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AN RB-SR WHOLE-ROCK STUDY OF SOME
PROTEROZOIC ROCKS,
RICHMOND GULF, NOUVEAU QUEBEC

BY

PETER CHARLES HEWS B.Sc. (HONOURS)

A THESIS SUBMITTED TO THE FACULTY OF
GRADUATE STUDIES IN PARTIAL FULFILMENT
OF THE DEGREE OF MASTER OF SCIENCE

CARLETON UNIVERSITY,
OTTAWA ONTARIO.
APRIL 1976

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PETER CHARLES HEWS, B.Sc. (HONOURS), IN PARTIAL FULFILMENT
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ABSTRACT

Rocks of the Richmond Gulf area, Quebec, are thought to be the basal succession of the eastern margin of the Belcher Fold Belt, within the Circum-Ungava geosyncline.

Arkosic sediments of the Richmond Gulf Formation are sandwiched between two geochemically similar volcanic units. The underlying volcanics are part of the Pachi Group; the overlying volcanics belong to the Nastapoka Group. This favourable geological situation, in which the Richmond Gulf Formation is both overlain and underlain by volcanic units, provides one possible way of testing the reliability of the Rb-Sr whole-rock method of dating sedimentary material.

Rb-Sr data were obtained from each of the three units. Unfortunately, the isotopic data are difficult to interpret. The two volcanic units give an age of approximately 1300 m.y., but one of these isochrons is poorly defined. An approximate age obtained from the analyses of ten samples of the Richmond Gulf Formation argillites gives a value of 1800 ± 160 m.y. The data points show some scatter and broadly define an isochron.

The data can be interpreted in three different ways: (i) the 1800 m.y. age for the Richmond Gulf Formation is consistent with the ages obtained from other areas in the Circum-Ungava geosyncline. The ages of 1300 m.y. from the volcanic rocks could represent a later event which reset the volcanic ages but which did not affect the sediments; (ii) the 1300 m.y. ages from the volcanics reflect the time of extrusion, while the 1800 m.y. age from the sediments reflects the age of the source terrian; (iii) it is also possible that the Pachi volcanic unit may be, in part, intrusive in character. Its chemical similarity to the Nastapoka flood basalts suggests that these two volcanic units may be related.

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INTRODUCTION

Over the last few years, the Rb-Sr whole-rock method of dating geological material has been applied to an increasing number and variety of rocks. It is only relatively recently, however, that the technique has been applied to the dating of sedimentary material. The application of the method to Precambrian sediments is particularly important because there is no palaeontological control to the stratigraphy. The interpretations of the ages from whole-rock isochrons for sediments has recently become the subject of much debate, and it is fundamental to investigate the mechanisms by which a sedimentary isochron can be produced.

The main object of the present study was to place some constraints on the whole-rock method for dating sedimentary material, thus helping to clarify some of the assumptions necessary for a realistic interpretation of the isotopic data.

Dasch (1969) and Gebauer and Grünenfelder (1974) have demonstrated that it is unlikely that the processes of transportation and deposition could bring about a uniform $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio in a sediment. It is surprising, therefore, that some occurrences of unmetamorphosed sedimentary material have been dated, with apparent success, using the whole-rock Rb-Sr method. To further test the reliability of this method for dating sediments, Precambrian strata of the Richmond Gulf area in Nouveau Quebec were selected for study. In the Richmond Gulf area, a thick sedimentary unit is sandwiched between two volcanic units. It was hoped that by dating the volcanic units, a bracketing age could be placed on sedimentation, thus allowing any age subsequently obtained from the sediments to be formulated into a working model.

Three formations from the Manitousuk Supergroup were sampled in the Richmond Gulf area: the Pachi volcanics, consisting of flows

and/or sills of andesitic material; the Richmond Gulf Formation, consisting of red and grey arkoses with minor red shale horizons; the Nastapoka volcanics, consisting of fine-grained basaltic flows and sills, locally porphyritic.

The Manitounuk Supergroup has been assigned to the western arc of the Circum-Ungava geosyncline (Dimroth et al., 1970) on the basis of similarities to other constituent areas regarding lithology, structural style and degree of metamorphism. Fryer (1971) has claimed that continuity of the Circum-Ungava geosyncline is valid on geochronological grounds. The implication, then, is that all constituent parts of the Circum-Ungava geosyncline must be pre-Hudsonian in age. Rb-Sr whole-rock ages obtained from the Belcher Islands indicate that volcanism and sedimentation took place around 1800 m.y. (Fryer, 1971). Dimroth et al. (1970) consider the succession in the Richmond Gulf area to be at least the lateral equivalents of, if not older than, the strata of the Belcher Belt.

REGIONAL SETTING

Richmond Gulf occupies an eastward-extending depression on the east coast of Hudson Bay, 150 km. north of Poste de la Baleine, Nouveau Quebec (Fig. 1). The Gulf is a roughly triangular tidal inlet of the sea, 48 km. in length from north to south and 30 km. wide at the widest point along the southern shore. The tidal inlet is separated from Hudson Bay by a gently westward-dipping cuesta that rises up to 500 m. above sea level, broken only by the narrow entrance to the Gulf. Rounded hills with elevations generally less than 300 m. surround the Gulf.

The rocks of the area have been assigned to the Manitounuk Supergroup by Dimroth et al. (1970). The Manitounuk Supergroup forms an isolated exposure of basal Proterozoic rocks, supposedly of Aphebian age, bordering the western part of the Superior Province of Ungava. The Supergroup comprises all the sedimentary and basic igneous rocks that form the Nastapoka Islands, the Hopewell Islands, the Manitounuk Islands, the offshore islands as far south as Cape Jones and the region bordering Richmond Gulf (Fig. 1). Probable extension of the Supergroup into the Sutton Lake inlier to the west of James Bay has been suggested by Hawley (1926) and Hood (1966). Sanford et al. (1968) do not directly correlate the Sutton Lake succession with the Richmond Gulf succession, but they do suggest a correlation with the Belcher Island strata.

Strata of the Richmond Gulf area rest unconformably on the Archean basement and are presumed to represent the eastern extension of the basal part of the Belcher Basin (Moore, 1918; Kranck, 1951). The whole basin was affected by the Hudsonian orogeny (Stockwell, 1961), and the term Belcher Fold Belt has been extended to include adjacent areas by Dimroth et al. (1970).

Bell (1879), Leith (1910) and Cooke (1933) noted the

Fig. 1 Location Map and Distribution of the Manitounuk Supergroup (Black).

similarity of lithology and structure to certain Huronian sediments of the Lake Superior basin, particularly the banded ironstones and associated volcanic rocks. Low (1902) noted the lithologic similarity of the rocks of the east coast of Hudson Bay to those of parts of Labrador. Wahl (1953) was the first to suggest a correlation between the rocks of the Belcher Fold Belt, the Labrador Trough and the Mistassini area of Quebec on the basis of similar stratigraphy, lithology and geologic history. Bergeron (1957) extended the correlation to include the Cape Smith Belt and he postulated that these belts formed a continuous geosynclinal deposit. This suggestion is supported by Jackson (pers. comm., 1975) and Dimroth et al. (1970). The latter workers introduced the term Circum-Ungava geosyncline for the depositional basin.

The east-west graben system in which the rocks of the Richmond Gulf area were deposited (Kranck, 1951) may be chronostratigraphically equivalent to a similar fault-bounded basin on the western margin of the Labrador Trough (Dimroth, 1968) that was the site for deposition of the Chakonipau Formation, the Alder Formation and the Attikamagen Subgroup. The rocks of the Richmond Gulf area are lithologically similar and were probably deposited in a similar tectonic setting.

STRATIGRAPHY

The naming of stratigraphic units within the Manitounuk Supergroup has led to a great deal of confusion. This has been discussed by Eade (1966) and Stevenson (1968). A historical summary of the nomenclature is given in Table 1. The stratigraphy of Woodcock (1960) will be used because it provides the most detailed and workable subdivision of units in the Richmond Gulf area (Table 2 and Fig. 3).

Woodcock (1960) described three distinct sequences separated from one another by unconformities. The oldest group lies unconformably above the granitic basement in the Richmond Gulf area. These are, in ascending order: the Pachi Group, the Richmond Gulf Formation and the Nastapoka Group.

The Pachi Group comprises the Pachi sediments and the overlying Pachi volcanics. The Pachi sediments consist of pinkish arkoses, arkosic quartzites, grits and pebble conglomerates. Argillaceous units appear to be more abundant near the top of this unit. The Pachi volcanics consist of fine-to medium-grained basaltic andesites with locally developed potassium feldspar phenocrysts. The volcanics can be divided, megascopically, into two types. Firstly, those that exhibit spherical or sub-spherical structures up to 4 m. across (Plate 1). Leith (1910) described these structures as pillows, but Woodcock (1960) considered the concentric pattern of these rocks to be the result of alteration along fractures. Secondly, those that exhibit columnar jointing. The andesites have been described as both flows and sills (Woodcock 1960). Field evidence as to the exact nature of the Pachi volcanics is, in many cases, masked by the extensive alteration and associated "pillow-like" structures. It is possible that some, if not all, of the Pachi volcanic unit might be intrusive in nature.

The Richmond Gulf Formation consists of pink and grey arkoses, grits and conglomerates. Argillaceous horizons tend to be more common near the base of the formation. Ripple marks and cross bedding are common and help distinguish the Richmond Gulf Formation from the Pachi sediments (Woodcock, 1960).

BELL, 1879	LOW, 1902	LOW, 1903	LEITH, 1910 YOUNG, 1922	KRANCK 1951	WOODCOCK, 1960	EADE, 1966	STEVENSON, 1968	DIMROTH et al. 1970
Mantlounuk Group		Nastapoka Group or Nastapoka Series	Nastapoka Group	Nastapoka Series	Nastapoka Group			
	Thrust		Thrust		Uncon.	Uncon.	Uncon.	Nastapoka Group
			Richmond Group		Richmond Gulf Formation		Possible Uncon.	Richmond Gulf Formation
	Thrust	Thrust			Uncon.			Uncon.
					Pachi Group			Pachi Group
	Mantlounuk Group					Mantlounuk Group	Mantlounuk Group	Mantlounuk Supergroup

Table 1 Nomenclature Used for the Rocks of the Richmond Gulf Area
(adapted and modified from Dimroth et al., 1970).

Table 2 Table of Formations for Richmond Gulf (after Woodcock, 1960).

ERA	FORMATIONS	LITHOLOGY	APPROXIMATE THICKNESS
Proterozoic	Wiachuan Sill	Gabbro	60 m.
	Nastapoka Group		
	Volcanic Rocks	Basaltic Flows Sills and Tuffs	130 m. +
	Sedimentary Rocks	Dolomites, Quartzites and Siltstones	150 m. +
UNCONFORMITY			
	Richmond Gulf Formation	Pink and Grey Arkoses and Conglomerates	500 m. +
UNCONFORMITY			
	Pachi Group		
	Volcanic Rocks	Andesitic Flows and Sills	30 m.
	Sedimentary Rocks	Arkose, Arkosic Quartzites and Conglomerates	150 m.
UNCONFORMITY			
Archean		Granitic Rocks

Fig. 2 The Circum-Ungava Geosyncline (adapted from Dimroth et al., 1970).

Fig. 3 Geology of the Richmond Gulf Area (after Woodcock, 1960).

The Nastapoka Group can be broadly divided into the mainland and island successions. The mainland sediments consist of basal breccia, orthoquartzites, dolomitic limestones and pink quartzites. A basaltic cap-rock, at the top of the mainland succession, forms much of the outcrop on the east coast of Hudson Bay and is made up of thick basaltic flows, thin pyroclastic units and porphyritic basalt sills near the base of the unit (Woodcock, 1960). The Nastapoka Island succession consists of thinly bedded quartzites and shales, overlain by iron formation. Minor basaltic sills form a cap-rock on the northernmost Nastapoka Islands and on the Hopewell Islands (Bell, 1879). The stratigraphic relationship between the mainland and island successions of the Nastapoka Group is discussed later.

A gabbroic intrusion, the Wiachuan sill, occurs near the base of the Richmond Gulf Formation. The relationship between this sill and volcanic rocks in the area is not known (Stevenson, 1968).

The Manitounuk Supergroup rests with angular unconformity on the Archean gneisses (Leith, 1910; Kranck, 1951; Woodcock, 1960; Eade, 1966; Stevenson, 1968; Dimroth et al., 1970). A regolith is locally developed beneath the Manitounuk Supergroup sediments (Eade, 1966 and Stevenson, 1966).

Kranck (1951), Woodcock (1960) and Dimroth et al., (1970) favour the idea of an east-west graben system in the Belcher Basin, centered on the Richmond Gulf area, in which most of the faulting took place prior to the deposition of the Richmond Gulf Formation. Woodcock (1960) noted that vertical faults or breccia zones in the Nastapoka Group are locally associated with lead-zinc deposits.

At least one unconformity is present in the Richmond Gulf area (Bell, 1879; Leith, 1910; Young, 1922; Woodcock, 1960; Eade,

1966; Stevenson, 1968; Dimroth et al., 1970). Low (1902) inferred, however, that all the unconformities in the area are thrust contacts. Evidence for tectonic contacts between formations has not been found by subsequent workers. It is now thought that the present stratigraphic distribution of the units is a result of normal faulting of the generally westward-dipping strata. Woodcock (1960) described at least two unconformities in the area, one between the Richmond Gulf Formation and the Nastapoka Group, and another, of only local importance, at the base of the Richmond Gulf Formation.

Because the contact between the mainland and island successions of the Nastapoka Group lies beneath the water of Nastapoka Sound, the stratigraphic relationship between them is conjectural.

Low (1903) maintained that a thrust fault at the base of the Nastapoka Island succession has brought that part of the group into tectonic contact with the mainland succession. On the other hand, Bell (1879) and Leith (1910) concluded that the strata under Nastapoka Sound is conformable with the mainland succession. Kranck (1951) postulated a steeply dipping fault, striking parallel to the present coastline, that has upthrown the rocks which form the island succession relative to the mainland outcrops. Positive evidence for the stratigraphic position of these rocks is presently lacking.

GENERAL STRUCTURE

Strata of the Richmond Gulf area generally dip less than 5° to the west, and rocks of the Manitounuk Supergroup elsewhere have similarly shallow dips towards the centre of the Belcher Basin. Bedding attitudes not consistent with these observations define folds of only minor importance. These minor folds trend approximately east-west and are most abundant near the margins of the graben system.

Some folds are traceable for several hundreds of metres.

The general shallow dip of the strata of the Manitounuk Supergroup may be parallel to an original palaeoslope, with the present outline of the basin more or less inherited from the ancient basin of deposition (Hawley, 1926). The basin has a clearly defined eastern margin, outlined by the coastline of Hudson Bay. The coastline represents an almost perfectly circular arc whose centre of curvature is just west of the Belcher Islands. It has been suggested that this structure might have been caused by meteoritic impact (Beals et al., 1963 and Innes et al., 1968) but field evidence to support this hypothesis is lacking.

The structural setting of the Belcher Islands on a regional scale is still poorly understood. The Belcher Islands are presently inferred to represent the southerly continuation of the Cape Smith to Wakeham Bay Belt. However, the structural trend of the Belchers is north-northeast whereas the Cape Smith Belt is east-west.

The Belcher Island succession displays more complex folding than the supposed counterparts in the Richmond Gulf area. Hood (1966) claimed that there must be a geological boundary in the area south of the Belcher Islands to account for a change in the structural trend from north-northeast in the Belcher Islands to east-west in Long Island. If this is true, then it may well be that the Manitounuk Supergroup succession was not deposited contemporaneously with the Belcher Island succession or indeed formed any part of the Circum-Ungava geosyncline.

PREVIOUS AGE DATA FOR RICHMOND GULF AND NEIGHBOURING AREAS

Isbister (1855) claimed that the sedimentary strata of the Richmond Gulf area was Silurian in age and correlated the rocks with those of the Hudson Bay lowlands. On the basis of similarity to Proterozoic rocks elsewhere, Low (1902) classified the succession in the Richmond Gulf area as Precambrian, and a Phanerozoic age has not been seriously considered by subsequent workers.

Published isotopic work for the Belcher Islands, Sutton Lake inlier and parts of Nouveau Quebec are summarized in Figure 4 and Table 3.

K-Ar ages from the granitic terrain east of Richmond Gulf indicate the basement to be Archean (Stevenson, 1966c). K-Ar ages, obtained for basalts from the Belcher Islands, can be divided into two groups, one corresponding to 1620-1693 m.y. and the other to 830-1010 m.y. (Jackson, 1965, 1967). The older age is attributed to low-grade metamorphism developed during the Hudsonian deformation, while the younger ages may represent a minor event in Neohelikian times, possibly corresponding to the intrusion of numerous diabase dykes (Hofmann and Jackson, 1969). K-Ar whole-rock age determinations on basalts and diabases from the Ottawa Islands, the cap-rock of Richmond Gulf and the Sutton Lake inlier, confirm the Proterozoic age of the strata in these areas, but are inconsistent with the ages obtained from the Belcher Islands. Considering all these determinations, the Belcher Fold Belt would appear to have been deposited between 2500 m.y. and 1650 m.y. (Fryer, 1972).

Rb-Sr whole-rock analyses by Fryer (1972) indicate that volcanism and sedimentation for rocks near the presumed stratigraphic top of the Belcher Basin succession occurred at about 1798 m.y.

Fryer (1972) also suggested that Rb-Sr whole-rock ages of 1870 m.y. and 1790 m.y. for sedimentary rocks from the Labrador Trough and the Lake Mistassini area, respectively, are close to depositional ages. He concluded that the "Circum-Ungava geosyncline is valid on geochronological grounds and that geosynclinal development terminated with the onset of the Hudsonian orogeny at about 1800 m.y."

An Rb-Sr whole-rock age of 1651^{+51} m.y. has been obtained from argillites in the Richmond Gulf area and is interpreted as a Hudsonian overprinting (Esquevin and Menendez, 1973). An Rb-Sr age of 1293^{+61} m.y. was obtained by the same authors on acid-leached argillites from the same area and this is thought to reflect an Elsonian orogenic event. Unfortunately, their data have been published only in abstract form, and are, therefore, difficult to evaluate.

Until recently, no age determinations had been published for the Richmond Gulf area and the criteria for correlation with other sedimentary basins were based on comparisons of lithology, structure and degree of metamorphism. Metamorphism of the Belcher Basin strata has been slight. Workers in the area have reported only minor recrystallization during either diagenesis or low-grade regional metamorphism (Lee, 1965; Eade, 1966; Hofmann and Jackson, 1969; Stevenson, 1968).

Lee (1965) has documented quartz-albite-epidote-biotite subfacies of the greenschist facies metamorphism in Aphebian strata of the Hopewell Islands, and Eade (1966) described minor development of white mica in the matrix of sandstones of the Manitounuk Supergroup. Metamorphism thus appears to have been slight, suggesting that Rb-Sr whole-rock ages of Manitounuk sediments should closely approximate the age of deposition.

Table 4 Rb-Sr Whole-Rock Sedimentary Isochrons, in Addition to Those Listed by Gebauer and Grünenfelder (1974).

Bonhomme et al.	(1966)
Moorbath et al.	(1967)
Fairbairn	(1971)
Fryer	(1971)
Esquevin and Menendez	(1973)
O'Nions et al.	(1973)
Bath	(1974 a,b)
Spears	(1974)
Crawford and Davies	(1975)

Table 3 Published Age Data for Richmond Gulf and Adjacent Areas

Author	Rock Type and Name	Age (m.y.)	Metamorphic Effects	Interpretation
Quirke et al., 1960	Basement and sedimentary rocks, Mistassini Territory	K-Ar, whole-rock 1610 and 1290	Yes	Partial resetting by Grenville and/or Hudsonian orogenies.
Stockwell, 1961	Manitounuk Gp.	Pre-Hudsonian	?	Group lies within Churchill Province.
Jackson, 1965	Centre of Diabase sill, Belcher Is.	K-Ar, Whole-rock 1620	Deuteric and secondary alteration	Possible age of map-unit 13 and 14 of Jackson, 1960.
Stevenson, 1966a	Basalt, Ottawa Is.	K-Ar, 1595-210	?	Confirms Proterozoic age.
Stevenson, 1966b	Basalt, west-side Richmond Gulf	K-Ar, 1385-125	?	Confirms Proterozoic age of Manitounuk Gp. May reflect post-Hudsonian intrusion of younger dykes.
Jackson, 1967	Chilled margin of pillow-spilitic basalt, Belcher Is. Dyke Cutting diabase sill, Belcher Is. Centre pillow spilitic basalt, Belcher Is. Chilled rim of pillow, spilitic basalt, Belcher Is.	K-Ar, 830 $\pm$ 110 K-Ar, 881 $\pm$ 80 K-Ar, 1625 $\pm$ 210 K-Ar, 1010 $\pm$ 150	? ? ? ?	Two groups of ages. 1625, 1693 agree with 1620 age from sill (Jackson, 1965). Age when spilitic flows and basic intrusives emplaced and/or altered. Younger ages - episode of hydrothermal activity and/or mild disturbance that coincided with intrusion of the late basaltic trap dykes.

Table 3 Continued

Author	Rock Type and Name	Age (m.y.)	Metamorphic Effects	Interpretation
Jackson, 1967 (Cont.)	Core of the above basalt pillow	K-Ar, 1693 $\pm$ 230	?	
Jackson, 1968	Core of pillow, spilitic basalt from Belcher Is.	K-Ar, 1054 $\pm$ 160		Effects of later geological event such as a mild disturbance and/or emplacement of younger trap dykes.
Hofmann and Jackson, 1969	Same rock types as interpreted by Jackson, 1967, Belcher Is.		Lower greenschist and contact metamorphism in adjoining sediments	Folding of Belcher Group during Hudsonian orogeny. Intrusion of gabbro (trap) dykes of unit 17 - thermal event or mild disturbance at time of Grenville orogeny.
Fryer, 1971/2	Upper volcanics and slate, Flaherty Fm., Belcher Is.	Rb-Sr, whole-rock composite isochron, 1796 $\pm$ 138. 1.39 decay const.	Yes	Age of deposition of upper volcanics.
Bostock, 1972	Diabasic intrusions, Sutton Lake Inlier	K-Ar, 1055 $\pm$ 90 1455 $\pm$ 170	?	Inconclusive as to whether they are part of the Mackenzie dyke swarm.
Esquevin and Menendez, 1973	Argillites from Richmond Gulf and Belcher Is.	Rb-Sr, whole-rock 1651 $\pm$ 59	Yes	Hudsonian metamorphism most significant event having produced the mineral components of the rocks. Minerals subsequently overprinted by Elsonian and Grenville orogenies. Latter events affected Richmond Gulf more than the Belcher Is.

THE RB-SR WHOLE-ROCK METHOD FOR DATING SEDIMENTARY MATERIAL

A comprehensive list of published Rb-Sr isochrons for sedimentary rocks, together with an interpretation of the ages obtained, is given by Gebauer and Grünenfelder (1974). Since the time of their compilation, several other Rb-Sr isochrons for sedimentary material have appeared in the literature and are summarized in Table 4. Also included are sedimentary isochrons which were omitted from Gebauer and Grünenfelder's review.

The isochron model is now well established for a wide variety of rock types. The model assumes that for a rock,

$$\text{Sr}^{87}/\text{Sr}^{86} = (\text{Sr}^{87}/\text{Sr}^{86})_0 + \left[\text{Rb}^{87}/\text{Sr}^{86} \right] (e^{\lambda t} - 1),$$
 where $\text{Sr}^{87}/\text{Sr}^{86}$ = the ratio of these isotopes as measured at the present day; $(\text{Sr}^{87}/\text{Sr}^{86})_0$ = the ratio of these isotopes at the time of formation of the rock; $\text{Rb}^{87}/\text{Sr}^{86}$ = the ratio of these isotopes in the sample, as measured at the present day; t = the time that has elapsed since the Sr in the sample had a uniform isotopic composition. The isochron itself can be expressed by the general equation of a straight line $y = b + mx$. The slope of the line is $m = e^{\lambda t} - 1$ and is directly related to the age of the rocks. The intercept is $b = (\text{Sr}^{87}/\text{Sr}^{86})_0$, the initial ratio, which reflects the initial Sr isotopic composition at $t = 0$. If the rocks have remained closed chemical systems since the time of their formation and that at time $t = 0$ the rocks had a uniform $\text{Sr}^{87}/\text{Sr}^{86}$ ratio, the major conditions for the isochron model will have been fulfilled. In the case of igneous rocks, a uniform $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio can be attained by isotopic homogenization before crystallization. For sedimentary material, there are several possible mechanisms which can produce a uniform $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio. These processes will now be discussed, as background to interpretations of the isotopic data.

Gebauer and Grünenfelder (1974) pointed out that most whole-rock isochrons from sedimentary material in the literature are interpreted either as corresponding to the time of sedimentation or to the time of metamorphism. In the case of Precambrian rocks, "...no clear decision could be made whether the obtained age was that of deposition or metamorphism". The types of processes which occur within a sediment to enable Sr isotopic homogenization to take place (and thus create a uniform $\text{Sr}^{87}/\text{Sr}^{86}$ ratio for the rock at $t = 0$, irrespective of the Rb/Sr ratio) are shown in Table 5.

Dasch (1969) and Murthy and Belser (1968) have demonstrated that Sr in recent marine sediments is not in isotopic equilibrium with the almost constant $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.709 for sea water, but rather that the ratio is controlled by the isotopic composition of the source regions.

A study by Hart and Tilton (1966) of bottom sediment samples from Lake Superior showed that for freshwater environments too, the Sr isotopic composition of the sediments is controlled by the isotopic composition of the source terrain and not by the water of the lake. Only two near-bottom samples were taken for analysis, but their $\text{Sr}^{87}/\text{Sr}^{86}$ values did agree with the $\text{Sr}^{87}/\text{Sr}^{86}$ value for a mollusk shell from the same lake (Faure et al., 1963). However, in a study of Lake Vanda and the surrounding area of Victorialand, Antarctica, Jones and Faure (1967) have shown that the water of the lake, the water of the inflowing river, the valley soil and the lake sediment all have approximately the same $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.7148. This value is significantly greater than the Sr isotopic ratio obtained from a glacier and bedrock in the area. They concluded that the Sr contained within the sediment is in isotopic equilibrium with the water in which it is transported and deposited and

Table 4 Rb-Sr Whole-Rock Sedimentary Isochrons, in Addition to Those Listed by Gebauer and Grünenfelder (1974).

Bonhomme et al.	(1966)
Moorbath et al.	(1967)
Fairbairn	(1971)
Fryer	(1971)
Esquevin and Menendez	(1973)
O'Nions et al.	(1973)
Bath	(1974 a, b)
Spears	(1974)
Crawford and Davies	(1975)

Table 5 Mechanisms and Processes by which Samples of Sediment and Sedimentary Rock May Exhibit or Acquire Homogenous Sr Isotope Composition (adapted from Dasch, 1969).

MECHANISMS/PROCESSES	INTERPRETATION
<ol style="list-style-type: none"> 1. Equilibration of detritus by contact with marine water. 2. Diagenetic equilibration of detritus with marine water. 3. Inheritance of homogeneous isotope composition. 4. No low-temperature modification of either Rb, Sr or Sr^{87}/Sr^{86} ratios of detritus. 5. Low-temperature modification of Rb, Sr ratios, and to a lesser degree the Sr^{87}/Sr^{86} ratio, whereby the effect of inherited radiogenic Sr is minimized. 6. Authigenic formation of bulk of sample from an isotopic medium (sea water). 7. Mixing of detritus with marine carbonate. 8. Complete mixing of detritus which may contain radiogenic Sr. 9. Equilibration of Sr between phases as a result of metamorphism. 	<p>Depositional age.</p> <p>Equal to, or less than depositional age.</p> <p>Time of deposition.</p> <p>Age of source rock.</p> <p>Maximum age of deposition.</p> <p>Near to depositional age.</p> <p>Masks detrital component.</p> <p>Near to depositional age.</p> <p>Minimum age of deposition.</p>

they attribute the source of the Sr to chemical weathering of the bedrock. Possibly isotopic equilibrium of Sr between sediment and water may be achieved in any area where chemical weathering takes place and where deposition is in a freshwater environment. Thus, dates obtained from unmetamorphosed sedimentary rocks deposited under conditions similar to the one just described may closely approximate their time of deposition.

Diagenetic equilibration of detritus with the interstitial water is favoured by Perry and Turekian (1974) and Gebauer and Grünenfelder (1974) who would interpret any isochron from unmetamorphosed sediments as indicating the probable time of diagenesis and, therefore, the minimum age of sedimentation. The latter work is the first serious attempt to critically evaluate the Rb-Sr whole-rock system for sedimentary material in which the validity of a "depositional age" is questioned. Many more cases need to be investigated before anything conclusive can be said about the behavior of Sr isotopes during diagenesis.

An isochron could be drawn for a sediment in which the components were derived from a source region of homogeneous composition. Only in certain cases, where deposition occurred soon after the erosion of a relatively young volcanic belt, for example, might the isochron age even approach the time of deposition. Rapidly deposited rocks, such as arkoses or greywackes, might satisfy such conditions.

Authigenic formation of the bulk of the sediment's components would minimize the effects of the detrital components and provide an age which would be close to that of deposition. It may be possible to extract the clay-sized fraction from a sediment and examine its isotopic composition, although this may be complicated by the problem of recognising and separating authigenic minerals from detrital minerals.

Bath (1974b) separated a clay mineral fraction from the Marloes Shales, South Wales and found that the isochron obtained gave, within the range of analytical error, the same age as that obtained from the whole-rock. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio was significantly lower for the clay separate, but this may have been a result of "...small-scale (intergranular) remobilization of nuclides subsequent to closure of the whole-rock system and not to any leaching process during size fractionation" (Bath, pers. comm., 1974). The clay-size minerals in the above case may well have been detrital in origin.

Although complete mechanical mixing of detritus that contains radiogenic Sr is feasible within a sedimentary basin, this does not appear to have occurred in sediments dredged from the Atlantic Ocean (Dasch, 1969). If physical mixing did occur, then not only would the Sr isotopes be averaged, but also the Rb and Sr contents, thus giving a uniform Rb/Sr ratio in the resulting rocks. By sampling only fine-grained sedimentary rocks the detrital component is minimized, thereby enhancing the chance for obtaining material which underwent Sr isotopic equilibration during sedimentation and/or diagenesis.

Fig. 5 Sample Locations in the Richmond Gulf Area.

ANALYTICAL TECHNIQUES AND REPRODUCIBILITY

Samples from the Pachi volcanics, the Richmond Gulf Formation and the Nastapoka volcanics were collected from the Richmond Gulf area (Fig. 5). The island outcrops of the Nastapoka sediments were not sampled because of their slaty appearance, a feature previously noted by Woodcock (1960) and Stevenson (1968).

The Rb-Sr ratios were determined for each sample by X-ray fluorescence and checked, where necessary, by isotope dilution. The $\text{Sr}^{87}/\text{Sr}^{86}$ ratios were measured on a solid-source mass spectrometer and the data plotted on an isochron diagram, and an age was calculated using the $1.47 \times 10^{-11} \text{ yr}^{-1}$ decay constant for Rb^{87} . Limits of uncertainty for both the ages and the initial ratios were calculated at the 95% confidence limits.

The analytical uncertainty attached to the $\text{Sr}^{87}/\text{Sr}^{86}$ ratios was based on duplicate analyses carried out during the course of investigation and are summarized in Table 6. Although some of the samples are not from the study area, these reflect the analytical uncertainties of measurements during the period 1973 to 1976. Also tabulated is the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the Eimer and Amend SrCO_3 standard, which was run several times during the course of this study.

Unfortunately, reproducibility of the Sr isotopic composition of three samples from the study area was found to be well outside the limits of analytical uncertainty estimated from the measurements shown in Table 6. The laboratory at Carleton considers the reproducibility of data to be 5 parts in 7000 at the 95% confidence level. The samples affected were numbers 6, 12 and 56. The $\text{Sr}^{87}/\text{Sr}^{86}$ ratio for sample 6, for example, was determined on nine separate occasions, the range of values being 0.7329 to 0.7555.

Table 6 Replicate Analyses, Period 1973 - 1976.

Sample No.	$\text{Sr}^{87}/\text{Sr}^{86*}$ Ratio	Rock Name
ND 117	0.7370 0.7363 0.7364	Cape St. John Volcanics, Nfld.
ND 114	0.7570 0.7561	Cape St. John Volcanics, Nfld.
LD 464	0.7297 0.7296	Terra Nova Granite, Nfld.
20	0.7028 0.7024 0.7031 0.7026 0.7023	Azores Volcanic
90	0.7101 0.7103	Nastapoka Volcanic
92	0.7149 0.7144	Nastapoka Volcanic
48	0.7106 0.7103	Pachi Volcanic
E. and A.	0.7078 0.7078 0.7076 0.7077 0.7076 0.7076	Eimer and Amend SrCO_3 Standard

*The variation in 2σ , for each run, normally varies between 3 - 7 parts in 7000.

✓ The variation in $\text{Sr}^{87}/\text{Sr}^{86}$ ratios for samples 6, 12 and 56 is disturbing because these are the only three samples in which difficulty in reproducibility was encountered. It was suspected that these samples may have contained large amounts of a mineral phase enriched in radiogenic Sr. Thin-section examination, however, showed that the only possible phases sufficiently enriched in radiogenic Sr were micaceous minerals. However, the micaceous minerals are not solely confined to the samples which failed to give good analytical agreement.

The causes of the lack of reproducibility of data could be threefold: (a) sample inhomogeneity; (b) incomplete dissolution; (c) contamination. Several different approaches were taken to try and overcome these possibilities. In the case of (a), three separate 500 mg. aliquots of sample were taken into solution and then combined, and one-third of the final solution run through the ion-exchange columns. In the case of (b), X-ray diffraction analyses of the residues, left behind after the samples had been HF treated, failed to detect any mineral phases which had not been taken into solution. Finally, in the case of (c), samples of 1 gm. were taken into solution and then split into two aliquots, placing each on different ion-exchange columns, to test the possibility of Sr leaching from the columns. Each aliquot produced the same $\text{Sr}^{87}/\text{Sr}^{86}$ ratio, within the analytical uncertainties shown in Table 6.

✓ The problem, thus, was not satisfactorily solved, and samples 6 and 56 were omitted from the isochron plot. The $\text{Sr}^{87}/\text{Sr}^{86}$ ratio for sample 12, as plotted on the isochron diagram, was obtained by averaging the relatively small range of values on six separate runs (0.7667 to 0.7747). At the present time the three problematic samples are being further investigated, in an attempt to discover the cause of the lack of reproducibility of the Sr isotopic compositions.

ANALYTICAL RESULTS AND INTERPRETATIONS

1. ISOTOPIC RESULTS

Pachi Volcanics

The Rb-Sr analytical data for the Pachi volcanics are presented in Table 7. The five whole-rock data points do not, however, define a satisfactory isochron despite duplicate runs on samples to check reproducibility (Fig. 6). Furthermore, the isochron is drawn between a lower grouping of points and a single upper point. It is unfortunate that sample number 6 did not give a reproducible $\text{Sr}^{87}/\text{Sr}^{86}$ value. This sample was initially selected for isotopic work because of its "middle-range" Rb/Sr ratio.

The best-fit isochron for the five points gives an age of 1300^{+200} m.y. with a $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio of $0.7068^{+0.0015}$.

The large uncertainty attached to both the age and the initial ratio reflects the scatter of the data points as shown in Fig. 6.

Nastapoka Volcanics

The analytical data for the Nastapoka volcanics are presented in Table 8. The six whole-rock data points define an isochron which gives an age of 1360^{+50} m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of $0.7057^{+0.0003}$ (Fig. 7).

At first glance the isochron appears to be defined by a group of basalts with Rb/Sr ratios <1 and a single point, 12, with a relatively high Rb/Sr ratio. Even if we were to ignore sample 12, the remaining points would still define an isochron which gives an age of 1520^{+200} m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of $0.7051^{+0.0005}$ (Fig. 8). The figure of 1520^{+200} m.y. still falls within the same range as the age obtained from the six-point isochron. The high range of uncertainty for the obtained figure is a result of the very low spread in Rb/Sr ratios.

Table 7 Rb-Sr Analytical Results for the Pachi Volcanics.

Sample No.	Rb (ppm)	Sr (ppm)	$\text{Rb}^{87}/\text{Sr}^{86}(\text{a})$ (atomic)	$\text{Sr}^{87}/\text{Sr}^{86}(\text{b})$ (atomic)
35	9.8 (8.33)	358.2	0.067	0.7090
48	5.67 (5.7)	379.0	0.042	0.7106
59	55.4	37.7	4.29	0.7916
77	19.8	141.2	0.408	0.7134
79	28.4	228.0	0.362	0.7104

Table 8 Rb-Sr Analytical Results for the Nastapoka Volcanics.

Sample No.	Rb (ppm)	Sr (ppm)	$\text{Rb}^{87}/\text{Sr}^{86}(\text{a})$ (atomic)	$\text{Sr}^{87}/\text{Sr}^{86}(\text{b})$ (atomic)
1	4.37 (4.64)	337.0	0.04	0.7059
3	12.4 (12.1)	115.0	0.226	0.7117
12	56.3	50.3	3.26	0.7714
88	9.1 (11.51)	170.6	0.195	0.7086
90	16.3	215.0	0.22	0.7102
92	25.3	164.0	0.446	0.7149

Table 9 Rb-Sr Analytical Results for the Richmond Gulf Formation

Sample No.	Rb (ppm)	Sr (ppm)	Rb ⁸⁷ /Sr ⁸⁶ (a) (atomic)	Sr ⁸⁷ /Sr ⁸⁶ (b) (atomic)
7	100.0	47.7	6.17	0.876
11	88.2	53.2	4.87	0.8622
25	130.0	21.0	18.69	1.174
26	116.4	29.7	11.68	1.046
27	112.0	25.4	13.23	1.063
29	132.0	35.0	11.26	0.9897
52	122.4	21.0	17.64	1.163
60	112.7	117.7	2.79	0.7773
73	107.8	25.3	12.69	1.037
74	62.8	75.5	2.43	0.771

(a) The maximum error for Rb⁸⁷/Sr⁸⁶ is $\pm 3\%$.

(b) The maximum error for Sr⁸⁷/Sr⁸⁶ at the 95% confidence limits is 1 part in 700.
 Ratios normalized to a Sr⁸⁶/Sr⁸⁸ value of 0.1194.

Figures in brackets indicate the results of isotope dilution for selected samples.

Fig. 6 Whole-Rock Isochron, Pachi Volcanics.

Fig. 7 Whole-Rock Isochron, Nastapoka Volcanics.

Fig. 8 Whole-Rock Isochron Nastapoka Volcanics. Detail of Lower Five Points.

Fig. 9 Whole-Rock Isochron, Richmond Gulf Formation.

Thin-section examination showed that most of the samples are fine-grained (< 0.5 mm.) with sparse plagioclase phenocrysts. Sample 12, a basic crystal tuff, is distinct from the other samples. Although the tuff is intimately associated with the basaltic units and was, no doubt, deposited at the same time, its higher Rb/Sr ratio probably reflects a variation prior to or at the time of its deposition.

The basalts predominantly consist of plagioclase and pyroxene with minor pyrite and magnetite. Although alteration to sericite, chlorite and epidote is locally extensive, igneous textures are still preserved. Amygdules are relatively common, with infillings of calcite, chlorite, epidote and chalcedony. The patchy nature and localized alteration, together with a mineralogy similar to the amygdale infillings, provides evidence in favour of deuteric alteration closely associated with volcanism.

It is interesting to note that the age obtained from the six-point isochron (Fig. 7) is in excellent agreement with the K-Ar date already available for the basalt (Stevenson, 1966b).

Schwartz* (pers. comm., 1975) has evidence to show that there are three basaltic units in the vicinity of Richmond Gulf, each characterized by a different palaeomagnetic polarity. He is of the opinion that in order to preserve the polarity of the individual layers, the temperature could not have risen above $150 - 200^{\circ}\text{C}$ since the time the basalt units were extruded. This evidence suggests that a later heating event has not occurred in the area.

Richmond Gulf Formation

The analytical data for the Richmond Gulf Formation are presented in Table 9. The isochron (Fig. 9) gives an age of 1800 ± 160 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.7066 ± 0.0006 .

*Dr. Eric Schwartz, Geological Survey of Canada

Table 10 X-ray Diffraction Results of Clay Mineralogy for Dithionite-Treated Samples.

Sample	Quartz	Feldspar	Muscovite	Chlorite	Illite
7 RG	X	X	X	X	X
25 RG	X		X	X	X
27 RG	X		X	X	X
29 RG	X	X	X	X	X
74 RG	X	X	X		X

All untreated slides produced the above results, but for the occurrence of haematite in each case.

All glycolated, dithionite-treated samples produced no change from the above results.

The iron content of each sample was found to be about 6% using the atomic absorption technique.

As can be seen from Fig. 9, the data points do not fit a unique line, but scatter about the isochron, well outside the limits of experimental uncertainty. Clearly, one or more of the criteria on which the isochron model is based have not been satisfied. One of the most likely reasons for the scatter shown in Fig. 9 would be one of incomplete mixing of detritus at the time of deposition, resulting in a non-uniform $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio.

Gebauer and Grünenfelder (1974) suggested that Sr isotopic homogenization within sedimentary material probably took place during diagenesis. Isochrons produced from unmetamorphosed sedimentary material most likely record some event closely related to, and associated with, diagenesis. Gebauer and Grünenfelder (1974) also observed (p. 120) that muscovite and chlorite "...did not equilibrate with the clay mineral matrix and, consequently, give higher apparent ages than the whole-rock samples". The ages from these two mineral species could, in fact, yield valuable information as to the provenance of the rock.

X-ray diffraction of the clay-sized fraction ($<2\mu$) for five of the Richmond Gulf Formation shales indicates that muscovite and/or chlorite are the major clay mineral components of the rock (Table 10). This is also verified by thin-section examination of all shales. The whole-rock age, shown in Fig. 9, may, therefore, reflect the provenance of the detrital components.

The origin of chlorite as a clay mineral component is worthy of note. Weaver (1958) and Blatt et al. (1972) regarded the presence of chlorite in unmetamorphosed sediments to be indicative of a detrital origin for the mineral in an arid environment in which chemical weathering was inhibited. They considered the formation

of chlorite during diagenesis to be negligible and concluded that diagenesis will have little effect on the clay minerals in the rock.

In order to establish that the recrystallization of chlorite and muscovite in the Richmond Gulf Formation was the result of diagenesis and not of regional metamorphism, six interbedded sandstones and conglomerates were examined in thin-section (Appendix B). The matrix is almost exclusively recrystallized chlorite and muscovite (Plates 2 and 3). The clastic components of the rocks have sharp grain boundaries with slight intergranular penetration. In addition there is slight deformation of schistose fragments around more competent grains, indicating compaction. The clastic feldspar grains show varying degrees of alteration, although most grains are fresh and exhibit sharp grain boundaries, suggesting that alteration was probably a pre-depositional feature.

Alteration comparable to that shown by the volcanic units is not apparent in the Richmond Gulf Formation. The recrystallization of the matrix and the shales in the Richmond Gulf Formation can thus be probably attributed to lithification and diagenesis.

The age of 1800 ± 160 m.y. obtained for the whole-rock isochron is difficult to interpret. However, there are features which suggest that this age may reflect, in part, an older detrital component inherited from an older source terrain: (a) the scatter of data points about the isochron suggests that at the time of sedimentary deposition, the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio may not have been uniform; (b) the difficulty in forming chlorite during diagenesis, lends support to a detrital origin. The high percentage of chlorite as a clay mineral component within the

Richmond Gulf Formation further enhances this line of reasoning; (c) the Richmond Gulf Formation does not exhibit alteration comparable to that of the volcanic units above and below. This alteration of the volcanic rocks is probably deuteric in origin and not a metamorphic overprint. The whole-rock age for the Richmond Gulf Formation could, therefore, be interpreted as being a minimum age of the source terrain for the shales. There is a problem, though, of locating the source terrain for the argillites. The coarser units of the Richmond Gulf Formation are undoubtedly derived from a granitic terrain, which is characteristic of the Archean basement to the east of Richmond Gulf. If the argillites were derived from the same terrain, they might be expected to exhibit Archean rather than Proterozoic ages.

Alternatively, if the succession at Richmond Gulf is, in part, the lateral equivalent of the succession on the Belcher Islands, then the age of 1800 ± 160 m.y. (Fig. 9) is consistent with Rb-Sr ages, not only from the Belcher Islands, but also from other parts of the Circum-Ungava geosyncline. If this is so, then the ages obtained from the Pachi and Nastapoka volcanics must be interpreted as corresponding to later events which are not recorded in the sediments.

Both interpretations are possible, but it would be unwise to favour one or the other because of the uncertainty in interpreting the isotopic data obtained from the volcanic units.

2. WHOLE-ROCK GEOCHEMISTRY

Seven selected samples of Pachi volcanic rocks and six selected samples of Nastapoka volcanics were analysed for the major elements as well as eight selected trace elements. These results are given

in Tables 11 and 12. The reasons for analysing the volcanic rocks were threefold: (1) to chemically identify the rock types; (2) to see if those samples giving reproducibility problems (6, 12 and 56) showed any unusual geochemical features; (3) to assess the similarities between the two volcanic units. Firstly, using the classification of Irvine and Baragar (1971), most of the rocks are tholeiitic basalts. Although these samples were identified despite the lack of CO_2 and H_2O analyses, all but one are basaltic in composition. Sample 56, from the Pachi volcanic unit is a calc-alkaline (high alumina) andesite. This result is somewhat surprising, however, considering the low silica content (44.6), the high alumina content (20.21), the high magnesia content (18.33) and the low calcium content (0.20) (Goodwin, 1968). The Ti content is comparable with the other samples from the Pachi volcanics and may be an indication that this particular sample is highly altered. Unfortunately, there are no distinctive features about those samples which gave problems of reproducibility, and this major problem remains unsolved.

From Table 12, it can be seen that the most abundant trace elements are Ba and Cr, with ranges of 54 to 783 ppm and 19 to 363 ppm, respectively.

There is an overall similarity in chemistry between the Pachi and Nastapoka volcanics, and thus the Pachi, rather than being an older volcanic unit, may be an intrusion emplaced contemporaneously with extrusion of the Nastapoka flows. Unfortunately, evidence for the contact relationships of the Pachi volcanics is generally lacking because of the extensive alteration, brecciation and fracturing, all probably associated with the "pillow-like" structures. It may well be possible that further detailed field work may show

Table 11. Chemical Compositions - Weight percent oxides, Pachi and Nastapoka Volcanics.

Sample No.	PACHI VOLCANICS							NASTAPOKA VOLCANICS					
	6	35	48	56	59	77	79	1	3	12	88	90	92
SiO ₂	47.23	51.46	51.81	44.60	52.85	49.62	49.07	49.14	48.43	57.37	51.13	52.29	57.24
Al ₂ O ₃	18.66	16.05	14.12	20.21	17.13	14.90	16.46	15.12	15.75	12.63	14.03	14.60	15.14
Fe ₂ O ₃	1.68	2.79	3.72	3.17	1.09	3.59	2.52	3.38	3.73	2.90	3.59	3.35	2.80
FeO	4.65	7.70	10.24	8.74	3.04	9.87	6.97	9.31	10.26	8.00	9.88	9.22	7.70
MgO	12.48	7.79	7.22	18.33	11.06	10.12	9.40	10.67	9.34	5.05	8.18	6.75	6.23
CaO	5.16	9.41	7.25	0.20	6.97	6.21	10.30	8.03	7.17	7.94	8.29	8.50	4.38
Na ₂ O	0.17	2.57	3.22	2.61	1.66	2.74	1.37	2.73	3.43	0.04	2.64	2.50	2.88
K ₂ O	8.46	0.92	0.36	0.63	4.11	1.68	2.68	0.25	0.50	3.92	0.77	1.27	2.02
TiO ₂	1.18	0.99	1.53	1.22	1.57	1.01	0.95	1.02	1.07	1.61	1.11	1.14	1.25
P ₂ O ₅	0.17	0.14	0.22	0.10	0.17	0.14	0.12	0.15	0.13	0.32	0.16	0.15	0.20
MnO	0.14	0.16	0.20	0.11	0.29	0.09	0.14	0.16	0.17	0.17	0.23	0.22	0.15
TOTAL	99.98	99.98	99.89	99.92	99.94	99.97	99.98	99.96	99.98	99.95	100.01	99.99	100.00

Analyst: Dr. G. Holland, University of Durham, England. XRF method.

Table 12. Trace Element Concentrations in ppm, Pachi and Nastapoka Volcanics.

Sample No.	PACHI VOLCANICS								NASTAPOKA VOLCANICS							
	6	35	48	56	59	77	79		1	3	12	88	90	92		
Ba	346	222	195	54	154	167	287		82	216	783	275	442	764		
Nb	6	4	9	4	9	4	3		2	4	15	5	5	8		
Zr	102	77	145	96	145	101	68		73	73	325	90	90	137		
Y	24	20	33	21	22	26	14		19	18	39	27	27	23		
Zn	45	90	85	72	23	98	91		105	101	83	113	112	126		
Cu	18	91	178	1	5	57	8		34	48	12	19	96	33		
Ni	104	58	31	101	115	63	76		101	67	12	31	34	70		
Cr	276	287	63	321	164	164	363		145	184	19	220	211	91		

Analyst: Dr. G. Holland, University of Durham, England. XRF method.
Error, ± 4 ppm

that parts of the so-called Pachi volcanic unit may be intrusive, and that this is much more extensive than was previously acknowledged. If this is the case, and the ages obtained from the two volcanic units in the Richmond Gulf area are true formational ages, then there may have been a period of volcanic activity in the Richmond Gulf area which was approximately 500 m.y. later than the deposition of the Richmond Gulf Formation.

SUMMARY AND DISCUSSION

The 1300 ± 200 m.y. age calculated for the Pachi volcanics (Fig. 6) is difficult to interpret for the following reasons: firstly, the points do not define a unique line and, therefore, there is a high analytical uncertainty; secondly, great difficulty has been experienced in attempting to obtain reproducible results for the two samples; lastly, the possibility exists that the volcanic units may not be flows at all, but may represent younger intrusions into the arkoses. More detailed field work is necessary to determine the nature of the Pachi volcanics.

The 1360 ± 50 m.y. age calculated from the six-point isochron for the Nastapoka volcanics (Fig. 7) is in excellent agreement with the 1385 ± 125 m.y. K-Ar age already available for the basalt. The basal part of the Nastapoka volcanic succession is, however, locally intruded by a coarsely porphyritic, gabbroic sill, up to 30 m. thick. Possibly this sill was intruded at a date much later than the main basaltic flows, thus resetting the age. It should be noted that the sill is not present on the Manitounuk Islands and occurs only locally in the vicinity of Richmond Gulf. The sill is best developed in the coastal cuesta near Little Whale River, 20 km. south of Richmond Gulf. However, preservation of the palaeomagnetic polarity of each basaltic unit (Schwartz, pers. comm., 1975) is evidence that excessive heating has not affected the volcanic units subsequent to initial cooling. Again, further investigation is necessary to establish the geological relationship between the porphyritic sill and the basaltic flows. The 1360 ± 50 m.y. age may well represent the time of volcanism. An isotopic resetting of the age during intrusion of the sill still cannot be completely excluded.

It is possible that the age of 1800 ± 160 m.y., obtained from the Richmond Gulf Formation sediments, could represent the time of)

diagenesis during which Sr isotopic homogenization took place. In this case, the succession at Richmond Gulf must be considered to be part of the Circum-Ungava geosyncline.

The age can also be interpreted as an inherited age from the source terrain. The presence of chlorite in the sediments is an indication of its detrital origin rather than diagenetic formation. Gebauer and Grünenfelder (1974) suggested that chlorite and muscovite may retain the age of their source terrain, despite recrystallization. If this is so, then it would appear that the rocks of the Manitounuk Supergroup are significantly younger than their supposed equivalents on the Belcher Islands and the other constituents of the Circum-Ungava geosyncline. In other words, the Manitounuk Supergroup at Richmond Gulf may represent an isolated basin of sedimentation and volcanism associated with east-west rifting in the area.

Another possibility is that because of the similarity in chemical composition between the Pachi and Nastapoka volcanics, these two units may be genetically related. If further field work demonstrates the Pachi volcanic unit to be intrusive rather than extrusive, then it is possible that this unit may be an intrusive equivalent of the undoubted flows of the overlying Nastapoka volcanics. The ages obtained from the two volcanic units may thus represent the time of a volcanic event which affected the Richmond Gulf area significantly later than the 1800 m.y. age obtained from the Richmond Gulf Formation.

APPENDICES

APPENDIX A

Sampling Techniques and Sample Preparation

Fine-grained rocks were sampled from shoreline exposures and from outcrops encountered on inland traverses from the shores of Richmond Gulf. Fresh, hand-sized specimens were obtained and all weathered surfaces were removed in the field. The samples were placed in heavy-gauge plastic bags to which sample number tags were attached. All samples were chosen from areas where faults, joints, igneous contacts and slickensides were absent.

Eight samples of Pachi volcanics, ten samples of Richmond Gulf Formation sediments and eight samples of Nastapoka volcanics were selected for isotopic analysis, and additional samples of Pachi sediments were obtained for possible future isotopic work. Each rock selected was broken into centimetre-sized chips in a jaw crusher, and then powdered to at least 200-mesh size in a tungsten carbide Bleuler Mill. The powder obtained from each sample was stored in numbered, plastic vials. To avoid cross contamination, great care was taken to clean all the breaking and crushing apparatus. The tungsten carbide mill was thoroughly cleaned before each sample was crushed. The cleaning involved washing the interior of the mill with singly distilled water, and drying. About 150 gms. of quartz chips were then crushed in the mill, which was re-washed with singly distilled water and wiped with an acetone-soaked tissue to ensure the maximum possible dryness.

The powdered samples were formed into pellets and analyzed by X-ray fluorescence techniques, as described by Doering (1968), to determine their Rb/Sr ratios using the U. S. G. S. standard AGV-1. Samples with a wide range of Rb/Sr ratios were selected from each of the formations, and the Rb and Sr contents for each sample were

calculated, using the method of Norrish and Chappell (1967), in which their mass absorption coefficients are measured directly. Samples having < 20 ppm Rb were spiked and their concentrations measured by isotope dilution analysis.

Each rock selected for isotopic study was examined in thin-section to seek evidence for any low-grade metamorphic effects. The presence of features such as the development of zeolites or recrystallization might indicate a partial chemical opening of the Sr isotope system within the rock units and a possible resetting of the age. The clay-size fraction of the sediments was examined to establish the degree to which recrystallization of the components had taken place. This approach might reveal evidence of low-grade metamorphic effects, where the chemical composition precluded the growth of zeolites, for example. For the volcanic rocks, there are problems as to whether such minerals as chlorite, epidote, carbonate and chalcedony were formed by late-stage deuteric alteration or in response to a distinctly younger thermal event. Results of the thin-section examination are tabulated in Appendix B and discussed in the section of the text dealing with the description of rock units.

Preparation of Samples for Mass Spectrometer Analysis

Samples of between 250 and 500 mg. were placed in teflon evaporating dishes and digested in HF and HClO_4 . After evaporation to dryness, the samples were passed through ion-exchange columns to separate the Sr. The samples were loaded onto single Re filaments in the nitrate form.

Analyses were carried out on a 90° sector, 6" radius, solid source mass spectrometer. Ion-beam intensities for each isotope were

measured by an electron multiplier, the output of which was read by a Cary Model 31 vibrating reed electrometer with a 10^{10} ohm resistor. The output current was displayed on a chart recorder and a Dymec 2401C integrating digital voltmeter. The signal from the digital voltmeter was analysed on a PDP-11 computer. On average, each sample run consisted of 120 scans of the Sr spectrum, the isotopic ratios $84/86$, $87/86$ and $88/86$ being printed out and normalized values calculated. The sequence of measurements for a Sr spectrum scan is 88, $87\frac{1}{2}$, 87, $86\frac{1}{2}$..., $83\frac{1}{2}$ and then back to 88 in the reverse order.

Several runs were carried out on the Eimer and Amend standard to check internal precision, accuracy and reproducibility of data. $\text{Sr}^{87}/\text{Sr}^{86}$ for the Eimer and Amend SrCO_3 standard, measured under the same conditions as the samples, was 0.7077 ± 0.0001 at the 95% confidence level.

Preparation of Sediments for X-ray Diffraction of Clay Mineralogy

Preparation of the sediments for X-ray diffraction required the clay-size fraction ($< 2\mu$) to be separated from the coarser particles.

Approximately 10 gms. of sample, previously crushed to about 200-mesh size by the Bleuler Mill, were placed in a 250 ml. bottle, filled with a mixture of distilled de-ionized water and Calgon in the proportions 10:1 by volume. The bottles were corked and shaken overnight to disaggregate the particles. The samples were then individually placed in marked, 500 ml. beakers, and distilled de-ionized water added to bring the level up to 10 cms.

The beakers were placed in a constant temperature (room temperature) water bath, in a room where vibration from air-conditioning units, for example, was minimal, and left overnight to allow the

temperature of the sample and water bath to equilibrate.

The samples were stirred until all the particles were in suspension and allowed to stand for a time determined from a graph of particle settling time (Tanner and Jackson, 1947). After the prescribed time, the upper 90% of the beaker's contents was siphoned off and 30 ml. of 1N CaCl was added to enable the clay-sized particles to flocculate and settle. The supernatant liquid was siphoned off and the sample washed with H_2O until free of chloride and then freeze-dried.

500 mg. of each sample was treated by the dithionite, iron extraction method described by Mehra and Jackson (1960). The resulting samples were freeze-dried and the supernatant liquid, collected during the washing process, was analysed by atomic absorption techniques for its iron content. The dithionite extraction was necessary to enable the clay mineralogy of the samples to be determined with the least masking effect and background that often occurs in iron-rich samples when examined with Cu radiation. The untreated samples were also examined to determine the species of iron minerals present.

Basally oriented specimens were obtained by thoroughly mixing 2 ml. and H_2O and 40 mg. of sample and transferring this suspension, by pipette, to a 3.5 x 3.5 cm. glass slide, and then drying at room temperature. One slide of each sample not treated by the dithionite extraction process was prepared in addition to two slides of each treated sample. Once dried, one set of the dithionite-treated samples was glycolated. X-ray diffraction analysis was carried out on a Siemens diffractometer using Ni-filtered Cu radiation. The results are summarized in Table 10.

APPENDIX BThin-Section DescriptionsPachi Volcanics

Igneous texture generally well preserved. Plagioclase composition in the range andesine to labradorite.

- Sample 6 . Porphyritic texture with orthoclase phenocrysts up to 4 mm. across. Groundmass consists of euhedral plagioclase up to 1.5 mm. across, orthopyroxene, pyrite cubes and disseminated haematite. Extensive alteration of the plagioclase, and to some extent the orthoclase, with development of carbonate, muscovite, chlorite and epidote. Plagioclases display local fringes of biotite.
- Sample 35. Generally equigranular, maximum grain size 0.5 mm. Fresh to highly altered plagioclase laths. Some 1 mm. maximum plagioclase phenocrysts present. Pyrite as disseminated grains. Epidote, chlorite and muscovite as alteration products of the plagioclase. Minor epidote veining.
- Sample 48. Fresh but more commonly sericitized plagioclase laths with a maximum grain size of 0.5 mm., phenocrysts of orthopyroxene with a maximum grain size of 3 mm., displaying a felty texture (quench texture?), fresh groundmass clinopyroxene. Disseminated sulphide and quartz are minor components. Epidote laths are common in the groundmass and may be a result of alteration. Patchy chloritization of the mafic components is common together with sericitization of the plagioclase.
- Sample 56. Collected from the rim of one of the ellipsoidal structures. Plagioclase laths with plagioclase phenocrysts, with a

maximum grain size of 4 mm. Orthopyroxenes occur as scattered grains, but display optical continuity. Quartz <5%. Plagioclase extensively chloritized with local development of epidote and muscovite. Haematite occurs extensively as fracture fillings and may be a result of local brecciation.

- Sample 59. 1 mm. maximum laths of plagioclase, orthopyroxene, equigranular pyrite, haematite and quartz. Amygdules up to 2 mm. contain infillings of epidote and calcite cores. Local recrystallization of the groundmass to chlorite, epidote and muscovite.
- Sample 77. 1 mm. maximum laths of plagioclase occurring as phenocrysts set in a groundmass of < 0.3 mm. plagioclase and pyroxene. The rock is locally altered to chlorite and sericite with minor haematite. Pyrite occurs as disseminated grains.
- Sample 79. Maximum grain size 0.7 mm. Mineral components are plagioclase, orthopyroxene, disseminated haematite and pyrite. Extensive sericitization of plagioclase with minor chlorite and epidote development. Carbonate locally developed in the groundmass. Amygdules up to 2 mm. across are filled with calcite.

Nastapoka Volcanics

Primary igneous textures well preserved. Plagioclase composition in the range andesine to labradorite.

- Sample 1. Plagioclase phenocrysts, maximum grain size 4 mm. set in an equigranular groundmass of plagioclase and pyroxene, maximum grain size 0.1 mm. Disseminated pyrite grains present. Local amygdules filled with chlorite, epidote and chalcedony rims. Rock is extensively altered, the development of chlorite being the most noticeable.

- Sample 3. Generally equigranular, with maximum grain size 0.2 mm. Mineral constituents: plagioclase, pyroxene, disseminated pyrite and magnetite, and minor quartz. Amygdules infilled with calcite and quartz. Local veins of quartz and muscovite appear to be associated with the amygdules. Extensive sericitization of plagioclase and local development of patchy chlorite.
- Sample 12. Relict pyroxenes, now broken crystals, 2.5 mm. maximum grain size, set in a virtually structureless groundmass. Groundmass contains well rounded quartz grains (<1%), purple chlorite, muscovite and pyrite cubes. Groundmass extensively sericitized and chloritized. Amygdules, up to 5 mm. across, infilled with chlorite and chalcedony with associated veins of quartz and chalcedony. A lack of an igneous texture indicates that this sample is probably a crystal tuff.
- Sample 88. Fresh plagioclase laths, 0.2 mm. maximum grain size, with minor pyroxene, now locally altered to chlorite and epidote. Disseminated grains of magnetite present. Late-stage chalcedony and haematite occurs as localized veins associated with chlorite-filled amygdales.
- Sample 90. Generally equigranular, with maximum grain size 0.2 mm. Abundant fresh plagioclase, some of which displays zoning, and magnetite and quartz as minor components. Amygdules, up to 2 mm. across, are filled with quartz, chlorite and calcite. Minor chlorite and muscovite as alteration products.
- Sample 92. Phenocrysts of plagioclase, maximum grain size 2 mm., set in a ground mass of plagioclase crystals, some of which are

fresh and display zoning. Disseminated grains of pyrite present. Amygdules of epidote, chlorite and chalcedony. Chalcedony locally occurs as cross-cutting veins. Patchy alteration of rock with development of muscovite and chlorite.

Richmond Gulf Formation

- Sample 7. Maximum grain size 0.5 mm. Framework consists of clastic grains of quartz, orthoclase and microcline in a matrix of sericite, chlorite and muscovite. Abundant haematite cement. Bedding defined by slightly elongate grains.
- Sample 11. Maximum grain size 0.1 mm. Framework consists of subrounded to angular clasts of quartz and microcline in a matrix of sericite, chlorite and muscovite. Haematite as cement and individual clasts. Well defined bedding.
- Sample 25. Maximum grain size 0.7 mm. Framework consists of subrounded to subangular grains of quartz, orthoclase and biotite. The biotite occurs as rounded laths which may be an indication of its detrital origin. Matrix consists of chlorite muscovite and epidote. Sericitic overgrowths occur on some clasts. Bedding is fairly well preserved.
- Sample 26. Maximum grain size 0.1 mm. Framework consists of subrounded to subangular clasts of quartz and microcline with local overgrowths of sericite. Haematite occurs as cement and clastic grains. Matrix consists of chlorite, muscovite and epidote. Patchy alteration of feldspars to chlorite and muscovite.
- Sample 27. Maximum grain size 0.1 mm. Framework consists of sparse clasts of quartz, microcline and orthoclase in a matrix of chlorite, muscovite, haematite cement and calcite rhombs.

- Sample 29. Maximum grain size 0.2 mm. Framework consists of clasts of quartz, microcline and orthoclase in a matrix of chlorite, muscovite and epidote. Abundant haematite cement.
- Sample 52. Maximum grain size 0.1 mm. Framework consists of angular to subrounded clasts of quartz and microcline in a matrix of chlorite, muscovite and sericite. Abundant haematite cement. Elongate clasts define good bedding.
- Sample 60. Maximum grain size 0.1 mm. Framework consists of poorly defined clasts of quartz, microcline orthoclase and well rounded grains of pyrite and magnetite. Matrix consists of muscovite and minor chlorite. Feldspar grains display various stages of sericitization, and mafic detrital components are extensively chloritized. Haematite as grain coatings and locally, cement in the matrix. Lack of well defined bedding.
- Sample 73. Maximum grain size 0.2 mm. Framework consists of angular to subrounded grains of quartz, orthoclase and biotite in a matrix of muscovite and minor chlorite. Abundant haematite as cement. Well defined bedding.
- Sample 74. Maximum grain size 0.3 mm. Framework consists of subangular grains of quartz, microcline and orthoclase in a matrix of chlorite, muscovite and haematite cement. Bedding defined by alignment of clasts and haematite concentrations.

Richmond Gulf Formation Sandstones and Conglomerates

The detailed description of Sample no. 41 below is considered to be typical of this lithology.

- Sample 41. Quartz, 30%; orthoclase/microcline, 20%; plagioclase feldspar (oligoclase-andesine), 15%, biotite, <5%; sericite and chlorite matrix, 25%; specular haematite

clasts, <5%; haematite cement, <5%; zircon, <1%.

Maximum grain size 3 mm. Framework consists of subangular to subrounded clasts which display moderate sorting. Feldspars display both fresh and altered features, probably reflecting their pre-depositional history. Grain boundaries are generally well defined, although there is some local intergranular penetration. The detrital nature of biotites is displayed by deformation of the laths around more competent grains during compaction. The matrix consists of an intricate intergrowth of chlorite and sericite.

PLATE 1

Brecciated, sub-spherical structure in the Pachi volcanics,
showing iron-rich and carbonate banding. Location, south shore of
Richmond Gulf.

PLATE 2

Photomicrograph of Richmond Gulf Formation showing sub-rounded to rounded grains of quartz and K-feldspar set in a matrix of fine-grained chlorite and muscovite. Feldspars show various stages of alteration. Slight intergranular penetration. Sample No. 41 (uncrossed nicols).

PLATE 3

Photomicrograph of Richmond Gulf Formation showing rounded grains of quartz, microcline and specular haematite (opaque) set in a fine-grained matrix of chlorite and muscovite. Sample No. 8 (crossed nicols).

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