



GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

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PAPER 64-17 (Part II)

AGE DETERMINATIONS AND GEOLOGICAL STUDIES

PART II. GEOLOGICAL STUDIES

Fourth Report on Structural Provinces, Orogenies, and Time-
Classification of Rocks of the Canadian Precambrian Shield

C. H. Stockwell

Notes on the Orogenic History and Isotope Ages in
Botwood Map-area, Northeastern Newfoundland

H. Williams

(Report and 4 figures)



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ABSTRACTS

Fourth Report on Structural Provinces, Orogenies, and Time -
Classification of Rocks of the Canadian Precambrian Shield —
C. H. Stockwell

The three previous progress reports (Stockwell 1961, 1963a, 1963b) summarized results up to the end of 1962. The present report adds results of work done since that time. A minor change has been made in the boundary of the Slave province, an additional orogeny has been added to the previous three, a new time-stratigraphic nomenclature is suggested in place of the cumbersome terminology of Lower, Middle, and Upper Proterozoic and their subdivisions, a few additional rock units have been placed in the time-stratigraphic classification, and new data pertaining to anomalous ages across the Grenville front are discussed.

Notes on the Orogenic History and Isotopic Ages in Botwood
Map-Area, Northeastern Newfoundland — H. Williams

Geological evidence indicates that Botwood map-area has been affected by at least two major orogenic events in Palaeozoic time, one in the Middle to Upper Ordovician, and another in the post-Middle Silurian. Isotopic ages range from 450 to 335 m.y., i.e. from late Ordovician to early Carboniferous. Isotopic dates of 410 and 423 m.y. set an upper age limit for the Botwood Formation, and a date of 415 m.y. sets an upper age limit for the Springdale Group, so supporting the lithological correlation of these stratigraphic units. Some difficulties remain in relating isotopic ages to geological field relationships.

FOURTH REPORT ON STRUCTURAL PROVINCES, OROGENIES,
AND TIME-CLASSIFICATION OF ROCKS OF THE
CANADIAN PRECAMBRIAN SHIELD

by C. H. Stockwell

The three previous progress reports (Stockwell 1961, 1963a, 1963b) summarized results up to the end of 1962. The present report adds results of work done since that time. A minor change has been made in the boundary of the Slave province, an additional orogeny has been added to the previous three, a new time-stratigraphic nomenclature is suggested in place of the cumbersome terminology of Lower, Middle, and Upper Proterozoic and of their subdivisions, and a few additional rock units have been placed in the time-stratigraphic classification. An interpretation of the stratigraphic and tectonic history of the Grenville province is given and new data pertaining to anomalous ages across the Grenville front are discussed.

STRUCTURAL PROVINCES

The named structural provinces of the Canadian Shield are material units with geographic boundaries and contain rocks of many ages. They are given names for the purpose of reference to particular regions and for comparing or contrasting one region with another. By contrast, orogenies, being periods of mountain building, are non-material units of time.

A minor change has been made in the position of the boundary between the Slave and Churchill provinces. This results from recent reconnaissance mapping (Fraser 1964) which indicates that the boundary, instead of following the east contact of the Bathurst fold belt, extends northeasterly from it (Figure 1). The boundary is gradational and in a general way is marked by an increase in metamorphic grade toward the east and by an accompanying change in regional trend from northwest in the Slave province to northeast and north in the Churchill. The Bathurst fold belt is now classed as a subprovince of the Slave.

The Nain province is divided into two parts, an eastern part and a western part. This division is based on geological considerations together with generally contrasting ages.

For convenience in description and discussion, names have been given to three subprovinces of the western part of the Superior province (Figure 1). These are called the Cross Lake, English River,

and Quetico belts. The subprovinces are set apart mainly by their linear structure which trends easterly, as contrasted with irregular, circular, and curvilinear structures in intervening territory. The English River and Quetico belts consist mainly of paraschist, paragneiss, and migmatite, and granitic bodies which are formed largely by granitization of the pre-existing sediments. The Cross Lake belt consists of both sedimentary and volcanic rocks mainly forming long thin belts in predominantly granitic terrain. The broad, intervening, unnamed belts that are characterized by curvilinear structures consist of sedimentary and volcanic rocks invaded by granitic batholiths. Both the Cross Lake and English River belts show a scattering of potassium-argon ages younger than the prevalent Kenoran dates of the Superior province and, apparently, have been variously modified by the Hudsonian orogeny. Only Kenoran dates have been found in the Quetico belt. The Quetico belt appears to end rather abruptly at the Kapuskasing positive gravity anomaly which trends southwest from James Bay.

OROGENIES

Ages obtained on minerals of orogenic significance are shown in the histogram (Figure 2). Those on other materials such as post-orogenic diabase dykes, post-orogenic alkaline intrusions, and unmetamorphosed volcanic rocks are not shown, as their inclusion would confuse the orogenic picture.

New dates on the histogram are mainly from the Slave, Churchill, and Nain provinces. Those from the Slave show a spread from the Kenoran orogeny to the Hudsonian and this is interpreted as being due to a widespread but variable overprint of the Hudsonian on the Kenoran, a feature that prevails throughout much of the western and northern parts of the province. New dates from the Churchill province are mostly somewhat older than those found previously.

In the eastern part of the Nain province potassium-argon ages vary between 2,665 and 1,235 m.y., those older than 2,000 m.y. predominating. The great range in ages indicates that the region has had a complex history starting in the Archaean.

Ages so far obtained in the western part of the Nain province form a much closer group and indicate the presence of an orogeny with an average age of 1,370 m.y. This has been named the Elsonian orogeny after Elson Lake at 54°50'N, 64°25'W in an area recently mapped by Emslie (1964a). The Elsonian of the province as a whole is characterized by intrusions of anorthosite, troctolite, gabbro, adamellite and granite, and either by the formation of charnockitic and other gneisses or by the reworking of older, possibly

Archaean gneisses. Age determinations, given in Part I of this and previous reports, are assembled below for convenient reference.

GSC No.	Rock name	Material dated	K-Ar age (m. y.)
62-138	migmatite	biotite	1,220
62-179	anorthosite	whole rock	1,260
62-172	adamellite	biotite	1,275
63-176	migmatite	biotite	1,300
63-175	adamellite	hornblende	1,325
63-174	adamellite	biotite	1,340
63-177	gneiss	hornblende	1,350
63-165	granite	biotite	1,360
61-197	granite	biotite	1,395
63-164	anorthosite	biotite	1,400
62-177	gneiss	biotite	1,430
63-148	paragneiss	biotite	1,455
B4016 (Beall et al., 1960)	adamellite	biotite	1,480
60-129	granulite	biotite	1,500
63-163	paraschist	biotite	1,520
Average			1,375

Three dates from the western part of the Nain province are not included in the above list, one on paragneiss at 1,615 m. y. (GSC 62-173), one on garnet gneiss at 1,175 m. y. (GSC 60-143), and a third at 1,140 m. y. (Beall et al., 1960) from pegmatite cutting troctolite. Evidently these represent both older and younger events within the main orogen. The orogenic belt trends northerly, apparently pinches out to the north and broadens to the south where it is in part overlain unconformably by the Seal Group and, farther south, is cut off almost at right angles by the Grenville orogen. As stated in last year's report, one has only to glance at the Geological Map of Canada (GSC map 1045A) to see that the belt of scattered bodies of anorthosite and gabbro extends from the Nain province south and southwest through a large part of the Grenville province to become covered eventually by Palaeozoic rocks of the St. Lawrence lowlands. Although these anorthosites of the Grenville province give Grenville ages, the writer agrees with Emslie (1964b) that their true age of emplacement in all probability is the same as that of the western Nain. Therefore the Elsonian orogenic belt, modified by the Grenville orogeny, probably extends through much of the Grenville province (see Figure 3, to be described later).

Statistical studies of ages are helpful in the definition and correlation of orogenies. It is difficult to determine the true age of an orogeny or of the time from the beginning to the end of its activity.

This is because isotopic dates vary with the analytical error, the material dated, and the method used, and with the varying geological conditions that may alter the normal ratio of decay products. However, a close approximation to a true age is probably obtained in cases where essential agreement is found by two or more methods on the same material or by the same method on different coeval minerals. In any case, although it is highly desirable to know the true age, this is not necessary for purposes of correlation because orogenies may still be correlated approximately with one another by comparing ages determined by the same method on similar materials. The geologist, however, has to use his judgement as to whether geological conditions are similar in both cases. The distinction between true ages and apparent ages points to the necessity of having type regions for the orogenies. The true age never changes and the type region serves as a standard for the unit.

All ages considered in the following statistical study have been determined by the potassium-argon method and virtually all are on micas. The data have been taken from the histogram of Figure 2 with, however, the omission of those dates that for geological reasons are considered to be non-indicative of the orogeny in question; omitted are those regarded as being due to partial reworking of an older orogen by a younger one, survival values of an older in a younger, and anomalous ages found along or near contacts between orogens of different ages. The dates that remain have been analysed statistically by F. P. Agterberg of the Geological Survey of Canada who also offered suggestions in the interpretation of the results. For each of the orogenies, in the several provinces, he has calculated the mean (M), the Gauss curve (normal or probability curve) and the standard deviation (SD). He also applied Pearson's normality test to each of the three orogenies for which the largest number of dates are available and found no significant departure from normality. It will be convenient to have names for the two time horizons marked by the standard deviation. The younger of the two is the mean minus the standard deviation and will be called the MM horizon (mean minus); the older is the mean plus the standard deviation and will be called the MP horizon (mean plus). The results of the statistical study are given in Table I.

When the data are confined to one type of material and one age method, as has been done, the effects of these two variables are eliminated. Still having an effect on the Gauss curve, however, are the analytical error, the time span of the orogeny, and geological conditions that may alter the normal ratio of decay products. But the curve is still useful for comparing the numerical value of one orogeny with another of comparable age for the reason that the analytical error is much the same in both and the geological conditions are probably not very different.

Table I

Statistical Analysis of Potassium-Argon Ages on Orogenic Micas

TYPE OROGENY AND PROVINCE	NUMBER OF DETERMINA- TIONS	MILLIONS OF YEARS				
		RANGE OF DETERMINATIONS	SD	MM	M	MP
Grenville (Grenville province)	66	770 - 1,090	65	880	945	1,010
Elsonian (W. Nain province)	15	1,220? - 1,520?	90?	1,280?	1,370?	1,460?
Hudsonian (Churchill province)	141	1,450 - 2,010	95	1,640	1,735	1,830
Kenoran (Superior province)	131	2,230 - 2,730	100	2,390	2,490	2,590
OTHER OROGENY AND PROVINCE						
Hudsonian (Southern province)	31	1,500 - 1,900	76	1,605	1,681	1,757
Hudsonian (Bear province)	16	1,700? - 1,920?	56?	1,724?	1,780?	1,836?
Kenoran (Slave province)	29	2,300 - 2,640	80	2,393	2,473	2,552
Mazatzal (S. W. U. S. A.)	28	1,120 - 1,540	107	1,227	1,334	1,441

The mean and the standard deviation define the Gauss curve. That is, the MM, M, and MP values define an orogeny in terms of ages measured by a particular method on a particular mineral. Also they may be used as convenient numbers for the purpose of giving an objective standard for an orogeny at its type locality and for correlation of other orogenies with the type. Thus the potassium-argon mica standard for the type Kenoran orogeny of the Superior province is MM2390, M2490, MP2590. The Kenoran of the Slave province, with MM2393, M2473, MP2552, correlates very well with that of the type locality. Similarly, as shown in the table, correlation of the Hudsonian (Penokean) orogeny of the Southern province with the standard Hudsonian of the Churchill province is reasonably good although it may be slightly younger. Dates for the Hudsonian of the Bear province are too few in number to give reliable statistics but the available information suggests a fairly good correlation with the type Hudsonian. Data for the type Elsonian are also unreliable because of lack of a sufficient number of dates for a good statistical study. However, this correlates well with the Mazatzal orogeny (Wilson 1939) in southwestern United States of America, mainly in Colorado and Arizona. The data for this orogeny are given by Aldrich et al. (1958), Griffen and Kulp (1960), and Giletti and Damon (1961). A few younger and older dates are also reported from this region but these probably indicate other events and are not included in the statistical analyses. Structures in the Mazatzal trend mainly northeast to north and the question naturally arises as to whether the Mazatzal and Elsonian orogens (and the reworked extension of the latter through the Grenville province) do not join beneath the intervening cover. Possible extension beneath the cover is suggested by Gastil (1960, Figure 5). The satisfactory number of dates for the type Grenville orogeny give good standards for this event. It may be mentioned that standards also could be set up, and comparisons made, in other ways but this has not been done in the present preliminary account. For example, it would be interesting to make separate calculations for muscovite and biotite; or, if a large province such as the Churchill were studied area by area, some significant age divisions might be made.

Because of the variables involved, it is difficult to define the duration of an orogeny. The interval between the MM and MP horizons contains $2/3$ of the total number of age determinations; only $1/6$ are younger than the MM horizons and only $1/6$ are older than the MP horizon. But the duration of the orogeny is shorter than the span between the zero limits of the base of the Gauss curve. This is because the analytical error, if subtracted from the total curve, would shorten the base and cut off at least some of the dates on the extreme limits of the curve. Accordingly, the analytical error being considerable, it is estimated that the span between the MM and MP horizons gives a better value for the probable duration of the orogeny than the total range of values, which is sometimes used for this

purpose. For example, it is estimated that the span of the type Kenoran is better represented by the range from 2,390 to 2,590 m. y. than by the total measured range of from 2,230 to 2,730 m. y. The problem is seen to have practical importance in the following section where an attempt is made to draw time-stratigraphic boundaries at the ends of orogenies. The MM value is a convenient and objective horizon for this purpose as it meets, reasonably well, the objective of placing a boundary, if not precisely at the end, at least near the end of the main period of orogenic activity.

TIME-STRATIGRAPHIC CLASSIFICATION

Knowledge of time-stratigraphic relationships in the Precambrian of the Canadian Shield has now reached the stage where it seems advisable to introduce some new names in order to facilitate classification and discussion. Only future experience will show whether the classification and terminology proposed for the Canadian Shield are of international or world-wide application but they are presented with the hope that they may promote the study of these large problems.

The names Archaean and Proterozoic are retained for units of eon rank but new names are proposed for Lower, Middle, and Upper Proterozoic and for their subdivisions. This is mainly to avoid lengthy and awkward terminology such as, to take an extreme example, late Early Middle Proterozoic.

Excepting the Archaean, names now in use for eons and eras refer to various stages of life, as Phanerozoic, Palaeozoic, Mesozoic, Cenozoic, and Proterozoic, all of Greek derivation. For subdivision of the Proterozoic, however, it is considered best to abandon this custom because life in the Precambrian has no practical value in time-stratigraphic classification. Instead, it is proposed that names having only age significance be used. Thus, the Proterozoic as a whole, being intermediate between the old Archaean and the young Phanerozoic, may be thought of as mature in age. For the three subdivisions of the Proterozoic, then, three names are needed to suggest old, middle, and young maturity. Fitting this idea reasonably well are the three Greek words: aphebos (past the prime of life) for old maturity; helikia (maturity) for middle maturity; and hadrynes (coming to maturity) for young maturity. It should be noted that the names are given in order from oldest to youngest, as for people, and that this sequence should not be confused with stages of growth and development which is in reverse order. By adding adjectival endings -ian or -an to the roots of these words the proposed new names become: Aphebian, to replace Lower (Early) Proterozoic; Helikian, to replace Middle Proterozoic; and Hadrynian, to replace Upper (Late) Proterozoic (Table II). The Proterozoic is classed as an eon and it is

Table II

Time-Stratigraphic Classification and Nomenclature for the Canadian Shield
Showing Standard MM Horizons for Orogenic Micas
Determined by the Potassium-Argon Method

(Letters in parenthesis are suggested symbols for geological or tectonic maps.)

EON	ERA	SUB-ERA	K-AR AGE (m. y.) and OROGENY
			— 600 —
PROTEROZOIC (P)	HADRYNIAN (HN)		
		NEOHELIKIAN (HK ")	MM 880 GRENVILLE (G)
	HELIKIAN (HK)		MM 1280 ? ELSONIAN (E)
		PALAEOHELIKIAN (HK')	
			MM 1640 HUDSONIAN (H)
	APHEBIAN (ÆB)		
			MM 2390 KENORAN (K)
ARCHAEAN (A)			

proposed that the newly named subdivisions be called eras. Subdivisions of the eras may be formed simply by prefixing the words neo, meso, and palaeo to the era name as may be required. Only the Helikian has so far been formally subdivided: into a younger unit, the Neohelikian, and an older unit, the Palaeohelikian. These are called sub-eras which is a departure from custom followed in the Phanerozoic where units of next lower rank below eras are known as systems (and periods). By way of explanation for this departure it is pointed out that a system is a subdivision of rocks deposited during a specific interval of time (Amer. Comm. Stratigraphic Nomenclature, 1961) but, in the Precambrian, it is not yet possible to measure the time from the beginning to the end of deposition of sedimentary rocks. Sub-eras are of broader scope and may include time occupied by hiatuses and intrusions as well as by deposition of sedimentary and volcanic rocks. Already named Precambrian systems and series have only local significance for they cannot yet be well correlated with one another and are best treated as rock-stratigraphic units. The proposed new names may be used in two senses, either as abstract geological-time units or as concrete time-stratigraphic units.

The large first order units, Archaean and Proterozoic, are useful for comparing or contrasting gross features of the Precambrian and they also permit classification of some rock units which because of lack of data, cannot yet be classified more closely. Similarly, the large second order unit, the Helikian, supplied a name for some units that cannot yet be classed as either Palaeohelikian or Neohelikian. Other rock units may span a boundary between named units, and may be classed, for example, only as Helikian and/or Hadrynian. Similar difficulties are also encountered in classification of rocks of the Phanerozoic. Still other rock units cannot yet be placed into any of the named time-stratigraphic units, mainly because only a minimum age is known. These may be assigned a limiting classification such, for example, as Helikian or older. The Archaean contains at least one unconformity over older granite but has not yet been formally subdivided because of difficulties in obtaining any clearly pre-Kenoran isotopic ages. Consequently, correlation of the units has not been possible and there is no point in making formal local subdivision until such time as correlation, which is the prime object of time-stratigraphic classification, becomes practical. Time-honoured methods of Precambrian correlation by means of lithological similarity, comparison of sequences, and relation to unconformities and intrusions are still useful where isotopic age methods fail.

The upper limit of the Proterozoic is defined by the base of the Cambrian. The lower limit of this unit as well as both the upper and lower limits of the other eons, eras, and sub-eras are defined approximately by the end of an orogeny. Normally this is followed by an erosional interval and then, unconformably, by the next overlying

stratigraphic unit. An advantage in drawing the boundaries at the ends of orogenies is that no hiatuses are left unnamed. The dividing horizon between the time-stratigraphic units is drawn, ideally, at the true age of the end of an orogeny. It is difficult to determine the true age but, for purposes of correlation, as with fossils, this does not greatly matter because orogenies may still be correlated with one another by comparing ages determined by the same method and on similar material.

It is not possible to choose a type locality for the major time-stratigraphic units as is done with fossiliferous rocks. This is because no one section contains a complete stratigraphic record over the long time span of the units but contains hiatuses and intrusive rocks as well. Instead, the type area for one orogeny serves as the type for the beginning of a time-stratigraphic unit and the type area for another orogeny serves as the type for the end of the same time-stratigraphic unit.

For the purpose of setting standards for time-stratigraphic boundaries it is helpful to use the results of the statistical analysis of orogenies as given previously. The MM horizon, which is an apparent age, is useful for this purpose as it occupies about the same relative position to the peak of the orogeny as does the true age of the end of the main orogenic episode. Thus, the potassium-argon, mica, MM horizon for each of the orogenies, at their type localities, may be used as a numerical standard for the time-stratigraphic boundaries (Table II). The MM horizons in areas geographically separated from the type region may then be compared with the standard for correlation purposes. Thus the MM value of 2,390 m.y. for the type Kenoran of the Superior province is the numerical standard for the boundary between the Archaean and the Proterozoic. In the Slave province an MM value of 2,393 m.y. is obtained and, because of the excellent agreement with the standard, the boundary in this area is well correlated with the standard Archaean-Proterozoic boundary. The MM value of 1,640 m.y. for the type Hudsonian of the Churchill province is the standard for the boundary between the Aphebian and Helikian. In the southern province an orogenic MM value of 1,604 m.y. is obtained and, considering the variables involved, correlation with the standard is reasonably good. A somewhat greater divergence from the standard is found in the Bear province where the MM value is 1,724 m.y. but the number of determinations in this area are too few for a good statistical result. The MM value of 1,280? m.y. for the type Elsonian of the western Nain province serves for the standard boundary between the Palaeohelikian and Neohelikian but because of the small number of determinations, the figure for this boundary is tentative. The MM value of 880 m.y. for the type Grenville orogeny of the Grenville province is the standard for the boundary between the Helikian and Hadrynian.

Each of the named eons, eras, and sub-eras may be further subdivided, informally, into early, middle, and late, or merely early and late, as may be required. For example, granitic rocks emplaced during an orogeny are late phases of the major time unit to which they belong: as late Aphebian for the granites of the Hudsonian orogeny. As is customary in the Phanerozoic it is preferable to classify intrusive rocks according to time-stratigraphic nomenclature rather than to tectonic nomenclature. Thus the granite mentioned is better called late Aphebian rather than Hudsonian. This is because orogenies, with good reason, are commonly given local geographic names but the time-stratigraphic nomenclature has no geographic limits.

For the most part, rock-stratigraphic units are placed into one or the other of the time-stratigraphic categories by the indirect method of dating their maximum and minimum limits. The maximum is commonly obtained from an unconformably underlying orogen and the minimum from a younger orogen that affects the rock unit concerned. Unmetamorphosed igneous rocks, either intrusive or extrusive, may be dated directly and so placed in the time scale. Ages on dykes have proven to be particularly useful in giving a minimum for sedimentary rocks not involved in orogeny. However, some caution must be exercised in comparing the face value of ages on non-orogenic material with the standards on orogenic material because the geological conditions are so very different. For example, a gabbro dyke that cuts the type Kenoran is dated at 2,505 m.y. which is much older than the standard MM value of 2,390 m.y. for the Archaean-Aphebian boundary; clearly, the geological relationships take preference and the dyke is classed not as Archaean but as early Aphebian. The direct method of dating unmetamorphosed volcanic rocks by the whole rock potassium-argon method offers encouraging possibilities but so far only a few such determinations have been made and their margin of error may be considerable especially when the potassium content is low.

Surprisingly good progress has been made in placing many of the named rock-stratigraphic units of the Canadian Shield into one or other of the time-stratigraphic categories. As each year's work progresses a few more units have been added and further progress may be expected in the future. Progress up to the present time is given in Table III. It should be especially noted that rock units in any one time-stratigraphic unit of the table are not necessarily contemporaneous nor arranged in order of age. Pertinent data for the time classification of each rock unit is given below. Further description, localities, authors, and references to maps may be found in Part I of this and previous reports and in other publications cited.

Table III

Precambrian Time and Rock Units of the Canadian Shield

EON	ERA	SUB-ERA	TYPE OROGENY MM in m. y.	ROCK-STRATIGRAPHIC UNITS In any one category not necessarily contemporaneous nor in order of age			
PROTEROZOIC			600				
		HADRYNIAN		Double Mer			
				Chatham-Grenville stock			Upper Keweenawan
			880				Lower and Upper Coppermine River
			GRENVILLE	Killarney, Doloro and other granites			
				Seal	Ulukan		Duluth, Muskox, Logan, Lackner, and Coldwell intrusions
				Wakeham	Equalulik		
			1280 ?				
			ELSONIAN	Granite, adamellite and anorthosite Martin Dubawnt Sims Chukotat	Athabasca Et-Then		Lower and Middle Keweenawan Hornby Bay
			1640				
		HUDSONIAN	Kaminis and other granites, Sudbury irruptive. Huronian Animiki Kaniapiskau Povungnituk Belcher Great Slave Snare Echo Bay - Cameron Bay Goulburn	Epworth Nonacho Tazin Hurwitz Chantry Great Island Cross Lake San Antonio Grenville		Nipissing diabase Matachewan diabase	
ARCHAEOAN			2390				
			KENORAN	Algoman, Giants Range, Prosperous, and other granites Knife Lake	Sickle, Kisseynew, Missi	Timiskaming	Ridout Windigokan
			-----?-----	Saganaga Granite	Cliff Lake Granite		Rice Lake Seine
				Keewatin - Couthiching	Wasekwan, Kisseynew, Amisk	Abitibi, Pontiac	Yellowknife

Archaean Eon

Sedimentary and volcanic rock units classed as Archaean have been involved in the Kenoran orogeny and no distinctly older ages have been found. A few rocks are inferred to be Archaean even though affected by a still younger orogeny. Because of difficulties in correlation from one region to another, the Archaean has not been subdivided but the relative geological relations are indicated where known. In the southwestern part of the Superior province the oldest rocks are the Keewatin and Couthiching whose relative ages are uncertain; the Keewatin is intruded by the Saganaga Granite which is overlain unconformably by the Knife Lake. Typical ages determined representing minimum ages for the time of deposition or emplacement, are: Keewatin 2,550 m.y. (GSC 60-93), Couthiching 2,495 m.y. (GSC 61-131), Saganaga 2,475 m.y. (GSC 63-116), and Knife Lake 2,600 m.y. (Sample 200, Goldich, 1961). In the Churchill province of Manitoba the succession is similar at two nearby localities: at Lynn Lake it is Wasekwan, "quartz-eye granite", and Sickle; at Flin Flon it is the lithologically similar Amisk, Cliff Lake Granite, and Missi. Between the two areas is the Kiseynew Gneiss, which is the metamorphic equivalent of the others. A clue to the Archaean age of the whole is given by a muscovite age on metamorphosed Sickle of 2,670 m.y. (GSC 62-99). The others all give Hudsonian dates: Wasekwan 1,610 m.y. (GSC 60-75), Amisk 1,745 m.y. (GSC 60-74), Kiseynew 1,735 m.y. (GSC 60-73), Cliff Lake Granite 1,620 m.y. (GSC 63-106) and Missi 1,620 m.y. (GSC 61-120). In the Kirkland Lake-Noranda area of the Superior province the Abitibi and Pontiac, whose relative ages are unknown, are overlain unconformably by the Timiskaming. Minimum dates obtained for these formations are: Abitibi 2,630 m.y. (GSC 59-70), Pontiac 2,460 m.y. (GSC 59-77), and Timiskaming 2,475 m.y. (GSC 60-104). Stratigraphic relations between the following are unknown: in the Superior province, the Ridout 2,565 m.y. (GSC 61-152), Windigokan 2,555 m.y. (GSC 61-140), Rice Lake 2,670 (GSC 60-89) and Seine 2,285 m.y. (GSC 62-102) and, in the Slave province, the Yellowknife 2,615 m.y. (GSC 61-66). Late Archaean rocks emplaced during the Kenoran orogeny include the Giants Range (Algoman) Granite 2,500 m.y. (sample 236B, Goldich, 1961), the Prosperous Granite 2,540 m.y. (GSC 60-49), and many others.

Aphebian Era

A large number of rock units are assigned to the Aphebian on the basis of the following considerations. The following five lie unconformably on the Archaean basement of the Superior province and are separated from it by a long erosional interval. The basement beneath the Huronian has a mica age of 2,455 m.y. (GSC 60-105) and

ages of 2,550 m.y. and 2,450 m.y. for detrital monazite and zircon in basal Huronian (Mair, 1960); a minimum age of 1,625 m.y. (GSC 59-43) is found on metamorphosed Huronian and another of 2,095 m.y. (GSC 61-157) is obtained on a diabase sill which age, if reliable, places the Huronian in the lower Aphebian. The Animiki is bracketed between a basement age of 2,505 m.y. (GSC 60-99) and a metamorphic age of 1,640 m.y. (sample 39, Goldich, 1961). The Kaniapiskau is bracketed between 2,440 m.y. (GSC 60-126) and 1,800 m.y. (sample 4135, Beall, 1960). The Povungnituk lies on a basement which is almost certainly Archaean although somewhat affected by the Hudsonian orogeny; a date of 1,650 m.y. (sample B4025, Beall, 1960) is obtained on metamorphosed Povungnituk. The Belcher Group forms part of a succession lying unconformably on the Archaean of the Superior province and is cut by a sill of diabase dated at 1,620 m.y. (GSC 63-93).

The Great Slave and Snare Groups lie unconformably on the Archaean of the Slave province. The basement under the Great Slave gives 2,465 m.y. (GSC 61-69); intrusive into the Great Slave is a granite at 1,845 m.y. (GSC 61-78) and a dyke of gabbro at 2,170 m.y. (GSC 62-93), the latter placing the group, at least in part, in the lower Aphebian. The basement beneath the Snare has been variously affected by the Hudsonian but some dates on muscovite retain an Archaean age such as 2,460 m.y. (GSC 60-47); granitic rocks intruding the Snare give 1,850 m.y. (GSC 60-45). The Echo Bay-Cameron Bay appears to be Aphebian also although only a minimum age has been determined, at 1,765 m.y. (GSC 61-58).

The Goulburn and Epworth Groups unconformably overlies Archaean rocks of the Slave province and are cut, respectively, by gabbro dykes dated at 1,215 m.y. (GSC 63-27) and 920 m.y. (GSC 63-49) and are therefore Aphebian or Helikian. More probably they are Aphebian, for the Goulburn is gently folded probably at the same time that its basement was somewhat affected by the Hudsonian and the Epworth becomes metamorphosed westward as a Hudsonian orogen is approached and no unconformity has been recognized there.

The Nonacho Group is found within the Churchill province where Hudsonian ages prevail but a maximum is given at 2,420 m.y. (sample 5, Burwash, 1962a) on a granite boulder in Nonacho conglomerate; regional metamorphism that no doubt affected the group gave 1,800 m.y. (sample 1, Burwash 1962a) and an augen gneiss mapped as intruding the Nonacho gave 1,810 m.y. (GSC 61-81). The Tazin Group may be a metamorphosed equivalent of the Nonacho. The Hurwitz, Chantry, and Great Island Groups are also found in the Churchill province and apparently have been affected by the Hudsonian orogeny and so are Aphebian or Archaean but their lithology and structural setting is similar to that of the Nonacho and they are probably Aphebian.

The Cross Lake Group occurs within a part of the Superior province in which the Kenoran orogen has been variously affected during the Hudsonian. An Archaean age of 2,500 m.y. has been preserved in pre-Cross Lake gneiss and a post-Cross Lake granodiorite is dated as 1,840 m.y. (samples 206 and 207, Burwash, 1962b). The San Antonio Formation has similar relationships but is less certainly assigned to the Aphebian; it unconformably overlies a granite similar to one dated at 2,670 m.y. (GSC 60-89) and was probably affected by an orogeny dated some distance to the south at 1,700 m.y. (GSC 60-90). The Grenville Series of the Grenville province has been strongly involved in the Grenville orogeny giving the series a minimum age of 850 m.y. (GSC 60-122) and placing it in the Neohelikian or older; but, on the basis of tracing its rather characteristic crystalline limestone and quartzite members through terrain that is only sporadically mapped, the series appears to join with the Kaniapiskau at one end and the Huronian at the other and so is tentatively assigned to the Aphebian (see Figure 3).

A date of 2,485 m.y. (GSC 63-119) on a Matachewan diabase, if taken at face value, would place this in the Archaean but as the dyke is post orogenic and cuts rocks of the Kenoran orogen it belongs to the lower Aphebian. A date of 2,095 m.y. (GSC 61-157) on the Nipissing Diabase places this rock in the middle Aphebian. The Kaminitis Granite at 1,865 m.y. (GSC 63-108) and many other granites were emplaced during the Hudsonian orogeny and accordingly, are late Aphebian. Five potassium-argon ages have been determined on the Sudbury irruptive and the four most consistent results range from 1,630 to 1,700 m.y. (Fairbairn et al. 1960), placing the irruptive in the late Aphebian. A post orogenic nepheline syenite cutting the Archaean of the Slave province is assigned to the same category because it gives an age of 1,785 m.y. (GSC 62-92).

Helikian Era

On northern Baffin Island, the nearly flat-lying Equalulik Group of the Churchill province overlies the Hudsonian orogen unconformably and is followed by the Ulukan Group; both of these groups are cut by gabbro dykes dated at 1,140 m.y. (GSC 63-20). The Et-Then Group unconformably overlies the Great Slave Group of the Churchill province and is cut by diabase sills dated at 750 m.y. (GSC 63-83); the Et-Then is, with some doubt, assigned to the Helikian although it could be somewhat younger. The nearly flat-lying Athabasca Formation lies unconformably on the Hudsonian orogen of the Churchill province here dated at 1,670 m.y. (GSC 60-67) to 1,825 m.y. (GSC 61-107) and is cut by a diabase dyke on which an age of 1,230 m.y. has been obtained (sample AK 263, Burwash, 1962b).

Palaeohelikian Sub-Era

The gently folded Martin Formation of the Churchill province is placed in this sub-era for it overlies the Hudsonian orogen unconformably and is cut by dykes and sills of gabbro dated at 1,410 and 1,490 m.y. (GSC 63-97, 98). The Chukotat Group overlies the Povungnituk unconformably and gives whole rock ages on slate at 1,430 and 1,490 m.y. (Beall, 1960); because of the uncertainty in dating such material the Chukotat is placed in the Palaeohelikian with reservations. The Sims Formation is also placed, with some doubt, in the sub-era; it unconformably overlies the Kaniapiskau and is cut by sills of olivine gabbro that resemble some of the intrusions of the Elsonian orogeny. Difficulty has been encountered in determining the age of the Dubawnt Group (see GSC 61-101) but it overlies the Hudsonian orogen unconformably and is cut by a gabbro dyke at 1,360 m.y. (GSC 63-44) so that the group is probably Palaeohelikian. The anorthosite, adamellite, and granitic rocks that were emplaced during the Elsonian orogeny are classed as late Palaeohelikian; representative ages on these rocks are, respectively, 1,400 m.y. (GSC 63-164), 1,340 m.y. (GSC 63-174), and 1,360 m.y. (GSC 63-165).

Neohelikian Sub-Era

The Seal Group unconformably overlies the Elsonian orogen which, close beneath the unconformity, gives dates of 1,430 m.y. (GSC 62-177) and 1,350 m.y. (GSC 63-177); the group is cut by a diabase sill dated at 865 m.y. (GSC 63-178) and, farther south, was metamorphosed during the Grenville orogeny at 975 m.y. (GSC 62-185). (In this reference due to a typographical error, the word Snare should read Seal). The Wakeham Series lies within the Grenville province and its age is problematical. The group is apparently unconformable on gneiss but both the Wakeham staurolite schist at 845 m.y. (GSC 60-134) and underlying gneiss at 870 m.y. (GSC 60-133) were involved in the Grenville orogeny; the Wakeham, therefore, is Neohelikian or older. However, it is much less folded and metamorphosed than the basement and is probably younger than nearby anorthosite which is correlated with the Elsonian; therefore the Wakeham is probably Neohelikian. The Doloro Granite at 875 m.y. (GSC 63-115) and many other granites were emplaced during the Grenville orogeny and are late Neohelikian. The Killarney Granite at its type locality gives 1,170 m.y. (GSC 61-158) but this age may be anomalous due to proximity to the Grenville front; the Killarney was probably emplaced during the Grenville orogeny and, if so, is late Neohelikian.

Although not in the Canadian Shield it is interesting to note that the Apache Group of southwestern United States of America also falls in the Neohelikian for it lies unconformably on the Mazatzal

orogen and is intruded by a sill of diabase dated at about 1,075 m.y. (Silver, 1960).

Hadrynian Era

The nearly flat-lying Double Mer lies unconformably on the Grenville orogen dated nearby at 955 m.y. (GSC 60-145) and is Hadrynian or younger. The Chatham-Grenville stock is a post-orogenic intrusion in the Grenville province; it cuts a gabbro dyke of 790 m.y. (GSC 63-151) which in turn cuts the Grenville orogen here dated at 850 m.y. (GSC 60-122). The stock gives a feldspar date of 540 m.y. (GSC 63-133) but as the feldspar age is probably too young the stock is classed as Hadrynian.

Helikian-Hadrynian

Orogenies have limited geographic extent and, as they are used as standards for time-stratigraphic subdivisions, uninterrupted successions beyond their limits are difficult to subdivide and classify. Of assistance in this problem are dates on non-orogenic intrusions and on unmetamorphosed volcanic rocks.

The Duluth Gabbro and Muskox intrusions are helpful in this regard for they give a time horizon separating rocks below from those above. The Duluth is dated at 1,060 m.y. and 1,090 m.y. (sample 65 and 295, Goldich, 1961) and the Muskox at 1,095 m.y. and 1,155 m.y. (GSC 63-90 and GSC 60-38); both intrusions are somewhat older than the Grenville orogeny and may be placed approximately in the middle Neohelikian.

The Lower and Middle Keweenawun unconformably overlie the Hudsonian, which is dated at 1,640 m.y. (sample 39, Goldich, 1961), and are older than the Duluth Gabbro; the Hornby Bay unconformably overlies the Hudsonian dated at 1,745 m.y. and 1,765 m.y. (GSC 60-37 and GSC 60-39) and is cut by the Muskox; accordingly these formations were laid down during the Palaeohelikian and/or early Neohelikian.

The Upper Keweenawun Fond du Lac and Hinckley sedimentary formations are stratigraphically above the Middle Keweenawun flows, appear to be younger than the Duluth Gabbro, and are overlain by Upper Cambrian strata (Goldich, 1961); accordingly, the Upper Keweenawun could be Lower or Middle Cambrian but more probably is late Neohelikian and/or Hadrynian. The Coppermine River lies conformably on the Hornby Bay and is divided into a lower part consisting of basaltic flows and an upper part of sediments.

Basalt near the base gives a whole rock age of 1,200 m.y. (GSC 63-91), which is about contemporaneous with the Muskox, and basalts higher in the series give whole rock ages of 915 m.y. and 740 m.y. (GSC 63-78, 77); sediments of the upper part are cut by dykes of gabbro dated at 770 m.y. and 705 m.y. (GSC 63-56, 57). The Coppermine River Group, therefore, appears to span the Neohelikian-Hadrynian boundary.

Other rocks that fall about in the middle Neohelikian, along with the Duluth and Muskox, include the Logan intrusions of diabase at 1,000 m.y. (GSC 61-138) and 1,060 m.y. (sample 131, Goldich, 1961) and two post-orogenic alkaline intrusions in the Superior province, the Lackner Complex at 1,090 m.y. (GSC 61-144) and the Coldwell Syenite at about 1,050 m.y. (Hurley 1958).

THE GRENVILLE PROBLEM

Sufficient progress has been made in unravelling the extremely complex stratigraphic and orogenic history of the Grenville province to justify the presentation of a working hypothesis. All potassium-argon ages determined so far give only the time of the last major event, the Grenville orogeny, and are of no help in determining the earlier history. For this we must rely on geological evidence, the two main keys to the problem being the age of deposition of the Grenville Series and the age of emplacement of the anorthosites. A full discussion of the problems could proceed endlessly but for the present purpose only a bare outline of the hypothesis need be given. This is presented in the form of a tectonic sketch map Figure 3.

Many years ago Quirke and Collins (1930) recognized the possibility that the Grenville Series was the metamorphosed equivalent of the Huronian and they traced what they regarded as metamorphosed Huronian strata for a considerable distance into the Grenville province. Recently Duffell and Roach (1959) have recognized that metamorphosed equivalents of Labrador Trough rocks (Kaniapiskau Supergroup) can be traced into the Grenville province. At its type locality, near Grenville, Quebec, the Grenville Series contains two readily recognized lithological types, namely, crystalline limestone and quartzite. These rock types in less metamorphosed condition, are also found in the Huronian and Kaniapiskau but are virtually lacking in the Archaean. The writer has merely traced, from published maps, the distribution of crystalline limestone and quartzite in the Grenville province with the result that the area so outlined appears to join with the Huronian at one end and with the Kaniapiskau at the other. Both of these are Aphebian and it is postulated that the Grenville Series also belongs to this era. On the accompanying sketch map H (for Hudsonian) indicates the areas of Aphebian rocks beyond

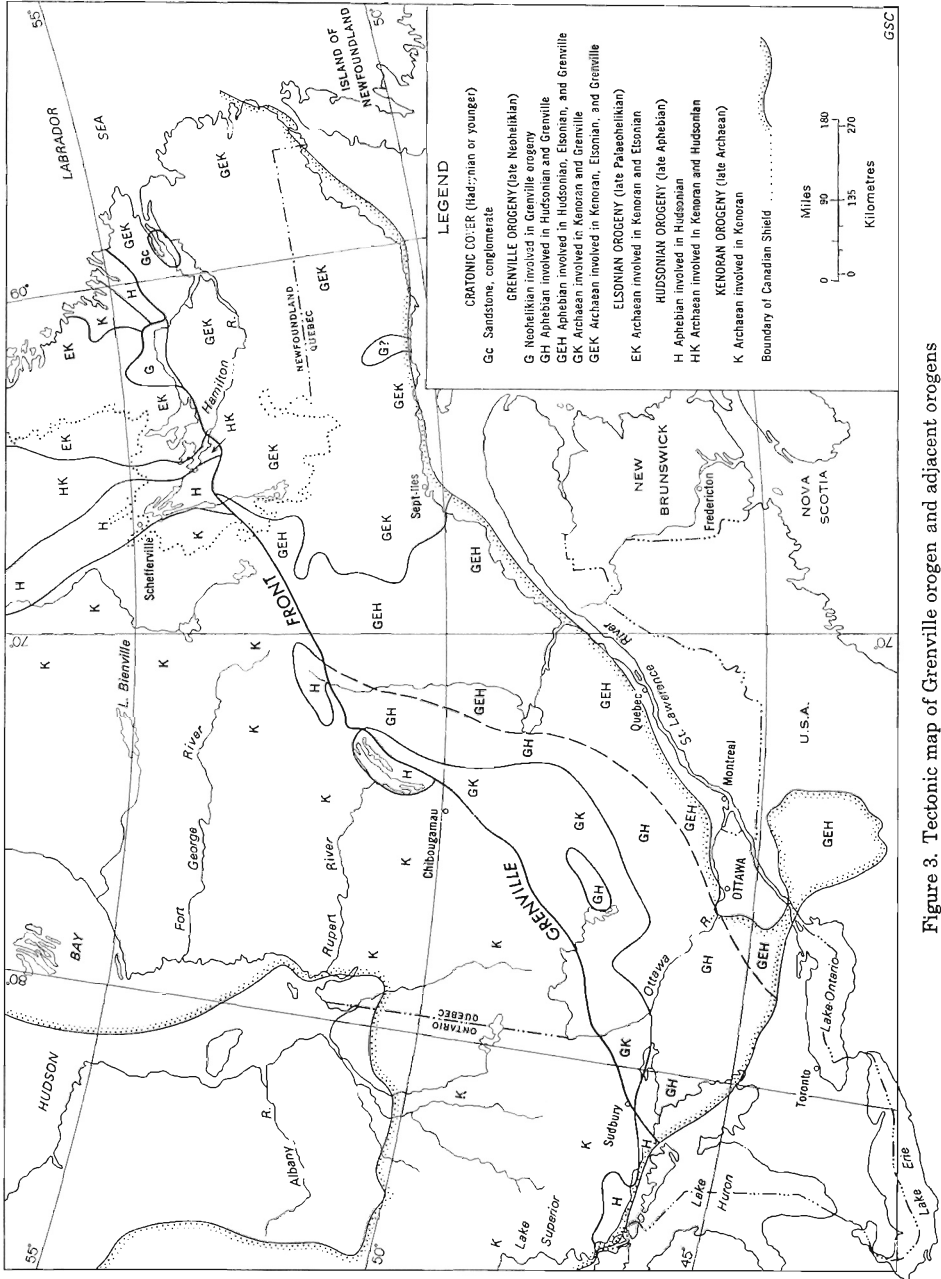


Figure 3. Tectonic map of Grenville orogen and adjacent orogens

the Grenville front while H combined with G or GE indicates the presumed extent of the Aphebian in the Grenville province. Of course, the contacts shown in the sketch are far from being accurate, for the limestone and quartzite are discontinuous have been intricately folded with paragneisses and injected by granitic and other intrusives, and much of the region is unmapped.

Presumably the Grenville Series was first folded, like the Huronian and Kaniapiskau, during the Hudsonian orogeny and was then refolded, highly metamorphosed, and invaded by batholithic intrusions during the Grenville orogeny. The area presumed to be so affected is indicated on the sketch map by the symbol GH. Structures are complex and the area, more than likely, includes upfolds of Archaean rocks not differentiated from the Grenville Series. An elongate belt (GK) between this area and the Grenville front lacks significant amounts of the well-sorted sediments, limestone and quartzite, grades across the Grenville front through a zone of decreasing metamorphism, into rock of the Superior province (K) and is probably Archaean. The presumed Archaean of this area (GK) was involved in the Kenoran orogeny and was reworked during the Grenville orogeny.

In the western Nain province the late Palaeohelikian anorthosite and other rocks were emplaced during the Elsonian orogeny which event modified the probable Archaean country rocks that had been already affected by the Kenoran (area EK). The anorthosites of the Grenville province are, on rather convincing evidence already given, the same age as those of the western Nain, and, accordingly were also emplaced during the Elsonian. The limits of the Elsonian in the Grenville province can only be conjectured because the rocks involved, other than anorthosite and related gabbroic intrusions, are difficult to distinguish from gneisses and granites of other ages. In the accompanying figure the outer limit of scattered occurrences of anorthosite and gabbro is indicated by a broken line contact. In the northeast part of this area (GEK), which lies beyond the limits of the Grenville Series, the age of the country rock is quite unknown but is indicated in the sketch map as being mainly Archaean. If so, this region was first involved in the Kenoran, was then invaded by anorthosite and gabbro during the Elsonian, and was finally modified during the Grenville. The belt of anorthosites overlaps on the eastern part of the region underlain by the Grenville Series so that the series there was folded during the Hudsonian, modified during the Elsonian, and reworked during the Grenville orogeny (area GEH).

The Seal Group which lies unconformably on the Elsonian and is of Neohelikian age was folded during the Grenville orogeny (area G). The relationships of the Wakeham Group (area G?) are less certainly known but this group appears to lie unconformably on immediately surrounding rocks and is probably younger than the

anorthosites; accordingly, it may also be Neohelikian folded during the Grenville. The Double Mer (Gc) forms a cratonic cover on the Grenville orogen and is Hadrynian or younger.

ANOMALOUS AGES ACROSS THE GRENVILLE FRONT

Attention is drawn to the results of further work on the problem of highly anomalous dates found along and near the Grenville front at the Chibougamau highway locality, as discussed in previous reports. The most recent results are given under GSC 63-147. Briefly, it is found that, on the Kenoran side, muscovite gives discrepantly young ages for at least 2 1/2 miles from the front. This is no doubt due to loss of argon because of the effect of the Grenville orogeny. Biotite dates are much more erratic. For example, a most unusual result was found in a single sample, also on the Kenoran side, where biotite gave 3,300 m.y., muscovite 1,630 m.y., and whole rock 1,673 m.y. It seems apparent that argon has been added to the biotite. Experiments by Karpinskaya (1961) have demonstrated that large quantities of argon can be added to muscovite under conditions of high temperature and pressure and that the argon is held firmly in the mineral apparently entering into its lattice. Geological evidence along the Grenville front indicates that argon can be added to biotite more readily than to muscovite.

NOTES ON THE OROGENIC HISTORY AND ISOTOPIC AGES
OF BOTWOOD MAP-AREA, NORTHEASTERN NEWFOUNDLAND

by H. Williams

Geological evidence indicates that Botwood map-area has been affected by at least two major orogenic events in Palaeozoic time. The older is inferred from a variety of indirect geological reasons and most evidence suggests that it occurred in the Middle to Late Ordovician. It is considered equivalent to Taconic orogeny, which apparently was widespread elsewhere throughout the Canadian Appalachians (Neale, et al., 1961). The second orogenic event is well-defined and is clearly indicated by folding, metamorphism, and igneous intrusion. It is dated on geological evidence as post-Middle Silurian in Botwood map-area and is considered equivalent to the Acadian (Devonian) orogeny, recognized throughout much of the Canadian Appalachians. The areal extent of the first (Taconic) orogeny is indefinite and the event is not considered to have been either as widespread or as intense as the second orogeny which affected all of the central Palaeozoic mobile belt in Newfoundland.

Isotopic ages in Botwood map-area, distributed as shown in Figure 4, present certain problems in the reconciliation of isotopic and geological data. All eight determinations date intrusive or metamorphic events and fall within the time interval between 450 and 335 million years (m.y.), that is from late Ordovician to early Carboniferous time, according to recent time scales (Kulp, 1961). Those ages that are Middle Silurian (415 m.y.) or later are not hard to interpret, and are assumed to date the second orogenic event to affect the map-area. This event, although considered equivalent to the Acadian (Devonian) orogeny, probably commenced in the map-area as early as middle or late Silurian time, as suggested by the ages 410, 415, and 423 m.y. Two of the rocks dated are lithologically alike and are composite intrusions that cut Middle Silurian rocks of the Botwood Group (Williams, 1962). Each intrusion is composed of an intermediate to basic older component and a granitic younger component. The younger granitic component of one is dated at 380 m.y. and the older basic component of the other at 410 m.y. This suggests that perhaps the lithologically similar components of each intrusion is of the same age, with the basic to intermediate components intruded in Silurian time followed by the granitic components in Devonian time. Possibly this intrusive activity lasted until early Carboniferous time, as suggested by the determination of 335 m.y., but this is considered unlikely as, throughout Newfoundland, Carboniferous strata are much less metamorphosed than the older rocks and are nowhere cut by intrusive rocks.

More difficult to reconcile are the ages 440 and 450 m.y. These dates, although apparently dating intrusions related to the late Ordovician (Taconic) orogeny, are suspect on geological evidence. The intrusion dated at 450 m.y. cuts Middle Ordovician strata of the Exploits Group, but not more than 15 miles to the northeast similar Middle Ordovician strata are conformably overlain by several thousand feet of greywacke, siltstone, and conglomerate, which are in turn overlain by Silurian conglomerates, all apparently forming a continuous and uninterrupted stratigraphic sequence (Williams, 1963). The other intrusion dated at 440 million years cuts conglomerate and greywacke beds that are possibly of Silurian age and are overlain conformably by Silurian conglomerates not more than 5 miles east of the intrusive contact. The hypothesis that strata are cut by large Ordovician intrusions in one place and grade upward into Silurian strata nearby seems untenable. The geological evidence therefore suggests that both intrusions are post-Middle Silurian, in which case the significance of the 440 and 450 m.y. dates is uncertain.

The isotopic ages 410 and 423 m.y. are of special interest as they date an igneous and metamorphic event that sets an upper time limit to the age of the previously controversial Botwood 'Formation' (Twenhofel, 1947). The age 410 m.y. dates an intermediate border phase of a large composite intrusion that definitely cuts the Botwood 'Formation' and this date is reasonably close to the other date, 423 m.y., that of the formation of metamorphic biotite in the intruded rocks. Similarly, the 415 m.y. age dates an intrusion interpreted to cut rocks of the equally controversial Springdale Group (MacLean, 1947; Kalliokoski, 1953; Neale and Nash, 1963), and sets an upper time limit to its geological age. These dates substantiate recent fossil evidence indicating that the Botwood Group is of Silurian age, and confirm the lithological correlation of the Springdale and Botwood Groups (Williams, 1962).

Table IV

K-Ar Ages Determined for Botwood Map-area, Newfoundland

GSC No.	Rock	Mineral Dated	%K	Ar_{40}/K_{40}	Radiogenic Argon (%)	Age (m.y.)
63-184	Biotite Granite	Biotite	6.70	0.02159	93	335
63-183	Garnetiferous Muscovite Granite	Muscovite	8.50	0.02330	88	360
63-169	Biotite Granite	Biotite	7.61	0.02454	97	380
63-182	Hb-Bio Qtz. Dior	Biotite	5.90	0.02689	86	410
63-170	Hb-Bio Gndior	Biotite	7.43	0.02705	99	415
62-188	Bio Gneiss	Biotite	7.30	0.02770	100	423
62-187	Bio Granite	Biotite	7.24	0.02906	100	440
63-168	Hb-Bio Gndior	Biotite	7.86	0.02970	100	450

For sample numbers 63- see Paper 64-17, Part I; for sample numbers 62-187 and 62-188 see Paper 63-17, Part I.

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