emplaced, deforming the metasediments in roughly annular patterns (Grout *et al.*, 1951, Fig. 3). Biotite from the granite at Ben Island is dated at 2.41 b.y. (K-A) and 2.36 b.y. (Rb-Sr). Granite from a small island just south of Goose Island, representing a second pluton, gives an age of 2.45 b.y. (K-A) and 2.34 b.y. (Rb-Sr). Similar ages are given by a sample (KA-272) of granite gneiss from Emerson Lake, east of Kenora (Pl. 3); the K-A age is 2.36 and the Rb-Sr age, 2.38 b.y.

Analysis of the Data. A number of interpretations can be made of the radioactivity ages which have been presented for northern Minnesota and southern Ontario. A period of folding at 2.6 b.y. is suggested by the ages from Briarcliffe Lake. Kindle (1931) mapped the metasediments as Coutchiching, but according to E. R. Mead (personal communication, Oct. 1956), geologists working in the area within recent years favor a correlation with the Timiskaming or Knife Lake groups. A similar age (2.6 b.y.) was found for the Northern Light gneiss in the Saganaga granite area, but the gneiss was called an early Laurentian intrusion by Grout. In this report, it is called a paragneiss derived from sediments below the Keewatin greenstone and hence Coutchiching. Thus different interpretations are possible.

If the schist at Briarcliffe Lake is Tismiskamian in age, the Algoman folding dates back at least 2.6 b.y., and the Northern Light gneiss must be older than 2.6 b.y. The determined age then is a survival value. If, however, the Briarcliffe rocks are Coutchiching, and correlative with the Northern Light gneiss, the 2.6 b.y. age may approximate the time of the Laurentian folding. A third suggestion is that the data are too limited and the similarity in ages simply a coincidence. The limitations of the geologic studies now available as a control for interpretation of the radioactivity ages must be considered, but at the same time the uncertainties in the age determinations do not permit using them as an independent tool to determine the basic geologic relationships. For example, the Coutchiching schist of Rice Bay is dated at 2.5 b.y., although it is certainly pre-Laurentian.

Averaging the radioactivity ages has the effect of minimizing the analytical errors, but at the same time the relative importance of the individual samples may be obscured. Averages of the K-A ages for groups of the Ontario samples give three age groupings. The oldest, 2.6 b.y., may be essentially the time of the Laurentian folding. A second group, averaging 2.54 b.y., might be said to date the main period of the Algoman orogeny, and the third group, 2.4 b.y., is a younger group of postkinematic granites. The Rb-Sr determinations are fewer in number, but they suggest similar divisions. There is, of course, danger that this scheme is an oversimplification, but it will serve as a basis of discussion, and conclusions may be considered tentative.

The metasediments at Briarcliffe Lake, because they were involved in the earliest dated folding, probably are not Timiskamian, and tentatively they can be assigned to the Coutchiching (Ontarian). The data for the Northern Light gneiss are in good agreement with the Briarcliffe age; however, because of the lack of Rb-Sr ages, a definite statement cannot be made with regard to the Burntside gneiss of the Vermilion granite region. It does appear likely, however, that the samples from localities near belts of Ely greenstone, in the vicinity of Burntside Lake (KA-46 and 47), and north of Virginia (KA-105 and 317), may date back to the older (Laurentian) period of folding on the basis of their K-A ages (2.6 b.y.).

The average K-A age for the samples from Kashabowie Lake, Steeprock Lake, and Rainy Lake is 2.54 b.y.; the average for the dated samples from the Vermilion granite region is 2.55 b.y. The samples of the Knife Lake slate (KA-147, 200, and 228) give approximately the same age, the time of the main Algoman orogeny. Closely related to the 2.55 b.y. ages, and possibly not to be differentiated, are a number of samples dated at 2.5 b.y. These include the pegmatite (KA-328) on Gold Island in Saganaga Lake, the aplite of upper Rice Bay (KA-320), and the pegmatites of the Northwest Angle (KA-17 and 88).

The youngest group of granites in the Rainy Lake area (2.4 b.y.) cannot be related to a post-Algoman sedimentary cycle. It is possible that the Snowbank stock represents a similar high-level pluton, and phases of the Giants Range granitic complex may also be of this period, but the data are not at all conclusive, and additional work is needed.

Some of the ages which are anomalously low on the basis of the known geologic relationships can be explained. For example, the low ages of the Giants Range granite at Babbitt (KA-8; 1.1 b.y.) and of the Snowbank granite (KA-106; 1.2 b.y.) are attributed to metamorphism as a result of intrusion of the Duluth gabbro. Variable ages obtained for samples of the Knife Lake slates south and east of Knife Lake, however, are not easily explained and suggest unknown events. Lamprophyre dikes were thought by Grout to have been intruded in a late stage of consolidation of the Saganaga granite, which on the basis of the age of the pegmatite on Gold Island, must have been prior to 2.5 billion years ago; yet the biotite from one of the lamprophyres (KA-70) is dated at 1.8 b.y. Caution is obviously required in the interpretation of this age. It may be the time of intrusion of the dike, but it may also represent the time of alteration of a pre-existing dike, or the time of regional deformation to which the dike rock, because of its composition, was sensitive; whereas the Northern Light gneiss was not. A problem for further geologic and laboratory investigation is indicated.

The Vermilion granite region has been deeply eroded, and unlike the area of the Knife Lake slates to the east, the schists and gneisses of the Vermilion granitic complex are in the garnet-amphibolite facies, and there are vast expanses of coarse-grained granite. This is indeed a region which one might expect to be firmly welded and stabilized; yet dated samples show considerable variations. For example, granite (KA-239) from near Echo Lake (Pl. 1) is dated at 2.57 b.y. (K-A) and 2.47 b.y. (Rb-Sr), whereas Laurentian tonalite from Grassy Island (KA-307) is dated at 2.38 b.y. (K-A and 2.28 b.y. (Rb-Sr). The tonalite normally should be expected to give a greater age than the granite, but thin sections show that it has been sheared, so that the low age may be correlated with later deformation. It should be noted that although the Rb-Sr ages for the two samples are lower than the corresponding K-A ages, the difference between the ages by the two methods is essentially the same; 0.18 b.y. for the K-A method and 0.19 b.y. for the Rb-Sr method. Regardless of the explanation offered for the anomalous ages discussed above, it is evident that even the old and thoroughly metamorphosed Vermilion granite region of northern Minnesota has not remained completely stable.

The Saganaga granite also presents a complicated history since the time of its emplacement. It is possible that the original intrusive was a tonalite whose composition was modified during later metamorphism. It was intruded in an anticlinal fold of Keewatin and underlying rocks during the Laurentian diastrophism. The quartz eyes in the granite and in the Northern Light gneiss probably had the same origin which is here related to folding prior to the main Algoman folding, because boulders of the Saganaga granite with well-developed eyes were transported and deposited in the conglomerates of the Knife Lake group. At Ensign Lake, 20 miles southwest of Saganaga Lake, the cobbles were deformed during the folding of the Knife Lake, and the quartz eyes were deformed and elongated parallel to the long dimensions of the pebbles and cobbles.

The boulders of Saganaga granite in the basal conglomerate of the Knife Lake at Cache Bay are locally sheared but are not stretched or deformed to the extent of the cobbles in the beds within the tightly folded Knife Lake metasediments, as for example, at Ensign Lake or at Midway in the Mesabi district (Fig. 17). Grout (1936) suggested that the Saganaga granite and the overlying conglomerate were tilted to the west as a single unit during the Algoman folding with little deformation of the contact zone. He wrote: "The two rocks are firmly attached, and there is no sign of shearing." Northeast of Cache Bay in the vicinity of Silver Falls, however, the conglomerate has been extensively sheared, and the boulders are stretched and fractured. Graywacke beds in this area are schistose and mineralized with sulfides. Northward extension of Gruner's fault (Fig. 13) would carry it through the sheared area.

A sample of the Knife Lake slate (KA-240, Fig. 13) from Cypress Lake is dated at 1.9 b.y. Two additional samples (KA-243 and 244) from localities southwest of Cypress Lake (Pl. 1) give K-A ages of 1.9 and 2.2 b.y., respectively. These samples suggest, as does the 1.8 b.y. age for the lamprophyre dike (KA-70) in the Saganaga granite mass, that some deformation or thermal events occurred in the region much later than the Algoman folding (2.5–2.6 b.y.).

Summary Statement. As a result of the present investigations, the time division between Early and Middle Precambrian eras has been set at 2.5 billion years ago. This coincides approximately with the time of the Algoman orogeny, but it is well known from geologic studies that orogenies are not planes in time and that major orogenies may represent a number of periods of folding or pulses acting at different times in different areas. In Table 2 it will be noted that the orogenies are not included in the time scale. It is more logical to think of the periods of orogenies as events superimposed on the time scale; hence to speak of the Algoman orogeny as having been initiated in Timiskamian time and as ending in the Huronian, or of the older Laurentian folding as having started in late Ontarian time and as ending in Timiskamian.

Although the time scale should be independent of special events, such as periods of peneplanation and periods of orogeny, it is obvious that to be geologically useful for Precambrian rocks the time scale must be coordinated with some features of the geologic record which are recognizable to the field geologists. Radioactivity dating methods inherently make the periods of orogeny the logical basis for subdivision. In the earlier classification of the Minnesota Geological Survey (Table 1), the division between the Earlier and Medial Precambrian eras was made on the basis of the Laurentian orogeny. In large part this usage followed earlier work, and in part, it may have been influenced by the results of early efforts at dating using the helium content of magnetite. On this basis, an age of 750 million years was assigned to the Algoman granites (Grout *et al.*, 1951, p. 1020, 1040). An age of approximately 2300 million years was assigned to the pre-Knife Lake granites on the basis of Ahrens' (1949) early work on lepidolites from Lake of the Woods. It was therefore concluded that "The time between these two granites is long and may need subdivision" (Grout *et al.*, 1951, p. 1020).

The present investigation, however, shows that the Laurentian, or pre-Knife Lake intrusives are not separated by a billion or more years from the Algoman, or pre-Animikie granites, and it is more logical to assume that, except locally, there was no great time break between the Keewatin and the Knife Lake rocks.

Much of the discussion of the history of Early Precambrian time in northern Minnesota can be considered interpretative or speculative; however, if the discussion proves useful in outlining the problems and possibly revealing something of their magnitude, it will have served some purpose, for the need of new work is clearly indicated.

MESABI DISTRICT

General Statement

The Mesabi district probably has been more intensely studied than any other area in Minnesota because of its important iron deposits which have been mined since 1892. Total ore shipments to 1958 amounted to over 2.2 billion tons (Wade and Alm, 1959). The geology is well known through the writings of J. W. Gruner and many others. The stratigraphy and structure are described in Bulletin 38 of the Minnesota Geological Survey (White, 1954), and a review of the district and its geological problems has recently been given by Gruner (1956). The descriptions of formations given here are brief, and the reader is referred to White (1954) and to the paper by Gruner (1956) which appears in *Precambrian of Northeastern Minnesota* (Schwartz, 1956a). The latter volume includes shorter descriptions of special areas and three geologic maps (Pls. 3, 4, and 5) of the Mesabi district compiled by geologists of the Oliver Iron Mining Division of the United States Steel Corporation.

Animikie Group

Type Locality. The name Animikie group was introduced by Hunt (1873, p. 339) for dark-colored argillites and sandstones in the Thunder Bay area, on the north shore of Lake Superior (Pl. 3). Hunt noted that the beds which he referred to the Animikie group are overlain with slight discordance by red and white sandstone which he considered to be the same as that of the copper district of Michigan. Tanton (1931) made a detailed study of the type locality and reviewed the development of the terminology. He introduced the term Kaministikwan group for the beds resting unconformably on Early Precambrian rocks and consisting of Animikie and younger strata now generally assigned to the Keweenawan. He also included in the group the dikes and sills which intrude the Kaministikwan strata.

Tanton adopted Hunt's term Animikie for the lower beds and referred to them as the Animikie series. He included the overlying beds of conglomerate, sandstone, argillite, and some limestone in his Sibley series. The basal conglomerate of the Sibley includes pieces of Animikie iron-formation, granite, greenstone, and vein quartz. Tanton assigned a maximum thickness of 500 feet to the Sibley series, but on the average the thickness of these rocks is much less. Disconformably overlying the Sibley series is a succession of lavas and sediments which Tanton called the Osler series. At the base of this series is a conglomerate which may be as much as 200 feet thick. Tanton concluded that the Osler series is equivalent to the Keweenaw group of Hunt (1873).

The Animikie group consists of three formations: a basal Kakabeka sandstone and quartzite, the Gunflint iron-formation, and the Rove argillite and graywacke. The Rove and Gunflint formations can be traced across the border into Minnesota where they have been described by Broderick (1920). Goodwin (1956) recently described the facies changes in the Gunflint formation and emphasized the importance of volcanism in the cyclical sedimentation of iron- and silica-bearing rocks. The formation has an average thickness of 400 feet. The most detailed description of the Rove argillites and graywackes is given by Tanton (1931, pp. 36–44) who estimated a thickness of more than 2000 feet in the Thunder Bay area. The correlation of the Pokegama, Biwabik, and Virginia formations with the Kakabeka, Gunflint, and Rove formations is generally accepted.

Pokegama Formation. The Pokegama quartzite rests on an erosion surface that was cut in a variety of Early Precambrian rocks. The contact between the Pokegama and underlying rocks can be seen in a number of places in the Mesabi district. It is well exposed at Babbitt, in the East Mesabi, where the basement rock is the Giants Range granite. Here the Pokegama may be absent or may consist of a thin veneer of conglomerate, but it attains a maximum thickness of 30 feet (Grout and Broderick, 1919, p. 7). At Midway, a subdivision of the city of Virginia, the Pokegama conglomerate rests on vertical beds of the Knife Lake (Fig. 17). Pebbles and cobbles of white quartz are common in the Pokegama conglomerate; other rock types include graywacke, greenstone, and a variety of aphanite porphyries. The formation above the basal conglomerate consists principally of fine- to coarse-grained quartzite. Some fine-grained, dark beds are laminated and resemble argillite, and these commonly are micaceous. The Pokegama formation probably does not exceed 200 feet in thickness and in most places is much less. In general the thickness increases from east to west in the district.

Biwabik Formation. The Biwabik iron-formation is essentially a ferruginous chert, averaging approximately 30 per cent of total iron (Fe). The unaltered formation in Minnesota is commonly called taconite. The mineralogy and stratigraphy have been described by Gruner (1946) and White (1954). The principal components of the taconite are chert; iron silicates, which include minnesotaite, stilpnomelane, and greenalite; iron oxides, magnetite, and hematite; and carbonates, siderite, calcite, and dolomite. The iron-bearing minerals commonly are aggregated into small ovoid or ellipsoid structures, called granules, and these characterize the taconite. Layers with abundant iron silicates are generally fine-grained and thinly laminated and are commonly referred to as slaty. Taconite has been variously classified on the basis of mineral composition, texture, and layering. Four major subdivisions are recognized, and in the older literature these are called divisions; however, White (1954) and Gruner (1956) refer to them as members. From oldest to youngest the members are: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. The thickness of the members varies with different localities in the Mesabi district, and the Biwabik formation ranges from 340 to 800 feet (White, 1954, p. 22).

The Biwabik iron-formation is generally considered a chemical sediment, but its origin is controversial. The chert is microcrystalline, and there is little evidence of clastic quartz. Locally there are intraformational conglomerates and algal horizons. The more prominent algal beds occur in the Lower and Upper Cherty members.

Although the primary taconite now is being mined and utilized as iron ore, the production which made the Mesabi district famous has come from the soft iron ores formed by oxidation and leaching of the taconite. As in the case of the taconite, there is also considerable controversy concerning the origin of the iron ore. The formation of the Lake Superior iron ores through ordinary processes of weathering was probably first suggested by Irving and Van Hise (1892, p. 283). Gruner (1930, 1937) presented a hypothesis for the oxidation and concentration of the soft iron ores by hydrothermal leaching. White (1954) reviewed the theories of origin and concluded in favor of the weathering hypothesis.

Virginia Formation. The Virginia formation is a clastic sediment which marked the end of iron deposition. The formation consists mostly of fine-grained, thin-bedded, black and gray argillite. The original thickness of the formation in the district is not known; the overlying beds are Cretaceous or Pleistocene. Considerable thicknesses of the Virginia argillite have been penetrated in drill holes, and White (1954, p. 27) states that 2000 feet was penetrated in a drill hole southwest of Aurora in the SE¼ NE¼ Sec. 30:58–15.

Relationships. The contacts between the three formations of the Animikie group appear to be conformable. Natural outcrops are exceedingly few, and the contact between the Biwabik and Virginia formations can be seen only in two pits. White (1954, p. 30), whose study of the Mesabi district involved examination of many drill cores, concludes that it is improbable that unconformities exist between the Animikie formations. In the Gunflint district the Rove formation is overlain essentially concordantly by Keweenawan sandstone and flows (Grout and Schwartz, 1933).

Intrusive Rocks

The major intrusive in the Mesabi district is the Duluth gabbro, which metamorphosed the Biwabik iron-formation at the east end of the district. Grout and Broderick (1919) mapped several diabase sills and small dikes, and these were assigned to the Keweenawan; however, they appear to predate the main mass of the Duluth gabbro and have been metamorphosed to a granoblastic texture by the gabbro.

A sill of syenite is intrusive into the Upper Cherty member of the Biwabik formation near Aurora. White gives a detailed description of the sill, including a chemical analysis. The Aurora sill has been traced by drilling for a distance of 3.5 miles from the west side of Sec. 4:58–15 to the center of Sec. 36:59–15. According to White (1954, p. 63) the sill increases in thickness southward, and the maximum known thickness is 121 feet. There are a number of small dikes, some of which have been altered to kaolin. These attain a width of as much as 10 feet. The individual occurrences have been summarized by White.

Age of the Animikie Group

Chemical analyses given by White (1954, p. 17) show that the lower part of the Virginia formation, commonly a graphitic argillite, is relatively high in K_2O, and petrographic examination shows the presence of very fine-grained sericite or illite. Two samples of the Virginia argillite, from Eveleth (KA-137) and from the West Mesabi, southeast of Grand Rapids (KA-212) were dated by the K-A method to see if this fine-grained material might be useful. Sample KA-137 gives an age of 1.5 b.y. and sample KA-212 an age of 1.2 b.y. These ages are not considered significant.

The argillite contains a very large amount of graphite or carbonaceous matter which causes considerable difficulty in purifying the extracted argon. Sample KA-212, which gives the lower of the two ages, was analyzed for CO_2 and total carbon. The CO_2 content is 1.12 per cent (SSG), and the carbon is 7.9 per cent, as determined by C. O. Ingamells. The results indicate that the finely divided material is variable in its retention of argon, or that the difficulties encountered in the analytical procedure are of sufficient moment to make the results very uncertain.

Efforts to use stilpnomelane, potassium-iron silicate, which is widely distributed in the iron formations of the Lake Superior region, proved unsuccessful; the mineral does not retain argon (Goldich, Baadsgaard, and Nier, 1957, p. 548).

HISTORY OF MIDDLE PRECAMBRIAN TIME FOR NORTHERN MINNESOTA

The Animikie strata in northern Minnesota, before intrusion of the Duluth gabbro in Late Precambrian time, extended from their present southwestern end, approximately 20 miles southwest of Grand Rapids, to Gunflint Lake on the Ontario boundary — a distance of well over 150 miles. The beds continue from Gunflint Lake without serious interruption to the type locality in the Thunder Bay area, a distance of approximately 100 miles, so that the total length in Minnesota and Ontario is well over 250 miles. Throughout this extent the Animikie formations rest with angular unconformity on an erosion surface developed on Early Precambrian rocks.

Eparchean Interval

Lawson (1902, 1913b, 1930, 1934) considered the unconformity at the base of the Animikie group to be one of the most profound and extensive in the geologic record and suggested the name Eparchean Interval for the period of time during which the Algoman Mountains were eroded to a peneplain. Lawson (1934) calculated the duration of the Eparchean Interval to be of the order of 200 million years. In this computation he assumed that, following the maximum development of the mountains during the Algoman, the general altitude of the region was approximately 3 kilometers and that a prism of rocks approximately 12 kilometers thick was removed by erosion. The assumptions made by Lawson may be questioned, but his efforts to treat the problem quantitatively emphasized the importance of unconformities.

In the present investigation the division between the Early and Middle Precambrian is placed at 2.5 b.y. The Animikie group is assigned to the Middle Precambrian, the duration of which was approximately 800 million years, from 2.5 to 1.7 b.y. The age determinations made on the Virginia argillites do not permit assignment of the relative position of the Animikie group within the Middle Precambrian, but an estimate of 200 million years for the time hiatus represented by the unconformity at the base of the Animikie in Minnesota probably is too low.

NORTH SHORE REGION

General Statement

The North Shore of Lake Superior between Duluth and Pigeon Point (Pl. 1) is characterized by lava flows of Keweenawan age. The area northwest of Lake Superior is the north limb of a geosyncline in which the rocks dip 10°–15° to the southeast. The other limb of the geosyncline is composed of flows exposed on Keweenaw Point, Michigan, where they dip at angles as great as 70° to the northwest. Geologically, the area in Minnesota, which is here called the North Shore region, is dominated by the Duluth gabbro, a huge sill-like intrusive in the lavas. The gabbro is one of the largest of the masses commonly referred to as stratiform intrusives because of their layered structure. The Duluth gabbro, however, is composed of a number of intrusives and probably is better called the Duluth complex (Taylor, 1956).

The outcrop pattern of the gabbro (Pl. 1) is crescent-shaped, extending from Duluth to a point near Hovland, a distance of nearly 150 miles, and attaining a maximum width of about 30 miles in Lake County. The Keweenawan flows, which dip to the southeast and disappear beneath Lake Superior, are the roof of the complex. The floor is composed of a variety of rocks. As one travels along the base, the underlying rocks are the Keweenawan flows and the Thomson formation, west of Duluth; the Virginia and Biwabik formations in the East Mesabi; the Giants Range granite, the Knife Lake group, and Ely greenstone in the Vermilion district; the Gunflint and Rove formations in the vicinity and east of Gunflint Lake; and again the Keweenawan flows in the vicinity of Hovland. The apparent transgression is best explained (Grout, 1918a) as the result of intrusion of gabbro along or near the erosion surface on which the Keweenawan flows came to rest.

Thomson Formation

The Thomson formation, exposed just west of Duluth in Sec. 17:49–15, is composed of interbedded slates and graywackes which strike N. 85° E. and dip 80–85° S. The formation in the Duluth area has been described by Schwartz (1949) and is considered in more detail in a later section on east-central Minnesota.

Puckwunge Formation

N. H. Winchell (1897) discovered and named the Puckwunge conglomerate along a creek called the Puckwunge by the Indians and now known as Stump River in Sec. 25, T. 64 N., R. 3 E. In subsequent accounts Winchell (1899a, b) described 18 feet of coarse conglomerate grading upward into 18 feet of fine conglomerate and gritstone. Winchell considered the Puckwunge to be the basal Keweenawan sediment and included in the formation similar conglomerate and sandstone in the Grand Portage area and in the vicinity of Duluth. Van Hise and Leith (1911) assigned the Puckwunge to the Lower Keweenawan, and this classification has been followed by the Minnesota Geological Survey. The beds, however, are largely sandstone, and the name Puckwunge formation is used in preference to Winchell's original Puckwunge conglomerate.

West of Duluth in Secs. 17 and 20:49–15, the Puckwunge overlies the Thomson formation with angular unconformity. The lower part of the formation is covered, but the total thickness probably does not exceed 100 feet. The formation poses some stratigraphic problems. At the type locality the Puckwunge conglomerate apparently overlies the Rove formation and is overlain by Keweenawan flows. West of Duluth the formation overlies the Thomson formation and is overlain by flows. Along the St. Louis River, in the NE$\frac{1}{4}$ Sec. 16:48–16, the Puckwunge is the surface formation and rests on the Thomson formation (Schwartz, 1949, Pl. 6); however, in the bed of Little River, a tributary of the St. Louis River, in Sec. 1:48–16, a similar conglomerate is overlain by sandstone and shale (Fig. 18). The lower contact of the conglomerate is not exposed, but a short distance upstream good exposures of the Thomson beds strike essentially east-west and are nearly vertical. The conglomerate contains pebbles and cobbles of milky quartz apparently derived from veins in the Thomson formation. It is well indurated, and the matrix contains abundant pyrite. Downstream from the outcrop, and in the hill above it, beds of sandstone and shale of the Fond du Lac formation occur above the conglomerate. The Fond du Lac is generally considered to be Upper Keweenawan, so it must

FIGURE 18. — Late Precambrian Puckwunge (?) conglomerate overlain by sandstone and shale of the Fond du Lac formation. Bed of Little River, Sec. 1:48-16, Jay Cooke State Park. Photograph by Paul Lindberg, 1956.

be assumed that the sandstone and siltstone overlie the conglomerate disconformably, or that the conglomerate along Little River is not the same as the conglomerate of the type locality.

The problem is further complicated by a description given by Winchell (1899b) of the rocks encountered in drilling a deep well in Short Line Park in Duluth. No log was kept of the drilling for the first 231 feet; however, the drill then penetrated 217 feet of flows, 48 feet of pyritiferous quartzite and quartz conglomerate, and 91 feet of flows before encountering the Thomson slate. The well log, as Schwartz (1949, p. 36) points out, casts doubt on the position of the Puckwunge formation and on its assignment to the Lower Keweenawan.

North Shore Volcanic Group

The Middle Keweenawan rocks are a thick sequence of lava flows, tuffs, and interflow sediments. These rocks were included in the Keweenaw Point volcanics, named by Grout and Schwartz (1933, p. 13) for the exposures on Keweenaw Point, Michigan. During the course of a restudy of the Beaver Bay complex by Harry M. Gehman, Jr., it became apparent that a locality name for the Minnesota sequence would be more suitable, and G. M. Schwartz suggested the name North Shore volcanic group.

Sandberg (1938) has given a description of the flows and minor interflow sediments along the shore of Lake Superior from Duluth to Two Harbors. The extrusive rocks, including interflow fragmental rocks, total close to 21,000 feet. Sandberg estimated that rhyolitic flows make up nearly 10 per cent of the thickness and that the sediments are just over 1 per cent. He calculated a thickness of 2500 feet for the flows below the gabbro. A more recent estimate (Grout, Sharp, and Schwartz, 1959, p. 40) places the total thickness of the flows between Duluth and Tofte, 4 miles northeast of Schroeder (Pl. 1), at more than 25,000 feet.

The sandstones, or interflow sediments, appear to be local accumulations. They are fine to medium grained, gray to red, commonly thinly laminated, and many are cross-bedded. The thickest sandstone in the Duluth area is 114 feet (Sandberg, 1938, p. 810) and is well exposed along the lake shore in Leif Erikson Park in Duluth. In Cook County a maximum thickness of 205 feet is reported by Grout, Sharp, and Schwartz (1959, p. 38) for sandstone and shale between flows of basalt.

Sandberg classified the flows as basalt or rhyolite and was unable to recognize intermediate types. More recent work (Goldich, Taylor, and Lucia, 1956) indicates that some variations in composition may be expected. A chemical analysis of such an intermediate type, a dellenite porphyry flow, from the Enger Tower area in Duluth is given in Table 17. Thin sections of the flows in the vicinity of Beaver Bay show a range in composition of the plagioclase indicating intermediate types; however, their abundance cannot be estimated at the present time.

Duluth Complex

Early Work. The Duluth gabbro was first intensively studied by Grout (1918a, b, c, d). The broader geologic relationships at Duluth have been summarized by Schwartz (1949). The early studies by Grout contributed some concepts which have been fundamental to the study of layered or stratiform intrusions. Grout (1918b) distinguished two types of structure. The first is banding (Fig. 19) resulting from alternating layers with differing amounts of the same minerals which he ascribed to convection in the crystallizing magma. The banding is referred to by Wager and Deer (1939) as rhythmic layering. The second structure was called fluxion structure by Grout, and igneous lamination by Wager and Deer. It is formed by the parallel orientation of minerals, principally the tabular plagioclase crystals.

A third type of layering, mineralogic rather than structural, is called cryptic layering by Wager and Deer, and this type is fundamental to the concept of the layered intrusions as typified by the Skaergaard intrusion of East Greenland. Cryptic layering consists of a progressive change in the composition of the mineral phases, such as plagioclase, pyroxene, or olivine, from base to top of the intrusions. The change in composition is a consequence of the crystallization of the basaltic magma accompanied by settling of the crystals.

Grout showed differences in composition within the gabbro and recog-

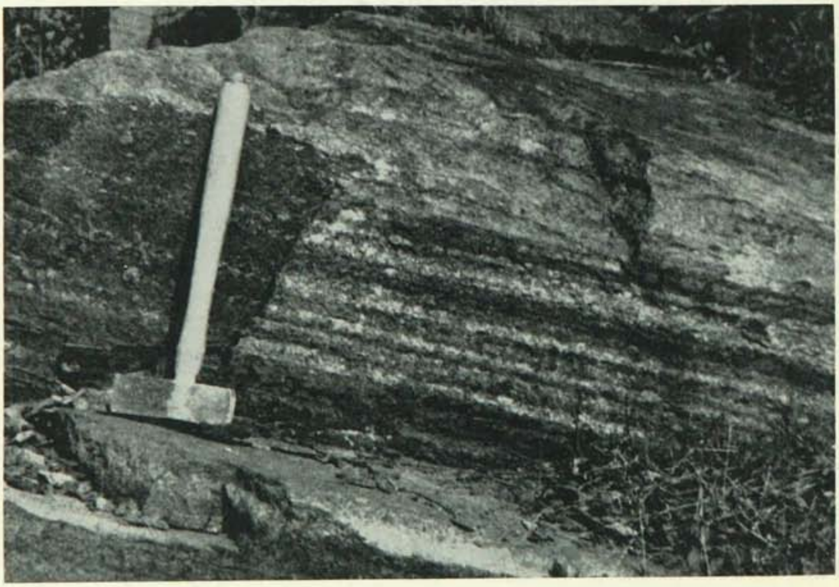

Figure 19. — Rhythmic layering in troctolite of the layered series, Skyline Drive near Bardon's Peak, Duluth.

nized a number of rock types ranging from peridotite, normal gabbro, troctolite, and feldspathic gabbro to granite or "red rock." He emphasized that the rocks at Duluth are principally of two types, gabbro and granite, and concluded that immiscibility played a dominant role in the differentiation of the original basaltic magma. The immiscible granitic liquid, in this interpretation, was segregated at the top of the chamber, and reaction between the granitic liquid and gabbroic rock types produced intermediate rocks.

Multiple Intrusions. Taylor (1956) studied the gabbro at Duluth to determine whether cryptic layering, such as that which characterizes the Skaergaard intrusion, could be established. The results of his field and laboratory studies show that the commonly accepted version of the Duluth gabbro, a large mass of gabbroic rocks grading to "red rock" or granite at the top, is oversimplified and that the gabbro is a complex of a number of separate intrusions in which each of the principal rock types shows transgressive relationships with one or more of the older units.

The oldest intrusive at Duluth is a coarse-grained feldspathic gabbro which Taylor calls the anorthositic gabbro. It had been previously recognized by Grout (1918d, p. 627), who referred to it as feldspathic gabbro. The anorthositic gabbro contains 75–90 per cent of calcic labradorite. It is commonly brecciated and appears to be an autoclastic rock in which the inclusions probably represent early phases broken up and incorporated in the magma. The upper contact is approximately concordant with the flows, but Taylor found that locally the anorthositic gabbro intrudes the flows. The basalt flows are recrystallized to a granoblastic texture, and inclusions of basalt in the gabbro near the contact are numerous.

The anorthositic gabbro is intruded by a younger gabbro which typically is banded, and to this unit Taylor applied the name layered series. The layered series makes up the lower two-thirds of the gabbro at Duluth and consists of troctolite, olivine gabbro, feldspathic gabbro and syenogabbro. Taylor estimated the thickness of the layered rocks to be 15,000 feet, so that the total thickness of the gabbro is in excess of 20,000 feet. The layered series shows rhythmic banding, igneous lamination, and gravity stratification, but only limited development of cryptic layering, and in this regard the Duluth gabbro is different from the Skaergaard intrusion.

The limited development of cryptic layering at Duluth is explained by Taylor by the renewal of magma from time to time which prevented a change in composition that normally is expected in the crystallization of basaltic magma. Taylor demonstrated multiple intrusions in the layered series by cross-cutting relations and mapped a separate intrusive which he designated as the Bardon's Peak gabbro. Others were found, but because of the limited outcrop and the similarity in composition and texture of the gabbroic rocks, the separate intrusives could not be mapped. The absence of chilled contacts indicates that the intrusions were not greatly separated in time.

Ferrogranodiorite and Granophyre. The layered series, as well as the older anorthositic gabbro, is intruded by granodioritic and granitic rocks and by dikes of basalt and aplite. The granodiorite and granophyre commonly are localized along the contact between the anorthositic gabbro and the layered series. This zone of earlier intrusion remained one of weakness and was followed by later intrusions. Granodiorite and granophyre are well exposed in the Enger Tower area in Duluth (Goldich, Taylor, and Lucia, 1956). The succession of rocks in this area is (1) lava flows of the North Shore volcanic group, intruded by (2) anorthositic gabbro, intruded by (3) quartz gabbro of the layered series and by (4) granodiorite, (5) granophyre, and (6) late dikes. These different rocks, all part of the complex at Duluth, serve to emphasize that the gabbro was not emplaced as a single thick layer of basaltic magma which differentiated into banded gabbro at the base and "red rock" at the top.

The granitic magma reacted with the intruded gabbroic rocks to produce contaminated rock previously described as intermediate rock (Grout and Longley, 1935). The intermediate rock produced in this manner is easily recognized in thin sections and in chemical analyses and should not be confused with magmatic rocks of intermediate composition approaching granodiorite and adamellite which intrude the anorthositic gabbro. Tex-

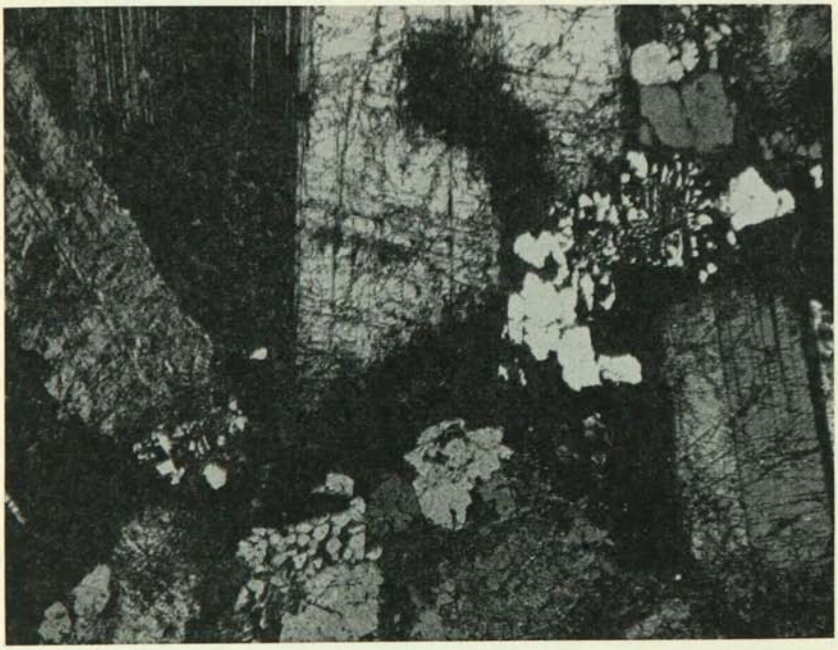

FIGURE 20. — Photomicrograph of anorthositic gabbro with introduced quartz and K-feldspar in graphic intergrowth. Crossed nicols, 23X. Quarry on 1st Street, southeast of Enger Tower, Duluth.

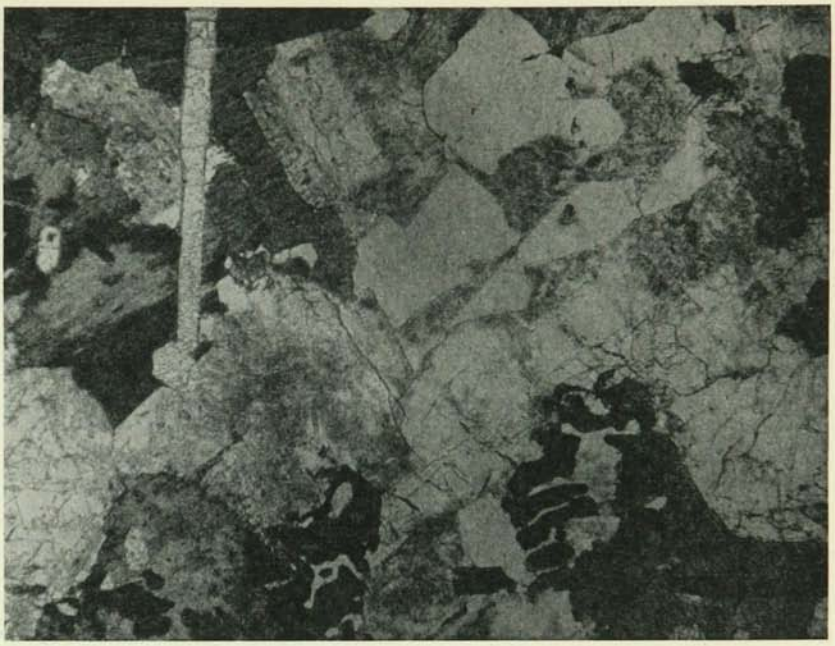

FIGURE 21. — Photomicrograph of medium-grained adamellite composed of andesine, quartz, and K-feldspar in irregular graphic intergrowth, hornblende, skeletal magnetite, and elongated apatite. 85X. Coffee Creek, SW¼NE¼ Sec. 29:50-14, northwest of Enger Tower, Duluth.

turally, the intrusive granodiorite and adamellite are very different from the intermediate rock that resulted from the infiltration-replacement of anorthositic gabbro (compare Figs. 20 and 21). Chemically the intermediate rock is different from the intrusive ferrogranodiorite as can be seen in chemical analyses (Table 17).

Dikes. Dikes are numerous in the Enger Tower area and range from an inch to 80 feet in width. They are of four types: (1) granodiorite, (2) granite, (3) basalt, and (4) aplite. The granodiorite dikes contain plagioclase, averaging An_{47}, a light-colored pyroxene which is usually altered to uralite, and small amounts of quartz and dusty alkali-feldspar with minor amounts of micropegmatitic intergrowth. Magnetite-ilmenite, sphene, zircon, and apatite are accessory. The dikes trend N. 10° E.

The granitic dikes are red to dark-red, fine- to medium-grained rocks which range from stringers to dikes several feet wide. They cut every rock type in the Enger Tower area and are composed of quartz and alkalic feldspar with small amounts of ferromagnesian minerals. A chemical analysis is given in Table 17.

Basalt dikes are numerous and range from 2 inches to 4 feet in width. They usually are vertical in attitude and strike N. 65° E. The basalt dikes

TABLE 17. CHEMICAL ANALYSES OF FERROGRANODIORITE, GRANOPHYRE, AND RELATED TYPES FROM DULUTH

	1	2	3	4	5
SiO_2	50.36	64.95	66.92	73.55	51.97
Al_2O_3	14.88	12.58	12.73[b]	12.05	18.97
Fe_2O_3	7.19	4.70	4.36	2.37	1.98
FeO	8.14	4.83	3.93	1.09	7.07
MgO	2.36	.93	1.66	.51	2.67
CaO	7.06	2.07	1.20	.76	8.60
Na_2O	3.74	3.46	3.45	2.85	3.18
K_2O	1.68	4.21	3.98	5.40	1.43
BaO	n.d.	.12	.06	.07	n.d.
TiO_2	2.15	.82	.69	.27	1.90
P_2O_5	.82	.15	.11	.05	.41
MnO	.20	.16	.16	.05	.14
H_2O+	.87	.54	1.25	.38	1.31
H_2O-	.21	.32	.20	.09	.17
CO_2	.02	.03	.02	.16	n.d.
S	n.d.	.03	.04	.01	n.d.
	99.71	99.90	100.76	99.67	99.79
$<O \equiv S$		.01	.01		
Total	99.71[a]	99.89	100.75	99.67	99.79

[a]Includes SrO, 0.03. [b]Includes ZrO_2, 0.22, originally reported.

1. Ferrogranodiorite from outcrop along Skyline Drive, northeast of Enger Tower, just southeast of Twin Lake, R. B. Taylor, analyst (Goldich, Taylor, and Lucia, 1956, p. 82).

2. Dellenite porphyry flow above anorthositic gabbro, 8th St. and 3rd Ave. W., S. S. Goldich and Deane K. Smith, analysts (*Ibid.*).

3. Granophyre ("red rock"), NW cor. Sec. 27:50-14, F. F. Grout, (1918d, p. 650, No. 25) analyst.

4. Granite dike intruding dellenite porphyry flow, 8th St. and 3rd Ave. W., R. B. Taylor, analyst (Goldich, Taylor, and Lucia, 1956, p. 82).

5. Contaminated granophyre, quarry on 13th Ave. W. southeast of Enger Tower, W. W. Longley, analyst (Grout and Longley, 1935).

are younger than the granodiorite dikes. The largest, a granophyric microgabbro, was intruded into the anorthositic gabbro and overlying flows. This dike is approximately 80 feet wide and can be traced for a distance of approximately 4000 feet. Chemical analyses are given in Table 18.

Origin of the Gabbro Complex at Duluth. The gabbroic rocks at Duluth represent at least two major periods of intrusion, sufficiently apart in time, so that the older anorthositic gabbro was cold enough to chill the younger gabbro at contacts. Anorthosite of the Beaver Bay type, containing 90 per cent or more of calcic plagioclase, occurs as inclusions in the anorthositic gabbro, but the origin of the anorthosite is not known (Taylor, 1956, p. 49). The rocks of the layered series were formed by a number of intrusions, apparently closely spaced in time and generally indistinguishable except locally where cross-cutting relationships are found. Rhythmic layering, gravity stratification, and igneous lamination indicate that these rocks are bottom accumulates of crystals and that there was an active circulation or convection of the magma.

TABLE 18. CHEMICAL ANALYSES OF BASALTIC ROCKS FROM THE DULUTH AREA

	1	2	3	4	5
SiO_2	49.18	49.21	47.50	43.27	47.92
Al_2O_3	13.82	14.24	12.94	13.90	18.87
Fe_2O_3	2.46	2.36	3.94	3.30	1.18
FeO	10.99	10.59	11.52	13.31	8.65
MgO	5.44	5.73	5.62	3.73	7.82
CaO	9.16	9.14	8.38	6.50	10.46
Na_2O	2.72	2.72	2.39	1.95	2.44
K_2O	.98	.97	1.07	1.37	.19
TiO_2	2.99	2.83	3.74	4.10	1.40
P_2O_5	.56	.50	.69	.45	.07
MnO	.20	.19	.22	.66	.11
H_2O+	1.04	1.00	1.31	3.64	.41
H_2O-	.20	.19	.68	.94	.10
CO_2	.04	.02	n.d.	2.71	.06
S	.09	.07	n.d.	n.d.	.05
	99.87	99.76	100.00	99.83	99.73
$<O\equiv S$	.03	.03			.02
Total	99.84	99.73	100.00	99.83	99.71

1. Basalt, chill zone of microgabbro dike. Sec. 28:50-14. Eileen H. Oslund, analyst (Goldich, Taylor, and Lucia, 1956, p. 82).
2. Microgabbro, from same dike as No. 1, about 8 feet from contact. Eileen H. Oslund, analyst.
3. Diabase, Northland sill, shore of Lake Superior at foot of 30th Ave. E., Duluth, S. S. Goldich, analyst (Schwartz and Sandberg, 1940, Table 1).
4. Chill zone of Northland sill at base, same location as No. 3. S. S. Goldich and C. O. Ingamells, analysts.
5. Average of marginal olivine basalt from the Skaergaard intrusion (Wager and Deer, 1939, p. 141, analysis XIIIa; Wager and Mitchell, 1951, Table A, analysis Y).

Closely related to the layered series gabbros are intrusive granodiorite and granophyre. The granodiorite is a high-iron, low-silica, pyroxene-bearing rock which is called ferrogranodiorite. It is relatively deficient in quartz (5–15 per cent) compared to normal granodiorite but is relatively enriched in iron and commonly has 10 per cent of magnetite. The more silicic intrusions are granophyres, ranging from adamellite to granite, which have been called "red rock" in the past. The transgressive ferrogranodiorite and granophyres indicate the progressive enrichment in iron and the late enrichment in alkalies and silica that are expected in a rock series as a result of magmatic differentiation. The rock and mineral series (Taylor, 1956, p. 61) follows:

gabbro. . . . syenogabbro. . . . ferrogranodiorite. . . . granophyre

An_{65-60} An_{55} An_{45} An_1

titanaugite ferroaugite

Iron enrichment reaches a maximum in the granodiorites and falls off in the granophyres. These rocks are considered to be magmatic differentiates derived from the magmas of the layered series, but some of the grano-

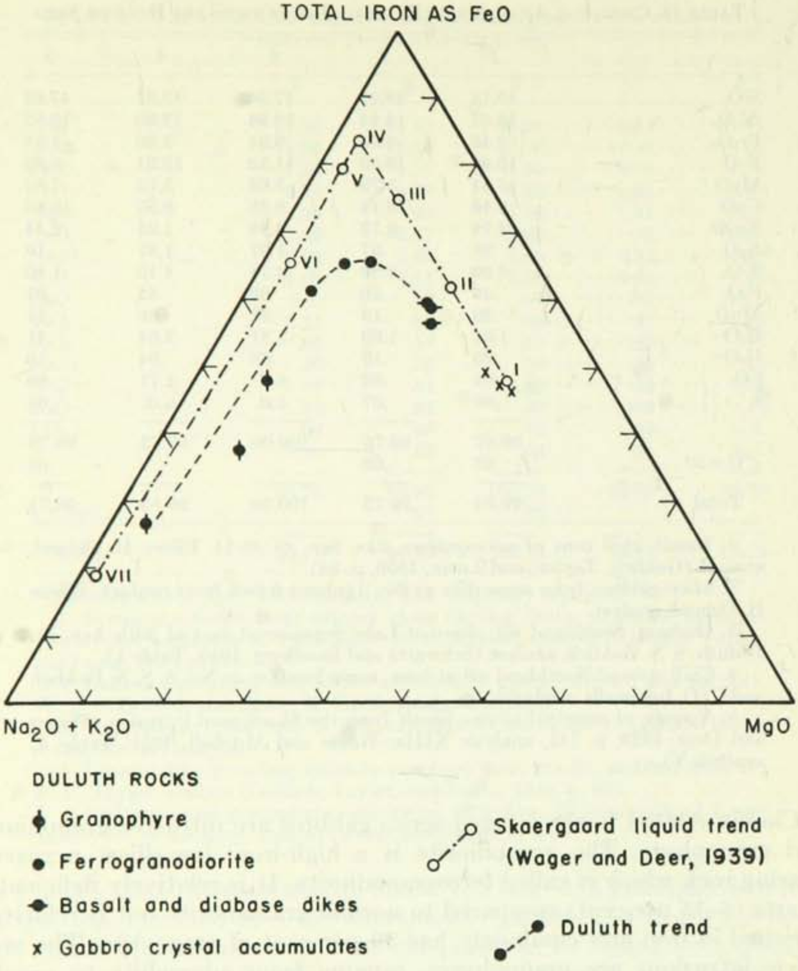

FIGURE 22. — Iron-enrichment diagram comparing the gabbro complex at Duluth with the Skaergaard intrusion (Taylor, 1956).

phyres, as suggested by the K-A ages, appear to be old intrusives in the flows, and these may be related to older magmatic cycles in the Duluth area.

The rock series at Duluth shows the same differentiation trend as the Skaergaard intrusion (Wager and Deer, 1939), and the similarity can be seen in the iron-enrichment diagram of Figure 22 (Taylor, 1956) in which the chemical analyses of rocks of the Duluth complex are compared with the Skaergaard liquid line of descent. The differences in the rock series of the Skaergaard intrusion and of the Duluth complex have at least two

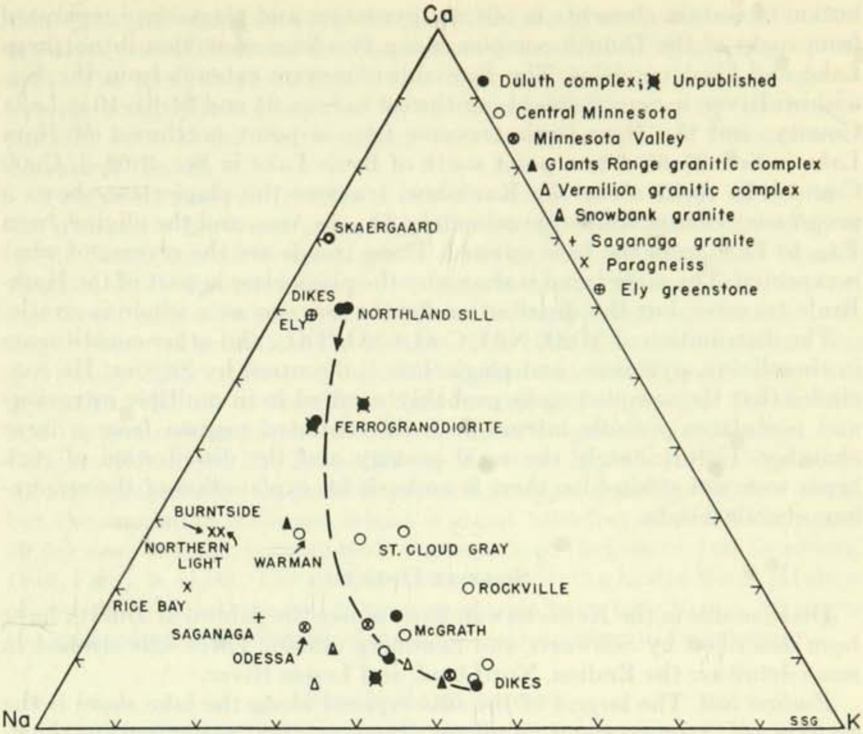

FIGURE 23. — Alkali-enrichment diagram, mol ratios Ca:Na:K. The Duluth complex rocks are Late Precambrian (Keweenawan); central Minnesota rocks are Penokean; Vermilion, Giants Range, and Snowbank granites are Algoman; Minnesota Valley rocks are Algoman and Penokean; Saganaga granite is Early Precambrian (Laurentian); the paragneisses and the Ely greenstone are Early Precambrian (Ontarian). The Skaergaard rock represents the average marginal olivine gabbro of the Skaergaard intrusion of East Greenland of Tertiary age.

fundamental causes. The Skaergaard intrusion is relatively small and apparently crystallized under conditions of tectonic stability, whereas the complex at Duluth is very large, and the area was one of periodic movement resulting in multiple intrusions, interrupted crystallization, and separation of differentiated magma to form the transgressive ferrogranodiorite and granophyre.

A second important difference between the Duluth and the Skaergaard rocks appears to be in the composition of the parent magma. The best indication of the parental magma at Duluth is in the composition of the basalt dikes (Taylor, 1956). A comparison of the analyses of the Duluth dike rocks with the average marginal olivine diabase from the Skaergaard intrusion (Table 18) shows considerable differences as can be seen in the plots of Figures 22 and 23.

Duluth Complex in Northern Areas. Snyder (1959) studied the distribution of certain elements in olivine, pyroxene, and plagioclase separated from rocks of the Duluth complex along two lines of section in northern Lake and Cook counties. The Kawishiwi traverse extends from the Kawishiwi River, in Sec. 33:62–11, southwest to Secs. 31 and 32:61–10 in Lake County, and the Ham-Brule traverse from a point northwest of Ham Lake in Sec. 27:65–4 to a point south of Brule Lake in Sec. 3:62–3, Cook County. In rocks along the Kawishiwi traverse the plagioclase shows a progressive change from approximately An_{65} to An_{80}, and the olivine, from Fa_{45} to Fa_{30}, from the base upward. These trends are the reverse of what is expected. The same trend is shown by the plagioclase in part of the Ham-Brule traverse, but the distribution for the traverse as a whole is erratic.

The distribution of MnO, NiO, CoO, CuO, TiO_2, and other constituents in the olivine, pyroxene, and plagioclase is discussed by Snyder. He concludes that the sampled rocks probably resulted from multiple intrusions and postulates periodic intrusion of differentiated magma from a large chamber. Unfortunately the areal geology and the distribution of rock types were not studied, so there is no basis for explanation of the anomalous chemical data.

Sills at Duluth

Diabase sills in the Keweenawan flows above the gabbro at Duluth have been described by Schwartz and Sandberg (1940). Three sills studied in some detail are the Endion, Northland, and Lester River.

Endion Sill. The largest of the sills exposed along the lake shore is the Endion sill. Schwartz and Sandberg (1940, p. 1139) estimated its thickness at 1300 feet, the upper one-fourth of which is granite or granophyre. They considered various possible modes of origin, including multiple intrusions, and concluded that the granite resulted from differentiation but pointed out the difficulty in explaining the rocks on the basis of crystallization-differentiation alone. If the granite were derived by differentiation, the parent magma must have been more silicic than basalt to produce the volume of granite.

Northland Sill. The Northland sill was intruded into rhyolite 445 feet above the Endion sill. It is only 31 feet thick on the shore but thickens to the north, and according to Schwartz and Sandberg may merge with the Endion sill. Along the lake the Northland sill is dark, medium-grained diabase with well-developed columnar jointing. The base of the sill at the contact with the rhyolite is regular, but the top is irregular, and apparently the magma broke through the roof of rhyolite flow or ignimbrite. No granite is associated with the diabase of the sill on the shore, and the chemical analysis of the diabase (Table 18, No. 3) is similar to the analyses of the microgabbro dike rock (Table 18, Nos. 1 and 2). A sample of the fine-grained basalt from near the base of the Northland sill, where the magma was chilled against the underlying rhyolite, gives a different composition (analysis No. 4), and the large contents of H_2O and CO_2 indicate alteration. A similar example is the chemical analysis given by Cornwall (1951, p. 185) of the chill zone of the Greenstone flow of the Michigan copper district. The analysis bears much the same relationship to the weighted-average composition computed for the Greenstone flow as the analysis of the chill zone of the Northland sill does to the analysis of the unaltered diabase of the sill.

A chemical analysis (Schwartz and Sandberg, 1940, Table 1, No. 1) of the diabase in the lower part of the Endion sill is similar to the analysis of the Northland sill diabase, and it is unlikely that the original basaltic magma, which was intruded in the sills, was much different from the normal basalt of the Duluth area. An alternate explanation for the relatively large volume of granite in the Endion sill is that the granitic magma was derived by differentiation of basaltic magma but that it migrated or was injected at the top of the sill, so that the relative volumes of the diabase and the granophyre in present outcrops have no genetic significance.

Lester River Sill. The Lester River sill is 3350 feet above the Northland sill stratigraphically. On Lake Superior it is approximately 950 feet thick, but the maximum thickness inland is about 1200 feet of which the upper 30 per cent or more is composed of granophyre (Schwartz and Sandberg, 1940, Fig. 7, p. 1158). The analyzed samples from the Lester River sill show considerable variations and no regular change from base to top. In places the granophyre is irregularly distributed and appears to be intrusive.

Beaver Bay Complex

The intrusive gabbroic rocks which were emplaced in the North Shore volcanic group in the vicinity of Beaver Bay (Pl. 1) were called the Beaver Bay complex by Grout and Schwartz (1939). The complex includes diabase, granite, and anorthosite, the latter consisting of large boulders included in the diabase. The complex has been restudied by H. M. Gehman, Jr. (unpublished Ph.D. thesis, Univ. Minn., 1957) who found the relationships more complicated than is indicated in the earlier work. Gehman found three distinct intrusions, and sample KA-92 is biotite separated by Gehman from a sample of the oldest diabase. Igneous lamination, rhythmic layering, and cryptic layering of the Skaergaard type are all well developed in one of the intrusives, and the petrology will be described in a paper being prepared by Gehman.

Logan Intrusives

The Logan intrusives (sills) were named by Lawson (1893, p. 48) and defined as intrusives in the Rove slate. On this basis they are distinguished from the Beaver Bay complex and the sills at Duluth which are intrusive into the North Shore volcanic group. The Logan sills in Ontario have been studied recently by Blackadar (1956) who concludes that they are composite intrusions of diabase and granite and that the granite in part resulted from assimilation of granite or sedimentary rocks.

Origin of the Keweenawan Igneous Rock Series of Minnesota

The Keweenawan igneous series of Minnesota is comprised of the extrusive and intrusive igneous rocks of the North Shore region, including the North Shore volcanic group, the Duluth complex, the sills at Duluth, the Beaver Bay complex, the Logan sills, and the related intrusive rocks such as the dikes.

The available chemical analyses of these rocks were compiled by A. P. Ruotsala (unpublished M.S. thesis, Univ. Minn., 1955). Many of the older analyses are of questionable reliability and were eliminated, and the remaining 42 analyses were plotted in variation diagrams. The lime-alkali index of the Keweenawan series is approximately 55, placing it near the upper limit of the alkali-calcic classification of Peacock (1931). For comparison with the Keweenawan series the chemical analyses of 18 samples of granite, syenite, monzonite, granodiorite, and other types, ranging in SiO_2 from 55 to 73 per cent, and representing the Saganaga, the Giants Range, and the Vermilion granitic complexes as well as rocks from central Minnesota, were plotted in similar diagrams. The points for these analyses showed considerable scattering, not only in the conventional SiO_2 variation diagram, but also in Larsen's (1938) modification in which the abscissa represents ($\frac{1}{3}$ $SiO_2 + K_2O$) — ($CaO + MgO$ + total Fe as FeO).

Some striking differences are apparent in comparing the plutonic rocks with the Keweenawan rocks. The older rocks are relatively enriched in alumina, magnesia, lime, and soda, whereas the Keweenawan series is relatively enriched in iron, titania, potash, manganese, and phosphorus. The Laurentian, Algoman, and Penokean granites and related types are definitely calc-alkaline. The Keweenawan rocks of the North Shore are best explained in terms of crystallization-differentiation of basaltic magma (Taylor, 1956, p. 65); however, the older plutonic tonalites, granodiorites, monzonites, granites, and related gneisses are the products of processes which accompany the deformation of geosynclinal belts during periods of mountain building.

Figure 23 is a plot of the ratios Ca:Na:K for the samples for which chemical analyses of all but three are given in the tables in this report. The points representing the samples from the gabbro complex at Duluth determine the line that shows the expected trend of alkali-enrichment. Three unpublished analyses of Duluth rocks have been plotted and are designated on the diagram. Points representing the Laurentian, Algoman, and Penokean granites are distributed on either side of the line for the Duluth complex. The chemical analyses of the Northern Light gneiss, the Burntside gneiss, and the gneiss from Rice Bay are separately grouped, reflecting the sedimentary parentage which has been suggested on the basis of petrography and field relationships for these rocks.

The Saganaga granite also falls a considerable distance from other samples, and the origin of this rock deserves further study because, as men-

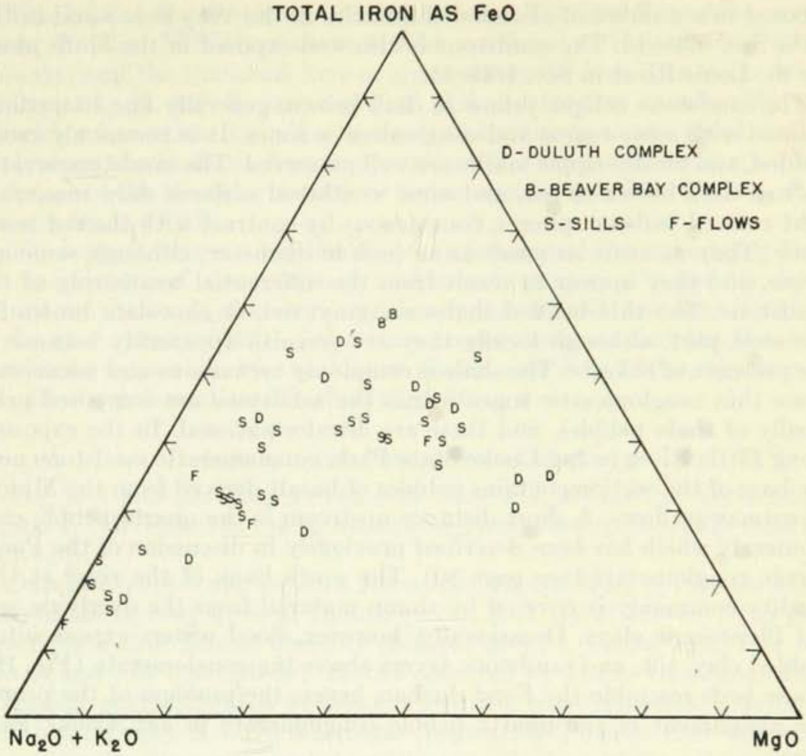

FIGURE 24. — Iron-enrichment diagram for Keweenawan igneous rock series of the North Shore region.

tioned earlier in the description of the granite at Gull Lake, the presence of orthoclase in veins suggests potash metasomatism.

At the lower end of the curve, in the granite field (Fig. 23), there appears to be a convergence of rocks of different origin to a type, and the orogenic granites plot similarly to the granophyres of the Duluth complex.

An iron-enrichment diagram for the Keweenawan igneous series is shown in Figure 24. In this diagram the rocks of the Duluth complex, the sills, and other occurrences are distinguished by symbols.

UPPER KEWEENAWAN SANDSTONES

The Upper Keweenawan in Minnesota is represented by two clastic formations; the older is the Fond du Lac, and the younger the Hinckley formation.

Fond du Lac Formation. Dark-red to gray shale and sandstone are well exposed along the St. Louis River southwest of Duluth, and Winchell (1899b, p. 567) referred to these beds as the Fond du Lac. The formation is exposed in a number of abandoned quarries in the W½ Sec. 5 and in the SE¼ Sec. 6:48–12. The sandstone is also well exposed in the bluffs along the St. Louis River in Sec. 1:48–15.

The sandstone is light yellow to dark brown, generally fine to medium grained with some coarse and conglomeratic zones. It is commonly cross-bedded, and locally ripple marks are well preserved. The sandstone weathers to a dark brown or red, and some weathered surfaces show numerous light-colored balls or spheres, conspicuous by contrast with the red sandstone. They measure as much as an inch in diameter, although some are larger, and they appear to result from the differential weathering of the sandstone. The thin-bedded shales are gray, red, or chocolate brown for the most part, although locally they are greenish apparently because of the presence of chlorite. The shale is commonly arenaceous and micaceous. Some thin conglomeratic zones within the sandstone are composed principally of shale pebbles, and these are intraformational. In the exposure along Little River in Jay Cooke State Park, conglomeratic sandstone near the base of the section contains pebbles of basalt derived from the Middle Keweenawan flows. A short distance upstream is the quartz pebble conglomerate which has been described previously in discussion of the Puckwunge conglomerate (see page 80). The south bank of the river at this locality commonly is covered by slump material from the overlying soft red Pleistocene clays. Occasionally, however, flood waters expose interbedded clay, silt, and sandstone layers above the conglomerate (Fig. 18). These beds resemble the Fond du Lac; hence, the problem of the proper age assignment of the quartz pebble conglomerate in Jay Cooke Park arises.

The Fond du Lac sandstone is approximately 200 feet thick in the bluff of the St. Louis River; however, thicknesses greater than 2000 feet have been encountered in deep wells (Grout *et al.*, 1951, p. 1058). Structural observations (SSG) in the Fond du Lac area indicate that the beds strike N. 25–30° E. and dip 8–11° S.E. The Puckwunge sandstone west of Duluth strikes N. 10° W. and dips 15° E. The Keweenawan flows are variable in dip and strike, but in the Duluth area they dip approximately 15° E., so that there appears to be some discordance between the Fond du Lac formation and the older rocks; however, the principal reason for assignment of the Fond du Lac to the Upper Keweenawan is the absence of basalt dikes or other indications of later igneous activity.

Hinckley Formation. The Hinckley sandstone was named by N. H. Winchell (1886) who considered it to be of Cambrian age. The sandstone commonly is medium to coarse grained and bright yellow to salmon colored. The beds are commonly massive, but locally there are thin-bedded, fine-grained layers of shaly composition. The sandstone is cross-bedded, and ripple marks are abundant. It is well exposed along the Kettle River in Pine County, and near Sandstone, it forms bluffs which are 100 feet high. The Hinckley was once extensively quarried at Sandstone.

The best of the northerly outcrops of the Hinckley formation occurs along the East Net River about 2 miles northeast of Holyoke in Carlton County, and the thickness here is greater than 70 feet. The strike is approximately N. 20° E. and dip is 8° S.E., so that at this locality, the Hinckley formation is similar in structural attitude to the Fond du Lac beds along the St. Louis River, approximately 15 miles to the north. Most outcrops of the Hinckley sandstone to the southeast in Pine County show a lower dip, 3–5° S.E.

The contact between the Hinckley sandstone and the underlying Fond du Lac formation is not exposed, and in well samples it is usually determined on the basis of texture and heavy minerals (Grout and Thiel, *in* Tyler *et al.*, 1940, p. 1511). Subsurface records indicate that the Hinckley sandstone is overlain by the Mount Simon and Eau Claire members of the Dresbach formation (Thiel, 1947, p. 19).

Ages for the North Shore Region

The K-A and Rb-Sr ages (Table 14, Secs. I, J, K) for the North Shore region are all related to the Keweenawan igneous rocks and range from 0.9 to 1.2 b.y.

Duluth Complex and Related Intrusives. Biotite from pyroxenite (KA-295) of the layered series at Duluth gives a K-A age of 1.09 b.y. The gabbro from a drill hole at Babbitt (KA-65) gives a similar age, 1.06 b.y. (K-A) and 1.09 b.y. (Rb-Sr). Biotite collected by James Gundersen from a granitic pegmatite (KA-296) in the Biwabik iron-formation is dated at 1.12 b.y. (Rb-Sr). KA-176 is a coarse (pegmatitic?) diorite that was cored in exploration for copper-nickel sulfides near the base of the gabbro in the vicinity of Aurora. This sample is dated at 1.2 b.y. Sample KA-92, dated at 1.0 b.y., is from the Beaver Bay complex.

Contact Rocks. As was found for the intrusive rocks, the ages determined for various contact rocks range from 1.0 to 1.2 b.y. Whether the ages indicate older intrusions or incomplete loss of argon during recrystallization is uncertain.

Two samples of the argillite from the Thomson formation (KA-232, 233), west of Duluth near the base of the gabbro, give K-A ages of 1.2 b.y. Possibly the ages reflect the time of the earlier flows rather than that of the intrusion of the gabbro. A sample of the Rove argillite (KA-131) along the Gunflint Trail was collected to date the time of intrusion of one of the Logan sills. The K-A age of 1.06 b.y. dates the contact action which recrystallized the Rove slate in this locality.

Sample KA-177, a contact rock as indicated by its granoblastic texture, was cored near Aurora; it is dated at 1.04 b.y. Sample KA-176 from the same area gave 1.20 b.y. Precise locations of the drill holes are not available. The Giants Range granite at Babbitt (KA-106) has been recrystallized, apparently by intrusion of the gabbro, and gives an age of 1.2 b.y.

Granite at Mellen, Wisconsin (KA-93), intrudes the gabbro; however the K-A age for biotite from the granite is 1.0 b.y., and the A^{40}/K^{40} ratio for K-feldspar suggests that the granite may be older. Tyler and Marsden (Tyer *et al.*, 1940, p. 1468) found three granites in the Mellen area. A Keweenawan granite north of Mellen and a pre-Huronian granite south of Penokee Gap were known from field relationships. The pre-Huronian granite was assigned to the Laurentian or Archean by Irving (1880, p. 92) and Van Hise and Leith (1911, p. 226). Tyler and Marsden found malacon zircon in granite south of Penokee Gap, indicating a third granite of intermediate age.

Granophyre in the Duluth Area. Biotite is rare in the granophyres of the Duluth area, and the age determinations (Table 14, Sec. K) reported here are K-A determinations made on the whole rock. These determinations are experimental and cannot be completely evaluated in the light of the known loss of argon from K-feldspar. A correction for argon deficiency of the magnitude indicated by the mica-feldspar pairs (Fig. 8) would make the ages for the granophyres unreasonable. Although the ages 0.9 to 1.2 b.y. are within the range of the other samples from the North Shore region, more work is needed. Possibly some of the granophyres are amenable to Rb-Sr dating, but this has not been attempted.

HISTORY OF LATE PRECAMBRIAN TIME FOR NORTHERN MINNESOTA

Late Precambrian time, as defined in Table 2, represents a billion years, but the geologic record in Minnesota for this great length of time is scanty. The one event that can be dated with confidence is the time of intrusion of the Duluth gabbro and related rocks at 1.1 billion years ago, and there is no basis for assigning time intervals to Early, Middle, and Late Keweenawan subdivisions.

Lower Keweenawan

The subdivisions, Lower, Middle, and Upper Keweenawan apply to rock units and are relative terms. In the final analysis the only reason for assigning the Puckwunge formation to the Lower Keweenawan is that the outcropping beds lie below the Middle Keweenawan flows. The conglomerate and sandstone at the type locality and the beds in Secs. 17 and 20:49–15, west of Duluth, probably were deposited shortly before the overlying flows were extravasated. The drilling log of the deep well in Short Line Park in Duluth suggests that the beds in the Duluth area which are assigned to the Puckwunge may have been deposited after lava extrusion was initiated, and these beds, therefore, are better classified with the Middle Keweenawan rocks. The stratigraphic relationships of the conglomerate and sandstone along Little River in Jay Cooke State Park require further study.

West of Duluth the angular unconformity between the Puckwunge and the Thomson formations represents a hiatus on the order of 500 million years or more, between the Penokean orogeny at approximately 1.7 b.y., when the Thomson beds were folded, and the Keweenawan igneous activity at approximately 1.1 b.y. This time hiatus is as great or greater than that represented by the unconformity at the base of the Animikie group. The lack of marked discordance between the Rove and the Puckwunge formations in northern outcrops is an unreliable criterion for determining the relative importance of the unconformity.

Middle Keweenawan

The extrusive and intrusive rocks of the North Shore region constitute the Keweenawan igneous rock series and represent a period of igneous activity at approximately 1.1. b.y. Further studies are needed to determine the duration of this activity which cannot be appraised from the present investigation.

Lake Superior Geosyncline. Outcrops of Keweenawan flows in the Lake Superior region indicate an original lava field much greater than the present area of Lake Superior. The flows extend southwest of the lake and, in Minnesota, underlie a large part of Pine County between the Douglas fault and the St. Croix River (Pl. 2). The accumulation of flows and sediments is closely related to the development of the Lake Superior basin, syncline, or geosyncline, as it has been referred to by different writers.

Edward Thiel (1956) has traced a large positive anomaly, averaging 30 miles in width, with an amplitude of 100 mgals above the regional gravity value, from Lake Superior southwest into Kansas. Over most of this distance, the positive anomaly is flanked by belts of negative anomaly. In the Lake Superior region Thiel correlated the positive anomaly with the Middle Keweenawan flows and intrusive rocks, and the negative anomaly with the Upper Keweenawan sandstones and shales. The flows have been thrust up in a horst, and the Douglas fault (Pl. 2) marks the western side of the upthrown central part of the Lake Superior geosyncline. South of Pine County the cover of Paleozoic rocks makes it impossible to correlate the gravity data with rock types, but it is apparent that the geosyncline is much more extensive than the present Lake Superior basin with which it is commonly associated.

Van Hise and Leith (1911) suggested that compressive forces were involved in the downwarping of the rocks in the Lake Superior region; however, Grout (1918a), Hotchkiss (1923), and Aldrich (1929) suggested that foundering resulted from withdrawal of magma to form the Keweenawan igneous rocks, although Aldrich noted that compressive forces were involved in the thrust faults on the southern limb of the structure. Hotchkiss (1923) showed that the synclinal structure was in process of development during the accumulation of the flows because the lower flows on the south side of the lake dip more steeply than those higher in the section. A similar relationship among the flows in Minnesota was demonstrated by Sandberg (1938) in the progressive decrease in the dip of the flows from Duluth to Two Harbors.

In the earlier writings it was generally assumed that the flows issued from vents near the axis of the geosyncline and flowed towards the margins. White (1957), however, notes that the thick succession of flows in the Michigan copper district lies closer to the center of the present basin than any other part of the Lake Superior region in which Middle Keweenawan lavas are exposed, but in this district there are no known dikes which might have served as feeders. In the North Shore region of Minnesota, the numerous dikes may represent feeders marginal to the lava field, and similarly in Wisconsin and in Michigan there are many dikes which suggest that the feeders for the flows might have been marginal to the vast area of flow accumulation. It is illogical to assume that the great thickness of lavas came entirely from centrally located sources with the lava rising upward against a constantly increasing lithostatic head.

The Keweenawan flows in Michigan attain a thickness of the order of 20,000 feet (White, 1957). Conglomerate beds between flows were derived, according to White, from the south or southeast. The accumulation of lavas and conglomerate is best explained in terms of continuous downwarping. White suggests that the topography of the lava field in the Lake Superior basin was essentially flat and that the lavas, extruded within or on the margins of the basin, flowed to the lowest point and spread out. During periods of little or no volcanic activity the continued downwarping produced topographic depressions into which streams flowed and deposited the conglomerate beds.

Duluth Complex. Taylor (1956, p. 63) concluded that the gabbro complex at Duluth was closely related to the development of the Lake Superior geosyncline, which must have been initiated at the time of, or prior to, the first outpourings of the Middle Keweenawan flows. He writes: "the gabbroic intrusion was related in some way to the forces producing the geosyncline, but it was the result of these forces and not the cause of the basining." Taylor's explanation of the rock series at Duluth is based on the concept that the area was tectonically unstable and that the various intrusions are related to periodic orogenic movements.

Leighton (1954, p. 410) found that deformation preceded and followed the intrusion of gabbro west of Mellen in northern Wisconsin where the Keweenawn flows were tilted and the "intrusion has followed and cut across the Keweenaw thrust fault formed during tilting." The single radioactivity age for the granite (KA-93) from the Mellen area serves only to show that the dated granite was intruded or metamorphosed at 1.0 b.y. The field relationships indicate that the granite is younger than the gabbro and the Keweenawan flows in this area. Two interpretations seem possible; the gabbro west of Mellen may be of approximately the same age as the gabbro at Duluth as suggested by Leighton, or it may be older. From either of the two suggested interpretations it follows that the thrust fault which the gabbro followed must represent an earlier movement than the displacement on the Keweenaw fault in the Michigan copper district along which the Jacobsville sandstone, of late Keweenawan or Cambrian age, occurs in juxtaposition with the Middle Keweenawan flows.

Taylor's work in Minnesota and likewise that of Leighton in northern Wisconsin raise considerable doubt concerning the structure of the Duluth gabbro, described by Grout (1918a) as the type lopolith.

Upper Keweenawan

The Fond du Lac and the Hinckley sandstones are stratigraphically above the Middle Keweenawan flows, and therefore are referred to the Upper Keweenawan, but in the absence of fossils and of younger intrusive rocks, the age of these beds is problematical. From time to time the suggestion has been made that the sandstones may be of Cambrian age. The problem of the age of the sandstones above the Keweenawan flows in the Lake Superior region was reviewed by Leith, Lund, and Leith (1935, p. 12). They concluded in favor of an Upper Keweenawan assignment, but pointed out the difficulty of evaluating the time represented by unconformities and the possibility and even probability that the so-called Upper Keweenawan sandstone may be continental deposits of Lower and Middle Cambrian age.

Atwater and Clement (1935) studied the relationships of the Hinckley and overlying Cambrian formations in Minnesota and Wisconsin and found the contact to be unconformable. They suggested that a long period of time intervened between deposition of the Hinckley formation and the fossiliferous Upper Cambrian Mount Simon formation and assigned the Hinckley to the Keweenawan.

The Fond du Lac and Hinckley formations have been correlated with the sandstones of the Bayfield group of Wisconsin and Michigan. The stratigraphic succession given by Tyler and Marsden (Tyler *et al.*, 1940, p. 1479) is shown in the accompanying tabulation.

Revised Sequence of the Upper Keweenawan

	Feet
Bayfield Group	
Chequamegon sandstone	1,000
Devils Island sandstone	300
Orienta sandstone	3,000
Oronto Group	
Freda sandstone	12,000
Nonesuch shale	350
Outer conglomerate	1,200
Total	17,850

East of the Keweenaw fault in Michigan, the Jacobsville sandstone has generally been considered the equivalent (Eastern sandstone) of the Bayfield group. An excellent description of the Jacobsville formation is given by Hamblin (1958) who confirms the presence of an unconformity between the Jacobsville and the overlying fossiliferous Upper Cambrian rocks. The base of the formation also is unconformable, and the sandstone rests on Precambrian granite, Middle Keweenawan flows, and the Michigamme slate. The Keweenawan flows were tilted and eroded prior to the deposition of the Jacobsville. Hamblin follows the precedent of the Michigan Geological Survey in assigning the Jacobsville formation to the Cambrian, but his recent investigations indicate that the age of the formation cannot be considered settled (letter, Dec. 7, 1959).

Grout and Thiel (Tyler *et al.*, 1940, p. 1515) noted some similarities between the heavy minerals of the Fond du Lac formation and those of the lower part of the Orienta formation of the Bayfield group and between the heavy minerals of the Hinckley and Devils Island sandstones. In their discussion the Fond du Lac formation was included in the term Red Clastic series, and they give a maximum thickness of 2458 feet for the series penetrated in the deep well at Stillwater, Minnesota. Compared to the sequence in northern Wisconsin and Michigan, the so-called Upper Keweenawan sandstones have a limited development in Minnesota. The age of these rocks must be considered uncertain.

4. EAST-CENTRAL MINNESOTA

INTRODUCTORY STATEMENT

The rocks of east-central Minnesota (Pl. 2) are of great interest to the present investigation, supplying the evidence for a major period of orogeny, the Penokean, dated at approximately 1.7 b.y. Outcrops in this part of Minnesota are relatively few because of a thick cover of glacial drift. For example, Crow Wing County, which contains a large part of the Cuyuna mining district, does not have a single natural exposure. With regard to the outcrops, Margaret Skillman Woyski (1949, p. 1001) observes, "Central Minnesota is remarkable for the diversity as well as the paucity of rock outcrops. Within the area included in this report are 3 sedimentary formations, 16 igneous rock types, and 4 metamorphic rocks." In Carlton and Pine counties, there are relatively good outcrops in the area of the Thomson formation.

The literature dealing with the geology as related to the iron-mining and the quarrying industries in east-central Minnesota is voluminous. The first comprehensive report on the Cuyuna district is that of Harder and Johnston (1917, 1918). In 1918 the United States Geological Survey published a detailed bulletin on the building stones of Minnesota (Bowles, 1918) in which the geology of east-central Minnesota is reviewed. The geology of the district was briefly summarized by Leith, Lund, and Leith (1935), and the building stones of the area were described by Thiel and Dutton (1935) in Bulletin 25 of the Minnesota Geological Survey. The Thomson formation in Carlton and Pine counties has been studied by Schwartz (1942a, b, c). Woyski (1949) conducted field and laboratory studies of the granites of central Minnesota over a number of years. Grout and Wolff (1955) have given the most recent comprehensive review of the Cuyuna district, and Schmidt and Dutton (1957) and Schmidt (1958a, b; 1959) have published some of the results of studies conducted by the United States Geological Survey.

In the present investigation, attention has been focused on the Thomson formation, the McGrath gneiss, the metasediments of the Cuyuna district, and the granites. The broader geologic classification of the rocks of east-central Minnesota, as given by Grout and Wolff (1955), is shown in Table 19, and a summary of the age relationships of the granites as proposed by Woyski (1949), is given in Table 20. Twenty-two rocks from the region have been dated, and the results are given in Table 21. Samples from Wisconsin and from Michigan are included, as these have important bearing on the Penokean orogeny.

TABLE 19. GEOLOGIC SECTION OF ROCKS OF EAST-CENTRAL MINNESOTA
(After Grout and Wolff, 1955, p. 7)

PLEISTOCENE
- Recent alluvium
- Wisconsin till and outwash
- Pre-Wisconsin till and outwash

CRETACEOUS
- Sands, clays, and conglomerates, with fossils

CAMBRIAN
- Upper Cambrian sandstones

PRECAMBRIAN
- Later
  - Keweenawan
    - Thick sandstone
    - Flows, intrusives, gabbros, and granites
    - Thin sandstone
  - Animikie
    - Igneous flows (?), sills and dikes
    - Virginia formation, argillite and slate
      - Upper slates
      - South Range iron-bearing member
      - Lower slates
    - Biwabik iron formation
    - Pokegama formation, quartzite and slate
- Medial
  - Algoman granite
  - Thomson formation
    - Slates and graywackes
    - Local dolomites
- Earlier
  - Granites and gneisses
  - Greenstones, schists

THOMSON FORMATION

GENERAL DESCRIPTION

According to Spurr (1894b) the name Thomson was introduced by N. H. Winchell for the slates near the village of Thomson on the east bank of the St. Louis River. These rocks have been referred to as Thomson slates, St. Louis slates, Cloquet slates, and Carlton slates, but the term Thomson formation is more applicable (Schwartz, 1942b). At the type locality the formation is folded into a series of anticlines and synclines which strike approximately E-W and pitch 10 to 30° E. (Schwartz, 1942a). According to Schwartz, the pitch is largely the result of the regional easterly dip which resulted from the formation of the Lake Superior geosyncline in Keweenawan time.

Hall (1901) and Schwartz (1942b) demonstrated that the sequence of slates and graywackes at Thomson can be traced to the southwest and that there is a progressive change in character due to metamorphism which is particularly noticeable in the slate. This change involves the appearance of phyllite in the vicinity of Atkinson, 10 miles southwest of Thomson, of

TABLE 20. CLASSIFICATION OF IGNEOUS AND RELATED ROCKS IN CENTRAL MINNESOTA
(After Woyski, 1949)

- PROTEROZOIC
  - Keweenawan
    - Upper Keweenawan
      - Hinckley sandstone
      - Fond du Lac arkose
    - Middle Keweenawan
      - Late dikes
        - Granite porphyry
        - Basalt
          - Hypersthene melatrachybasalt porphyry
      - Stearns magma series
        - St. Cloud Red granite
        - Rockville quartz monzonite
        - Porphyritic granite
        - Quartz latite porphyry
        - Crystal Gray quartz monzonite
  - Keweenawan or Late Algoman
    - Hornblende norite *
  - Animikie
    - Crow Wing formation *
- ARCHEOZOIC
  - Algoman
    - Late Algoman
      - Freedhem tonalite
        - Hornblende gabbro *
      - Warman quartz monzonite
      - Hillman gneissoid tonalite
      - St. Cloud Gray granodiorite
        - Melagranodiorite
      - Hornblende granodiorite
    - Early Algoman
      - Actinolite gabbro *
      - McGrath gneiss
  - Knife Lake
    - Thomson formation

* Proper position in the outline uncertain.

schist and metagraywacke in the vicinity of Moose Lake, and finally of garnetiferous mica schist and gneiss in the vicinity of Denham, approximately 35 miles southwest of Thomson. The continuity of the Thomson beds between the type locality and Denham has been well established on structural and lithologic criteria.

The slate and graywacke contain numerous concretions that are composed largely of calcite with smaller amounts of siderite, pyrite, and clastic material. The concretions weather to a characteristic yellow-brown color and may be completely removed by leaching. The cavities are as useful as the original concretions in identifying and in tracing the Thomson formation. It is largely on the basis of the concretions, as well as the distinctive lithology of alternating slate and graywacke beds, or their metamorphic derivatives, that the schists in the Little Falls area, approximately 70 miles

TABLE 21. AGES FOR ROCKS OF EAST-CENTRAL MINNESOTA
(Including data from Wisconsin and Michigan)

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
	(A) Thomson Formation Metasediments						
35	Slate, Thomson	1.63		3.61	3.62	0.505	0.140
						.601	.166
38	Phyllite, Atkinson	1.64		1.24	1.24	.193	.156
						.188	.152
39M	Phyllite, Barnum	1.64		5.16	5.17	.787	.152
						.818	.158
40M	Phyllite, Moose Lake	1.61		4.56	4.57	.685	.150
96	Phyllite, Little Falls	1.59		2.29	2.29	.336	.147
	Average	*1.62*					
	(B) McGrath Gneiss						
41B	Gneiss, west of Denham	1.68	1.68	8.63	8.65	1.38	.160
						1.37	.158
43B	Gneiss, southwest of Denham	1.65		7.58	7.60	1.17	.154
						1.20	.158
164B	Gneiss, McGrath	1.71	1.65	8.22	8.24	1.37	.166
						1.35	.164
63B	Gneiss, Dads Corner	1.50		8.89	8.91	1.20	.135
						1.21	.136
	(C) Metasediments from the Cuyuna District						
132	Phyllite, Mahnomen No. 1 pit	1.55		4.93	4.94	.700	.142
						.695	.141
33	Sericitic argillite, Mahnomen No. 2 pit	1.66		5.54	5.55	.878	.158
134	Sericitic argillite, Maroco pit	1.58		4.63	4.64	.677	.146
215	Sericitic argillite, Sagamore pit	1.67		4.05	4.06	.644	.159
	Average	*1.62*					
	(D) Older Tonalites and Related Rocks						
10B	Granodiorite, St. Cloud Gray	1.78		6.07	6.08	1.05	.173
						1.07	.176
						1.07	.176
						1.06	.174
10F	Granodiorite, St. Cloud Gray			12.77	12.79	1.41	.110
1B	Quartz monzonite, Warman	1.76	1.72	8.33	8.35	1.47	.176
						1.40	.168
61B	Quartz monzonite, Pierz	1.73		8.38	8.40	1.41	.168
61F	Quartz monzonite, Pierz			12.25	12.27	1.63	.133
						1.61	.131
						1.57	.128
64B	Tonalite, Hillman	1.78	1.69	7.76	7.78	1.35	.174
	Average	*1.76*					
60B	Gneiss, Freedhem	1.70		7.79	7.81	1.28	.164
59B	Schist, Freedhem	1.63		7.74	7.46	1.14	.153
62B	Quartz monzonite, Isle	1.68		7.31	7.32	1.15	.157
						1.20	.164

TABLE 21 — *Continued*

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
	(E) Younger Granites						
6B	Porphyritic granite, Rockville	1.64		7.51	7.52	1.14	0.152
						1.12	.149
						1.22	.162
6F	Porphyritic granite, Rockville			10.94	10.96	1.02	.093
58B	Granite, St. Cloud Red	1.64	1.65	6.58	6.59	1.02	.155
	(F) Data from Wisconsin and Michigan						
45B	Schist, Iron Co., Wis.	1.72		7.88	7.90	1.32	.167
						1.31	.166
						1.33	.168
184M	Granite, Butternut, Ashland Co., Wis.	1.66		9.23	9.25	1.46	.158
12B	Granite, Waupaca, Wis.	1.43		6.45	6.46	.816	.127
12F	Granite, Waupaca, Wis.			12.69	12.72	.885	.070
						.894	.070
330B	Augen gneiss, Neillsville, Wis.	1.48		9.38	9.40	1.25	.133
66B	Garnetiferous mica schist, Republic, Mich.	1.89		6.31	6.32	1.22	.192
278	Sericite schist, Republic mine, Marquette Co., Mich.	1.61		6.68	6.69	1.00	.150
68M	Granite dike, Groveland pit, Dickinson Co., Mich.	1.62		10.19	10.21	1.55	.152
OSA(F)	Pegmatite, Dickinson Co., Mich.		1.62	11.80	11.83	1.11	.0938
238	Fern Creek slate, Sturgeon Falls dam area, Dickinson Co., Mich.	1.35		7.13	7.14	.831	.116

southwest of Denham and over 100 miles southwest of Thomson, are correlated with the Thomson beds.

The distribution of the Thomson formation is shown on Plate 2, which has been modified from a map by Woyski (1949) and a more recent map by Grout and Wolff (1955). Woyski's original map shows more detail, particularly in the subdivision of the granites; however, in view of the scarcity of outcrops, even the generalized map (Pl. 2) may convey an impression of accuracy which is unwarranted by the available data.

DESCRIPTION OF UNITS

Graywacke and Slate at Type Locality. The massive beds of graywacke at Thomson are fairly representative of this rock type in the Lake Superior region. The graywacke is dark gray and poorly sorted. In thin section, the most abundant mineral is quartz, 40–50 per cent, with plagioclase, 10–20 per cent, second in abundance. Rock fragments, generally less than 5 per cent of the rock, include diabase pieces commonly with chlorite interstitial to plagioclase, quartzite or chert, and graphitic slates. The latter two types probably are derived from the Knife Lake or older sediments. Chlorite and sericite are the principal cementing materials and generally make up 20 per cent or more of the rock. Carbonate and graphitic material are much less abundant than the chlorite or sericite. Accessory minerals are zircon, apatite, leucoxene, magnetite, and pyrite. In summary, the characteristic features of the Thomson graywacke are (1) gray to black color, (2) poorly sorted grains, (3) high degree of angularity of grains, (4) rock fragments, (5) common to abundant plagioclase and (6) chloritic and sericitic cement, reflecting low-grade (greenschist facies) metamorphism.

Phyllite at Atkinson. Outcrops just west of Atkinson (Pl. 2) are easily recognized as derivatives of the Thomson formation by the thick beds of metagraywacke and gray phyllite. The strike is approximately east-west. Small drag folds are numerous, and vein-like masses of quartz are tightly folded concordantly with the drag folds. X-ray analyses of the phyllite (KA-38) show quartz, chlorite, muscovite, and plagioclase.

Phyllite at Barnum. In the vicinity of Barnum, metagraywacke and phyllite, or fine-grained schist, strike approximately east-west. The rock contains numerous pod-like masses of quartz which may represent replacements of the carbonate concretions. These give the schist a nodular appearance. Metacrysts of pyrite are common, and there are a few of garnet. X-ray analyses indicate that sample KA-39 consists principally of quartz and sericite with some chlorite and a small amount of plagioclase.

Schist at Moose Lake. Schist and metagraywacke are well exposed in the cuts along the Minneapolis, St. Paul, Sault Ste. Marie Railroad, north of the station in Moose Lake. The more massive beds of the metagraywacke strike N. 75° E. Numerous folds are accentuated by highly contorted lenses of quartz. Thin sections of concretions from the metagraywacke at Moose Lake show quartz and secondary silicates, primarily amphibole and garnet with minor penninite. X-ray analyses of sample KA-40 indicate quartz and muscovite with some chlorite and plagioclase (andesine-labradorite).

Paragneiss and Schist at Denham. Several kinds of metamorphic derivatives of the Thomson beds occur in the vicinity of Denham in Pine County. Northeast of the village, in the SE½NE¼ Sec. 19:45–20, there are excellent exposures in fresh cuts along the Minneapolis, St. Paul, Sault Ste. Marie Railroad tracks. The massive layers of garnetiferous paragneiss strike N. 75° E. The dips are variable, and there are many rolls or minor drag folds.

In thin section, the paragneiss from this locality is a schistose, porphyroblastic rock. Quartz and untwinned andesine are difficult to distinguish, but the quartz is estimated to make up 35–40 per cent of the rock, and plagioclase 25–35 per cent. Other essential minerals are biotite, 10–20 per cent, and garnet, 10–15 per cent. Accessory minerals include muscovite, magnetite, zircon, apatite, sphene, and a trace of chlorite. The garnet contains numerous residual grains of quartz. In some specimens the biotite and muscovite are wrapped around the garnet metacrysts in a manner suggesting rotation of the garnet at a late stage in the formation of the metamorphic rock.

At the southern end of the railroad cuts and just north of the county road, quartz lenses have been deformed into boudin. Large crystals of K-feldspar border the quartz pods. Potash feldspar is almost lacking in the garnetiferous, schistose paragneiss, and the appearance of the K-feldspar in the outcrops is suggestive of potash metasomatism which may have been an important process in the development of the gneisses to the southwest. Schwartz (1942b, p. 1012) has described similar quartz masses with borders of feldspar in quartz-biotite-muscovite schist in Sec. 4:45–20, northwest of the railroad cuts described above.

Coarse-grained hornblende schists and dolomitic marble occur southeast of Denham in the SE¼, Sec. 25:45–21. These have been described by Harder and Johnston (1918, p. 66) and by Schwartz (1942b, p. 1013). One-fourth mile south in Sec. 36:45–21, muscovite schist and granite crop out (Schwartz, 1942b, p. 1013).

Phyllite at Little Falls. Numerous outcrops of slate, phyllite, graywacke or metagraywacke, and schist occur in the vicinity of Little Falls, and the metasediments, commonly containing concretions, are correlated with the Thomson formation. North of Little Falls along Little Elk River, gray slate and phyllite are interbedded with thicker layers of graywacke in good outcrops on both sides of the stream. The strike is approximately northeast, and the dip is variable but generally at a high angle. Gray phyllite is represented in the dated sample KA-96. There are additional outcrops of slate and phyllite in Little Falls. Approximately 4 miles south of Little Falls, in the banks of the Mississippi River, are scattered outcrops of garnetiferous staurolite mica schist. Thin sections of this rock show principally quartz, large metacrysts of staurolite, poikilitically including remnants of quartz considerably smaller in size than the grains in adjacent areas, porphyroblastic garnet, muscovite, biotite, accessory apatite, zircon, magnetite, and tourmaline. Fine-grained graphite is disseminated throughout the rock which represents the staurolite subfacies of the amphibolite facies.

The outcrops of the metasediments of the Thomson formation in the vicinity of Little Falls are described in detail by Harder and Johnston (1918, p. 59–63), and they noted the lithologic change in the sequence as one proceeds southward from the outcrops on Little Elk River to the garnetiferous staurolite schist south of Little Falls. They attributed the increase in grain size and the higher grade of metamorphism to the granitic intrusives in the vicinity of St. Cloud (Pl. 2). There are, however, very few outcrops between Little Falls and St. Cloud.

Ages for Thomson Metasediments

The results of K-A age determinations on five samples of the metasediments from the Thomson formation are given in Section A of Table 21, and the locations are shown on Plate 2. The dating of these samples represents a first effort at the application of A^{40}/K^{40} method to fine-grained materials, such as slates and phyllites (Goldich, Baadsgaard, and Nier, 1957).

A sample of Thomson slate (KA-35) was crushed and sieved to eliminate fine material which would blow out of the crucible during the fusion. The slate presented some unusual problems in the extraction and purification of the argon, and the two runs show relatively poor agreement. The average age is 1.63 b.y., but the lower A^{40} value corresponds to 1.54 and the higher to 1.72 b.y. The phyllite sample (KA-38) from Atkinson was also too fine-grained to attempt a mineral separation, and like the slate, it was simply crushed to obtain a 40–60 mesh fraction. Duplicate determinations of argon on this sample are in much better agreement than those on the slate, and the average age is 1.64 b.y. Samples from Barnum (KA-39) and from Moose Lake (KA-40) are coarser in grain than the phyllite at Atkinson, and partial concentration of muscovite was achieved, as can be seen in the K_2O contents of the final samples (Table 21). Two argon runs on the Barnum sample are in good agreement, and the average age is 1.64 b.y. A single determination gives an age of 1.61 b.y. for the sample (KA-40) from Moose Lake. The sample (KA-96) from Little Falls is too fine-grained for concentration of the mica; it was ground, and the 40–60 mesh fraction was used for the age determination. The average age for the five samples is 1.62 b.y.

McGRATH GNEISS

Description

West and southwest of Denham, the metasediments of the Thomson formation give way rather abruptly to coarse-grained gneiss of granitic composition, named by Woyski (1949) the McGrath kaligranite augengneiss. The McGrath gneiss is an extensive unit (Pl. 2), extending from Denham west beyond Mille Lac Lake, a distance of 50 miles, and in a north-south direction, about 20 miles. The gneiss was named for the exposures southwest of McGrath, and there are additional outcrops at Dads Corner and at Arthyde. Most of the outcrops were described by Harder and Johnston (1918, p. 46), who ascribed the gneiss to deformation of a pre-existing, coarse-grained granite.

Good outcrops of the McGrath gneiss occur west and southwest of Denham (KA-41). Approximately 2.5 miles west of Denham, the gneiss and schist can be seen in a cut along the railroad. The foliation and banding strike N. 75° E., and the dip is approximately 80° N. The alternating layers of schist and gneiss, conforming to the regional structure of the Thomson beds, led Schwartz (1942b, p. 1014) to conclude that these exposures represent highly metamorphosed beds of the Thomson formation. Woyski

(1949, p. 1014) attributed the origin of the gneiss to the *lit-par-lit* injection of the Thomson formation and states: "following its *lit-par-lit* injection into the Thomson formation, the McGrath gneiss has been dynamically metamorphosed, as shown by the feldspars which are fractured, have mortar structure, augen structure, and granulated structure. Quartz has the sutured structure characteristic of recrystallization."

The large pink feldspar crystals in the "augen" gneiss west of Denham are porphyroblasts of microcline. They enclose small grains of quartz and sericitized plagioclase, and in part replace the plagioclase. Mutually sutured aggregates of quartz account for most of this mineral, 25–30 per cent. Biotite and muscovite, in roughly equal amounts, make up about 20 per cent of the rock. Microcline and oligoclase are estimated at 35 and 15 per cent, respectively. One mile south of this locality are low-lying outcrops of the gneiss in a pasture east of the county road in Sec. 34:45–21. The pink, coarse-grained gneiss is locally pegmatitic. It is distinctly foliated (E-W) but is not compositionally banded.

Approximately 2 miles west of Dads Corner (KA-63) and just south of the county road, the gneiss is exposed in a small quarry prospect in a glaciated knob which rises about 10 feet above the level of the road. Pink, coarse-grained porphyritic granite is partly banded. The large feldspar crystals are aligned with the foliation, N. 75° W., the direction of prominent joints. Quartz veins, up to 2 inches wide but commonly pinching out, follow a second joint set, N. 12° E. A similar gneiss is exposed approximately 10 miles east, south of Arthyde.

Southwest of McGrath the gneiss (KA-164) is banded with dark-colored micaceous and pink quartz-feldspar layers. Woyski (Skillman, unpublished Ph.D. thesis, Univ. Minn., 1946) estimates the composition as follows: quartz, 30; K-feldspar, 50; albite, 5; biotite, 10; and others, 10 per cent. The minor accessory minerals are zircon (hyacinth) sphene, apatite, magnetite-ilmenite, and hornblende. Secondary minerals, which Woyski attributes to metamorphism, are muscovite, sericite, chlorite, rutile, garnet, and cordierite (?). Muscovite makes up about 5 per cent of the rock.

Age

Four samples of the McGrath gneiss have been dated, two from near Denham, one from McGrath and one from Dads Corner. Biotite was concentrated from the samples, and the relatively high contents of K_2O indicate that the separations were satisfactory. The samples from Denham and McGrath give similar K-A ages, averaging 1.68 b.y. which is essentially the same as the Rb-Sr results for two of the three samples. The sample from Dads Corner, however, gives a younger K-A age of 1.5 b.y. These ages associate the McGrath gneiss with the Penokean rather than with the Algoman orogeny.

METASEDIMENTS OF THE CUYUNA DISTRICT

Description

The problem of the correlation of the metasediments of the Cuyuna district was reviewed by Leith, Lund, and Leith (1935, p. 15). They suggested that the Deerwood iron-formation of the Cuyuna district is a member of the Virginia formation, noting the similarity of the high phosphorous and manganese contents of the ore to those of the iron formation in the Michigamme slate in Michigan. The possibility of the correlation of the Cuyuna formation with those in the Mesabi districts, however, was not completely ruled out. Grout, Gruner, Schwartz, and Thiel (1951, p. 1050) list the arguments for and against the correlation of the strata of the Cuyuna and Mesabi districts, and Grout and Wolff (1955) accepted the correlation and adopted the formational names of the Mesabi district (Table 19).

Investigations by the United States Geological Survey have led to the publication of maps accompanied by brief explanatory texts (Schmidt and Dutton, 1957; Schmidt, 1958b, 1959). Three principal rock units are recognized: (1) older argillites and siltstones with quartzite lenses, (2) the main iron formation, and (3) younger argillites and interbedded upper iron formation. Volcanic rocks, including tuffs and possible basaltic flows, occur in the lower part of the upper unit. Intrusive igneous bodies, which were apparently dioritic to gabbroic in original composition, are found along the southeastern edge of the mined area. These rocks are considerably chloritized or completely altered to chlorite schists. Folds, trending N. 65° E., are the dominant structural features, and on the southeast, the Cuyuna metasediments are overturned and apparently displaced by thrust faults (Schmidt, 1958b).

Samples and Age Determinations

Four samples of sericitic schists or argillite from the Cuyuna district have been dated (Table 21, Sec. C). We are indebted to R. L. Blake whose interest in collecting material greatly facilitated the study. X-ray analyses of the samples show principally muscovite and quartz with minor amounts of chlorite, plagioclase, and clay minerals, the latter for the most part kaolinite. The K_2O content of the samples ranges from 4.05 to 5.54 per cent and indicates a fairly high content, on the order of approximately 50 per cent, of muscovite or sericite. The K-A ages range from 1.55 to 1.67 b.y., with an average of 1.62 b.y. Duplicate determinations of argon on sample KA-132 are in close agreement. The samples were handled in the same manner as the Thomson slate and were ground and sieved, the 40–60 mesh fraction being used for the determination. The average age of 1.62 b.y. is the same as that found for the Thomson metasediments and indicates that the rocks of the two areas, that is, the Cuyuna and the Thomson metasediments, were involved in the same orogeny.

The average age of 1.68 b.y. for three samples of the McGrath gneiss is slightly greater than the average of 1.62 b.y. for the metasediments of the

Cuyuna district and also for the Thomson metasediments. It is questionable whether any significance can be attached to this difference. Samples KA-33 and KA-215, from the Cuyuna, are dated at 1.66 and 1.67 b.y., respectively. It is likely that fine-grained materials, such as the slate and phyllite, give somewhat variable and possibly low K-A ages. The ages indicate, however, that the Thomson formation and the Animikie beds of the Cuyuna district were folded at approximately the same time, 1.6–1.7 b.y., and that the McGrath gneiss was also involved in the orogeny.

IGNEOUS ROCKS

General Description

Woyski (Table 20) concluded that three main periods of batholithic intrusion are represented in central Minnesota. The oldest is the McGrath gneiss which she assigned to the Early Algoman. The second period involved a number of intrusives of intermediate composition, including the Freedhem tonalite, the Warman quartz monzonite, the Hillman tonalite, the St. Cloud granodiorite, and related unnamed granodioritic to gabbroic rocks which Woyski assigned to the Late Algoman. A third period developed the St. Cloud Red granite and types such as the Rockville porphyritic granite or quartz monzonite. For the latter rocks Woyski suggested the name "Stearns magma series" and assigned them to the Middle Keweenawan.

The many inclusions of the St. Cloud Gray granodiorite in the St. Cloud Red granite and the crosscutting relationships indicate that the St. Cloud Red granite is the younger of the two. Both types are cut by numerous dikes of basalt and some of the granite porphyry; however, none of the igneous rocks, including the late dikes, has been found intruding the Fond du Lac sandstone, and it is generally accepted that the igneous activity took place prior to the deposition of the sandstone. The age assignments (Table 20) were made on the type of zircon in the units. The late dikes and the Stearns magma series, according to Woyski, contain normal zircons; intrusives of intermediate composition and the McGrath gneiss contain hyacinth zircon, but neither malacon nor normal zircon.

In the discussion that follows, the "Late Algoman" intrusives are referred to as older granodiorites and related rocks (Table 21), and the rocks of the Stearns magma series are called the younger granites.

Older Granodiorites and Related Rocks

St. Cloud Gray Granodiorite. The St. Cloud Gray "granite" has been quarried for many years and is probably the best-known rock of this group. It crops out in the vicinity of St. Cloud, in Stearns, Benton, and Sherburne counties. The structure is massive, and the texture is medium granitoid. The rock is gray to pink and consists of andesine, 50; K-feldspar, 10; quartz, 15; biotite, 10; hornblende with minor augite, 15 per cent; and accessory apatite, sphene, magnetite, and ilmenite. Four argon extractions were made on biotite (KA-10), and the determinations are in close agreement, giving an age of 1.78 b.y.

Warman Quartz Monzonite. The Warman quartz monzonite is a massive, light-gray rock occurring in Mille Lacs and Kanabec counties. Woyski gives the average composition as feldspar, 60 per cent, with roughly equal amounts of andesine and K-feldspar; quartz, 25–30 per cent; and biotite, 5–10 per cent. The accessory minerals include zircon, apatite, sphene, rutile, and magnetite. The extent and field relations of the Warman quartz monzonite are unknown because of the limited outcrops. Early descriptions indicate the presence of large inclusions or roof pendants in the granite. Dikes of basalt, aplite, and pegmatite are numerous, and in the quarry in the northern part of the village of Warman, there are two intrusives of gray granite. Age determinations on biotite from the quartz monzonite gave 1.76 b.y. (K-A) and 1.72 b.y. (Rb-Sr). A gray quartz monzonite in a small quarry two miles southwest of Pierz, in Morrison County, closely resembles the Warman quartz monzonite and was classified with this rock by Woyski. The age for the Pierz rock is 1.73 b.y.

Hillman Tonalite. The Hillman tonalite was named by Woyski for outcrops along Hillman Creek in Morrison and Mille Lacs counties. The tonalite locally is massive but very commonly is foliated and contains numerous inclusions which Woyski attributed to the Thomson formation. She described the inclusions as biotite or hornblende schist, generally in bands, most of which have been drawn out into schlieren. Essential minerals of the Hillman tonalite are andesine, 45; quartz, 40; biotite, 10; and hornblende, 5 per cent. Accessory minerals include K-feldspar, zircon, apatite, sphene, and magnetite. A sample of biotite is dated by the K-A method at 1.78 b.y. and gives a somewhat lower age of 1.69 b.y. by the Rb-Sr method.

Freedhem Tonalite. The Freedhem tonalite gneiss crops out in central Morrison County in the vicinity of the village of Freedhem and also just west of Little Falls. The rock is gray, fine- to medium-grained and massive, but locally it is foliated, and inclusions are fairly common. The approximate composition, given by Woyski, follows: andesine, 40; quartz, 20; K-feldspar, 5–10; and biotite and hornblende, 35 per cent. Zircon, apatite, sphene, and magnetite are accessory. Woyski concluded that the Freedhem tonalite is closely related to, but probably younger than, the Hillman tonalite. Two samples from just north of Freedhem were dated by the K-A method (Table 21). One of the samples represents a gneiss, and the second sample is apparently a schist layer in the Freedhem gneiss. The K-A ages of the gneiss and schist are 1.70 and 1.63 b.y. These ages are somewhat lower than those obtained for the Hillman tonalite. Possibly the younger St. Cloud Red granite, which locally intrudes the Freedhem tonalite and related rocks, may have affected the sampled rocks.

Isle Quartz Monzonite. A light-gray, coarse-grained biotite quartz monzonite is quarried 5 miles south of the village of Isle in Mille Lacs County (Pl. 2). This rock is considered part of the Warman quartz monzonite intrusive by Woyski. According to the earlier descriptions by Harder and Johnston (1918, p. 42), the quarry contains granite of two types, one a medium- to coarse-grained rock, and the other finer grained. Both are light-colored and contain only a small amount of biotite. Harder and Johnston concluded that the fine-grained granite is the younger and is intrusive into the coarse-grained rock. They state that the fine-grained rock resembles closely in appearance the quartz monzonite from the quarry southwest of Pierz. The K-A age determined for biotite from the Isle quartz monzonite is 1.68 b.y., which agrees with the age for the gneiss from Freedhem and is somewhat less than the age of 1.76 b.y. for the Warman quartz monzonite.

YOUNGER GRANITES

St. Cloud Red Granite. The St. Cloud Red granite and related types, such as the Rockville porphyritic granite, underlie a large part of Stearns, Benton, and Sherburne counties. Best exposures of the rocks are in the numerous quarries in the St. Cloud vicinity. Sample KA-58, of the St. Cloud Red granite, representing the typical medium-grained rock from a quarry one mile northwest of the village of Sartell, Stearns County, gives an age of 1.64 b.y. (K-A) and 1.65 b.y. (Rb-Sr).

Rockville Porphyritic Granite. The Rockville porphyritic granite is one of the main quarry products of central Minnesota. The rock is found mainly between St. Cloud and Richmond in Stearns County. It is pink to gray and contains large pink potash feldspar crystals in a coarse-grained groundmass of quartz, feldspar, and biotite. The structure is generally massive, but locally flow structure is found. The mode of the rock, as determined by Tatge (1939, p. 304), includes plagioclase, 36; microcline, 34; quartz, 23; and biotite and others, 7 per cent. The accessories are albite, hornblende, apatite, allanite, magnetite, zircon, sphene, and fluorite. Minor alteration products include sericite, chlorite, sphene, epidote, zoisite, calcite, kaolin, and pyrite. Tatge noted that the plagioclase grains are crowded with dark inclusions of biotite and that the microcline, which occurs in crystals commonly as much as two centimeters across, is zoned. In addition to the large crystals, microcline is also found as veins and stringers which penetrate every mineral in the rock. Two varieties of plagioclase are present, an early euhedral andesine-oligoclase, and a late albite in perthitic intergrowths bordering the early plagioclase. All degrees of microclinization of the plagioclase have occurred.

In discussing the history of the crystallization of the Rockville magma, Tatge (1939, p. 310) notes that the scattered xenoliths were partly digested by the magma and that crystallization may have started before the xenoliths were incorporated. The large crystals of microcline apparently did not result from early crystallization but were among the last of the minerals to crystallize. The growth of these crystals, accompanied by late quartz, albite, hornblende, and fluorite, is attributed by Tatge to long continued deuteric action. The mineral relationship suggests that possibly the Rockville porphyritic granite is the result of potash metasomatism of an earlier rock of granodioritic or dioritic composition. Biotite separated from a sample of the rock from the main quarry in Rockville gives an age of 1.64 b.y. which corresponds to the age for the sample of the St. Cloud Red granite.

PENOKEAN OROGENY

General Statement

Some of the more troublesome problems of Precambrian stratigraphy and correlation resulted from the failure to recognize the major orogeny, the Penokean, which followed the deposition of Huronian strata. In northern Minnesota there is no marked discordance between the Rove formation and the overlying Keweenawan flows. This relationship had undue influence in the interpretation of geologic events and probably in the assignment of the Animikie to the Late Precambrian (Table 1). The folding of the Cuyuna sediments, therefore, was related to the time of formation of the Lake Superior geosyncline, and the Thomson formation, correlated with the Knife Lake slate, was thought to have been deformed at the time of the older Algoman orogeny. The granite intrusions of central Minnesota further complicated the geologic interpretation because, in default of a post-Animikie (Penokean) orogeny, these granites were classified either with the Algoman granite (Giants Range granite) or with the much younger Middle Keweenawan granites related to the Duluth gabbro.

The results of the radioactivity dating help in clarifying the geologic history, and the revisions made (Table 2) are in accord with the interpretations which have been made for Wisconsin and Michigan (Tyler and Marsden, 1940, p. 1459; Marsden, 1955, p. 111). Some problems of correlation are discussed below, but it should be emphasized that the present discussion, of necessity, must be restricted to the framework of the rock units which have been previously recognized. Similarly, the interpretation is based on the dating of the metasediments, gneisses, and granite, and therefore is the history of deformation and metamorphism rather than a history of sedimentation and stratigraphic succession.

Thomson Formation Problem

The Thomson beds closely resemble the slate-graywacke sequence of the Rove formation. At the type locality in the Thunder Bay district, Ontario, the Rove beds contain abundant calcareous concretions which have been described by Tanton (1931) and more recently by Moorhouse (1957). Calcareous concretions are locally prominent in the Virginia formation of the Mesabi district and can be seen in the Embarrass and St. James mines near Aurora. They range in size from a few inches to several

TABLE 22. CHEMICAL ANALYSES OF CONCRETIONS FROM THE THOMSON FORMATION, MINNESOTA, AND FROM THE MICHIGAMME FORMATION, MICHIGAN

	1	2		1	2
SiO_2	23.89	20.91	TiO_2	.40	.66
Al_2O_3	6.71	3.72	P_2O_5	.13	.14
Fe_2O_3	.41	.51	MnO	.32	.28
FeO	2.37	2.59	H_2O+	.99	n.d.
MgO	1.20	1.46	H_2O-	.07	n.d.
CaO	34.10	37.93	CO_2	26.69	28.66
Na_2O	1.47	n.d.			
K_2O	.98	n.d.	Total	99.73	96.92

1. Composite sample of several concretions from the Thomson slate, SW ¼ Sec. 27:48–17, Carlton County, Minnesota. R. B. Ellestad, analyst (Schwartz, 1942c).
2. Concretion from the Michigamme slate, Kenton quarry, Sec. 2:46–37, Iron County, Michigan. W. R. Pasich, analyst, personal communication from Eiler L. Henrickson, 1959.

feet in diameter. F. L. Klinger (personal communication, August, 1959) has collected cone-in-cone structures developed peripherally to some of the concretions similar to those described by Tanton (1931, p. 42). Calcareous concretions also are abundant in the Michigamme slate in Iron County, Michigan. A chemical analysis (E. L. Henrickson, personal communication, August, 1959) of a calcareous concretion from the Michigamme slate from the Kenton quarry in Sec. 2, T. 46 N., R. 37 W., Iron County, Michigan, is remarkably similar to the analysis (Table 22) of a composite sample of concretions collected by Schwartz (1942c) from the Thomson formation.

The presence of graphitic or carbonaceous material in the Thomson formation, giving it a dark color, was early recognized by Hall (1901, p. 347), who noted that, on weathering and removal of the carbonaceous material, the slates become lighter in color. The presence of graphitic material in thin sections of the slate from the type locality has already been noted. Similarly there are graphitic inclusions in the staurolite metacrysts as well as in the groundmass of the schist in the Little Falls area. Hall also mentions that along the Kettle River there are graphitic slates in the Thomson which apparently contain more than the average abundance of carbon, although a chemical analysis was not made. Hall (1901, Pl. 30, Profile 2) was sufficiently impressed with the abundance of graphite to indicate a graphite belt in his cross-section. Harder and Johnston (1918, p. 71) described outcrops of graphitic schist in the NE ¼ NW ¼ Sec. 28:46–20, and state that "the rock has well-developed schistosity and shows crumpled and crenulated foliation planes along which graphite is developed abundantly."

Harder and Johnston (1918, p. 120) give a chemical analysis of black graphitic slate from a drill hole north of Blackhoof Lake, near Ironton in the Cuyuna district. The analysis (No. 14) shows 3.75 per cent of carbon. Analyses of graphitic argillite from the Virginia formation (White, 1954,

p. 17) give 4.25 and 6.83 per cent of carbon. Nanz (1953, p. 54) quotes a number of analyses of graphitic slates from the Iron River-Crystal Falls district of Michigan which range from 3.3 to 22.7 per cent in carbon, and Tyler, Barghoorn, and Barrett (1957) describe anthracite coal from this area. Dark-colored, graphitic slates are common in the Knife Lake group of Early Precambrian age, but local high concentrations of graphite have not been reported, whereas such concentrations in Huronian slates, associated with iron formations, are common in the mining districts of the Lake Superior region.

The lithologic similarity of the slate and graywacke beds, the presence of calcareous concretions and of graphitic layers, together with the fact that the formations were all involved in the Penokean orogeny, indicate that the Thomson formation is of Huronian age. A correlation of the Thomson with the Virginia, the Rove, and the Michigamme formations is suggested, as has long been favored by the geologists of the United States Geological Survey (Van Hise and Leith, 1911; Harder and Johnston, 1917, 1918; and Leith, Lund, and Leith, 1935).

The Granite Problem

Chemical analyses of granitic intrusives in east-central Minnesota are given in Table 23. The group of older granites includes two analyses of the St. Cloud Gray granodiorite and one of the Warman quartz monzonite. The younger granites include the Rockville porphyritic granite, the St. Cloud Red granite, the McGrath gneiss, and two dike rocks. Most of these analyses have appeared in older publications (Bowles, 1918; Thiel and Dutton, 1935) and were made in a study of the igneous rocks of Stearns County (Grout, unpublished M.S. thesis, Univ. Minn., 1908). Slightly different versions of the analyses have been given; the analyses in Table 23 are taken, as far as possible, from the original report cards in the files of the Department of Geology. The analysis of the St. Cloud Red granite (No. 5), unfortunately, is a poor one, but as nothing better is available, it has been included to represent the rock type.

The St. Cloud granodiorite and the Warman quartz monzonite are chemically similar, and these rocks are much more calcic than the younger granites. A plot of calcium, sodium, and potassium for the analyzed samples (Fig. 23) shows an apparent chemical similarity between the McGrath gneiss, analyzed by E. B. Sandell (Sandell and Goldich, 1943), and the St. Cloud Red granite. The dike rocks are relatively more potassic. The analyses show the usual chemical trend of granitic rocks in an orogenic province, with the oldest rocks being calcic and the younger ones potassic.

The early intrusives of quartz monzonite, granodiorite, and tonalite give an average K-A age of 1.76 b.y., whereas the younger granites give an age of 1.64 b.y. The St. Cloud Gray granodiorite is a massive rock, intruded prior to the main period of folding. The St. Cloud Red granite is also massive and is interpreted to be postkinematic. A difference of ap-

TABLE 23. CHEMICAL ANALYSES OF CENTRAL MINNESOTA GRANITES

	Older Granites		Younger Granites			Late Dikes		
	1	2	3	4	5	6	7	8
SiO_2	64.40	66.40	69.55	69.63	71.17	71.19	73.80	76.30
Al_2O_3	15.00	16.48	15.55	14.88	13.30	15.00	14.67	12.66
Fe_2O_3	1.63	.83	.14	.54	3.52	.67	.63	.47
FeO	3.13	2.85	3.29	3.53		1.49	1.19	1.20
MgO	3.05	2.28	1.61	.83	.30	.81	.32	.02
CaO	4.18	3.68	3.67	2.35	1.56	1.83	.99	.84
Na_2O	3.31	3.36	3.79	2.32	3.85	3.64	2.46	2.70
K_2O	3.95	3.09	2.12	4.34	4.33	4.57	4.87	5.00
TiO_2	.57	.42	.44	.37	.23	.30	.19	.15
P_2O_5	.57	.30	.07	.28	.23	.07	.04	.18
MnO	.09	n.d.	n.d.	.23	n.d.	.01	n.d.	.05
H_2O+	.15	.42	.40	.23	.64	.68	.69	.27
H_2O-	.07	.03	.10	.10	n.d.	.03	.04	.00
CO_2	.18	n.d.	n.d.	.11	.21	n.d.	n.d.	n.d.
Total	100.28	100.14	100.73	99.74	99.34	100.29	99.89	99.84

1. St. Cloud Gray granodiorite, NE¼ Sec. 28:124-28, Stearns County, F. F. Grout, analyst.
2. St. Cloud Gray granodiorite, Sec. 21:125-28, Stearns County, F. F. Grout, analyst.
3. Warman quartz monzonite, "Reynolds Granite Company" quarry, Warman, Kanabec County, F. F. Grout, analyst.
4. Rockville porphyritic granite, quarry in Rockville, Stearns County, F. F. Grout and F. F. Pettijohn, analysts.
5. St. Cloud Red granite, average of three analyses; G. H. Hammond, W. W. Willard, and F. F. Grout, analysts.
6. McGrath granite gneiss, small quarry west of Dads Corner in NW¼ Sec. 6:44-23, Aitkins County, E. B. Sandell, analyst (Sandell and Goldich, 1943, p. 110).
7. Aplitic dike, SE¼ Sec. 29:124-28, southwest of St. Cloud, Stearns County, F. F. Grout, analyst.
8. Granite porphyry dike, SE¼ Sec. 20:124-28, southwest of St. Cloud, Stearns County, F. F. Grout, analyst.

proximately 120 million years in the age of these rocks is suggested by the K-A ages. The Rb-Sr ages, fewer in number, suggest a shorter time interval of approximately 50–60 million years. Evaluation of the precision of the K-A and Rb-Sr ages is difficult; however, the ages by both methods are consistent so far as the relative ages of the three rock groups are concerned, and they indicate an interval of 50–100 million years between the early and late intrusives.

MIDDLE PRECAMBRIAN HISTORY

SUMMARY FOR MINNESOTA

The history of geosynclinal deposition which culminated in the Penokean orogeny is conjectural, but from the information available some major events may be postulated. In the Mesabi district, the Animikie formations rest on an erosion surface which was cut in granites, gneisses, and older rocks following the Algoman mountain-building period. As indicated in an earlier section, a great deal of Middle Precambrian time elapsed during the erosion of the terrain prior to the deposition of the

Pokegama quartzite. The Biwabik iron-formation is generally regarded to be a type of chemical sediment deposited under stable conditions, and the formation contains little clastic material. The original thickness of the Virginia formation is unknown, but undoubtedly it was much greater than the 2000 feet penetrated in drilling.

According to Grout and Wolff (1955), the Biwabik iron-formation in the Cuyuna district contains considerably more clastic material than in the Mesabi district, and the thickness estimated by Wolff for the main iron formation of the North range is 2500 to 3500 feet. The thickness of the Virginia formation is estimated to be more than 5000 feet. Although these figures are considerably greater than those given for the Mesabi district, it is seen that the known thickness of these strata is relatively small; however, in Carlton and Pine counties the Thomson slates and graywackes, which are presently assigned to the Huronian, were deposited in a thick wedge. Schwartz (1942a, p. 46) estimated the thickness of the Thomson formation to be more than 20,000 feet.

In early Huronian time eastern Minnesota was a lowland with Algoman mountains to the north and northwest. Similar mountains to the southwest are indicated by the old gneisses and granites of the Minnesota Valley which are discussed in Chapter 5. A geosynclinal trough, extending from Minnesota eastward through Wisconsin into Michigan, possibly connected with Labrador through the Mistassini district. The sedimentary rocks which accumulated in this trough were eventually folded and elevated in the Penokean Mountain range. The Animikie rocks of the Mesabi district represent a miogeosynclinal facies resting on a relatively firm foundation of Algoman granites and gneisses. To the southeast the shales and graywackes of the Thomson formation were deposited rapidly in the eugeosynclinal part of the basin. In the deeper parts of the geosyncline there may very well be older sediments below the Animikie formations, and it is likely that the high-grade gneisses and schists in central Minnesota and in northern Wisconsin may have been derived by metamorphism and intrusion of the older sediments.

In middle to late Huronian time, when the iron formations of the Mesabi and Cuyuna districts were being deposited in the relatively shallow waters of the marginal shelf area, an appreciable thickness of sediments had already been accumulated to the south and southeast. Into this sequence the granodioritic and related rocks of central Minnesota were intruded. These rocks are dated at approximately 1.8 b.y., and possibly at this time the early phase of deformation of the geosyncline was already in progress. The tonalites, granodiorites, and related rocks in central Minnesota probably were emplaced at a crustal level considerably above that represented by the Vermilion and Giants Range complexes to the north; however, there must have been a considerable thickness of sedimentary rocks overlying the intrusions. The various intrusives, collectively, were of sufficient size to form a mass which acted more or less as a stable unit and resisted folding in the later phases of the geosynclinal deformation.

Schmidt (1958, 1959) has emphasized the pyroclastic materials which accumulated subsequent to the deposition of the main iron formation of the North range of the Cuyuna district. He suggests that some of the materials may represent basaltic lavas which were poured out following the deposition of the iron formation. Altered masses of chloritic composition,

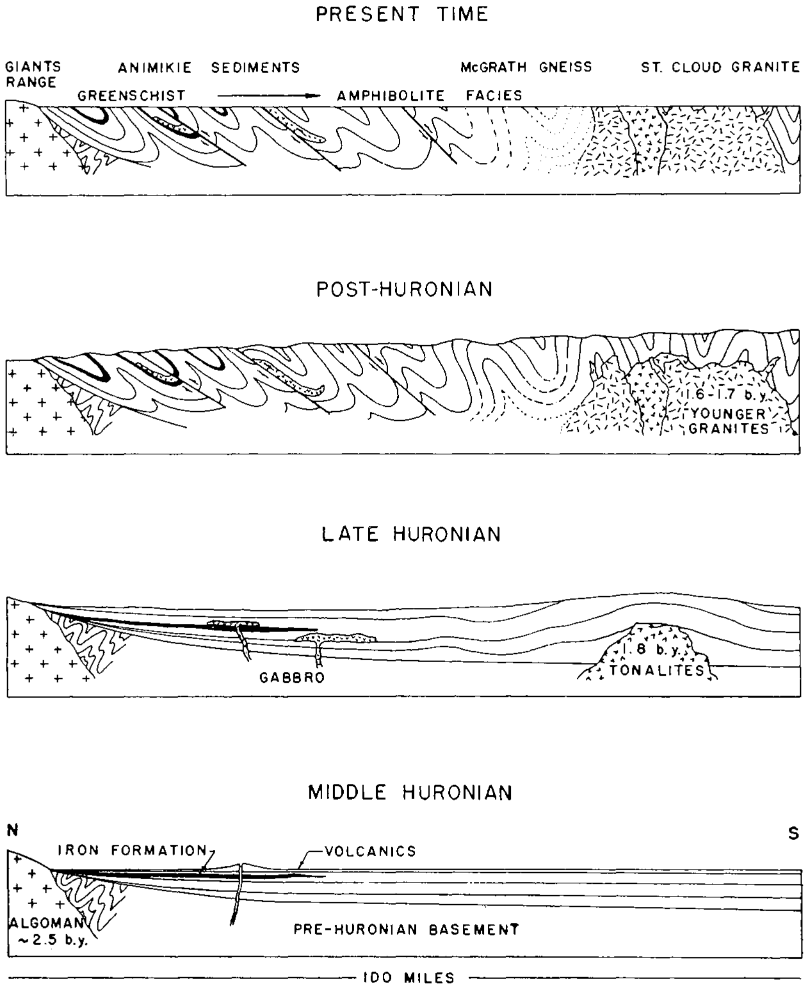

FIGURE 25. — Schematic diagrams illustrating the development of the Penokean orogeny in east-central Minnesota.

which are encountered in drilling and also in the mines of the Cuyuna district, are suggestive of former gabbroic and dioritic intrusives.

Following the deposition of the Virginia formation, and possibly younger rocks, the geosynclinal accumulation became unstable, and the major period of folding was initiated at approximately 1.7 b.y. The origin of the McGrath gneiss is uncertain. Possibly more than one rock type is represented, and the history suggested here may be oversimplified, but the McGrath gneiss, in part, must date to the Penokean orogeny, and the age (1.7 b.y.) suggests that it is synkinematic.

The origin of the Rockville porphyritic granite or quartz monzonite also is questionable. The Rockville is probably the coarsest-grained rock in east-central Minnesota; however, the large crystals of microcline were formed late in the history of the rock and may be related to potash metasomatism of an older granodiorite or tonalite. The St. Cloud Red granite is a massive, medium-grained, postkinematic intrusive. Like the older tonalites and granodiorites, however, the St. Cloud Red granite must have been emplaced under a considerable thickness of sedimentary cover. The rocks which formed the suprastructure of the Penokean Mountains apparently have been largely eroded and lost to the geologic record in Minnesota.

An attempt has been made to illustrate schematically some of the main features of the Penokean orogeny in east-central Minnesota (Fig. 25). The interpretation of the structure of the Animikie group of the Cuyuna district, shown in the diagram, is based largely on ideas obtained from Schmidt (1958, 1959). The Mesabi district to the north was not strongly affected by the Penokean orogeny. The mountains formed at the close of the Huronian time in central Minnesota extended east into Wisconsin and Michigan.

Correlation with Other Districts

The Huronian of the iron districts of northern Wisconsin and Michigan is represented by a considerably thicker and more diverse assemblage of rocks than that of Minnesota (Leith, Lund, and Leith, 1935; Marsden, 1956). James (1958) has summarized the recent work of the United States Geological Survey in northern Michigan which was done cooperatively with the Geological Survey of Michigan. He reviewed the main difficulties that have been encountered in the past 60 years during which the term Huronian was used for the rocks of the iron-bearing districts south of Lake Superior. The Federal Geological Survey has adopted Animikie series to replace Huronian series (James, 1958, p. 33).

The usage of Animikie series as a time-rock term is quite proper; however, the rocks embraced in this series in Michigan include a number of groups that are not represented in the Animikie of Minnesota or at the type locality in the Thunder Bay area of Ontario. The Animikie group in Ontario and Minnesota is well defined, and there may be no great danger of confusion between the Animikie group of Ontario and Minnesota and the Animikie series of Michigan; however, it would seem that final judgment on the undesirability of the term Huronian might be postponed until data from radioactivity dating and additional field studies can be assembled and properly appraised. The problem is discussed further in Part 6 of this report.

Iron formations in Quebec, in the Mistassini district and in Ungava, are similar to the iron formations of Minnesota, Wisconsin, and Michigan, and many Precambrian geologists favor a correlation of these rocks. There are striking similarities, not only in chemical composition and in lithology, but also in the sequence of beds. The problem of the possible correlation of the Quebec iron formations with those of the Lake Superior region is discussed in another paper (Quirke, Goldich, and Krueger, 1960).

Wisconsin. Results of dating of four samples from Wisconsin are given in Table 21, Section F. Sample KA-45 is a coarse-grained, mica-kyanite schist from a belt of metamorphosed rocks containing iron formation in Sec. 25, T. 42 N., R. 3 E., Iron County, Wisconsin (Pl. 4). Three determinations of argon were made on this sample at widely separated intervals, and the closely agreeing results give an age of 1.72 b.y. Sample KA-184 is pink, coarse-grained muscovite granite from a diamond drill hole in T. 41 N., R. 1 W. near Butternut, Wisconsin, and represents postkinematic granite that was intruded into the metamorphic rocks (KA-45). The muscovite gives a K-A age of 1.66 b.y. which corresponds to the age obtained for the St. Cloud Red granite of central Minnesota.

Two samples from southern Wisconsin give somewhat younger ages. Sample KA-330 is the porphyroblastic augen gneiss at Neillsville, Wisconsin (Pl. 4), and sample KA-12 is rapakivi-type of granite (Gates, in Emmons *et al.*, 1953) from Waupaca. The Neillsville gneiss gives a K-A age of 1.48 b.y. and the Waupaca granite, 1.43 b.y.

Michigan. Biotite from a garnetiferous mica schist (KA-66) below the oxidized iron formation south of the Republic pit, just east of Republic, Michigan, gives an age of 1.89 b.y. Gray sericitic schist (KA-278) from the Republic mine gives a K-A age of 1.61 b.y. Muscovite from a granite dike (KA-68) which cuts the iron formation in the Groveland pit near Randville in Sec. 31, T. 42 N., R. 29 W., Dickinson County, gives an age of 1.62 b.y. Microcline from a pegmatite in Sec. 19, T. 42 N., R. 29 W., Dickinson County, is dated at 1.62 b.y. by the Rb-Sr method (Table 7, Sec. E). Wasserburg, Hayden, and Jensen (1956, p. 159) dated muscovite from this pegmatite, and their A^{40}/K^{40} ratio of 0.160 gives an age of 1.67 b.y. Aldrich, Wetherill, Tilton, and Davis (1958) report Rb-Sr and K-A ages for feldspar and muscovite from a pegmatite at Felch in Dickinson County, probably the same samples analyzed by Wasserburg, Hayden, and Jensen, and at Minnesota. Their ages for the muscovite are 1.63 b.y. (K-A) and 1.62 b.y. (Rb-Sr), and for the feldspar, 1.65 b.y. (Rb-Sr). It is seen that the ages by different investigators are in good agreement and indicate that the rocks in Marquette and Dickinson counties, Michigan, were involved in the Penokean orogeny as were the rocks in northern Wisconsin. The somewhat older age of 1.9 b.y., obtained for the garnetiferous mica schist below the iron formation at Republic, indicates that this rock dates back to an earlier orogeny but was affected during the Penokean orogeny; the determined age is a survival value.

A sample of the Fern Creek slate (KA-238) from the Sturgeon Falls dam area is dated at 1.35 b.y by the K-A method. According to J. W. Trow (personal communication, April, 1959), the age probably should be related to the intrusion of diabase in the area. Aldrich, Wetherill, Tilton, and Davis (1958) have reported similar ages for the Mary Lake granite and for samples from the metamorphic zones described by James (1955).

5. SOUTHWESTERN MINNESOTA

INTRODUCTORY STATEMENT

The study by Lund (1956) of the igneous and metamorphic rocks exposed in the Minnesota River Valley (Fig. 26) provides a base for radioactivity-dating investigations. The present-day Minnesota River is a relatively small, meandering stream. It flows southeast from Big Stone Lake to Mankato, thence northeast to join the Mississippi River near Minneapolis. Its channel is cut largely in alluvium, but at a few places it flows on bedrock. The valley was cut in late Pleistocene time by the drainage from Lake Agassiz, as was first surmised by General G. K. Warren (1878) who surveyed the Minnesota River in 1866. Upham (1883) proposed the name River Warren for the ancient stream in honor of the general. The valley ranges in width from about half a mile to over 4 miles and in depth from approximately 100 feet to over 225 feet. In the 100-mile distance between Ortonville and New Ulm, there are numerous small and scattered outcrops of Precambrian igneous and metamorphic rocks. With the exception of the outcrops near New Ulm, most of the bedrock has been mapped by Lund.

Lund divided the igneous and metamorphic rocks into three main groups. The oldest rocks were referred to the "basic complex" of gabbroic and dioritic gneisses. The largest outcrops, in the vicinity of Granite Falls, have been mapped by Lund in detail. Remnants of the complex occur throughout the valley as inclusions in the granites and granitic gneisses which were emplaced in it. The granitic rocks constitute Lund's second major group which he named the Minnesota Valley granite series. Five rock types were distinguished, and from southeast to northwest in the valley they are (1) Fort Ridgely granite, (2) Morton quartz monzonite gneiss, (3) Sacred Heart granite, (4) Montevideo granite gneiss, and (5) Ortonville granite. Lund was aware of the possibility that the granites and gneisses might not be of the same age; however, the various units are similar in composition (Table 24) and are distinguished principally on textural and structural features. Thus, it did not appear unreasonable that "all the rocks could have been derived from a single magma or closely related magmas during a single period of igneous activity" (Lund, 1956, p. 1482).

The third and youngest group of rocks was referred by Lund to "post-granite intrusives," and includes numerous basaltic dikes, several small gabbroic and dioritic intrusives, roughly circular in plan, and small granitic masses. These rocks cut the granites and gneisses of the Minnesota Valley granite series as well as the older rocks of the basic complex.

For the purposes of the present discussion, the Minnesota River Valley

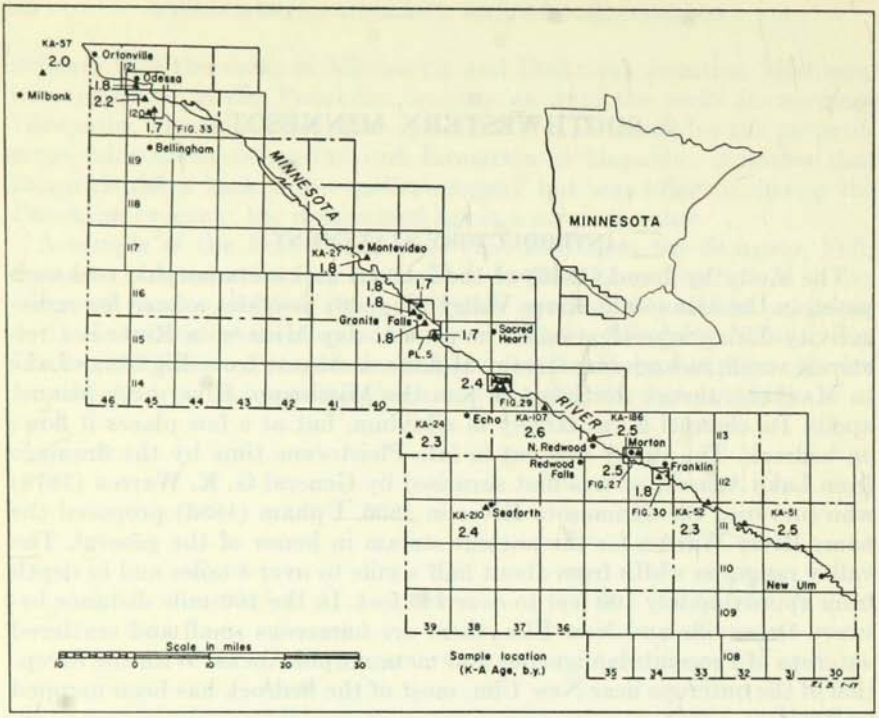

FIGURE 26. — Index map of the Minnesota River Valley showing locations of dated samples and areas of Figures 27, 29, 30, Pl. 5, and Fig. 33.

TABLE 24. COMPOSITION OF GRANITES AND GNEISSES ASSIGNED TO THE MINNESOTA VALLEY GRANITE SERIES
(Average of modal analyses by Lund, 1956)

	1 Fort Ridgely Granite	2 Morton Gneiss	3 Sacred Heart Granite	4 Monte-video Gneiss	5 Ortonville Granite Odessa	6 Ortonville Granite Bellingham
No. of samples	1	10	4	4	2	2
Potash feldspar	55	22	40	43	45	57
Plagioclase	10 (An_{18})	39 (An_{22})	29 (An_{18})	22 (An_{18})	20 (An_{18})	16 (An_{18})
Quartz	30	31	22	31	31	21
Biotite	4	6	6	3	3	5
Accessories	1	2	3	1	1	1
Magnetite	X	X	X	X	X	X
Apatite	X	X	X	X	X	X
Zircon	X	X	X	X	X	X
Sphene		x(6)	X	x(2)		
Epidote	X	x(8)				X
Allanite		x(6)	X			
Hornblende		x(5)				
Muscovite		x(3)	X	x(3)	X	X

X = usually less than 1 per cent, but found in all samples.
x = usually less than 1 per cent, found in number of samples indicated by number in parentheses.

is divided into three regions: (1) Morton-Sacred Heart, (2) Granite Falls-Montevideo, and (3) Odessa-Ortonville. The Morton-Sacred Heart region is the largest of the divisions and includes approximately 40 miles of the valley. It is characterized by the Morton quartz monzonite gneiss but also includes rocks of the basic complex and the Fort Ridgely and Sacred Heart granites. Two quarried rocks are also included in the discussion of this region, although they occur outside the Minnesota River Valley. These are the Seaforth gneiss, which bears a strong resemblance to the Morton gneiss, and the granite of the Larsen quarry southwest of Echo which simulates the Sacred Heart granite (Fig. 26).

The Granite Falls-Montevideo region covers approximately 15 miles of the valley and is characterized by the Montevideo granite gneiss. The Odessa-Ortonville region is underlain by the Ortonville granite. Included in the discussion of the Ortonville-Odessa region is the Milbank granite which is quarried in a number of places in eastern South Dakota (Fig. 26). Finally, a section is devoted to the discussion of the Sioux formation which crops out in southwestern Minnesota.

MORTON-SACRED HEART REGION

General Statement

Outcrops southeast of Fort Ridgely are the most southeasterly exposures of the Morton gneiss. Relatively large outcrops occur in the valley south of Franklin (Fig. 30) where the Morton gneiss is intruded by a roughly circular complex of granophyre gabbro and granite which makes a prominent hill, locally known as Cedar Mountain. Three similar plug-like intrusions resemble the Cedar Mountain complex in structure and in composition. Two parallel basalt dikes form a conspicuous ridge over 3 miles long and 500 feet wide.

In the vicinity of Morton (Fig. 27) the Morton gneiss crops out in irregular hills or rounded knobs that were shaped and scoured by the glacial river Warren. The Morton gneiss is a highly distinctive rock, characterized by its contorted structure that is emphasized by the contrasting colors of its compositional banding. Commonly the rock is variegated in red, pink, gray, and black. The structure and color give the rock a unique appeal, and it is probably the best known of the quarry products of the state and is widely used as a facing for large buildings as well as for monumental and ornamental purposes. The quarry operations in the vicinity of Morton have been described by Thiel and Dutton (1935) and by Lund (1953).

The Morton gneiss in the vicinity of Morton and Redwood Falls is deeply weathered (Goldich, 1938). Residual clays are exposed in the banks of the valley and along the tributaries of the Minnesota River, notably in the cliff-like banks of Redwood River between Redwood Falls and North Redwood. The residual clays were reworked and incorporated in the Cretaceous sediments of the area. Sedimentary kaolin is well exposed in clay

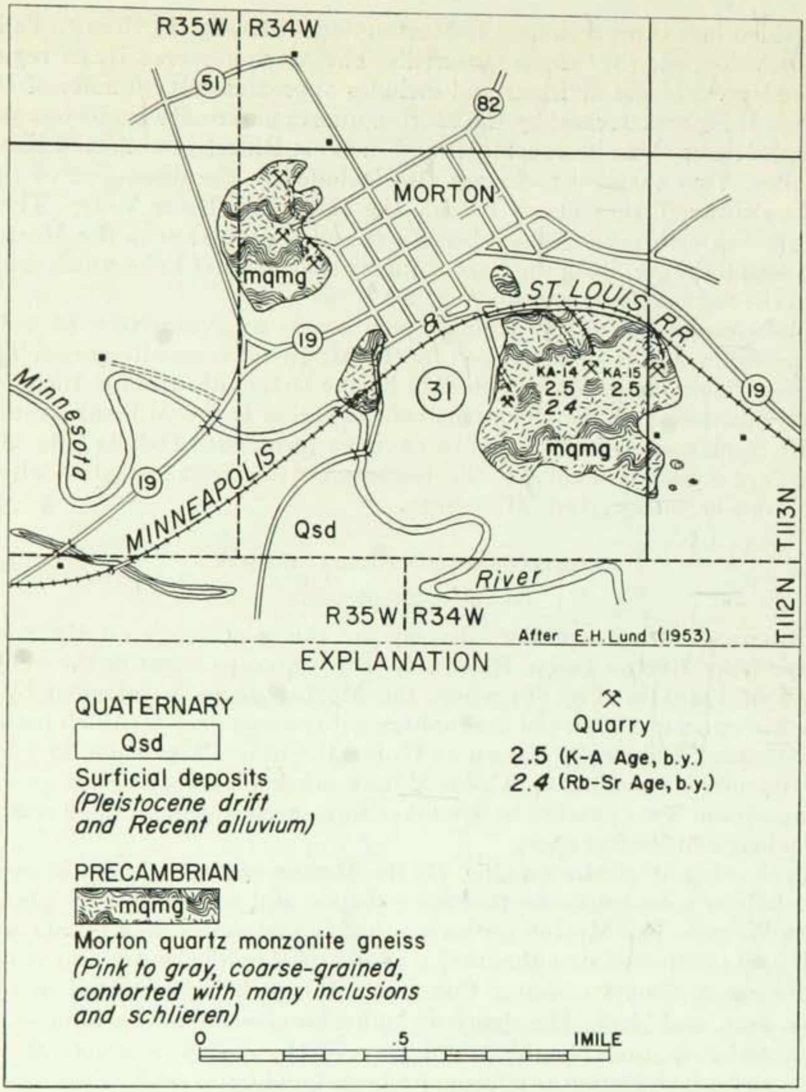

FIGURE 27. — Map of Morton area showing quarries and location of dated samples.

pits south of the highway between Redwood Falls and Morton in Sec. 2:112–35.

Numerous outcrops of the Morton gneiss have been mapped in the valley between Morton and Sacred Heart (Fig. 26), and there are a few openings which were made in prospecting for quarries, but none of these was

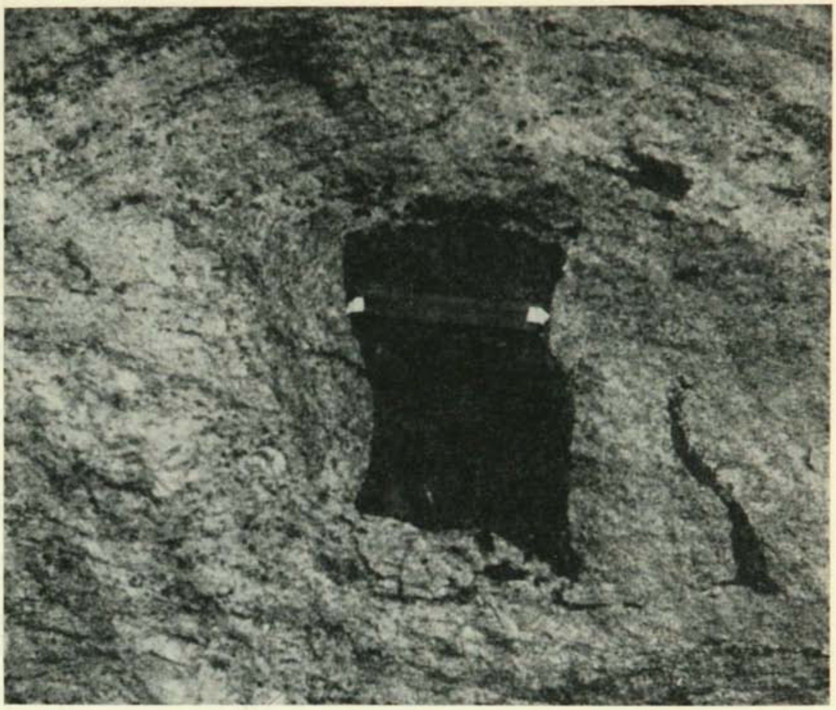

FIGURE 28. — Structure in the Morton gneiss around an inclusion of mafic rock derived from the pre-existing basement complex. Cold Spring Granite Company quarry, Morton. The K-A age is 2.5 b.y.; the Rb-Sr age is 2.4 b.y.

developed. The outcrops south of Sacred Heart (Fig. 29) are the most northwesterly exposures of the gneiss. The contorted structure of the Morton gneiss does not lend itself to precise structural observations, but the strike of the foliation, as well as the trend of dikes, is roughly east-west throughout the outcrops.

The outcrops of the Sacred Heart granite in a small area (Fig. 29) approximately 5 miles south of Sacred Heart are the sites of numerous quarries producing medium-grained red granite. A few of the quarries are still operated when there is a demand. The low granite hills and knobs have been scoured by stream abrasion, and large potholes are numerous. The ponds of the area mark some channels of former waterways.

Basic Complex

In the Morton-Sacred Heart region, the basic complex is represented by inclusions, many of which are large enough to be mapped. Gabbro and diorite are the principal rock types, and although the rocks commonly are foliated or banded, this structure appears to be secondary. Locally the

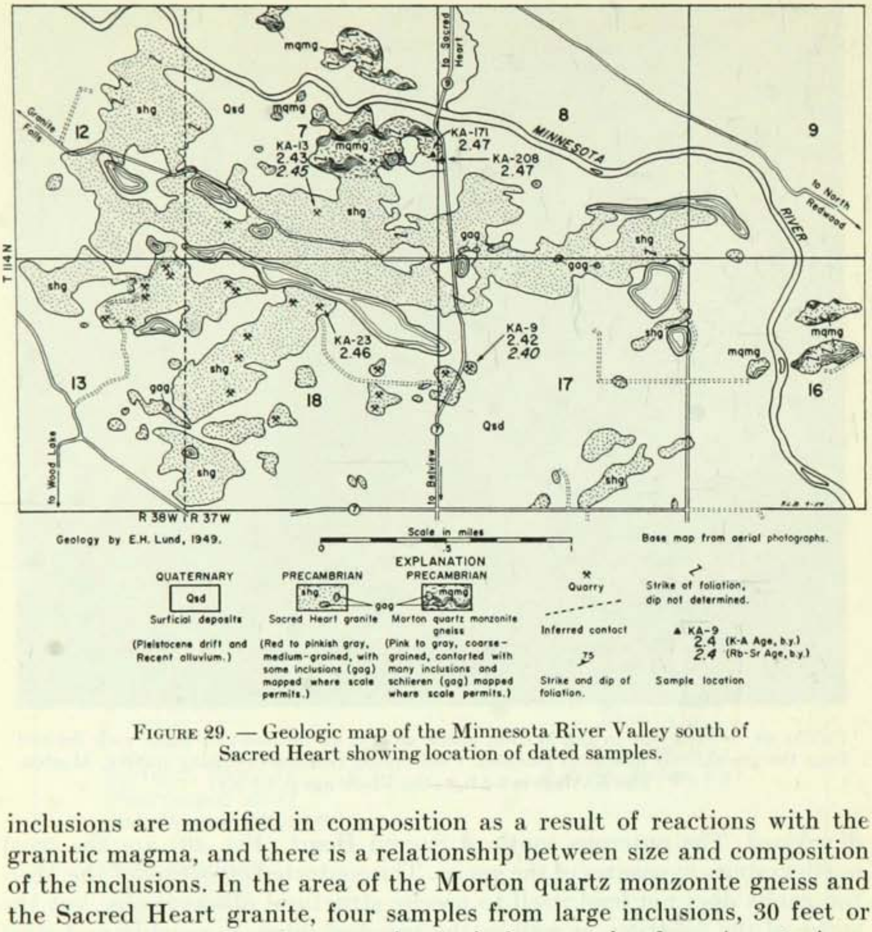

FIGURE 29. — Geologic map of the Minnesota River Valley south of Sacred Heart showing location of dated samples.

inclusions are modified in composition as a result of reactions with the granitic magma, and there is a relationship between size and composition of the inclusions. In the area of the Morton quartz monzonite gneiss and the Sacred Heart granite, four samples from large inclusions, 30 feet or more across, were found to contain plagioclase ranging from An_{48} to An_{56}, whereas the plagioclase in four samples from small inclusions (Fig. 28) range from An_{23} to An_{34} (Lund, 1956, p. 1480). Similarly, in other parts of the valley, Lund found a relationship between composition and size of xenoliths.

MORTON QUARTZ MONZONITE GNEISS

The Morton gneiss is a hybrid rock formed by the invasion of the basic complex of this part of the valley by granitic magma. Huge remnants remain, but a large amount of material has been incorporated and partially assimilated by reaction. Because of the variability of the banded and contorted gneiss, its composition is not easily determined. An average composition, based on 10 modal analyses by Lund (1956, p. 1484), is given in Table 24 and a chemical analysis in Table 25. The dark-gray layers are

TABLE 25. CHEMICAL ANALYSES OF MORTON QUARTZ MONZONITE GNEISS, ODESSA GRANITE, AND BELLINGHAM GRANITE

	1	2	3
SiO_2	71.54	72.59	74.13
Al_2O_3	14.62	15.10	13.72
Fe_2O_3	.69	.71	.48
FeO	1.64	.56	.94
MgO	.77	.43	.31
CaO	2.08	2.06	1.03
Na_2O	3.84	4.58	3.23
K_2O	3.92	3.20	5.28
BaO	.09	n.d.	n.d.
TiO_2	.26	.15	.14
P_2O_5	.10	.06	.06
MnO	.04	.01	.03
H_2O+	.30	.12	.26
H_2O-	.02	.03	.00
CO_2	.14	.12	n.d.
S	.02	.00	n.d.
Total	100.07	99.72	99.61

1. Morton quartz monzonite gneiss, main quarry, Cold Spring Granite Co., Morton. S. S. Goldich (1938), analyst.
2. Odessa granite, Cold Spring Granite Co. quarry, southeast of Ortonville, Eileen H. Oslund, analyst. Courtesy of the Cold Spring Granite Co., 1959.
3. Bellingham granite, quarry of the Bellingham Granite Co., Sec. 16:120-45. Eileen H. Oslund, analyst.

essentially quartz diorite in composition; the pink to red layers are granitic and contain as much as 50 per cent of K-feldspar.

Commonly the granitic phase is coarse-grained to pegmatitic, suggesting a highly mineralized granitic liquid. Potash-feldspar porphyroblasts were developed in the xenoliths, and the light-gray rock which surrounds the inclusions is largely a reaction product. Accompanying the intrusion and granitization, movements and plastic deformation resulted in the development of the schlieren-like layers and the highly contorted structure of the gneiss (Fig. 28).

SEAFORTH GNEISS

A small amount of granite gneiss has been taken out of a quarry in a small dome or knob in a pasture approximately 3 miles southwest of Seaforth (Fig. 26). Structurally this rock resembles the Morton gneiss, but the feldspar is white rather than pink or red. The banding is the result of concentration of biotite in schlieren or irregular layers. The strike is about N. 50° E., and the dip is approximately 30° S.E. The rock is locally pegmatitic and is cut by gray aplite.

SACRED HEART GRANITE

The Sacred Heart granite is medium-grained, gray to red, and fairly massive. Locally there are numerous inclusions of dark-colored, mafic

TABLE 26. MODES OF SACRED HEART GRANITE
(Volume per cent)

	Average[b]	KA-23	KA-24
Potash feldspar	40	30	36
Plagioclase	29	40	28
	(An_{18})	(An_{25})	(An_{20})
Quartz	22	23	32
Biotite[a]	6	5	2
Accessories	3	2	2
Magnetite	X[c]	X	X
Apatite	X	X	X
Zircon	X	X	X
Sphene	X	X	?
Allanite	X	?	?
Muscovite	X	X	
Calcite		X	X
Epidote		X	?
Hematite		X	X

[a] Includes chlorite. [c] Usually less than one per cent.
[b] Average of four modal analyses of Sacred Heart Granite from Table 24.
KA-23. Quarry, north-central Sec. 18:114-37 (Fig. 29).
KA-24 Larsen quarry (Fig. 26).

rock, but these are rarely deformed or incorporated as schlieren or wavy bands which are typical of the Morton gneiss. Four modal analyses by Lund show small variations; plagioclase (An_{18}) ranges from 27 to 32 per cent; microcline, 38 to 44 per cent; quartz, 17 to 26 per cent; and biotite and accessory minerals, 6 to 12 per cent. The average of the modes is given in Table 24 and also in Table 26 which includes new point-count analyses of samples KA-23 and KA-24 (Fig. 29). The Sacred Heart granite is typically granitoid, and although the plagioclase is somewhat altered to sericite and the biotite to chlorite, the rock on the whole is fresh.

GRANITE OF LARSEN QUARRY

The Larsen quarry is situated 8 miles west and 3 miles south of Echo (Fig. 26) in a red, medium-grained granite of the Sacred Heart type; however, the small knob-like outcrop is isolated in the glacial drift, and the correlation is a lithologic one.

A point-count analysis of two thin sections (Table 26) shows a ratio of microcline to plagioclase (An_{20}) approaching Lund's average, but the quartz content is considerably higher, 32 compared to 22 per cent. Texturally the granite of Larsen's quarry is very different, and apparently the rock has been granulated and recrystallized with the development of a mortar structure in which finely granular quartz and feldspar surround the larger grains as well as fill fractures. The biotite is fresh, with only minor alteration to chlorite. The large sphene grains, which are characteristic of the Sacred Heart granite, are not found. Myrmekitic intergrowths of oligoclase and quartz are well developed, both in the fine-grained plagioclase, and on the margins of the larger crystals. The granite has undergone metamorphism which involved shearing and granulation and some recrystallization.

Fort Ridgely Granite

A pinkish-gray, porphyritic granite was named the Fort Ridgely granite by Lund for the small outcrops northwest of the site of the old fort (Fig. 26, KA-52). The rock contains small inclusions which are strewn out into schlieren parallel to the lineation produced by the aligned feldspar phenocrysts. Although the granite bears some resemblance to the Morton gneiss, especially where inclusions are numerous, the contorted structure of the gneiss is lacking, and Lund concluded that the Fort Ridgely granite probably represents a less contaminated and more massive phase of the Morton gneiss. The mode (Table 24) indicates a potash-rich granite resembling the Ortonville type.

Post-Morton Gneiss Intrusives

The Morton quartz monzonite gneiss is intruded by the Sacred Heart granite, and by inference, also by the Fort Ridgely granite. There are many aplitic to fine-grained granitic dikes in the gneiss, but none has been studied in detail or dated. In addition to these granitic rocks, there are numerous small intrusives in the Morton gneiss, particularly in the area south and southeast of Franklin. These have been described and mapped by Lund, and they include dark-colored dikes, chiefly basalt, and small plugs of gabbro and granodiorite. There are also four small masses of serpentinized peridotite in badly weathered and isolated outcrops, and the age relationships of these are unknown. Lund (1956, p. 1482) assigned the peridotites to the basic complex, but it is likely that they were intruded in the Morton gneiss. Of the various intrusives only the Cedar Mountain complex (Fig. 30) will be considered here, and it has been restudied in some detail for the present investigation by C. A. Bury (unpublished M.S. thesis, Univ. Minn., 1958).

Cedar Mountain Complex. The Cedar Mountain complex (Fig. 30) is the most remarkable of several small, roughly circular intrusives in the Morton gneiss south and east of Franklin. Cedar Mountain is a local name, so-called for the small "cedar" (juniper) trees on top of a group of hills that rise abruptly to an altitude of about 100 feet above the alluvial bottom of the Minnesota River Valley. The "mountain" is situated 1 mile south of Franklin, from which it is readily accessible by county roads.

Three rock types are recognized in the complex. At the contact with the Morton gneiss, the intrusion was chilled to a border phase of fine-grained, olivine trachybasalt porphyry. From the contact the trachybasalt grades with increasing grain size to granophyre gabbro. The gabbroic rock forms an annular outcrop with broad, flat surfaces and cliffs, 25–30 feet high. The central part of the complex is granite. Careful search failed to reveal the contact between the granite and the gabbro; weathering has produced a circular depression conforming to the pattern of the intrusion at the contact. The topographic effect of the depression suggests a race track, with granite rising in low knobs in the central part and gabbro forming the outer wall.

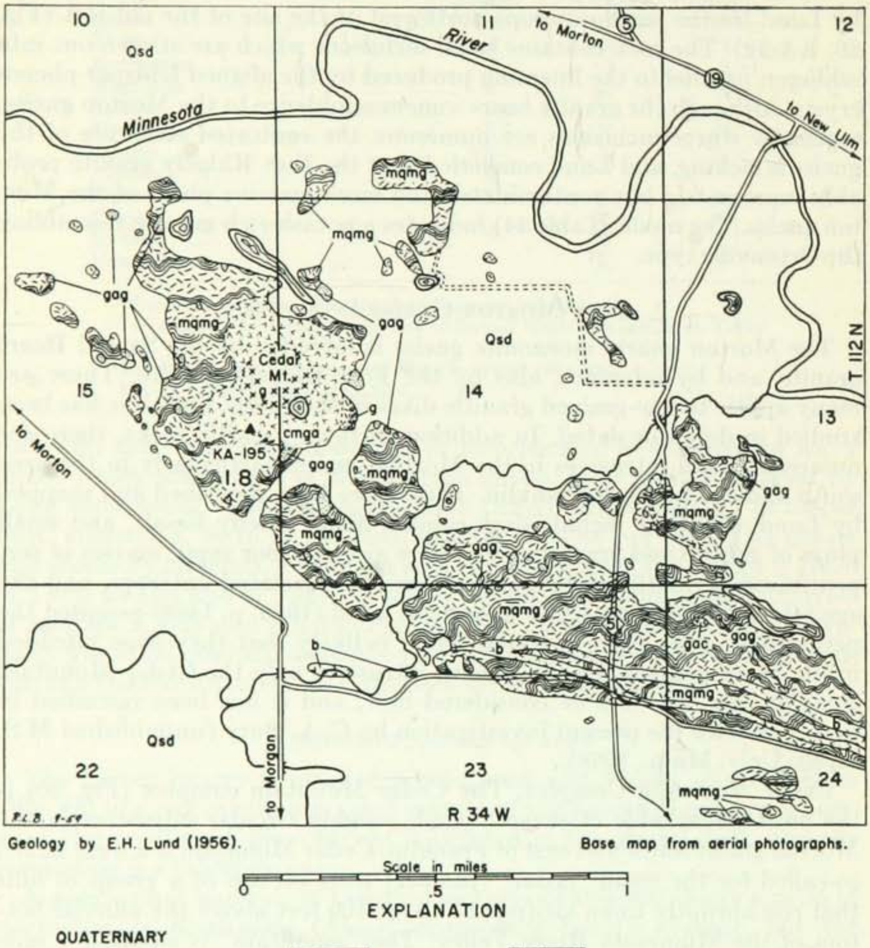

FIGURE 30. — Geologic map of the Cedar Mountain area south of Franklin.

The country rock of Morton gneiss is in no way exceptional and shows the usual contorted structure. A number of small xenoliths of the gneiss occur in the gabbro and are easily distinguished from the red granite of the core. A modal analysis of the olivine trachybasalt porphyry from the chilled border zone is given in Table 27. Phenocrysts of augite and olivine occur in a fine-grained diabasic groundmass. Orthoclase is interstitial to the laths of plagioclase (An_{54}). Olivine is largely altered to serpentine and magnetite.

Granophyre Gabbro. The gabbro is characterized by well-developed layering. On flat outcrops the banding shows swirl-like structures as though a crystallizing magma were slowly rotating as it rose. On the cliffs the layering appears as vertical, parallel bands. The structure is due to variations in the proportions of light- and dark-colored minerals. The light-colored layers are mostly feldspar laths, whereas the darker ones are chiefly augite, hornblende, biotite, and magnetite. The bands range in width from 1/8 inch to 6 inches or more. The light-colored layers commonly are wide and commonly stand above the dark bands on weathered surfaces. In thin sections the gabbro shows a very large amount of alteration. The hornblende and possibly the biotite may be classed as deuteric, but abundant chlorite, epidote, sericite, and magnetite are hydrothermal. The plagioclase (An_{55}) is extensively altered to sericite. An average of four modal analyses is given in Table 27.

Granite. The largest outcrops of granite occur near the center of the Cedar Mountain complex. A small patch of granite occurs outside of the gabbro on the southeast side, marginal to a dike-like mass of gabbro that may be an apophysis of the main mass. Small dikes of granite cutting the

TABLE 27. MODAL ANALYSES OF ROCKS FROM THE CEDAR MOUNTAIN COMPLEX
(Volume per cent; Curtis A. Bury, analyst)

	1	2	3	4	5
K-feldspar	11	18	47	39	41
Plagioclase	50	30	25	18	15
	(An_{54})	(An_{55})	(An_4)	(An_4)	(An_4)
Quartz		5	10	14	11
Augite	20	11			
Hornblende		15			5
Biotite	9	13	1	1	8
Chlorite		3	8	19	16
Sericite [a]	1		7	3	
Olivine	2				
Magnetite	6[b]	3	1	5	2
Apatite	1	1	1	1	1

[a] Includes small amount of hematite and unidentified alteration products.
[b] Largely formed from olivine.
1. Olivine trachybasalt, chilled border phase.
2. Granophyre gabbro, average of four thin sections.
3. Granite from center, average of three thin sections.
4. Granite from margin, average of two thin sections.
5. Granite dike cutting granophyre gabbro.

gabbro apparently represent magma which worked out from the central intrusion along fractures. The granite is fine- to coarse-grained and dull red, and because quartz is rare and inconspicuous, the rock resembles a red syenite, similar in appearance to some of the granophyre or "red rock" of the Duluth complex. Modes of the granite from various occurrences are similar (Table 27). Quartz ranges from 8 to 15 per cent. Alteration has been intensive, and chlorite and sericite are abundant. Finely divided hematite is disseminated throughout the K-feldspar, and in this respect the granite resembles the granophyre of the North Shore region. Accessory minerals are magnetite, apatite, and zircon of the normal type. On the basis of the zircons, Lund (1956, p. 1490) suggested a Keweenawan age for the small intrusives in the Franklin area.

The Cedar Mountain complex represents composite intrusions of magmas which were differentiated at depth. The banding of the gabbro is explained by movements of the crystallizing magma at the time of its emplacement. The relatively large amount of granite in the core precludes the possibility of its formation by differentiation after emplacement in the present site.

Age and Origin

Ages for the rocks in the Morton-Sacred Heart region are given in Table 28, Sections A through E. The K-A ages for the Morton gneiss range from 2.45 to 2.57 b.y. Some of this variation must be attributed to analytical error, but the average of 2.5 b.y. is considered to be significant and places the time of formation of the Morton gneiss in the Algoman orogeny. The more or less uniform Sacred Heart granite, which from field relationships is younger than the Morton gneiss, is a postkinematic intrusion. The average of three K-A age determinations for the Sacred Heart granite is 2.44 b.y., and the Rb-Sr determinations on two of the samples agree closely. The Rb-Sr ages on two samples of the Morton gneiss, however, give a similar age of 2.4 b.y., and the K-A age on the Seaforth gneiss is also 2.4 b.y.

The frequency of the 2.4 b.y. value in the region shows that this date marks a specific event and that the intrusion of relatively large amounts of Sacred Heart magma into the Morton gneiss at considerable depth resulted in recrystallization of the biotite. Apparently this recrystallization affected the Sr^{87}/Rb^{87} ratio more than it did the A^{40}/K^{40} ratio. It will be noted that the samples of the Morton gneiss (KA-171 and KA-208) taken near the contact of the Sacred Heart granite (Fig. 29) give ages of 2.47 b.y. This is further support for the hypothesis that the biotite in the Morton gneiss had been affected by the intrusion of the Sacred Heart magma at 2.4 b.y.

Subsequent to the main period of Algoman orogeny, the area was not stable, and there were local adjustments. Movements resulted in granulation and in recrystallization of the granite (KA-24) from the Larsen quarry which closely resembles the Sacred Heart granite to the north. Biotite

TABLE 28. AGES FOR ROCKS FROM SOUTHWESTERN MINNESOTA

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
	MORTON-SACRED HEART REGION						
	(A) Morton Quartz Monzonite Gneiss						
51B	Ridgely township	2.49		7.52	7.54	2.31	0.306
51F	Ridgely township			12.92	12.95	2.72	.210
14B	Morton quarry (KA-14-1)	2.54		8.20	8.22	2.59	.315
						2.62	.319
						2.62	.319
14F	Morton quarry (KA-14-1)			9.24	9.26	2.03	.219
						2.02	.218
14B	Morton quarry (KA-14-2)	2.53	2.43	8.29	8.31	2.62	.315
15B	Morton quarry (KA-15-1)	2.45		6.52	6.53	1.94	.298
15F	Morton quarry (KA-15-1)			7.87	7.89	1.91	.242
						1.83	.232
15B	Morton quarry (KA-15-2)	2.55		7.41	7.42	2.38	.320
107B	Northwest of Morton	2.57	2.42	7.99	8.01	2.60	.325
186B	North Redwood	2.51		8.45	8.47	2.63	.310
171B	South of Sacred Heart	2.47		7.22	7.23	2.18	.302
208B	South of Sacred Heart	2.47		5.84	5.85	1.76	.301
						1.77	.302
	Average	*2.50*					
	(B) Cedar Mountain Granophyre Gabbro						
195B	Cedar Mountain	1.75		4.62	4.63	.788	.170
	(C) Seaforth Gneiss						
210B	Seaforth	2.40		8.64	8.66	2.53	.292
						2.45	.283
	(D) Fort Ridgely Granite						
52B	Fort Ridgely	2.30		3.88	3.89	1.03	.266
	(E) Sacred Heart Granite						
9B	South of Sacred Heart	2.42	2.40	6.53	6.54	1.90	.291
9F	South of Sacred Heart			8.37	8.39	1.30	.155
13B	Northwest of KA-9	2.43	2.45	6.80	6.81	1.98	.291
						2.03	.299
23B	South of KA-13	2.46		4.82	4.83	1.45	.300
	Average	*2.44*					
24B	Larsen quarry	2.30		7.52	7.54	1.99	.263
						2.01	.267
						2.06	.273
						1.99	.264
24F	Larsen quarry			13.38	13.41	2.24	.167
	GRANITE FALLS-MONTEVIDEO REGION						
	(F) Montevideo Granite Gneiss						
27B	Montevideo (KA-27-1)	1.84		5.96	5.97	1.11	0.186
						1.09	.183
27F	Montevideo (KA-27-1)			10.46	10.48	1.24	.119
						1.22	.116
27B	Montevideo (KA-27-2)	1.85	1.74	7.73	7.75	1.44	.186
54B	Quarry, Granite Falls (KA-54-1)	1.75		6.67	6.68	1.11	.167
						1.16	.173

TABLE 28 — *Continued*

KA No.	Description	K-A Age b.y.	Rb-Sr Age b.y.	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}
54F	Quarry, Granite Falls (KA-54-1)			12.89	12.92	2.04	.158
						1.98	.153
						1.92	.149
54B	Quarry, Granite Falls (KA-54-2)	1.75	1.69	6.31	6.32	1.08	.171
25B	North of Granite Falls ...	1.83		5.97	5.98	1.11	.185
						1.09	.182
209B	Southeast of Granite Falls	1.71		7.78	7.80	1.29	.166
						1.28	.164
	Average	*1.79*					
	(G) Garnetiferous Quartz Diorite Gneiss						
22B	Granite Falls	1.78		7.12	7.13	1.22	.171
						1.29	.180
	(H) Granite of Section 28						
28B	North of Granite Falls ...	1.69		7.32	7.33	1.15	0.156
						1.22	.167
29B	North of KA-28	1.69	1.65	7.76	7.78	1.21	.155
						1.30	.168
	ODESSA-ORTONVILLE REGION						
	(I) Ortonville Granite						
55B	Bellingham quarry	1.67		8.48	8.50	1.30	.153
						1.39	.164
55F	Bellingham quarry			14.28	14.31	1.83	.127
56B	Bellingham quarry	1.67		9.15	9.17	1.46	.159
108B	Unique Granite quarry ...	1.67		8.44	8.46	1.36	.160
						1.33	.157
109B	Odessa	1.79		8.79	8.81	1.59	.180
						1.54	.175
57B	Milbank granite	1.97		7.62	7.64	1.60	.209
						1.54	.202
57F	Milbank granite			11.80	11.82	1.92	.162
	(J) Quartz-Pyroxene Granulite						
44B	South of Odessa	2.18		5.33	5.34	1.30	.243
	(K) Sioux Formation						
50	Argillite, Pipestone	1.20		5.17	5.18	.503	.097
						.518	.100

from the granite of the Larsen quarry gives a somewhat lower age of 2.3 b.y. Four argon extractions were made on KA-24 by two different operators. The first two runs (HB) were made in August and in September of 1956. A third run (HWK) was made in December of 1958 and the fourth run (HWK) was made in May of 1959. The minimum and maximum ages from these four runs are 2.28 and 2.33 b.y., and the deviation from the average age of 2.3 b.y. is less than 2 per cent.

Although the Fort Ridgely granite gives a similar age of 2.3 b.y., the data are inadequate to define an event in this area. In the Franklin area, however, the Morton quartz monzonite gneiss was intruded by basalt dikes and by the Cedar Mountain complex at approximately 1.8 b.y. Because of the similarity in the mineral composition of these basalt dikes to those of the Lake Superior region, and the similarity of the gabbro-granophyre association at Cedar Mountain to the Duluth complex, these rocks had been assumed to be of Middle Keweenawan age. The date of 1.8 b.y., however, for biotite from the granophyre gabbro of the Cedar Mountain complex places it in the Penokean orogeny which is late Huronian or early Keweenawan. It is clear that the Cedar Mountain complex is not contemporaneous with the Duluth complex which was formed at a much later time, approximately 1.1 b.y.

By analogy with the Giants Range and Vermilion granites in northern Minnesota, the geologic history in southwestern Minnesota in Early Precambrian time is interpreted to have involved the accumulation of a geosynclinal sequence of beds followed by the intrusion of gabbroic rocks. Near the close of Early Precambrian time (2.6–2.5 b.y.), the geosyncline is postulated to have foundered, and depression of the sedimentary sequence to great depths resulted in local melting and generation of a granitic magma which rose during the period of folding, producing the Morton quartz monzonite gneiss or migmatite as a synkinematic intrusion. The xenoliths in the Morton gneiss were derived from gabbroic rocks which were fractured and incorporated in the granitic magma at depth.

Subsequent to the main period of folding and formation of the Morton gneiss (2.6–2.5 b.y.), the Sacred Heart magma was generated and invaded the area under conditions which appear to have involved little stress. The postkinematic magma crystallized to a more uniform granite. The Sacred Heart granite is dated at 2.4 b.y., which is essentially the time of intrusion of the postkinematic granites in the Rainy Lake region of Ontario. It appears likely that the Fort Ridgely granite was intruded at the same time, but, like the granite which is now exposed in the Larsen quarry, it was subjected to later deformation which reduced the age of the biotite to 2.3 b.y.

GRANITE FALLS-MONTEVIDEO REGION

General Statement

The relatively good outcrops in the vicinity of Granite Falls (Pl. 5) are among the most instructive in the valley. The basic complex is represented by two units, gabbroic and dioritic gneiss, and a garnetiferous quartz diorite gneiss. These rocks form large outcrops south of Granite Falls. The older gneisses are intruded by the Montevideo granite gneiss, and relatively large outcrops of the gneiss occur west of Granite Falls. Although there are many inclusions of diorite-gabbro gneiss in the Montevideo granite gneiss, there are no inclusions of the garnetiferous quartz diorite gneiss.

Basalt dikes are numerous in this part of the valley and cut the Montevideo granite gneiss as well as the older rocks. A younger granite intrudes the Montevideo gneiss and basalt northwest of Granite Falls. Thus the sequence of geologic events indicated by the rock units includes intrusion of the basic complex by the Montevideo granite gneiss, the basalt dikes, and finally by the granite.

Garnetiferous Quartz Diorite Gneiss

The garnetiferous quartz diorite gneiss forms large outcrops south of the Minnesota River, just south of Granite Falls. The dark-gray rock is distinctly banded and is characterized by abundant pink to red garnet. It contains numerous quartz veins and granitic stringers which, for the most part, follow but also cut across the foliation. The structure appears to be uniform, and the foliation strikes east-west or a few degrees north of east and dips, on the average, 45° S. Only in one place (NW 1/4 Sec. 4:39–115) is the garnetiferous gneiss intruded by the granite gneiss. Three small outcrops of the garnetiferous gneiss occur approximately 4 miles northwest of Granite Falls in the SW 1/4 Sec. 13:40–116, beyond the map limit (Pl. 5). In these outcrops the foliation strikes east-west and dips 65° N. A small outcrop also occurs approximately 4 miles southeast of Montevideo, and it appears that the unit may underlie a large part of the valley which is now covered by alluvium.

Outcrops of the garnetiferous quartz diorite gneiss are usually weathered; however, fresh material is available in a roadcut along State Highway 67 and on the dump of an old prospect pit. The composition of a sample from the pit (Lund, 1956, Table 3, No. 20) is plagioclase (An_{40}), 52; pyroxene, 10; quartz, 16; garnet, 14; magnetite, 5; and accessory hornblende, biotite, and apatite, 3 per cent. The gneiss in the roadcut is variable, and the garnetiferous rock is interlayered with augite-hypersthene diorite gneiss. Some of the layers in the roadcut are exceptionally rich in biotite and contain 10–15 per cent of this mineral (KA-22).

Gabbro and Diorite Gneiss

Inclusions of gabbroic and of dioritic gneiss are abundant in the Montevideo granite gneiss. Commonly the inclusions are layers that conform to the structure of the granite gneiss, and the outcrop pattern of the inclusions is instructive in detailing the structure of the area. A wide band of gabbro gneiss south of Granite Falls intervenes between the outcrops of Montevideo granite gneiss to the northwest and of the garnetiferous quartz diorite gneiss to the southeast. The structure of the gabbro gneiss conforms to that of the garnetiferous gneiss, and although the contact between the two units is nowhere exposed, the dip of the gabbro gneiss would bring this unit beneath the garnetiferous gneiss.

The gabbro gneiss is gray, medium-grained, and usually distinctly banded. It is variable in texture, structure, and composition. The larger masses of the gneiss, south of Granite Falls, are gabbroic, whereas the small inclusions in the Montevideo granite gneiss are dioritic. It seems likely that there has been reaction between the inclusions and the magma similar to that described for the Morton gneiss. The modal analyses (Lund, 1956, Table 1, No. 1, 2) for samples from the larger outcrops average calcic plagioclase (An_{68}), 73; pyroxene, 17; hornblende, 8; and accessory minerals, 2 per cent. Six samples from smaller masses, for the most part inclusions in the Montevideo granite gneiss, show a range of 22 to 45 per cent plagioclase (An_{43-55}); 0 to 35 per cent pyroxene; 15 to 76 per cent hornblende; and 1 to 6 per cent accessory minerals.

Montevideo Granite Gneiss

Description. The type locality of the Montevideo granite gneiss, 1.5 miles southeast of Montevideo, is readily accessible from U.S. Highway 212. The gneiss is pink to red, medium-grained, and characterized by uniform, straight banding. Dark-colored minerals generally make up less than 5 per cent of the rock, except locally where mafic inclusions have been incorporated. Contorted banding, such as characterizes the Morton gneiss, is rarely developed, nor is the variation in grain size so pronounced; therefore, the Montevideo gneiss is readily distinguished in the field from the Morton gneiss.

At the type locality, the foliation strikes about N. 80° E. and dips approximately 60° to the south. Long, narrow bands of gabbro gneiss represent large inclusions in the Montevideo gneiss. A smaller outcrop of the gneiss just to the southeast contains a basalt dike or sill. The most extensive outcrops of the Montevideo granite gneiss are in the vicinity of Granite Falls, approximately 12 miles southeast of Montevideo. The gneiss of the two areas is similar.

Composition. Three modal analyses (Lund, 1956, Table 7) of the Montevideo granite gneiss from the Granite Falls vicinity are similar, with microcline ranging from 32 to 40 per cent; plagioclase (An_{18}), 24 to 30 per cent; and quartz, 31 to 36 per cent. The mode of the gneiss from the type locality at Montevideo shows a larger percentage of microcline, 61 per cent, and smaller amounts of plagioclase (An_{18}), 9 per cent, and of quartz, 27 per cent. The average of the 4 modal analyses is given in Table 24.

Structure. Lund's detailed mapping of the Granite Falls area shows that the rocks have been folded, and an anticlinal structure, plunging to the east, is indicated (Pl. 5). It is suggested that the Montevideo granite magma was intruded into the gabbro gneiss at or just below the contact of the gabbro gneiss with the overlying massive unit of garnetiferous quartz diorite gneiss. South of the Minnesota River, the garnetiferous quartz diorite gneiss strikes slightly north of east and dips at angles of 40 to 65° to the south, whereas the small outcrops, previously mentioned northwest of Granite Falls, strike east-west and dip 65° to the north. The latter outcrops represent the northern limb of the anticline.

A second fold is indicated in Sections 10 and 11, 1.5 miles south of Granite Falls, where a band of the Montevideo gneiss with included gabbro gneiss, south of the Minnesota River, dips at high angles, 50–85°, to the north. North of the river, the foliation of the garnetiferous quartz diorite gneiss dips at angles of 35–50° south. The Minnesota River thus flows along the axis of the syncline.

Basalt Dikes

Numerous basalt dikes cut the various gneisses of the Granite Falls-Montevideo area (Pl. 5). Although some appear to be concordant with the structure of the rock, and therefore might appropriately be called sills, they commonly show some discordance, as can be seen on the geologic map. For this reason all are included in the classification of dikes.

Most of the dikes are basaltic, but they have not been studied in detail, and some may be lamprophyres. The dikes range from less than one inch to many feet in width. The narrow dikes are aphanitic, but the larger ones commonly grade from fine-grained chilled contacts to coarse diabasic centers. The principal minerals are labradorite, augite, magnetite, and interstitial quartz-K-feldspar intergrowths. Late stage or hydrothermal alteration is responsible for the development of hornblende, epidote, sericite, calcite, and other secondary minerals.

Late Granite of Section 28

Small granite intrusives represent the youngest known igneous activity in the region. The relative age relations are well established in the field and are easily seen in the railroad cuts north of Granite Falls (Pl. 5). Lund (1956, p. 1489) notes a small outcrop of granite along U.S. Highway 212 northwest of Granite Falls in Sec. 13:40–116. A third occurrence, southeast of Granite Falls in Section 11 just south of the pond (Pl. 5), are dikelets of granite and of pegmatite. These are a few inches wide and cannot be mapped. They cut a basalt dike and the Montevideo granite gneiss. Undoubtedly there are additional occurrences of this younger granite, but in the field the granite can be readily identified only when it is found cutting the basalt dikes. Small granitic stringers and dikes in the gabbro gneiss and in the garnetiferous quartz diorite gneiss may be of the same age as the granite cutting the dikes.

The granite of Section 28 is well exposed in the railroad cut along the right-of-way of the Chicago, Milwaukee, St. Paul and Pacific Railroad. The granite appears to have been localized by an earlier intrusion of basalt in the Montevideo granite gneiss. The Montevideo granite gneiss, well exposed a few feet south in a cut along the Great Northern Railroad tracks, contains inclusions of the gabbro gneiss so that representatives of the principal rock types can all be seen within a small area.

The younger granite is gray to pink and medium-grained. The basalt was brecciated and incorporated in the granite, forming an unusual ag-

FIGURE 31. — Igneous agglomerate formed by intrusion of granite into basalt. Railroad cut in Section 28, north of Granite Falls.

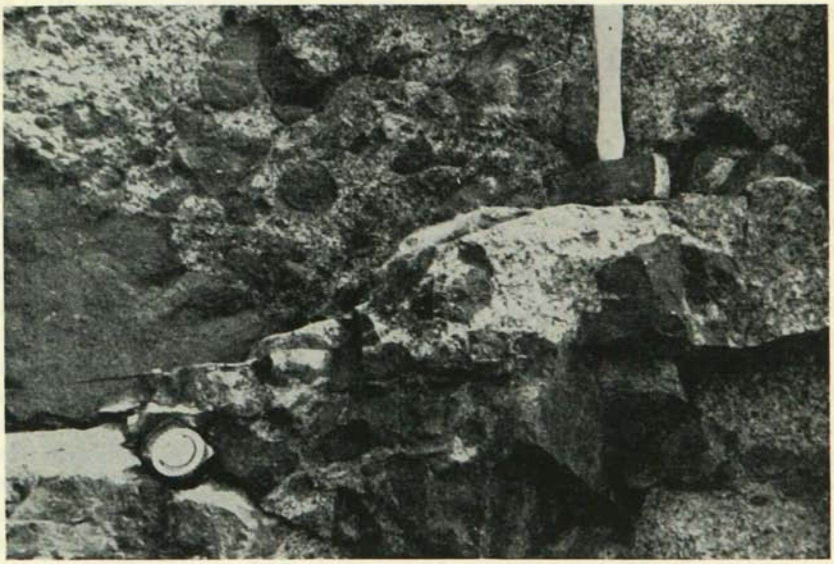

FIGURE 32. — Close-up view of the agglomerate shown in Figure 31. Note the rounded pieces of basalt in coarse-grained granite. Railroad cut in Section 28, north of Granite Falls. Determined age is 1.7 b.y.

glomerate. The fragments have been somewhat rounded, probably by attrition as well as by reaction with the magma, and the rock resembles a boulder conglomerate (Figs. 31, 32). Quartz is abundant, 32 to 34 per cent, and feldspar makes up 50 to 60 per cent of the rock, but the proportions of microcline and oligoclase vary greatly in different samples. Biotite, hornblende, and magnetite are the principal dark-colored minerals. In an outcrop in a pasture just north of the county road and north of the railroad cut, medium-grained pink granite is relatively free of basalt inclusions. Lund's mode (1956, p. 1486, No. 37) of this rock gives quartz, 32; K-feldspar, 30; plagioclase (An_{20}), 26; biotite, 11; and accessory magnetite, apatite, zircon, and sphene, 1 per cent.

Age and Origin

The radioactivity ages for rocks of the Granite Falls-Montevideo region are given in Table 28, Sections F, G, and H. The K-A ages fall within the limits of 1.69 b.y., for the granite of Section 28, and 1.85 b.y. for the Montevideo granite gneiss at the type locality near Montevideo. The average age for the Montevideo granite gneiss is 1.8 b.y., giving a difference of approximately 100 million years between the time of folding and the time of intrusion of the late granite. The three Rb-Sr age determinations, ranging from 1.65 to 1.74 b.y. lend support to the time difference indicated by the K-A ages. The ages are approximately those found for the intrusives in east-central Minnesota and mark igneous activity which accompanied the Penokean orogeny at the close of Middle Precambrian time.

The interpretation of the ages, in terms of the geologic relationships that are known from field and laboratory studies, is somewhat uncertain, if not speculative. The oldest rocks in the area were assigned by Lund to the basic complex; however, in the earlier work it was thought that the Montevideo granite gneiss and the Morton gneiss were of the same age, and the gneisses were assigned to the Minnesota Valley granite series. The difference in ages found for the Montevideo gneiss and for the Morton gneiss suggests the possibility that the rocks of the basic complex may not be of the same age in the two areas. The oldest rock would appear to be the garnetiferous quartz diorite gneiss.

The large folds in the Granite Falls area suggest the possibility that these rocks represent an original sedimentary series, but little evidence was found to substantiate this hypothesis. Some of the observations which conflict with this interpretation may be briefly considered. The garnetiferous quartz diorite gneiss south of Granite Falls is a metamorphic rock (garnet-amphibolite facies). If the assumption is made that an original sequence of sedimentary rocks was metamorphosed at considerable depth to produce the Montevideo granite gneiss and the garnetiferous quartz diorite gneiss at the same time, it is hard to understand why garnet was not developed also in the dioritic and gabbroic gneisses which are similar in composition to the garnetiferous quartz diorite gneiss and are found as inclusions in the Montevideo granite gneiss.

Lund found mechanical effects of shearing and granulation in the Montevideo granite gneiss, and there is a small amount of garnet in the rock in outcrops along County Road 4, east of U.S. Highway 212, southeast of Montevideo. These features suggest later deformation, but the garnet appears to be a local development. The Montevideo granite gneiss is fairly uniform in composition over a distance of 15 miles, and there is a marked absence of textural features which might be interpreted to indicate a possible sedimentary origin. The uniformity in composition of the leucocratic gneiss and the reactions which appear to have taken place, as is indicated by the differences in composition of inclusions related to their size, argue that the Montevideo granite gneiss is of magmatic origin.

The metamorphism which formed the garnetiferous quartz diorite gneiss is attributed to an earlier period, and the age of 1.8 b.y. obtained for sample KA-22 is not related to this period of metamorphism but to the time of the intrusion of the Montevideo granite magma. It is postulated that previous to this there was an intrusion of gabbro beneath or into the garnetiferous quartz diorite gneiss, forming a sill-like mass. The Montevideo granite magma, derived by melting of sediments at depth, was intruded into the gabbro at or near the present base of the garnetiferous quartz diorite gneiss. At the time of the granite intrusion or shortly following, 1.9–1.8 b.y., the area was folded. It was at this time that the biotite in the garnetiferous gneiss was recrystallized, and thus it gives an age similar to that of the Montevideo granite gneiss.

The period of folding was followed by intrusion of basalt dikes. Two periods are indicated by cross-cutting dikes mapped by Lund. Northwest of Granite Falls in Secs. 19 and 24 (Lund, 1956, Pl. 3), an east-west dike is cut by later dikes which trend northeast. West and northwest of Granite Falls the northeast trend of the basalt dikes is conspicuous and suggests some type of tensional relief following the folding. In Section 28, basalt was brecciated and intruded by granite. The Montevideo granite gneiss (KA-25) from just south of the basalt intrusion is dated at 1.8 b.y., whereas the granite (KA-28, 29) is dated at 1.7 b.y. The basalt dikes, which are post-Montevideo granite gneiss and pre-granite, were intruded between 1.8 and 1.7 b.y. Thus it seems reasonable that their time of intrusion was about the same as that of the Cedar Mountain complex in the Morton gneiss south of Franklin which is dated at 1.75 b.y.

In summary, the radioactivity ages for the Granite Falls-Montevideo region indicate folding and intrusion at approximately 1.8 b.y., approximately the time of the early phase of the Penokean orogeny in east-central Minnesota. The Montevideo granite gneiss is a synkinematic intrusion. Pre-existing rocks were metamorphic rocks, such as the garnetiferous quartz diorite gneiss of the Granite Falls area, and dioritic or gabbroic rocks intrusive into this series. In the late stage of folding, late kinematic or postkinematic basalt dikes were intruded, followed by intrusion of granitic magma. This sequence of events probably took place within a time interval of the order of 50 to 100 million years.

ODESSA-ORTONVILLE REGION

General Statement

Lund used the name Ortonville granite for the outcrops between Odessa and Ortonville but noted that a similar rock type occurs in a large area between Ortonville and Milbank, South Dakota. The granite of this region is variable in texture, color, and structure, and Lund distinguished two varieties but did not use specific names. In the area of main outcrop between Ortonville and Odessa, the granite ranges from pink to deep maroon red, and from medium-grained to coarse pegmatitic. Porphyritic texture is developed locally. Streaks and segregations of quartz-feldspar pegmatite make up a large part of the rock and give it a banded or marbled appearance. Dark inclusions are plentiful in some localities, and the rock commonly shows a pronounced gneissic structure. Polished surfaces of the gneissic granite are striking in the contrast between the medium-grained, dark-red rock and the lighter-colored, large, augen-like pegmatitic areas of coarse feldspar and blue quartz.

The granite in the many small knobs in the valley southeast of Odessa and north of Bellingham resembles the granite between Odessa and Ortonville, but mafic inclusions appear to be more numerous, and the rock is more porphyritic and less commonly foliated or banded. In the present report the term Ortonville is used in the sense of Lund's classification for all the granites in the upper part of the Minnesota Valley. The granite between Odessa and Ortonville is here referred to as the Odessa type, whereas the granite southeast of Odessa is called the Bellingham type.

Basic Complex

Larger inclusions are rare in the granite between Odessa and Ortonville; however, southeast of Odessa there are numerous inclusions as well as small isolated areas which are sufficiently large to be shown on a geologic map (Fig. 33). The inclusions in the Bellingham granite are fine-grained, sugary, schistose, and banded rock. Outcrops in the northeast corner of Sec. 9:120–45 are layered and are a metamorphosed sedimentary sequence. The layers strike N. 7° E. and are essentially vertical. A similar dark-colored, banded rock crops out on the west side of U.S. Highway 75 in the southeast corner of Section 4 (Fig. 33). This rock was described by W. S. Bayley (Diller, 1898, p. 358), who classified it as a quartz norite gneiss. A modal analysis by Lund (1956, p. 1481, No. 19) gives plagioclase (An_{37}), 57; pyroxene, including both augite and hypersthene, 15; biotite, 5; quartz, 21; and accessory magnetite and apatite, 2 per cent. Lund describes complicated folding and siliceous stringers which are deformed into small ptygmatic folds in the mafic inclusions.

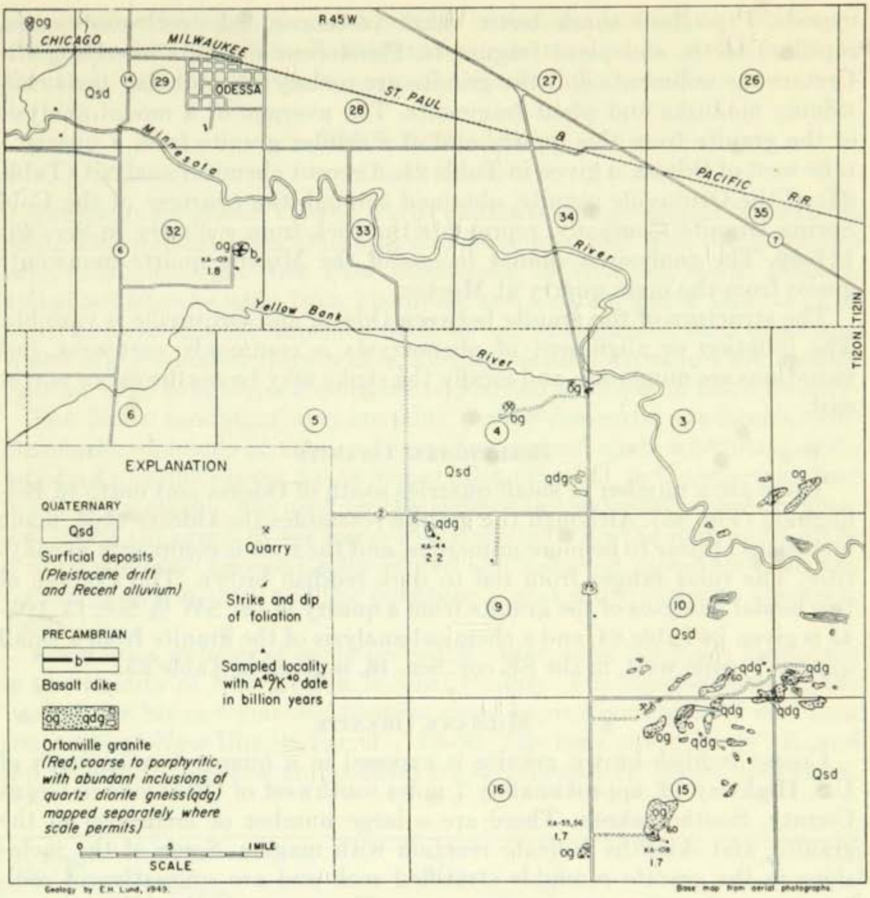

FIGURE 33. — Map of the Minnesota River Valley southeast of Odessa showing location of dated samples.

ODESSA GRANITE

The granite between Odessa and Ortonville is commonly red, but there are pinkish-gray to reddish-brown phases, and some are deep maroon red. It is generally medium- to coarse-grained or pegmatitic. Coarse-grained porphyritic granite of a dark-red color is quarried one mile south of Odessa. Inclusions are relatively few, and the rock shows no pronounced structure except for an alignment of large K-feldspar crystals. An east-west basalt dike cuts the granite. In the northwestern part of this quarry, stripping has exposed Cretaceous silts which lie unconformably on the granite. Large, well-rounded boulders of transported granite and other rock types mark the unconformity. Fossils from the Cretaceous sediments, collected by Robert C. Bright, include *Inoceramus* sp., unidentified pelecypods, *Ptycodont* shark teeth, shark vertebrae, fish teeth and scales, reptilian teeth, and plant fragments. Pleistocene deposits overlying the Cretaceous sediments and the granite are mainly silt and clay beds containing mollusks and plant fragments. The average of a modal analysis of the granite from this quarry and of a similar granite from a quarry 1 mile west of Odessa is given in Table 24. A recent chemical analysis (Table 25) of the Ortonville granite, obtained through the courtesy of the Cold Spring Granite Company, represents the rock from a quarry in Sec. 26: 121–46. The analysis is similar to one of the Morton quartz monzonite gneiss from the main quarry at Morton.

The structure of the granite between Odessa and Ortonville is variable. The foliation or alignment of phenocrysts is commonly east-west, but variations are numerous, and locally the strike may be northwest or northeast.

Bellingham Granite

There are a number of small quarries south of Odessa and north of Bellingham (Fig. 33). Although the granite resembles the Odessa type, mafic inclusions appear to be more numerous, and the rock is commonly porphyritic. The color ranges from red to dark-reddish brown. The average of two modal analyses of the granite from a quarry in the SW 1/4 Sec. 15:120–45 is given in Table 24, and a chemical analysis of the granite from a small quarry 1/2 mile west, in the SE cor. Sec. 16, is given in Table 25.

Milbank Granite

Coarse reddish-brown granite is exposed in a quarry 1 mile south of U.S. Highway 12, approximately 7 miles southwest of Ortonville in Grant County, South Dakota. There are a large number of inclusions in the granite, and skialiths indicate reaction with magma. Some of the inclusions in the granite resemble stratified rock and are suggestive of sedimentary rather than igneous parentage. The granite in the Milbank area is similar to that between Ortonville and Odessa.

Age and Origin

The K-A ages determined for samples from the Odessa-Ortonville region (Table 28) show a wide range, from 1.7 to 2.2 b.y. Biotite from the quartz-pyroxene granulite of the basic complex gives the oldest age of 2.2 b.y., and it seems quite likely that this is a minimum value and that the rock probably originated through high-grade metamorphism of a sedimentary sequence during folding in the Algoman or an earlier orogeny. The granite from the quarry 1 mile south of Odessa was dated at 1.8 b.y.; however, the Milbank granite is dated at 2.0 b.y. Biotite concentrates from the granites of the Bellingham type (samples KA-55, 56, and 108) give an age of 1.67 b.y.

The Odessa-Ortonville region is a disturbed area, with a number of periods of metamorphisms and granite intrusions, making the K-A ages difficult to interpret. The Bellingham granite may be of the same age as the late granite of Section 28, north of Granite Falls.

SIOUX FORMATION

Description

The Sioux formation (White, 1870) underlies a large area in Minnesota, South Dakota, and Iowa. Outcrops are found in an east-west belt 200 miles long, extending from New Ulm, Minnesota, to Mitchell, South Dakota, and about 50 miles wide, from Flandreau and Canton, South Dakota (Fig. 34). The formation is composed chiefly of red, fine-grained, hard quartzite, which is a prominent ridge maker, and the natural exposures are usually cuestas. Gray to light-pink quartzite is quarried at Jasper in Rock County.

The Sioux formation also contains poorly cemented sandstone, conglomerate, and beds of silty and very fine-grained shale with little or no quartz. An argillite layer, 15–18 inches thick (Fig. 35), in the quartzite just north of Pipestone, was used by the Indians in the manufacture of pipes, and this is the origin of the name Pipestone both for the rock and for the county and city. George Catlin visited and collected pipestone from the Indian quarry in 1836, and the pipestone is also called catlinite (Jackson, 1839).

There are a number of easily accessible outcrops of the Sioux formation in the vicinity of New Ulm in Nicollet County. The conglomerate at the base of the Sioux formation forms a ridge approximately 1000 feet long southeast of New Ulm, in Sec. 27:110–30. The beds strike N. 20° E. and dip 15–20° SE. Pebbles and cobbles are largely quartz, jasper, and chert.

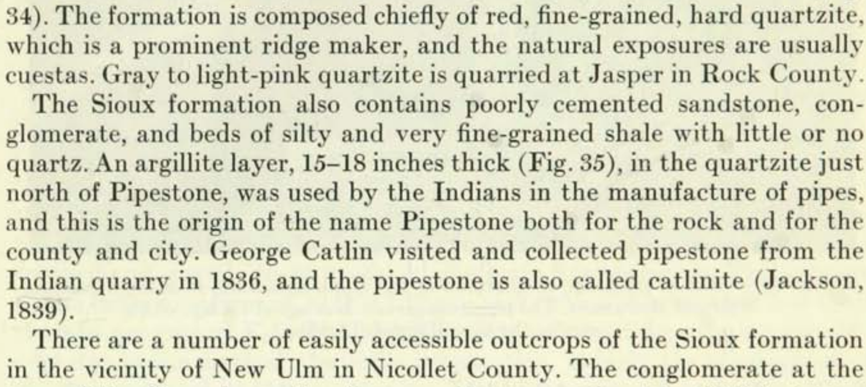

FIGURE 34. — Map showing location of dated sample (KA-50) of pipestone from the Sioux formation and of Cambrian glauconite samples. KA-113 and KA-114 are from the Franconia formation; KA-192 is from the Jordan formation. The ages in Wisconsin are for glauconite from the Franconia formation; at Sparta, K-A age by Wasserburg *et al.* (1956), at Readstown, Rb-Sr age by Herzog *et al.* (1958).

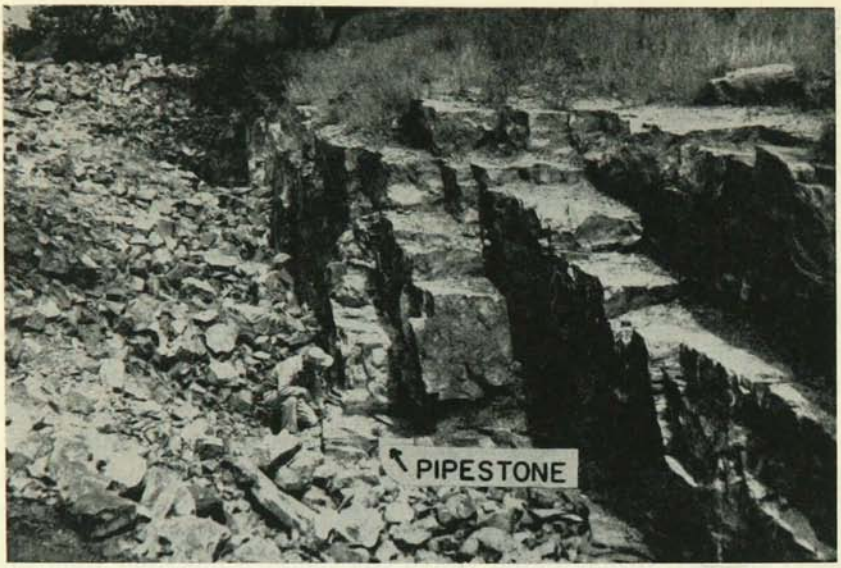

FIGURE 35. — Bed of pipestone in quartzite of the Sioux formation, Pipestone Quarries National Monument. The pipestone gives a K-A age of 1.2 b.y. which may be the time of regional folding.

Two hundred yards west of the ridge are some small outcrops of weathered, coarse, porphyritic granite. Southeast of this locality, in the vicinity of Courtland, the quartzite is quarried for crushed rock.

Baldwin (1949) estimated the thickness of the Sioux formation in exposures along Split Rock Creek near Garretson, South Dakota, to be approximately 3000 feet. This is the order of magnitude of an earlier estimate for this section by Irving (1885, p. 201). Todd (1895, p. 35) thought that Irving's estimate was in excess and suggested a maximum thickness of 1500 feet for the Sioux formation. The maximum known thickness in Minnesota is approximately 500 feet (Thiel, 1944).

The Sioux formation is folded, but the regional structure is poorly known. In the New Ulm-Courtland area, the strike of the beds ranges from N. 70° E. to N. 70° W., and the dip is also variable and may be as high as 30°. Similar variable dips are found in western Minnesota and in South Dakota.

Pipestone or Catlinite

The most detailed description of pipestone or catlinite is given by Berg (1938), who studied the Sioux quartzite outcrop north of Pipestone in the area that is now a National Monument. Here the beds dip east at approximately 15°. The pipestone is a blood-red argillite, in part replaced by a white to yellowish-white mineral which Berg identified as pyrophyllite.

The pyrophyllite has replaced the top and bottom of the catlinite bed to a depth of approximately one inch, and also occurs along the partings parallel to the bedding. The principal mineral is sericite, and in addition to the pyrophyllite, Berg identified diaspore, hematite, specularite, and pyrite. He concluded that the pipestone represents a fine-grained argillaceous layer, "converted into secondary mica (sericite) during consolidation and metamorphism." The sericite was partly altered to pyrophyllite which in turn was altered to diaspore. A thin, 6–10 inch, layer of fine-grained, red argillite occurs in the quartzite in Sec. 35:110–30, southeast of New Ulm. The layer resembles the pipestone in the quartzite north of Pipestone but is composed of sericite and very fine-grained quartz.

Age and Correlation

The pipestone from the Sioux formation (KA-50) has been dated by the K-A method at 1.2 b.y. (Goldich, Baadsgaard, Edwards, and Weaver, 1959, p. 660). This sample came from Berg's collection, and material from the same specimen was used in the chemical analysis made by R. B. Ellestad (Berg, 1958, p. 261). Weaver determined that 60 per cent of the sample is composed of 2M-illite. The sample used in the age determination was crushed and sieved (40–60 mesh) to eliminate fine materials. The average of two determinations of K_2O is 5.17 per cent, which is somewhat less than the 5.62 per cent of K_2O found by Ellestad, and the difference is undoubtedly due to the method of sample preparation, namely the elimination of the fine material in the samples used for the argon determination. Two extractions of argon were made, and the average gives an age of 1.2 b.y. (Table 28). This is considered to be a minimum age for the Sioux formation and very likely dates the time of folding.

Grout and co-authors (1951, p. 1051) report that some of the pebbles in the conglomerate beds of the Sioux formation resemble the granule-textured iron formation of the Biwabik, and they placed the Sioux formation "tentatively between the Animikie and the Keweenawan." The porphyritic granite beneath the conglomerate southeast of New Ulm is badly weathered, and material for dating could not be obtained; however, the granite at Fort Ridgley (Fig. 26), 15 miles northwest of New Ulm, is dated at 2.5 b.y. At Corson, South Dakota (Fig. 34), 30 miles south-southwest of Pipestone, the Sioux quartzite is intruded by diabase (Todd, 1895, p. 36; Beyer, 1897, p. 82). Sardeson (1908) reported dikes which cut the Sioux formation in the New Ulm area. These dikes may be of Middle Keweenawan age. The Sioux formation merits further study because it seems likely that the formation is of early Keweenawan age and was folded at approximately 1.2 b.y. This date roughly marks the beginning of the Keweenawan igneous activity in the North Shore region.

6. DEVELOPMENT OF A PRECAMBRIAN CLASSIFICATION

INTRODUCTORY STATEMENT

The development of the geologic time scale, familiar to every student of geology, has been a long and difficult task. The success that has followed with the use of fossils for relative age determinations and for correlation probably is the outstanding achievement of geological science. The Precambrian rocks, however, are essentially devoid of a useful fossil record, and in the absence of reliable methods of correlation, a world-wide classification has not been achieved. The development of a classification for the Precambrian rocks of Minnesota roughly parallels that of most regions. Various rock units have been named and renamed; original usages have been modified or completely changed; and efforts to correlate with other regions have won only modest acceptance.

A review of Precambrian literature is a major task quite outside the scope of the present report, but there are a number of reviews that are readily available to the interested reader. The older writings pertaining to the Canadian Shield were reviewed by Adams (1915) and Coleman (1915). Bulletin 769 of the United States Geological Survey (Wilmarth, 1925) compares the geologic classification of the Geological Survey with others in use at the time. The original definitions of the terms era, period, and epoch were compiled, and this material is helpful in understanding the evolution of the Precambrian terminology. A detailed review of geologic work in Canada from 1897 to 1912 is given by Young (1932, 1933). Professional Paper 184 (Leith, Lund, and Leith, 1935) summarizes the work of the United States Geological Survey and includes a geologic map of the Lake Superior region in the United States. Wilson (1939) has given an excellent summary of the geology of the Canadian Shield and has discussed some of the problems of correlation and nomenclature. Two recent volumes on the Precambrian geology of Canada, each including a number of papers, are *The Grenville Problem* (Thomson *et al.*, 1956) and *The Proterozoic in Canada* (Gill *et al.*, 1957).

Early efforts in the development of a classification of Precambrian rocks attempted to follow the principles developed for the younger rocks. By analogy with Cenozoic, Mesozoic, and Paleozoic, the terms Proterozoic and Archeozoic were introduced. The distinctions between rock units, time-rock units, and time units usually were followed. The lack of fossils, however, made the Precambrian rocks uninteresting to the stratigraphers, and the study of the older rocks was more or less relegated to the economic geologists and petrologists.

It must be conceded that there is much disagreement concerning the usefulness of the terminology that has been evolved, and in view of the complicated structural and metamorphic history of the Precambrian rocks, it is not remarkable that differences of opinion should have arisen about their ages and relationships. It should also be admitted that stratigraphic rules of nomenclature designed for the younger rocks are at times difficult to apply to Precambrian rocks and have not always been followed. Time terms and rock terms have been used interchangeably. For example, although the Animikie group of Ontario and Minnesota is a well-defined lithic unit, it has been convenient to speak of the time of deposition or of the seas in which the strata were deposited as Animikie or Animikian. These usages can be found in the literature, and generally no misunderstanding results, but the world-wide correlation of iron formations on the basis of lithologic similarities or on succession of similar beds is a much more dangerous undertaking. Correlations indicate time equivalence, and in the absence of fossils, correlation of Precambrian rocks has been difficult to achieve.

TIME SCALE

Radioactivity dating affords the best if not the only possibility for correlating Precambrian rocks. The early chemical methods of uranium-lead dating could not take into consideration the nonradiogenic lead in the analyzed minerals; nevertheless, these early efforts were far superior to the attempts to measure geologic time on principles such as the rate of accumulation of sediments, the rate of accumulation of salt in the oceans, and similar methods.

Principles

The establishment of a time scale and the establishment of a classification for the Precambrian rocks are not one and the same problem, but they are closely related. It is possible today to set up a time scale with an arbitrary interval, for example of 500 million years, to give convenient simple numbers at time boundaries of 1.0, 1.5, 2.0 b.y., and so forth. The intervals starting with the youngest could be called Precambrian 1, 2, 3, 4, etc. or by some other equally simple system. Geologically, such a time scale probably would have little to recommend it. Radioactivity dating as a useful geologic tool requires no defense and little elaboration, but it is recognized that if geologic mapping is reduced to collecting and dating samples, little progress can be envisioned for the near future.

Geologic time should be independent of special events, but like ordinary time or human chronology, there are some special considerations. A time scale as well as a classification of Precambrian rocks must be coordinated with geologic features that are recognizable to the field geologists.

Orogenies. Periods of mountain building accompanied by metamorphism and igneous activity can be dated and basically become of great importance to Precambrian chronology. Lawson (1913a) used Laurentian and

Algoman as time terms for two periods of granitic intrusive activity and inserted them in his stratigraphic column (Table 11). An objection to this practice was earlier raised by Lane (1905), whose position was well taken. The Laurentian and Algoman are periods of orogeny accompanied by metamorphism and igneous activity, and in the present report, the periods of orogeny are shown independently of the time scale (Table 2).

The granite of Laurentian age is defined as being post-Keewatin and pre-Seine (Knife Lake). Similarly, the Algoman granite is defined as being post-Seine and pre-Animikie; thus time connotations are given to lithic units. It is recognized, however, that during the intrusion of the Laurentian granite, rocks which are lithologically indistinguishable from typical Keewatin rocks may have been deposited. In relationship to such possible rocks, the Laurentian granite is not post-Keewatin.

Marsden (1955, p. 113) clearly anticipated the Penokean orogeny of this report in writing "a post-Huronian orogenic belt extending eastward from the Cuyuna Range may be responsible for the deformation and metamorphism of the Thomson Slates southwest of Duluth, Minnesota." He classified granites, which are assigned to the Penokean, as being of "post-Huronian and pre-Keweenawan age." It is evident that he meant these granites are intruded into rocks which locally are classified as Huronian and are overlain by rocks which are locally assigned to the Keweenawan. Calling these granites Penokean eases some problems of nomenclature.

Unconformities. Orogeny leads to erosion and to the development of unconformities which geologically are of great value. The Animikie group is defined and identified on lithologic characters, but everywhere in Minnesota and in Ontario the Animikie strata rest with angular unconformity on rocks of Early Precambrian age. Lawson was impressed with the importance of unconformities and with the time involved in their formation. He gave formal names, Epilaurentian Interval and Eparchean Interval, to two periods of time during which unconformities were formed.

The Eparchean Interval during which the Algoman Mountains were more or less eroded was calculated by Lawson to have a duration of over 200 million years, and a peneplain was thought to have been formed over most of the Canadian Shield. It is obvious that the materials eroded must have been deposited in adjacent areas, but there remains the problem of recognizing this material in the Middle Precambrian sedimentary record.

It is not here intended to make a case for world-wide orogenies or world-wide peneplains, and it is clearly recognized that neither periods of mountain building nor of peneplanation can be considered to be planes in time; however, because orogenies and unconformities can be recognized and the former dated, they are of primary importance in any scheme of Precambrian classification.

Correlation. Erosion and deposition are complementary, and the records of these processes cannot be found in a single restricted region. The larger record must be pieced together from work in many regions. In the discussion that follows, correlations of the events of Precambrian time in Minnesota and adjacent areas in the Lake Superior region with dated events in other parts of North America and on other continents are suggested. No attempt has been made to include all the data available in the literature. It is hoped, however, that a sufficient number have been selected to give the reader some idea of the progress that is being made. The potassium-argon and rubidium-strontium ages published by other investigators have been adjusted for decay constants so that they are comparable to the results of the present study. It is emphasized that the uncertainties in decay constants, in analytical procedures, and in geologic interpretations cannot be ignored and that the indicated correlations are tentative.

Nomenclature

The United States Geological Survey recognizes only local or provincial time divisions within the Precambrian. The Geological Survey of Canada recognizes two subdivisions, the Archean and the Proterozoic. The Minnesota Geological Survey found that a three-fold division is useful, and this classification has been revised in the present investigation. The eras are referred to as Early, Middle, and Late Precambrian, with time boundaries of 2.5 and 1.7 b.y. It will be seen in the discussion that follows that the Algoman and Penokean orogenies can be correlated, at least approximately, with similar orogenies in many parts of the world. Many of these orogenies or cycles of sedimentation and metamorphism have been given local names, and this seems to be a useful practice. With the refinement of the dating technique, correlation of these periods will be practicable.

That further work will show the desirability and the necessity for revision of the present classification is beyond question, and in view of this condition no new terms have been introduced in this report, although some of the old names have been used in a restricted sense.

Early Precambrian

It may be that a specific name such as Archean is desirable. For example, it is somewhat awkward, if not confusing, to speak of early Early Precambrian, whereas early Archean is simple and intelligible. In part this difficulty is avoided by the use of period names.

Ontarian. A committee of the Royal Society of Canada (Alcock, 1934) suggested Laurentian and Timiskamian as time divisions of the Archean (Table 29). Laurentian, however, is used to designate a period of orogeny and is unsuitable for a system. The Geological Survey of Canada (Harrison, 1957, Table 6, p. 27) has used Keewatin and Timiskaming as period names; however, Keewatin is used to define a specific lithic unit, and therefore Ontarian is retained in this report for informal use in the sense of Lawson's (1913a, b) precedent. The Coutchiching and Keewatin groups are included in the Ontarian.

Table 29. Classification of the Precambrian Recommended by the Canadian National Committee on Stratigraphical Nomenclature (Alcock, 1934, p. 118)

Precambrian	Proterozoic	Keweenawan	Upper Keweenawan
			Lower Keweenawan
		Huronian	Upper Huronian
			Lower Huronian
	Archean	Timiskamian	Upper Timiskamian
			Lower Timiskamian
		Laurentian	Upper Laurentian
			Lower Laurentian

Laurentian Orogeny. The time boundary between the Ontarian and the Timiskamian remains to be delimited, but it is marked geologically by the Laurentian orogeny. In the earlier classification of the Minnesota Geological Survey the Laurentian, following Lawson's concept, was considered a major orogeny, and the Earlier and Medial rocks were separated on this basis (Table 1). The present study, however, indicates that the Laurentian and Algoman orogenic movements were not separated by a billion or more years and favors the interpretation of the Laurentian folding as an early phase of the greater Algoman orogeny. Cooke (1926, p. 32) anticipated this possibility, and concluded that "The pre-Timiskaming folding, important as it was, was only a minor movement compared to the great folding that succeeded the Timiskaming deposition and closed the Archean era."

Timiskamian. A sedimentary cycle of the Timiskamian period is represented by the Knife Lake group of Minnesota which is correlated with the Seine group of Ontario. In the vicinity of Steeprock Lake, Ontario, a sequence of conglomerate, graywacke, argillite, carbonate rocks, iron formation, tuffs, and flows is referred to the Steeprock group. The age of these rocks is controversial. The group lies unconformably on a granitic complex that is assigned to the Laurentian and was intruded by granite classed as Algoman. A sample (KA-298) of the younger granite has been dated at 2.56 b.y. (Table 14), giving a minimum age for the Steeprock metasediments. Whether the group should be correlated with the Seine or with older rocks is uncertain.

Algoman Orogeny. The lack of positive geologic control and the uncertainties of the dating techniques, in regard to analytical errors and decay constants, make it impossible to place close limits on the time of the Algoman orogeny. The present age data suggest an interval of 200 million years between the development of the orogenic gneisses and accompanying synkinematic intrusive rocks and the postorogenic or postkinematic granite plutons.

Correlation. The Algoman Mountains extended eastward into Quebec where the orogenic belt is truncated by the younger Grenville orogenic belt (Fig. 1). Aldrich and Wetherill (1960) reported K-A ages of 2.54 b.y. for a pegmatite near Hearst, Ontario; 2.39 b.y. for granite near Timmins; and 2.52 b.y. for granite near Kirkland Lake. Their Rb-Sr ages for these samples are 2.44, 2.36, and 2.32 b.y., respectively. The general region of the Canadian Shield that was affected by the Algoman orogeny commonly is referred to as the Keewatin or Superior province.

Early Precambrian rocks, 2.5 b.y. or older, have been reported from many other parts of the world, as for example, from the Bighorn Basin of Wyoming and Montana (Gast *et al.*, 1958), from Australia (Jeffery, 1956), from Minas Gerais, Brazil (Hurley, personal communication, 1959), and from Africa. Holmes and Cahen (1957) have summarized the African data available in July 1956. They proposed seven Precambrian cycles of which the Shamvaian, dated at 2.65 b.y. (U-Pb), may be correlative with the general period of Laurentian-Algoman orogeny in the Canadian Shield. Two older unnamed cycles also are suggested, 2.8–3.1 b.y. and 3.2–3.4 b.y.

Extensive geochronologic studies are now in progress in the U.S.S.R. Potassium-argon dating of the rocks of the Baltic Shield indicate events older than 3.0 b.y., and Gerling and Polkanov (1958) have suggested a cycle of sedimentation and metamorphism from approximately 2.8 to 3.4 b.y. which they call the Katarchean cycle.

Middle Precambrian

The Middle Precambrian era as used here corresponds to the early part of the Proterozoic of the Canadian Geological Survey. Sedimentary rocks of this age are of limited known occurrence in Minnesota, and subdivision of the 800 million years of Middle Precambrian time is not possible. The Animikie group, formerly assigned to the Later Precambrian, and the Thomson formation are now placed in the Middle Precambrian (Table 2). A possible correlation of the Thomson with the Virginia formation is indicated.

The iron formations and related rocks of northern Michigan that were called Huronian are now referred to the Animikie series by the United States Geological Survey (James, 1958) and are assigned to the Middle Precambrian; however, the Federal Survey uses the terms Lower, Middle, and Upper Precambrian as informal divisions of rock units. As James points out, it is inevitable that these terms will be interpreted as time units, and he uses them informally in this sense. In the table of lithologic sequence of the Precambrian rocks, for example, James (1958, Table 1, p. 30) notes that the granitic rocks which were intruded into the Animikie series have a probable age of at least 1.4 b.y.

Huronian. It appears probable that the rocks of the type Huronian will prove to be in large part of Middle Precambrian age. Studies of the rocks of the Sudbury region, now being conducted by the geochronology groups of the Carnegie Institution of Washington and of the Massachusetts Institute of Technology, show that the region is a disturbed one, and there are some marked differences in the Rb-Sr and K-A ages for the same samples (Fig. 9). Feldspar from the Copper Cliff rhyolite has been dated (Rb-Sr) at 2.2 b.y., and biotite from the same rock has been dated (K-A) at 2.1 b.y. (Aldrich and Wetherill, 1958).

The term Huronian was not used by the Minnesota Geological Survey because of the uncertainty of the correlation with the type locality and because the former assignment of the Knife Lake group to the Lower Huronian and of the Animikie group to Upper Huronian resulted in the separation of the Huronian rocks by the great unconformity at the base of the Animikie group. The "disappearance of the Huronian" from the geologic terminology might well be postponed until definitive geologic and age studies are available.

Penokean Orogeny. The Penokean orogeny resulted in the deformation of a belt of Huronian rocks extending from Minnesota through Wisconsin into Michigan. The resulting mountains were south of the main belt of the earlier Algoman Mountains, but their general trend was the same. The eastern end of the Penokean orogenic belt, like that of the Algoman belt, is truncated by the Grenville orogenic belt. It is possible, however, that the original Penokean folds, or related belts of folding, extended through the Mistassini district and the Labrador trough (Fig. 1), but the severe metamorphism during the Grenville orogeny at approximately 1.0 b.y. has greatly complicated the geologic record.

In central Minnesota, igneous rocks of different ages are distinguished. Tonalites and related rocks were emplaced during an early phase of the Penokean orogeny. The average K-A age for four of these is 1.76 b.y. The St. Cloud Red and the Rockville granites give K-A ages of 1.64 b.y. The indicated time difference between the early tonalites and the younger granites is 120 million years, but results of the Rb-Sr dating, although fewer samples are represented, indicate a time difference of 60 m.y. Neither of the two values may be the absolute time difference, but they set a minimum limit of the order of 60 m.y. Three samples of the McGrath gneiss give closely agreeing K-A ages, averaging 1.68 b.y., but a fourth sample gives a lower K-A age of 1.50 b.y.

In Wisconsin, a biotite-kyanite schist (KA-45) is dated at 1.72 b.y. and corresponds to the synkinematic McGrath gneiss in the evolution of the Penokean orogeny. Granite near Butternut, Wisconsin, is dated at 1.66 b.y., and a granite dike cutting the folded iron formation in Michigan is dated at 1.62 b.y. These are the postorogenic or postkinematic granitic intrusions.

Because of the cover of glacial drift, the relationships between the rocks of central Minnesota and those of the Minnesota Valley are unknown. The average K-A age for seven samples of the Montevideo granite gneiss in the Granite Falls-Montevideo region is 1.79 b.y. The K-A ages for the gneiss range from 1.71 to 1.85 b.y. (Table 28). The Rb-Sr ages for two of the samples are lower than the corresponding K-A ages, 1.74 and 1.69 compared to 1.85 and 1.75 b.y. The postkinematic granite (KA-28, 29) in the Granite Falls area is dated at 1.69 (K-A) and 1.65 b.y. (Rb-Sr). The time difference between the synkinematic Montevideo granite gneiss and the postkinematic granite, indicated by the K-A ages, is of the order of 100 m.y., and by the Rb-Sr ages, of the order of 70 m.y.

The data for the Montevideo gneiss suggest that the variations in the K-A ages for the gneiss may be greater than the analytical error and may reflect local recrystallization of the biotite, perhaps at the time of intrusion of the postkinematic granite. It follows also that the ages obtained for the tonalite and related rocks of central Minnesota and for the McGrath gneiss may be minimum values and not the absolute ages. The Rockville porphyritic granite, for example, is unusual in the development of large crystals of microcline and in the replacement of plagioclase by K-feldspar, and the rock may represent an older tonalite that was altered by potash metasomatism at a later date.

Correlation. Radioactivity ages in the range from 1.6 to 1.9 b.y. have been reported from a large number of localities, and some of these date the time of folding of sedimentary sequences accompanied by metamorphism and granitic intrusion so that a correlation with the Penokean orogeny of the Lake Superior region is indicated.

Eckelmann and Kulp (1957, p. 1130) concluded that the pegmatites in the southern part of the Black Hills, South Dakota, were intruded at 1.62 b.y. on the basis of an analysis of a uraninite from the Bob Ingersoll mine. A similar value was previously reported by Wetherill, Tilton, Davis, and Aldrich (1956). Potassium-argon and rubidium-strontium ages (Aldrich, Wetherill, Davis, and Tilton, 1958, p. 1128) for micas from the Bob Ingersoll pegmatite are variable, and the determined ages for lepidolite are lower than the corresponding ages for muscovite. The pegmatites may be considered a late kinematic phase of the orogenic cycle following the deposition of a thick sequence of sediments that is well exposed in the northern part of the Black Hills.

Collins, Farquhar, and Russell (1954) have summarized the older data from the isotopic lead analyses of samples from uranium deposits in the Churchill geologic province (Fig. 1) in the northern parts of Alberta, Saskatchewan, and Manitoba and the southern part of the Northwest Territories. They date this province at 1.65 to 1.85 b.y. Burwash (1958, 1959) is currently studying the age of the Precambrian basement complex in southern Alberta and southern Saskatchewan and in northern Montana. He finds from K-A dating of biotites that the gneissic complex probably was formed 1.7 to 1.9 billion years ago.

Some interesting K-A and Rb-Sr ages were recently presented by Wasserburg, Wetherill, and Wright (1959) for minerals from schist and gneiss and from a pegmatite cutting these rocks in Death Valley, California. The determined ages for minerals from the pegmatite are greater than those of the country rock, and this suggests metamorphism to which the schist and gneiss were more susceptible than the pegmatite. The K-A and Rb-Sr ages for the muscovite from the pegmatite range from 1.56 to 1.73 b.y., whereas the ages for the biotite and muscovite from the schist and gneiss range from 0.99 to 1.5 b.y. The ages for the pegmatite suggest an event that possibly may have been contemporaneous with the Penokean igneous activity in the Lake Superior region.

Kouvo (1958, p. 58) has noted the similarity in age of the Svecofennidic and Karelidic orogenic belts of Finland to the post-Huronian or Penokean belt of the Lake Superior region. The Karelidic schist rests on a basement of gneissic granite, and zircon from the Sotkuma granite gneiss of this complex was dated by Kouvo at 2.5 b.y. (Pb 207/206). Biotite from the same rock gave a Rb-Sr age of 1.7 b.y. which is the approximate time of the post-Karelidic orogeny indicated in ages found by Kouvo for zircons separated from intrusive granitic rocks in the Karelidic and the Svecofennidic metasediments.

The average Pb 207/206 age determined for zircons of two granodiorites and a quartz diorite from the Svecofennidic range is 1.83 b.y. Two oligoclase granites and a microcline granite from the Karelidic range are dated at 1.80 b.y. The average for six samples of postkinematic granites is 1.65 b.y. The radioactivity ages for the intrusive rocks in the Svecofennidic and Karelidic orogenic belts determined by Kouvo may be compared with the ages from east-central Minnesota and the Minnesota Valley in Figure 36. Tie-lines connect samples dated by different methods. The Rb-Sr and K-A ages for micas found by Kouvo are lower than the corresponding Pb 207/206 ages for the zircons. Kouvo computed the instrumental error of his determinations to be approximately 3 per cent, but he notes that this figure does not include errors arising from incorrect decay constants or from geologic factors.

Gerling and Polkanov (1958, p. 717) date the Karelian cycle of sedimentation and metamorphism in the eastern part of the Baltic Shield, in Karelia and the Kola peninsula, from 1.5 to 1.9 b.y. Synorogenic intrusive rocks are dated from 1.76 to 1.86 b.y., and the postorogenic granites from 1.55 to 1.66 b.y.

Greenhalgh and Jeffery (1959) have summarized the ages of uranium minerals and of galenas for Australia. Analyses of davidite from Crockers Well and from Radium Hill, in the western part of the Willyama granitic complex in South Australia, give ages of 1.5 to 1.7 b.y. Investigations of the geochronology of the Northern Territory are now in progress at the Massachusetts Institute of Technology (Hurley, personal communication, 1959), and preliminary K-A ages for samples from the Katherine-Darwin

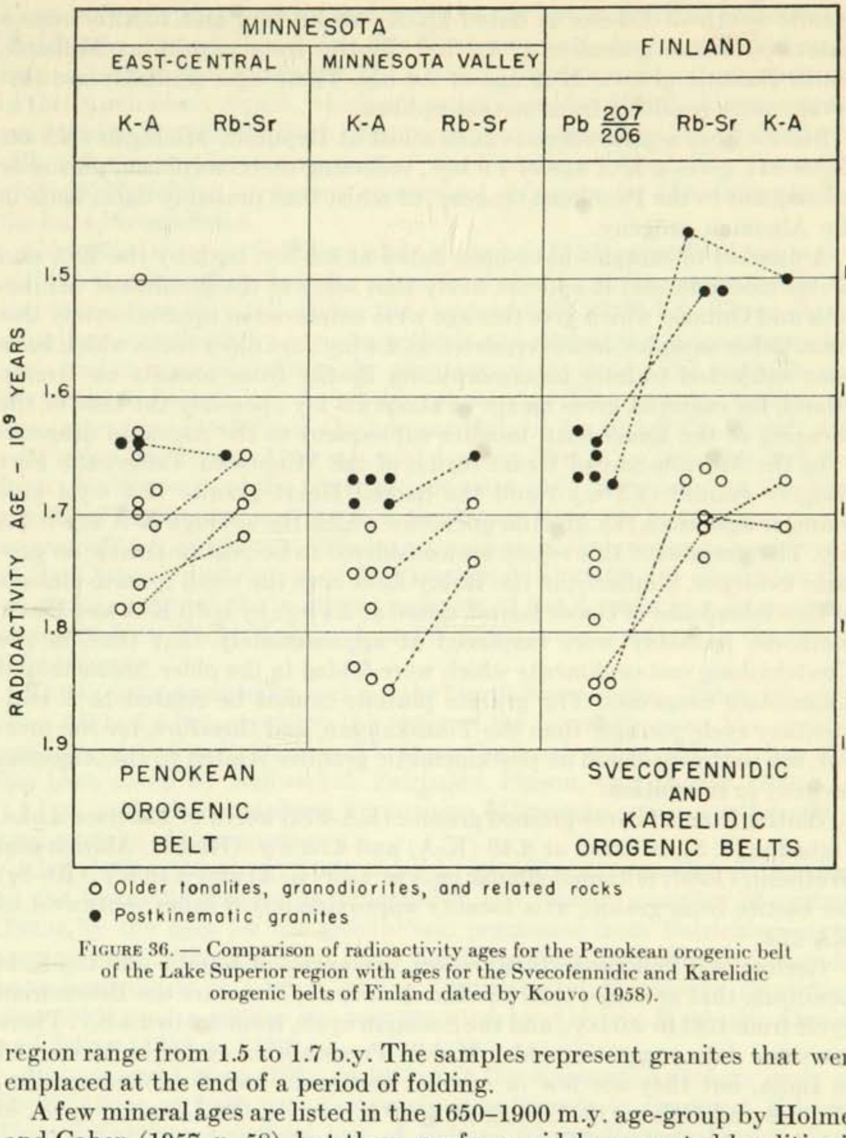

FIGURE 36. — Comparison of radioactivity ages for the Penokean orogenic belt of the Lake Superior region with ages for the Svecofennidic and Karelidic orogenic belts of Finland dated by Kouvo (1958).

region range from 1.5 to 1.7 b.y. The samples represent granites that were emplaced at the end of a period of folding.

A few mineral ages are listed in the 1650–1900 m.y. age-group by Holmes and Cahen (1957, p. 58), but these are from widely separated localities in Africa. It appears possible that orogenic belts of this general age occur in India (Aswathanarayana, 1956), but the available data are limited.

Older Cycles of the Middle Precambrian. A number of ages in the range, 1.9 to 2.5 b.y., have been determined for samples from Minnesota and adjacent areas, and the interpretation of these results generally is difficult. In the Odessa-Ortonville region of the Minnesota Valley biotite from granite south of Odessa is dated (K-A) at 1.8 b.y. and biotite from a quartz-pyroxene granulite at 2.2 b.y. Biotite from granite at Milbank, South Dakota, gives a K-A age of 2.0 b.y. These ages probably are survival values resulting from metamorphism.

Biotite from a garnetiferous mica schist at Republic, Michigan (KA-66, Table 21), gives a K-A age of 1.9 b.y., reflecting metamorphism, during or subsequent to the Penokean orogeny, of schist that probably dates back to the Algoman orogeny.

A number of samples have been dated at 2.4 b.y. both by the K-A and Rb-Sr methods, and it appears likely that some of the granites of Minnesota and Ontario which give this age were emplaced at approximately this time. Other samples, however, dated at 2.4 b.y., are older rocks which have been subjected to later metamorphism. Biotite from tonalite on Grassy Island, for example, gives an age of about 2.3 b.y., possibly the time of the shearing of the Laurentian tonalite subsequent to the Algoman orogeny.

In the Morton-Sacred Heart region of the Minnesota Valley, the Fort Ridgely granite (2.3 b.y.) and the Sacred Heart granite (2.4 b.y.) give younger ages than the Morton gneiss for which the average K-A age is 2.5 b.y. The granites of this region are considered to be postkinematic on geologic evidence. Similarly, in the Rainy Lake area the small granite plutons of Ben Island and of Goose Island, dated at 2.4 b.y. by both K-A and Rb-Sr methods, probably were emplaced at approximately that time in the Coutchiching metasediments which were folded in the older Algoman and Laurentian orogenies. The granite plutons cannot be related to a sedimentary cycle younger than the Timiskamian, and therefore, for the present, are best considered as postkinematic granites related to the Algoman orogeny or revolution.

Biotite from a coarse-grained granite (KA-272) north of Emerson Lake, Ontario (Pl. 3), is dated at 2.36 (K-A) and 2.38 b.y. (Rb-Sr). Aldrich and Wetherill (1960) obtained similar ages of 2.49 (K-A) and 2.40 b.y. (Rb-Sr) for biotite from granite at a locality approximately 8 miles southwest of KA-272.

Gerling and Polkanov (1958) report two cycles in Karelia and the Kola peninsula that are older than the Karelian cycle. These are the Belomorian cycle from 1.83 to 2.0 b.y., and the Saamian cycle, from 2.2 to 2.4 b.y. There are some data suggesting older Middle Precambrian cycles in Africa and in India, but they are few in number and some are of dubious quality. Holmes and Cahen (1957) suggest a 2.0 b.y. cycle, the Limpopo cycle, in Southern Rhodesia and Transvaal.

Late Precambrian

Late Precambrian time embraces approximately one billion years, and there is great promise that this interval may be subdivided in the near future; however, no formal divisions are proposed here.

Keweenawan. The term Keweenawan has been variously used for the

Keweenawan system, series, and group. As in the case of the Huronian, a decision to discard or redefine the Keweenawan is best postponed until more information is available. The Duluth complex and related intrusives of the North Shore region, which are assigned to the Middle Keweenawan, are dated at approximately 1.1 b.y., corresponding to the time of the Grenville orogeny in the eastern part of the Canadian Shield. The Grenville orogeny, therefore, becomes a convenient reference for the discussion of the Late Precambrian.

Grenville Orogeny. Shillibeer and Cumming (1956) assembled the radioactivity-age determinations for minerals of the Grenville province (Fig. 1) and found that they fall within the range of 0.8 to 1.35 b.y. These determinations were made by various methods and represent a large geographic area, and as a result, neither the accuracy of the analytical methods nor the geologic factors can be readily appraised. The samples include 20 uraninites from localities in Quebec and Ontario for which the Pb 207/206 ages range from 825 to 1100 m.y. and average 1000 m.y. Ten mica samples from granitic rocks of the Grenville province have been dated at the University of Minnesota, and the K-A ages range from 890 to 1000 m.y., with an average age of 950 m.y. The investigations of the geochronology group of the Carnegie Institution of Washington (see pp. 33–34) show that the crystalline rocks of the basement complex of the Appalachian Mountains region in New York, Maryland, and Virginia were involved in the Grenville orogeny.

The ages determined for rocks of the North Shore region (Table 14) vary from 0.9 to 1.2 b.y. or within the range of the Grenville ages. The syenite complex at Coldwell, Ontario (Pl. 3) on the north shore of Lake Superior has been dated by Bullwinkel, Fairbairn, Pinson, and Hurley (1958) at 1.1 b.y., and other complexes in northern Minnesota and in southern Ontario may be of the same age.

Correlation. Orogeny accompanied by granite emplacement at the time of the Grenville orogeny is indicated in the granitic complex of central Texas by the ages for the granite and pegmatite from Petrick's quarry (see page 26). Granitic rocks from the Pikes Peak batholith in Colorado have been dated at 1.1 b.y. at the University of Minnesota (Hutchinson, 1959), and a similar age was reported by Aldrich, Wetherill, Davis, and Tilton (1958, p. 1130).

Holmes and Cahen (1957, p. 101) date the Karagwe-Ankolean cycle of South Africa at 1040 m.y. Geosynclinal sediments in the great Kibara-Urundi-Karagwe-Ankolean belt of Belgian Congo-Ruanda-Urundi-Tanganyika Territory and Uganda, were folded and metamorphosed at this time. This cycle was formerly called the Gordonia (Holmes and Cahen, 1955, p. 34). The Pb 207/206 age of 995 m.y., obtained for a uraninite from the Gaya district in India (Holmes, Leland, and Nier, 1950), suggests that the Satpura orogenic belt may be contemporaneous with the Grenville orogeny.

A sample of cleveite from a pegmatite in the Arendal region of southern Norway was analyzed by Nier (1939) and the Pb 207/206 age is 1.09 b.y. A sample of biotite from arendalite, Langsev near Arendal, supplied by Olaf Holtedahl, was dated by the K-A method at the University of Minnesota at 1.03 b.y.

A period of orogeny and high-grade metamorphism that may be contemporaneous with the Grenville orogeny is indicated in East Antarctica. Three samples from the Windmill Islands off the Budd Coast in the vicinity of Wilkes Station (Lat. 66°15′ S., Long. 110°31′ E.) were dated at the University of Minnesota (Cameron, Goldich, and Hoffman, 1960), and the results are given in the tabulation below:

AGES OF SAMPLES FROM THE WINDMILL ISLANDS, BUDD COAST, ANTARCTICA

	K-A (b.y.)	Rb-Sr (b.y.)
Garnet-biotite gneiss, Haupt Nunatak, 20 miles south of Wilkes Station	0.95	
Migmatite gneiss, unnamed island, 5 miles north of Wilkes Station	1.12	1.12
Quartz diorite, Ardery Island, 10 miles south of Wilkes Station	1.07	

Forty samples from the coastal region of East Antarctica from the Budd Coast to Wilhelm II Coast have been dated by Starik, Ravich, Krylov, and Silin (1959), who made potassium and argon determinations on samples of the whole rock. The determined ages fall into a number of groups, and 16 samples, ranging from 720 to 1300 m.y., may be assigned to the Precambrian. Two of the samples, described as leucocratic granite and charnockite from the Grierson Oasis (Starik *et al.*, 1959), are from the Windmill Island, and the determined ages for these are 1050 and 800 m.y. The results are difficult to interpret geologically in view of the superimposed periods of metamorphism, and it is also difficult to compare the ages obtained for the whole rock with those for micas determined at Minnesota.

1.2–1.6 b.y. Ages. A number of samples were dated in the range from 1.2 to 1.6 b.y. in the present investigation. The Minnesota samples include, in addition to those from the North Shore region (Table 14), KA-63 of the McGrath gneiss (Table 21) and KA-50 of the Sioux pipestone (Table 28). Two samples from Wisconsin also give K-A ages in this range; the rapakivi-type granite (KA-12) near Waupaca, 1.4 b.y., and the augen gneiss (KA-330) near Neillsville, 1.5 b.y. (see Pl. 4).

A sample of the Fern Creek slate from the Sturgeon Falls dam area in Dickinson County, Michigan, is dated at 1.35 b.y. (Table 21, F). The Fern Creek is the basal formation of the Chocolay, the lowermost group of the Animikie series in the United States Geological Survey classification (James, 1958, p. 30). The K-A age, therefore, represents a period of metamorphism in this area at a much later time than the deposition of the Fern Creek formation. Aldrich (1958) dates this period of metamorphism at approximately 1.3 b.y. (Rb-Sr).

Aldrich and Wetherill (1958, p. 292) reported K-A and Rb-Sr age determinations on micas from pegmatites and granites from Arizona, New Mexico, Colorado, and Wyoming. The K-A ages for 12 samples range from 1.12 to 1.38 b.y., averaging 1.29 b.y. The Rb-Sr ages show a more restricted range, from 1.22 to 1.41 b.y., but they also average 1.29 b.y. K-A ages recently reported for four samples of the Precambrian rocks of Missouri range from 1.15 to 1.35 b.y. (Allen, Hurley, Fairbairn, and Pinson, 1959).

The numerous age determinations in the range from 1.2 to 1.4 b.y. are in themselves significant, but to date there has been no clear demonstration that the dated granitic rocks are related to metamorphism following a cycle of sedimentation. The importance of this question is evident, and geologic information is highly desirable because the metamorphism in Michigan is superimposed on older rocks. The Sioux formation in Minnesota, South Dakota, and Iowa represents sediments deposited in Late Precambrian time on a basement of crystalline rocks which date back to the Penokean and the Algoman orogenies. The Sioux formation is a platform-type of sedimentary sequence; it has been folded and mildly metamorphosed. The 1.2 b.y. age obtained for the pipestone suggests folding at approximately that time.

Younger Cycles. Precambrian rocks younger than the Middle Keweenawan igneous rocks of the North Shore region were not dated in the present investigation in Minnesota and adjacent areas, but have been reported from other regions by other laboratories, as for example, from Antarctica (Starik *et al.*, 1959). Holmes and Cahen (1957) have tabulated numerous U-Pb ages which give an average of 620 m.y., dating the youngest Precambrian orogenic cycle of equatorial Africa, the Katanga cycle. According to Holmes and Cahen (1955, p. 34) the Katanga group, in a geosynclinal belt in southern Katanga, Belgian Congo, and in Northern Rhodesia, was folded and intensely metamorphosed at this time.

Killarney Revolution. The concept of a major orogeny, the Killarney revolution, during or following the Keweenawan has had a complicated history which need not be reviewed at this time. So-called Killarney granites in central Minnesota and in Wisconsin are Penokean, whereas the granitic intrusives of the Duluth complex are of Grenville age. James (1955, p. 1459) showed that the granite called Killarney in northern Michigan was "emplaced during or immediately after the post-Huronian-pre-Keweenawan orogeny." This period of metamorphism in northern Michigan is dated at 1.3–1.4 b.y. In the Sudbury area mica and feldspar from pegmatites in the Cutler batholith give Rb-Sr ages of 1.7 b.y., whereas the granite of the batholith gives an age of approximately 1.3 b.y., and the Wavy Lake granite of the area gives an age of 1.0 b.y. (Aldrich and Wetherill, 1958, p. 271–272).

It is seen that the so-called Killarney granites are of widely separated ages, and none is late or post-Keweenawan, hence the concept of the Killarney revolution as a major period of orogeny accompanied by granite intrusion at the close of Precambrian time should be discarded.

Cambrian-Precambrian Time Boundary. Holmes (1947) estimated the time boundary between the Cambrian and Precambrian at 510 m.y. As a control point for the age of the Upper Cambrian, Holmes (1947, p. 130) used Nier's isotopic data for the Swedish kolm from Güllhögen, Westergotland, which is well defined stratigraphically. The U-Pb ages, however, are discordant, and Holmes used the Pb^{207}/U^{235} age of 440 m.y. The Pb^{207}/Pb^{206} age is much greater, 800 m.y. More recent analyses of the Swedish kolm (Cobb and Kulp, 1957, p. 1711) are similarly discordant. Four determinations give a range in age of 410 to 460 m.y. for the Pb^{206}/U^{238}; 440 to 485 m.y. for Pb^{207}/U^{235}; and 645 to 720 m.y. for Pb^{207}/Pb^{206}.

A large number of radioactivity-age determinations have been made by different investigators in a number of laboratories in an attempt to date points in the fossil time scale. The results indicate that revision of the time scale can be expected. The problems include not only the precise stratigraphic assignment of the dated samples but also analytical problems, possible loss or gain of the parent and daughter nuclides, and geologic problems relating to diagenetic and metamorphic history of the samples.

Considerable work has been done with glauconite, and a large number of samples ranging from Cambrian to Miocene have been dated by Amirkhanov, Magataev, and Brandt (1957), and Lipson (1958). Three samples of glauconite from Cambrian formations in Minnesota were dated by the K-A method in the present investigation (Table 30). Two samples from the Reno member of the Upper Cambrian Franconia formation were prepared by W. E. Crain. A third sample from the Jordan sandstone was prepared by D. W. Kohls. According to Kohls the glauconite probably represents reworked material in a silty dolomite near the top of the Jordan sandstone in outcrops along the St. Croix River

TABLE 30. K-A AGES FOR GLAUCONITE FROM THE FRANCONIA AND JORDAN FORMATIONS

Sample No.	Description	K_2O pct.	K^{40} ppm.	A^{40} ppm.	A^{40}/K^{40}	Age m.y.
KA-113	Reno member, Franconia formation	7.87	7.89	0.236	0.0299	450
KA-114	Reno member, Franconia formation	7.99	8.01	0.227	0.0284	430
KA-192	Jordan formation	7.73	7.75	0.225	0.0290	435

in Washington County. Stratigraphically, this sample comes from near the Cambrian-Ordovician contact.

The K-A ages (Table 30) agree within the analytical error of the method, and the average age is 440 m.y. Wasserburg, Hayden, and Jensen (1956) dated glauconite from the Franconia at Sparta, Wisconsin (Fig. 34), and found a similar K-A age of 435 m.y. Herzog, Pinson, and Cormier (1958) obtained an age of 410 m.y. by the Rb-Sr method for a sample of glauconite from the Franconia formation at Readstown, Wisconsin (Fig. 34). The determined ages for the glauconite samples from Minnesota and Wisconsin agree with the age assignment of the Holmes time scale, but the K-A age of 440 m.y. can be considered only as a minimum age (Goldich, Baadsgaard, Edwards, and Weaver, 1959). There appears to be a difference between the structure and chemical composition of early Paleozoic and Cretaceous or younger glauconites, but factors other than time may be involved. Investigations under way at the Massachusetts Institute of Technology and at other laboratories may resolve some of the problems.

A revision of the fossil time scale is suggested by Kulp (1959), who tentatively assigns an age of 540 m.y. to the Lower and Middle Cambrian boundary. Mayne, Lambert, and York (1959), however, favor an age of approximately 650 m.y. for the Upper Cambrian.

In addition to the problems of evaluating the radioactivity ages found for the various minerals, the stratigraphic problem of defining the base of the Cambrian is an exceedingly difficult one. The investigations in Minnesota add nothing to the solution of these problems.

In Tables 2 and 31 the time boundary between the Precambrian and the Cambrian is shown as 600 (?) m.y., but this is an arbitrary assignment to which no special significance should be attached.* As the studies in various laboratories provide new data, it can be expected that attention will be given to this problem.

CONCLUDING REMARKS

A world-wide classification of Precambrian rocks and an absolute time scale are worthy objectives, and work along these lines should be vigorously pursued. The difficulties of describing rocks, of showing their relationships on maps, and of properly interpreting their origin without reference to time have long been apparent to geologists. Experience has shown beyond doubt the futility of distinguishing rock types, such as Laurentian, Archean, or Algonkian, on the basis of their appearance, composition, or degree of metamorphism; hence the methods of radioactivity dating are welcomed by geologists.

Experience, however, has a second lesson to teach that commonly is

* Since this manuscript was completed, Holmes has published "A revised geological time-scale," Trans. Edin. Geol. Soc., 17:183–216, 1960, in which he places the Precambrian-Cambrian time boundary at 600 million years ago.

overlooked. In an earlier day the introduction of the petrographic microscope revolutionized the study of rocks, and similarly, the mineralographic, the X-ray, and other techniques have had great impact in the various fields of geology. The limitations of these new techniques gradually were determined, and the same must be done for the radioactivity-dating methods. Like the other techniques, the dating methods are powerful and much needed tools, but they cannot stand alone. The so-called classical geological investigations, all too frequently dismissed as being outmoded, are needed as much today as ever before.

Classifications, whether they be of minerals, rocks, or stratigraphic units, are in themselves not the ultimate ends of geological investigations, and radioactivity dating has more to contribute to geology than an absolute time scale. Read (1955, p. 409), for example, in writing of the origin of granites or of the *Granite Series* in relationship to mobile belts, states: "Possibly the most creative development in petrogenesis is that based on the realization that a given rock is not formed by chance at an accidental time or random place, but that it records precise stages in crustal evolution at definite times at circumscribed places. Petrogenesis has its role in Historical Geology as much as Stratigraphy." Basically the statement by Read underlines Historical Geology as an important objective, and exception is not taken to this view, but history which is not well documented in time has a predictable tendency toward becoming garbled.

Much work remains to be done in the study of the so-called batholiths of Minnesota and Ontario. These are granitic complexes whose origins are related to sedimentary, metamorphic, and magmatic processes spanning a great interval of time. Detailed studies, using a combination of methods, may resolve the time of the Laurentian orogeny which was not accomplished in the present work. Study of the huge Vermilion complex has scarcely been started, and the same is true of the complex of metamorphic and igneous rocks in east-central Minnesota assigned to the Penokean orogeny. In both of these areas and also in the scattered outcrops of the Minnesota River Valley, it is possible to reconstruct series of events which bear a marked resemblance to the sequences found by many writers in other parts of the world in attempting to relate sedimentary, metamorphic, and magmatic processes to orogeny and mountain building. Particularly useful are the papers by Knopf (1948), Wahl (1949), and Read (1955), whose analyses of the problems reflect their different approaches and their differing emphasis on sedimentary, metamorphic, and igneous processes.

The classification of synkinematic, late kinematic, and postkinematic to show the relative position of igneous rocks in the development of an orogenic cycle was suggested by Eskola (1932). Wahl (1936), Simonen (1948), and more recently Marmo (1955a, b) attempted to relate chemical differences in granitic rocks to their positions in the orogenic cycle. The synkinematic intrusions, which Wahl termed synorogenic, are calcic and mostly granodiorites, whereas the late and postkinematic intrusions are more typically granites characterized by abundant K-feldspar. The concept of the *Oberbau* or *Suprastruktur*, as opposed to the *Unterbau* was introduced by Wegmann (1935). In the present report, suprastructure and infrastructure have been used, although *Oberbau* has been translated as superstructure. The concept is a useful one.

A more detailed program of radioactivity dating in Minnesota and adjacent areas might well have as an objective the study of these petrological concepts, but detailed mapping and careful chemical analyses, including the determination not only of the major but also of the trace elements, are badly needed. The combination of methods will afford a more realistic basis for defining an orogenic cycle than is presently available. It is possible that rocks now assigned to an orogenic cycle may be further delimited and assigned to different cycles.

Further advances in radioactivity-dating methods through improvement of the analytical techniques and refinement of the decay constants may be anticipated. The effects of metamorphism on minerals require additional study. The K-feldspars from Precambrian rocks show an argon deficiency relative to the associated micas and must be considered to be unreliable for age determination, but A^{40}/K^{40} determinations on feldspar may be useful in indicating metamorphism as was found for the Babbitt and Snowbank Lake areas. Studies are also needed of the retention of argon and of the possible gain or loss of potassium, rubidium, and strontium in minerals and in the whole rock. The K-A ages found for the whole-rock samples of slate and phyllite agree, within the analytical error of the technique, with the ages for micas separated from the higher-grade metamorphic facies of the Thomson formation. The A^{40}/K^{40} determinations on the whole-rock samples of the granophyres from the Duluth area give ages conforming with geological interpretations, but without additional data from Rb-Sr and U-Pb determinations, the K-A ages of the granophyres cannot be properly evaluated.

Compilation of radioactivity ages from different parts of the world shows a marked frequency of dates at 2.6–2.5 b.y., 1.8–1.6 b.y., and 1.1–0.9 b.y. It is unlikely that this pattern is wholly the result of chance. Subsidence during sedimentation and the mountain building that follows, as interrelated in the geosynclinal theory, cannot be explained by processes or forces acting entirely within the crust of the earth. Appeal must be made to deep-seated, subcrustal forces, such as convection currents, and with such hypotheses the possibility of major orogenies being essentially contemporaneous in different parts of the world must be considered.

In the present report the geologic names that have been used previously for the Precambrian rocks in the Lake Superior region have been retained, and a plea is made that the names neither be discarded nor formally redefined until more definitive data are available. Dissatisfaction with our knowledge and present efforts to solve the problems of the Precambrian rocks commonly takes the form of renunciation of the older work. Few indeed are the geologic terms, including the time-honored names Archean, Laurentian, Huronian, and Keweenawan, that have escaped severe criticism generally, with the recommendation that the name should be relegated to the scrap pile of obsolete and worthless nomenclature. The names in themselves may not be of great significance, but there appears to be a danger that in our haste to free ourselves from an imagined bondage of an obsolete terminology we also throw out the geologic method and replace it with an elusory *passe partout*.

The classification of the Precambrian rocks of the Lake Superior region has gradually evolved through the efforts of many geologists working with the rocks. It is hoped that radioactivity dating in the region will eventually lead to a better understanding of the temporal relationships of the Precambrian rocks and also of their overall history. The present classification, summarized in Table 31, is based on the recognition of four periods of marked structural disturbance. From oldest to youngest in Minnesota and adjacent areas, these are (1) Laurentian, (2) Algoman, (3) Penokean, and (4) a phase of the Lake Superior structural disturbance which is essentially contemporaneous with the Grenville orogeny of the eastern part of the continent. A possible five-fold division of the Precambrian of the Lake Superior region is indicated in Table 31. For the present, however, the three-fold classification requires no new names and does no great violence to the scheme with which geologists are accustomed to work and may well serve as a basis for further growth.

TABLE 31. COMPARISON OF MAJOR DIVISIONS OF PRESENT CLASSIFICATION WITH OLDER AND POSSIBLE FUTURE DIVISIONS OF THE PRECAMBRIAN OF THE LAKE SUPERIOR REGION

Canadian Usage	Grout et al, 1951	This Report				Possible Future Revision
		ERA	SYSTEM	OROGENY	10^9 YEARS AGO	
Paleozoic	Paleozoic	Paleozoic	Cambrian			
					0.6	
Proterozoic	Later Precambrian	Late Precambrian	Keweenawan			I
				Grenville	1.0	
						II
				Penokean	1.7	
		Middle Precambrian	Huronian			III
				Algoman	2.5	
Archean	Medial Precambrian	Early Precambrian	Timiskamian			IV
				Laurentian	?	
	Earlier Precambrian		Ontarian			V
	(For details of rock units and unconformities, see Table 2)					

APPENDIX, REFERENCES, AND INDEX

APPENDIX

LOCATION AND DESCRIPTION OF DATED SAMPLES

The potassium-argon analytical data for 155 samples and the K-A ages for 134 samples are given in Tables 8, 14, 21, 28, and 30. Twenty-one of the samples are feldspars for which the K-A ages are not computed. The analytical data and the Rb-Sr ages for 35 samples are given in Table 7. Of these 31 were analyzed at Minnesota, and 4 in other laboratories. The distribution of the samples is summarized in Table 32. The locations and descriptions of 126 samples, supplementing information given in the text, are given in the sections of the appendix that follow. For location of specific counties see Figure 37.

TABLE 32. NUMBER AND DISTRIBUTION OF DATED SAMPLES

Area	K-A	Rb-Sr
Northern Minnesota (including Ontario and Mellen, Wisconsin)	64	19
East-central Minnesota (including Wisconsin and Michigan)	30	6
Southwestern Minnesota (including Milbank, South Dakota)	32	7
Southeastern Minnesota (Cambrian glauconites)	3	
Miscellaneous	5	3
Total	134	35

NORTHERN MINNESOTA (PL. 1, INCLUDING ONTARIO)

The samples in this section are listed in Table 14 and include 15 from Ontario and 1 from Mellen, Wisconsin.

VERMILION DISTRICT

(A) Soudan-Ely Area

KA-147 Knife Lake slate and graywacke beds at Soudan, Sec. 27:62-15, St. Louis Co. Location E, Stop 8, Fig. 14, p. 99 of Guidebook (Klinger, 1956). Dated sample is dark-gray phyllite. X-ray: quartz, muscovite, chlorite, calcic plagioclase.

KA-97 Sericite enclosing a boudin-like mass of red jasper 4 inches long. Soudan mine, crosscut north of main drift on 27th level. Courtesy of F. L. Klinger, Oliver Iron Mining Division, U.S. Steel Corp. X-ray: quartz, muscovite, chlorite. The jasper contains veins, related to fractures, of very fine-grained pyrite which also occurs in the sericite. According to Klinger (personal communication, March, 1958), the sample comes from an area that is not close to a known orebody.

KA-18 Sericite from the Soudan mine. Massive sericite from north wall of Shaft Vein orebody, approximately 25 feet above 27th level. Courtesy of F. L. Klinger. Sample comes from within 1 foot of the ore contact. Light-yellowish-gray sericite. X-ray film shows only muscovite.

(B) Knife Lake Area

KA-200 Knife Lake slate and graywacke, island near west end of Knife Lake, 2 miles east of the east end of portage from Knife Lake to Seed (Heron) Lake. Dark-gray to black slates interlayered with dark, fine-grained graywacke beds which show good graded bedding. For chemical analyses of slate and graywacke from this locality see Grout (1933, p. 997). Sample collected by Grout (M2409b). X-ray analysis of dated slate: quartz, muscovite, chlorite, calcic plagioclase. CO_2, 0.03 per cent (SSG); C, 0.12 per cent (C. O. Ingamells).

Base from State Highway Department's County Index Map.

FIGURE 37. — Counties of Minnesota.

KA-228 Knife Lake slate, south shore of Knife Lake, approximately 0.6 miles west of portage to Eddy Lake, SW¼ Sec. 20:65-6. From an outcrop mapped as an iron-bearing lens in the Knife Lake (Gruner, 1941, Pl. 1). Dark-gray, slickensided argillite. Thin section shows mostly feldspar, with quartz, hornblende, minor sericite; shards indicate pyroclastic origin, a crystal-vitric tuff.

KA-244 Knife Lake slate, just north of Eddy Lake and above waterfalls, along portage from Eddy to South Arm of Knife Lake, SE¼ Sec. 20:65-6. Dark-gray slate or argillite with poor secondary cleavage. X-ray: quartz, muscovite, chlorite, calcic plagioclase.

KA-243 Knife Lake graywacke-slate, along portage from Jean (Zeta) Lake to Eddy Lake, NE¼NW¼ Sec. 28:65-6. Dark-gray, fine-grained graywacke with subconchoidal fracture. X-ray: quartz, muscovite, chlorite, calcic plagioclase.

KA-242 Knife Lake slate, along portage from Ogishkemuncie Lake to Annie (Dike) Lake.

NW¼SW¼ Sec. 27:65-6. Dark-gray slate. X-ray: quartz, muscovite, chlorite, plagioclase.

KA-240 Knife Lake slate, south side of southernmost point on the east side of Cypress Lake, near middle of south line Sec. 23:66-6 (Fig. 13). Fine-grained, brittle rock, breaks with conchoidal fracture, producing sharp, glass-like edges. X-ray: quartz, chlorite, muscovite, plagioclase.

(C) Snowbank Lake Area (Fig. 14)

KA-106 Syenite, coarse-grained, with gray and pink feldspar, hornblende and biotite. From the southeast shore of Snowbank Lake, SE¼ Sec. 31:64-8, Lake Co. Collected by C. W. Sanders (1929, M2450).

KA-323 Knife Lake conglomerate. SE cor. Sec. 29:64-8, opposite north end of long island in Snowbank Lake. Collected by C. W. Sanders (1929, M2449). Biotite from selvage around 3-inch cobble of dark-gray diorite.

KA-229 Microgranite porphyry with phenocrysts of light-pink feldspar. North side of Snowbank Lake, NW¼ Sec. 26:64-9, Lake Co.

(D) Saganaga Lake Area (Fig. 13)

KA-328 Pegmatite on Gold Island in southwestern part of Saganaga Lake at the head of Red Rock Bay. Red K-feldspar and light greenish-yellow sericite collected from dump, representing material taken from a prospect hole on the northwest side of island.

CANADA

(E) Ontario (Pl. 3)

KA-76 Northern Light gneiss from north side near east end of Moose Island, Northern Light Lake (see Fig. 13). Light-gray, fine- to medium-grained biotite gneiss interlayered with dark-colored schist. Paragneiss: quartz, 30; plagioclase (An_{14}), 55; microcline, 10; biotite, 5 per cent.

KA-77 Northern Light gneiss from small island near east shore, southern part of Savage Bay, Northern Light Lake (Fig. 13). Light-gray, fine-grained, banded paragneiss similar to KA-76.

KA-262 Biotite granite gneiss, Highway 17, 7 miles east of English River and just south of Sheba station on Canadian Pacific Railway. Well-developed foliation strikes N. 85° E.; dips 65° S. Light-gray, medium-grained paragneiss with coarse-grained schlieren of biotite; cut by numerous dikes of granite, pegmatite, and aplite. Modal analysis by J. K. Frye: quartz, 25; oligoclase (An_{15}), 70; K-feldspar, 3; biotite, 2 per cent. Collected by D. H. Yardley.

KA-112 Quartz-biotite schist, Briarcliffe Lake iron prospect, diamond drill hole. F 115 at 260-foot depth, just east of Melchett Lake, 37 miles northwest of Nakina, Ontario. Fine-grained schist or graywacke gneiss containing minor intermediate plagioclase and garnet. Iron formation and schist strike N. 70° E.; essentially vertical. Collected by E. R. Mead, courtesy of Anaconda Company (Canada), Ltd.

KA-111 Quartz-plagioclase-muscovite pegmatite, Briarcliffe Lake iron prospect, diamond drill hole. F 113 at 340-foot depth, Nakina, Ontario. Coarse-grained, light-colored pegmatite cutting schist (KA-112). Collected by E. R. Mead, courtesy of Anaconda Company (Canada), Ltd.

KA-258 Granite from west side of small island near east shore of Kashabowie Lake, Ontario. Medium-grained, leucocratic; contains inclusions of schist. Modal analysis by J. K. Frye: quartz, 26; oligoclase (An_{15}), 38; microcline, 31; biotite and others, 5 per cent. (226″) adamellite. Collected by D. H. Yardley.

KA-298 Granite, composite of three samples of Algoman granite north of Eye Lake, west of Steeprock Lake. Coarse-grained, pink. Estimated composition: quartz, 20; oligoclase, 45; microcline, 30; biotite and others, 5 per cent. Courtesy of W. J. Huston, Steep Rock Iron Mines Ltd.

KA-21 Lamprophyre dike, Coldstream Copper Mines, approximately 8 miles southwest of Kashabowie and ¼ mile northeast of Burchell Lake, Thunder Bay District, Ontario. Dikes cut Keewatin complex; composition: biotite, 52; andesine (An_{32}), 26; calcite, 15; quartz, minor chlorite, and pyrite, 7 per cent, determined by H. L. Taylor (unpublished M.S. thesis, Univ. Minn., 1957). Collected by Taylor.

KA-191 Coutchiching paragneiss, from north shore of entrance to upper Rice Bay, Rainy

Lake, Ontario. Outcrop is cut by lamprophyric and aplitic dikes. Mode by Z. E. Peterman: quartz, 38; albite, 39; biotite, 21; muscovite, 1; microcline, 1 per cent.

KA-178 Porphyroblastic biotite-epidote gneiss, east side of largest island in Rocky Islet Bay, Rainy Lake, Ontario. Mapped by Lawson (1913a) as Algoman syenite gneiss. Dark-gray, micaceous paragneiss with abundant large porphyroblastic microcline. Estimated composition: quartz, 20; calcic oligoclase, 30; microcline-perthite, 25; biotite, 15; epidote, 10 per cent. Numerous granitic or aplitic dikes.

KA-320 Aplite dike cutting Coutchiching paragneiss, south side of upper Rice Bay, mapped by Lawson as Laurentian granite. Gray, fine-grained; modal analysis by Z. E. Peterman: quartz, 35; oligoclase (An_{15}), 42; microcline, 12; muscovite, 6; biotite, 3; epidote, 1 per cent. Leucogranodiorite.

KA-222 Granite, Ben Island, south of Rice Bay, Rainy Lake, Ontario, mapped by Lawson as an Algoman intrusive in the Coutchiching. Gray to pink, medium-grained, with local well-developed foliation. Estimated composition: quartz, 22; microcline, 43; albite-oligoclase, 25; biotite, 5; muscovite, 5 per cent.

KA-224 Granite gneiss, small island south of Goose Island, mapped by Lawson as Algoman syenite gneiss. This rock is considered a border phase of the Algoman granite which intrudes the Coutchiching. Dark-gray, medium-grained, with distinct foliation; contains quartz, feldspar, and 20–25 per cent of biotite.

KA-272 Granite gneiss, Highway 17, 1.5 miles north of Emerson Lake, east of Lake of Woods, 5 miles east of junction of highways to Kenora and to Fort Frances. Medium-grained, dark-red, biotitic gneiss; foliation strikes N. 70° E., attitude essentially vertical. Estimated composition: quartz, 20; K-feldspar, 15; oligoclase near albite, 40; biotite, 15; epidote, with minor sericite, chlorite, leucoxene, etc., 10 per cent. Collected by D. H. Yardley.

KA-70 Lamprophyre dike cutting Saganaga granite, black, coarse-grained, biotitic. Sampled at northern end of dike on small island in Ontario, approximately 1 mile north of Minnesota-Ontario boundary (Fig. 13).

VERMILION GRANITE REGION

(F) *Vermilion Granitic Complex*

KA-47 Vermilion granite. Biotite schlieren from granite of border phase of the Vermilion complex, from west end of Levorsen's Island, Burntside Lake, NE¼ Sec. 18:63-12. Collected by D. Alt.

KA-46 Vermilion granite gneiss, blasted outcrop, east side of Echo Trail, just south of junction with road to Everett Lake, NE¼ Sec. 31:64-12, St. Louis Co. Granite gneiss and migmatite. The regional structure trends E-W and was produced by granitization of a sedimentary sequence or by injection of granitic magma, probably a combination of the processes. Plastic deformation has resulted in crenulated folds which resemble ptygmatic folds, except that the axial planes are parallel to east-west foliation. Boudinage is well developed. The tightly folded material and the boudins are composed of quartz and white feldspar with little or no biotite. Biotite commonly is concentrated on the margins. Differential melting may have produced the leucocratic granite in the highly deformed structures. A north-south dike cuts the gneiss with the east-west foliation. The dike is deformed, suggestive of plastic or rheomorphic deformation.

KA-239 Vermilion granite. Black, biotite-rich schlieren in gray granite blasted in highway construction. Echo Trail, 8 miles east of intersection with Crane Lake-Orr road, Sec. 2:65-16, St. Louis Co.

KA-249 Vermilion granite gneiss in highway cut, 6.6 miles north of Cusson, Sec. 22:66-20, St. Louis Co. High-grade metamorphism (garnet-amphibolite facies) of a sedimentary sequence, originally composed of graywacke and shale. Light-gray, coarse-grained granite gneiss composed of quartz, microcline, oligoclase, with biotite-rich layers and schlieren. Crenulated folds and boudinage conspicuously developed (see Fig. 15). Some layers of the gneiss contain abundant garnet. Gneiss is intruded by a younger pink-colored granite.

KA-250 Graywacke gneiss. Blasted outcrop north side of U.S. Highway 53, at intersection with State Highway 73, middle west line of Sec. 19:63-19. Principal rock type is dark-gray, fine- to medium-grained graywacke gneiss, striking N. 85° W. and dipping 70° S. Quartz boudinage developed from original quartz veins. Some granite gneiss at west end of outcrop.

KA-94 Pegmatite, Net Lake. Outcrop in woods, north of road, approximately ¼ mile east of Net Lake, on outskirts of village. SE¼ Sec. 18:65-21, St. Louis Co. Black biotite schist, some very coarse-grained, cut by white sinuous pegmatite dikes, 4–6 inches across. Biotite in variously oriented books with gray interstitial material composed of sericitized plagioclase, epidote, and apatite. Collected by D. Alt.

KA-4 Pegmatite, approximately 4 miles northwest of Kinmount station and just east of Duluth, Winnipeg, and Pacific Railway. Prospect pit, 50 feet east of center line and 250 feet south of north line of SW¼SE¼ Sec. 9:67-21, St. Louis Co. Coarse, black and white biotite-oligoclase (An_{21}) pegmatite. Collected by G. M. Schwartz.

KA-83 Graywacke gneiss, small outcrops exposed by highway construction along U.S. Highway 53, approximately 1.5 miles south of International Falls, Koochiching Co. Light-gray, fine-grained gneiss, with lenses of coarse-grained quartz.

KA-82 Granitic gneiss, outcrop on north side of State Highway 11, ½ mile northwest of Birchdale, Sec. 33:160-27, Koochiching Co.

KA-307 Tonalite, from the south prong of the bay at the northeast end of Grassy Island, mapped by Lawson (1913a) and Grout (1925a) as Laurentian; as Algoman by Cram (1932) and by Grout *et al.* (1951). Grayish-pink, fine- to medium-grained, massive rock. Modal analysis by J. K. Frye: quartz, 23; plagioclase (An_{15}), 58; microcline, 4; biotite, 10; accessory and alteration minerals, 5 per cent.

(G) Northwest Angle (Pl. 3)

KA-17 Rader pegmatite, Sec. 6:167–33, Lake of the Woods Co. (Northwest Angle), Minnesota. Pegmatite was once mined by W. C. Rader for feldspar which occurs in large crystals, 1 foot or more in length. Feldspar is white albite, but there is also pink microcline-perthite. Both feldspars are intergrown with quartz. Muscovite is in large books, but most is not of commercial grade. Beryl is in well-formed crystals, as much as 8 inches across the hexagonal section. Some garnet occurs in small crystals. Muscovite sample was collected by Grout.

KA-88 Pegmatite, exposed in small uranium-prospect pit near the center of Sec. 32:168-34, approximately 4.5 miles west of the Rader pegmatite. Large crystals of microcline-perthite, oligoclase, quartz, and biotite. Country rock is granitic gneiss and schist; high-grade metamorphic rocks show relic folds.

GIANTS RANGE REGION

(H) Giants Range Granitic Complex

KA-236 Grayish-pink porphyritic granite, in field east of County Road 38, two miles north of Grand Rapids, NW cor. Sec. 4:55-25, Itasca Co. Approximate composition: plagioclase (An_{18}), 35; quartz, 30; microcline, 30; biotite and accessories, 5 per cent. Porphyroblasts of microcline include myrmekitic plagioclase, quartz, and biotite. Alteration products: chlorite, sericite, epidote.

KA-237 Dark-gray, coarse-grained gneiss with compositional banding and layers rich in biotite. Small outcrops in woods, approximately 1 mile northeast of Nashwauk, NW¼ Sec. 21:57-22, Itasca Co. Granoblastic, sutured grains, principally oligoclase with minor microcline, hornblende, epidote; granodiorite or tonalite.

KA-48 Granite from quarry north of Mountain Iron, NW¼SE¼ Sec. 28:59-18, St. Louis Co. Medium-grained pink gneissic granite, containing xenoliths and schlieren.

KA-105 Granite gneiss from E½NE¼ Sec. 28:59-17, St. Louis Co., approximately 3 miles northeast of Virginia. Collected by I. S. Allison (M2865).

KA-317 Gneiss, outcrops on west side of U.S. Highway 53, approximately 5 miles north of the city limits of Virginia, Sec. 18:59-17, St. Louis Co. Dark-gray coarse, foliated or rudely banded gneiss, with foliation striking E-W. Cut by younger pink granite; 10 miles north of this locality, roadcuts show fine- to medium-grained gray granite which is intruded by pink granite and tourmaline-bearing, pegmatitic granite.

KA-316 Gneiss, roadcut along U.S. Highway 53, approximately 1 mile north of Idington, in the SW¼ Sec. 21:61-18, St. Louis Co. Approximately at contact of Giants Range granite and older schist and gneiss (Allison, 1925). Medium-grained gneiss composed of plagioclase, quartz, and about 30 per cent of hornblende and biotite. Outcrops appear to be largely graywacke gneiss; leucocratic dikes deformed to boudinage.

KA-81 Granite, second large outcrop along State Highway 1, 2.7 miles south of the intersection of Highways 1 and 169 in Ely, along the west line of Sec. 11:62-12, St. Louis Co. Contaminated phase of the Giants Range granite; black and pink, medium-grained hornblende-biotite tonalite or granodiorite. This locality is 1 mile west of White Iron Lake where there are numerous inclusions of greenstone and other rock types in the granite.

KA-8 Granite, outcrops of the Giants Range granite overlain by the Biwabik formation, Reserve Mining Company property, former town of Babbitt, NW¼, Sec. 17:60-12 and in adjacent sections. Coarse-grained, pink hornblende granite with some biotite.

KA-137 Virginia argillite, cored sample from drill hole No. 8519, 20–25 feet, Virginia, Sec. 5:58-17, St. Louis Co. Fine-grained, black, graphitic argillite. R. W. Marsden, courtesy of Oliver Iron Mining Division, U.S. Steel Corp.

KA-212 Virginia argillite, cored sample from drill hole No. 3961, 162–171 feet, southwest of Grand Rapids, SW¼NE¼ Sec. 4:54-26, Itasca Co. Courtesy of R. W. Marsden. Fine-grained black argillite. CO_2, 1.12 per cent (SSG); C, 7.90 per cent (C. O. Ingamells). For a complete chemical analysis of the graphitic argillite of the Virginia formation from this area see White (1954, p. 17).

NORTH SHORE REGION

(I) Duluth Complex

KA-295 Pyroxenite, from near the base of the gabbro in Duluth, upper tracks of the Canadian National Railroad, SW¼ Sec. 33:49-15, St. Louis Co. Greenish-black, coarse-grained biotite pyroxenite.

KA-92 Diabase, from the Beaver Bay complex, mouth of Beaver River, Sec. 12:55-8, Lake Co. Collected and biotite sample prepared by H. M. Gehman, Jr.

KA-176 Ophitic diorite, diamond drill core from hole drilled in the vicinity of Aurora. Coarse-grained biotite in dark coarse-grained rock composed of andesine, pyroxene, biotite, ore minerals. Courtesy of Donald Wager.

KA-65 Gabbro, Duluth gabbro from D. D. H. No. 235, NE cor. Sec. 20:60-12, Babbitt. Biotite sample prepared by J. R. N. Gundersen, courtesy of Reserve Mining Company.

KA-296 Pegmatite, in Biwabik iron-formation at Babbitt, from main pit in NW¼SW¼ Sec. 16:60-12. Large flakes of green biotite associated with albite and quartz. Sample collected and prepared by J. R. N. Gundersen.

(J) Contact Rocks Related to Duluth Gabbro

KA-232 Thomson formation, north of Grandview golf course, west of Duluth, east side of Midway Road and approximately 1–¼ miles north of U.S. Highway 61, in NW¼SW¼ Sec. 17:49-15. Outcrops contain graywacke and slate; strike N. 85° E.; dip, 80–85° S.; approximately ¾ mile west of the base of the gabbro. Sample KA-232 is fine-grained graywacke-slate. X-ray: quartz, biotite, amphibole, plagioclase. Collected by F. F. Grout.

KA-233 Thomson formation from same locality as KA-232. Dark-gray, well-indurated slate or graywacke-slate. X-ray: quartz, biotite, plagioclase. Collected by F. F. Grout.

KA-131 Rove formation, roadcut along the Gunflint Trail, south of the west end of Gunflint Lake, in NW¼SW¼ Sec. 30:65-3, Cook Co. Dark-gray, hard, recrystallized argillite with a subconchoidal fracture, at contact with diabase sill. X-ray: quartz, biotite, amphibole, plagioclase.

KA-177 Contact rock, diamond drill hole in vicinity of Aurora. Light-gray, fine-grained sugary, with abundant fresh, black biotite flakes. Apparently a granoblastic contact rock probably derived from a sediment. Courtesy of Donald Wager.

KA-8 Granite at Babbitt, see Section H, above.

KA-106 Syenite at Snowbank Lake, see Section C, above.

KA-93 Granite, Mellen, Wisconsin, medium-grained, red granite from SW cor. Sec. 24, T. 45 N., R. 3 W., Ashland Co. Collected by George A. Moerlein, and described as post-gabbro granite. Courtesy of P. A. Bailly, Bear Creek Mining Company.

(K) Duluth Area Granophyres

KA-101 Granite dike in dellenite flow, 8th Street at 3rd Ave., Duluth, Sec. 27:50-14. (Goldich, Taylor, and Lucia, 1956, modal analysis No. 28, Table 5, p. 81.) Chemical analysis No. 4, Table 17.

KA-102 Granophyre intrusive near top of anorthositic gabbro, quarry on Woodland Ave., Duluth, SE¼SW¼ Sec. 2:50-14. (Taylor, 1956, modal analysis No. 1, Table 6, p. 60.)

KA-103 Granophyre intrusive in basalt flows above the gabbro complex, quarry on Kenwood Ave., Duluth, Sec. 15:50-14. (Taylor, 1956, modal analysis No. 2, Table 6, p. 60.)

KA-104 Granophyre intrusive along the contact of the layered series and the anorthositic gabbro. 27th Ave. at 12th St., Duluth.

East-Central Minnesota (Pl. 2, including Wisconsin and Michigan)

The 31 samples in this section are included in Table 21. Twenty-two are from east-central Minnesota; 9 from Wisconsin and Michigan.

(A) Thomson Formation Metasediments

KA-35 Dark-gray to black slate with well-developed secondary cleavage, from quarry, Sec. 5:48-16, just south of reservoir and west of Thomson, Carlton Co.

KA-38 Gray phyllite, Sec. 24:48-18, 0.4 mile west of Atkinson, on north side of road, Carlton Co.

KA-39 Dark-gray, crinkled phyllite. NW cor. Sec. 1:46-19. Cut along Northern Pacific Railway at station in Barnum, Carlton Co.

KA-40 Medium- to coarse-grained schist. Locally the micaceous minerals are wrapped around pod-like masses of milky quartz. NE¼ Sec. 20:46-19. Cuts along Minneapolis St. Paul Sault Ste. Marie Railroad, north of station in Moose Lake, Carlton Co.

KA-96 Gray, quartz-mica phyllite from outcrop on north side of Little Elk River, approximately 2 miles north of Little Falls, SW cor. SE¼ Sec. 31:130-29, Morrison Co.

(B) McGrath Gneiss

KA-41 Coarse-grained gneiss, banded with black micaceous and light-gray quartz-feldspar layers. Prominent porphyroblasts of red K-feldspar. SE¼ Sec. 21:45-21. Cut along Minneapolis St. Paul Sault Ste. Marie Railroad, 2.5 miles west of Denham, Carlton Co.

KA-43 Pink, coarse-grained gneiss, distinctly foliated but not banded. Large pink K-feldspar, locally pegmatitic. SW cor. Sec. 34:45-21, 3 miles southwest of Denham, Carlton Co.

KA-164 Coarse-grained gneiss, banded with biotite-rich and quartz-feldspar layers. SW¼ SW¼ Sec. 1:43-24, approximately 2 miles southwest of McGrath, Aitkin Co.

KA-63 Pink and gray, coarse-grained gneiss with distinct foliation and some banding. Quarry prospect, NW¼ Sec. 6:44-23, 2 miles west of Dads Corner, Aitkin Co.

(C) Metasediments from the Cuyuna District

KA-132 Gray sericitic phyllite or fine-grained schist from north wall, west end of Mahnomen No. 1 pit (Pickands Mather & Co.), NW¼NE¼ Sec. 10:46-29, Ironton. Collected by R. L. Blake (B. M. 35). The phyllite appears to be the footwall to the iron formation in a syncline.

KA-33 Sericitic argillite or slate from northeast wall of access road near east end of Mahnomen No. 2 pit (Pickands Mather & Co.), NW¼NW¼ Sec. 10:46-29. Collected by R. L. Blake (B. M. 114). Strike, E-W, with variable but high dips to the south; schistosity parallel to bedding.

KA-134 Light-gray sericitic argillite or phyllite exposed in floor of Maroco pit (M. A. Hanna Co., Agt.), NE¼NW¼ Sec. 4:46-29, approximately 1 mile north of Ironton. Collected by R. L. Blake (B. M. 91). The argillite is the footwall and is interlayered with reddish quartzite.

KA-215 Sericitic argillite or slate from north wall, west end of the Sagamore pit (M. A. Hanna Co., Agt.), approximately on W1/16 line, N½SW¼ Sec. 19:46-29. Footwall to iron formation. Collected by R. L. Blake (B. M. 356).

(D) Older Tonalites and Related Rocks

KA-10 St. Cloud Gray granite. Dark-gray, medium-grained granodiorite, collected by F. F. Grout. Probably Sec. 28:124-28, south of Waite Park, Stearns Co.

KA-1 Warman granite. Gray, medium-grained biotite quartz monzonite. NW¼ Sec. 8:41-23, southeast of the village of Warman, Kanabec Co.

KA-61 Pierz granite. Gray, medium-grained biotite quartz monzonite of the Warman type. SE¼ Sec. 13:40-31, 2 miles southwest of Pierz, Morrison Co.

KA-64 Hillman tonalite. Dark-gray, medium-grained biotite tonalite. Cut along Minneapolis St. Paul Sault Ste. Marie Railroad, SW¼ Sec. 10:40-30, approximately 2 miles southeast of Pierz, Morrison Co. Collected by A. F. Schneider.

KA-60 Freedhem gneiss. Dark-gray, coarse-grained gneiss. Roadcut along side road east of County Road 4, 0.1 mile north of Freedhem, SW¼ Sec. 1:41-31, Morrison Co.

KA-59 Schist in Freedhem gneiss. Location same as KA-60.

KA-62 Isle granite. Light-gray, coarse-grained biotite quartz monzonite from quarry of Cold Spring Granite Co., SE¼NE¼ Sec. 3:41-25, 5 miles south of Isle, Mille Lacs Co.

(E) Younger Granites

KA-6 Rockville granite. Pink and gray, coarse-grained porphyritic granite from quarry of Cold Spring Granite Co. in Rockville, Stearns Co.

KA-58 St. Cloud Red granite. Medium-grained red granite, Sec. 17:125-28, 1 mile northwest of village of Sartell, Stearns Co.

(F) Samples from Wisconsin and Michigan (Pl. 4)

KA-45 Mica-kyanite schist. Coarse-grained schist from belt of metasediments containing iron formation, Sec. 25, T. 42 N., R. 3 E., Iron Co., Wisconsin. Collected by E. L. Henrickson.

KA-184 Granite. Pink, coarse-grained muscovite granite from diamond drill hole, T. 41 N., R. 1 W., near Butternut, Ashland Co., Wisconsin. Sample from E. L. Henrickson, courtesy of Jones & Laughlin Steel Corp.

KA-12 Rapakivi-type granite from quarry 5.8 miles northeast of Waupaca, Waupaca Co., Wisconsin. Large pink feldspar with interstitial biotite and epidote. In thin section the K-feldspar appears to be porphyroblastic microcline-perthite that is rimmed with reddish dusty silicic plagioclase. Quartz in small individual grains or in aggregates with interlocking boundaries.

KA-330 Augen gneiss along Black River, 1 mile south of Neillsville, Clark Co., Wisconsin. Augen of granular pink feldspar in dark-gray schistose groundmass. Augen are in part aggregates of plagioclase, microcline, quartz, and myrmekitic quartz-plagioclase intergrowth. Estimated composition: silicic plagioclase, 30; quartz, 20; microcline, 15; biotite, 15; epidote, 15; and others, 5 per cent, including abundant sphene, apatite, and sericite.

KA-66 Garnetiferous biotite schist. Coarse-grained with large porphyroblasts of garnet. Footwall to oxidized iron formation, south of Republic pit, just east of Republic, Michigan. Collected by R. L. Blake.

KA-278 Sericite schist. Light-gray, very fine-grained, crinkled schist from Republic mine, Republic, Michigan. Sample supplied by James W. Villar, Marquette Iron Mining Co.

KA-68 Granite, intruded into iron formation. Pink, medium-grained muscovite granite dike, approximately 8 feet wide, in iron formation of the Groveland pit (M. A. Hanna Co., Agt.) on Highway M-69, near Randville, Michigan. Collected by R. L. Blake.

OSA Pegmatite in Sec. 19, T. 42 N., R. 29 W., Dickinson Co., Michigan. Feldspar collected and prepared by J. G. Wasserburg (Wasserburg, Hayden, and Jensen, 1956).

KA-238 Fern Creek slate. Dark-gray slate from Sturgeon Falls dam area, Dickinson Co., Michigan. Collected by J. W. Trow.

Southwestern Minnesota (Fig. 26)

The samples in this section are listed in Table 28 and include the granite from Milbank, South Dakota.

MORTON-SACRED HEART REGION

(A) Morton Quartz Monzonite Gneiss

KA-51 Quarry prospect, 200 feet northeast of farmhouse, NW cor. Sec. 22:111-32 (Fig. 26).

KA-14 Main quarry of the Cold Spring Granite Company at Morton (Fig. 27). Collected by F. F. Grout. Univ. Minn. collection No. GP 603A. KA-14-1 (Table 28) represents first biotite separation; KA-14-2 is a portion of the sample further purified.

KA-15 Quarry at Morton, same as KA-14. From a large inclusion in the gneiss. Lund's sample No. 33. KA-15-1 is first biotite separation, further purified to give KA-15-2 (Table 28).

KA-107 Quarry prospect in NW¼ Sec. 32:114-36, Redwood Co. (Fig. 26).

KA-186 Abandoned quarry, SW¼ Sec. 20:113-35, North Redwood, Redwood Co. (Fig. 26). Fine-grained, black and white granite gneiss, much finer in grain and lacking the contorted structure of typical Morton gneiss.

KA-171 Outcrop of Morton gneiss forming a hill approximately 250 feet west of County Road 7, 1.5 miles south of bridge on Minnesota River. Just south of point sampled, medium-grained granite assigned to the Sacred Heart granite intruded the gneiss. This granite is a marginal phase of the main mass of the Sacred Heart granite to the south (Fig. 29). Middle east section line, Sec. 7:114-37, Redwood Co.

KA-208 Fresh gneiss from a cut blasted in construction of county road, just east of KA-171

(Fig. 29). This cut was sampled to obtain a fresher sample of the Morton gneiss than that available at locality KA-171.

(B) Cedar Mountain Granophyre Gabbro

KA-195 Granophyre gabbro at Cedar Mountain, intrusive into the Morton gneiss. SW¼ Sec. 15:112-34, Redwood Co. (Fig. 30). Collected by C. A. Bury.

(C) Seaforth Gneiss

KA-210 Gray, wavy banded gneiss, resembling Morton gneiss, except for color. Sec. 1:111-38, Redwood Co. (Fig. 26).

(D) Fort Ridgely Granite

KA-52 Quarry prospect, east of small lake, NW¼ Sec. 2:111-33, Nicollet Co. (Fig. 26).

(E) Sacred Heart Granite

KA-9 Abandoned quarry, east of County Road 7, Sec. 17:114-37, Redwood Co. (Fig. 29).
KA-13 Quarry in Sec. 7:114-37 (Fig. 29).
KA-23 Quarry in Sec. 18:114-37 (Fig. 29).
KA-24 Larsen quarry, 8 miles west and 3 miles south of Echo, T. 113 N., R. 39 W., Yellow Medicine Co. (Fig. 26).

GRANITE FALLS-MONTEVIDEO REGION

(F) Montevideo Granite Gneiss

KA-27 Type locality, cut along U.S. Highway 212, 1.6 miles southeast of Montevideo, SE¼ Sec. 20:117-40, Chippewa Co. (Fig. 26). KA-27-1 is first biotite separation that was purified for KA-27-2 (Table 28).
KA-54 Quarry of Great Northern Railroad Co., Granite Falls, NW cor. Sec. 33:116-39, Yellow Medicine Co. (Pl. 5). KA-54-1 is first biotite separation further purified in KA-54-2 (Table 28).
KA-25 Cut along Great Northern Railroad track, northwest of Granite Falls, NW¼ Sec. 28:116-39, Chippewa Co. (Pl. 5).
KA-209 Small outcrop in east bank of Minnesota River, southeast of Granite Falls, SW cor. Sec. 11:115-39 (Pl. 5).

(G) Garnetiferous Quartz Diorite Gneiss

KA-22 Cut along State Highway 67, just southeast of Granite Falls, NW¼ Sec. 3:115-39, Yellow Medicine Co. (Pl. 5).

(H) Granite of Section 28

KA-28 Cut along Chicago Milwaukee St. Paul and Pacific Railroad track, northwest of Granite Falls, NW¼ Sec. 28:116-39, Chippewa Co. (Pl. 5, Fig. 31). Lund's "late granite."
KA-29 Outcrop in pasture, 400 feet east of KA-28 (Pl. 5).

(I) Ortonville Granite (Fig. 33)

KA-55 Quarry of the Bellingham Granite Co., SE cor. Sec. 16:120-45, Lac Qui Parle Co.
KA-56 Biotite-rich inclusion in granite of KA-55.
KA-108 Quarry, SW¼ Sec. 15:120-45.
KA-109 Quarry of the Cold Spring Granite Co., 1 mile south of Odessa, Sec. 32:121-45.
KA-57 Quarry No. 1, Hunter Granite Co., 1 mile south of U.S. Highway 12, between Ortonville and Milbank, Grant Co., South Dakota (Fig. 26).

(J) Quartz-Pyroxene Granulite (Basic Complex)

KA-44 Outcrop in farmyard, NW cor. Sec. 9:120-45, Lac Qui Parle Co. (Fig. 33).

(K) Sioux Formation

KA-50 Pipestone layer in quartzite, Pipestone Quarries National Monument, north of Pipestone (Figs. 34, 35). Univ. Minn. collection No. SQ-3a.

GLAUCONITES FROM SOUTHEASTERN MINNESOTA (FIG. 34 AND TABLE 30)

KA-113 Glauconite collected and prepared by W. E. Crain (unpublished M.S. thesis, Univ. Minn., 1957). From a sandy highly glauconitic layer in the Reno member of the Franconia formation, 6½ feet above the base of a roadcut on County Road 34, approximately 3 miles west of Red Wing, Goodhue Co., NE¼NW¼ Sec. 27:113-15.

KA-114 Glauconite collected and prepared by W. E. Crain. From a sandy glauconitic layer 22 feet above base of exposure at locality of KA-113, above.

KA-192 Glauconite collected and prepared by D. W. Kohls (unpublished M.S. thesis, Univ. Minn., 1958). From fine-grained, sandy, glauconitic dolomite, transitional from the Cambrian Jordan sandstone to the Ordovician Prairie du Chien dolomite. Kohls' locality 27, cliff, 427 yards northwest of the Hastings Lock and Dam on the Mississippi River. SE¼SE¼ Sec. 1:26-21.

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