TECTONIC SIGNIFICANCE
OF ND MODEL AGE MAPPING
IN THE GRENVILLE PROVINCE
OF WESTERN QUEBEC, CANADA

BY

ANLIN GUO, M.Sc.

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AUTHOR: Anlin Guo

B.Sc. (Northwest University)

M.Sc. (Northwest University)

SUPERVISOR: Dr. A.P. Dickin

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ABSTRACT

Detailed Nd model age mapping performed in the Grenville Province of western Quebec has identified biotite gneisses with crustal formation ages ranging from 1.4 to 2.8 Ga. These rocks represent different crustal units, which are now either in situ reworked terranes or allochthons.

The presence of Archean crust in the Parautochthonous Belt has been known for some time. However, Nd model age data from this work, coupled with geochemical and aeromagnetic data indicate that the Archean Parautochthon extends beyond the proposed location of the Allochthon Boundary Thrust, the proposed southern limit of Archean crust by previous studies. As a result, Archean crust can be traced 120 km and 130 km south of the Grenville Front in the Kipawa-Mattawa and Grand-Remous areas, respectively.

Biotite gneisses with crustal formation ages of 1.8-1.9 Ga exposed to the south of Archean crust geochemically possess an orogenic affinity. They are thus interpreted to represent the remains of a reworked early Proterozoic arc, which was developed along the southern margin of the Laurentian continent and finally collided with the continent. Between Archean crust and the arc-related material, an age boundary is defined. The age boundary is tentatively

interpreted as a suture due to lack of any evidence of shearing. The identification of plutons with model ages > 2.0 Ga to the north and < 2.0 Ga to the south of the age boundary also implies that the age boundary represents a division on a crustal scale.

Metasediments overlying Archean crust in the study area yielded model ages of 2.0-2.4 Ga. The trace and isotope geochemistry indicates that the sediments probably represent mixing deposits in a proposed foreland basin developed during a collision between the proposed early Proterozoic arc and Laurentia. Since 1.74 Ga and 1.68 Ga detrital zircons have been found in the sediments, the foreland basin may have evolved to a late marginal basin formed on the basement of a ca. 1.8 Ga orogen, accompanying a north-dipping subduction that reversed from the previous south-dipping direction.

In the central part of the study area, biotite gneisses and plutonic rocks from different allochthonous terranes yielded model ages spanning on a wide spectrum of 1.2-1.9 Ga. The rocks are lithologically and geochemically similar to plutonic rocks of the Coastal Batholith of Peru in the central Andes. Furthermore, in comparison with model age mapping results in the NW Central Gneiss Belt of Ontario, as a whole, the terranes show similar crustal age structure and thus represents crustal slices of a proposed Early-Mid Proterozoic continental margin. These crustal slices were probably thrust over from the south and stacked in the present site during Grenvillian thrusting and form an analogous structural complex to that of the NW Central Gneiss Belt.

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INTRODUCTION

1.1. Brief Grenville geology

The Grenville Province is the youngest tectonic division of the Canadian Shield. It forms a belt approximately 2000 Km long and 400 Km wide on the southeast margin of the Shield. To the north and northwest, the Grenville Province truncates the Archean and early Proterozoic provinces of Laurentia, while to the southeast, it is buried under Phanerozoic cover.

Wynne-Edwards (1972) subdivided the Grenville province, form north to south, into the Grenville Front Tectonic Zone (GFTZ), the Central Gneiss Belt (CGB) and the Central Metasedimentary Belt (CMB). In the central Grenville Province, the Central Granulite Terrane (CGT) was also defined (CGT) (Fig. 1.1).

A more recent tectonic subdivision of the Grenville Province has been proposed by Rivers et al., (1989), based on geological, geophysical and geochronological studies. These subdivisions include: the Parautochthonous Belt (PB), the Allochthonous Polycyclic Belt (APB) and the Allochthonous Monocyclic Belt (AMB, Fig. 1.2). The Allochthon Boundary

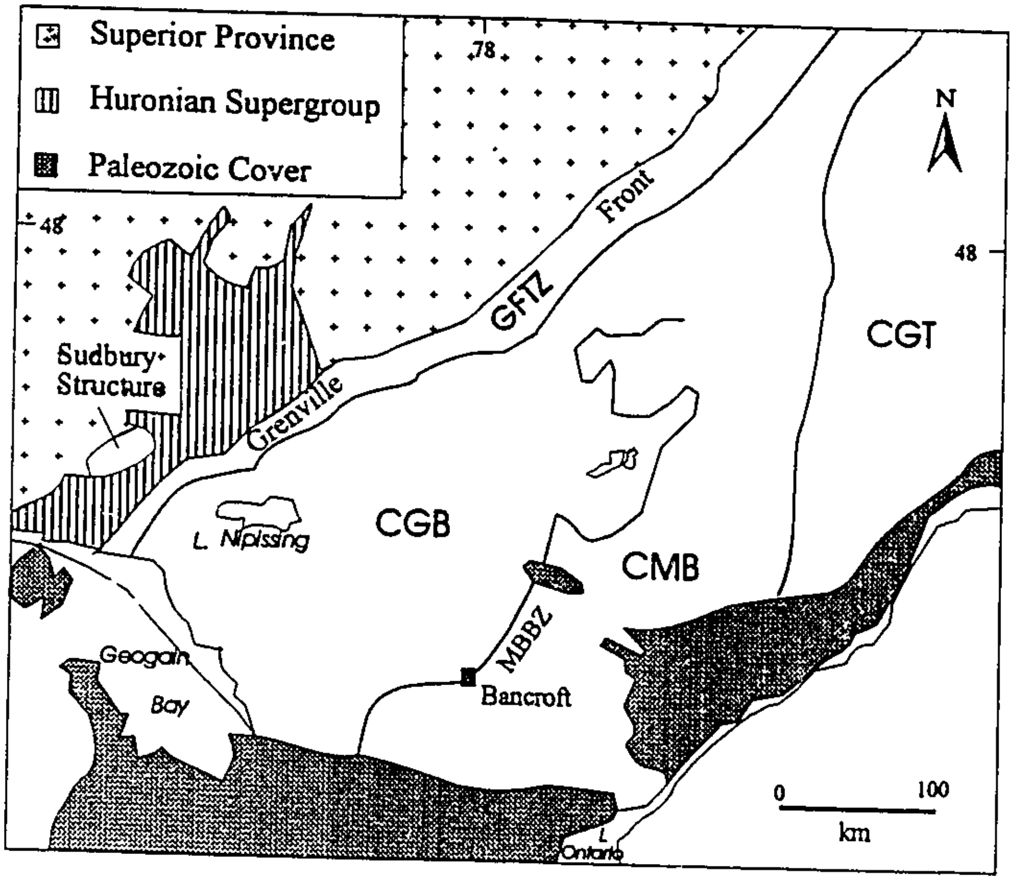
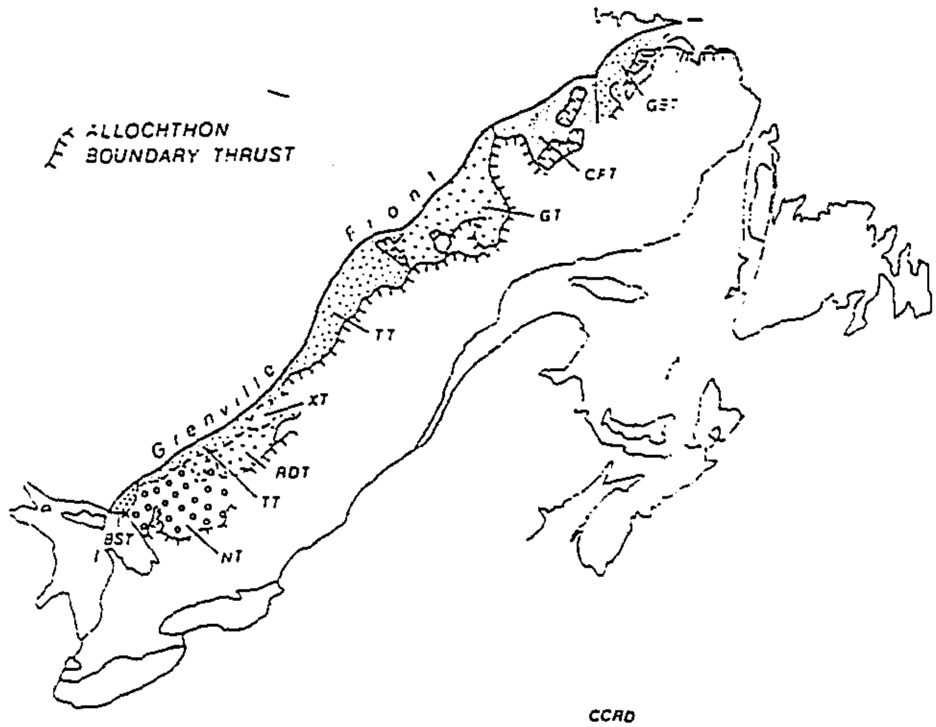


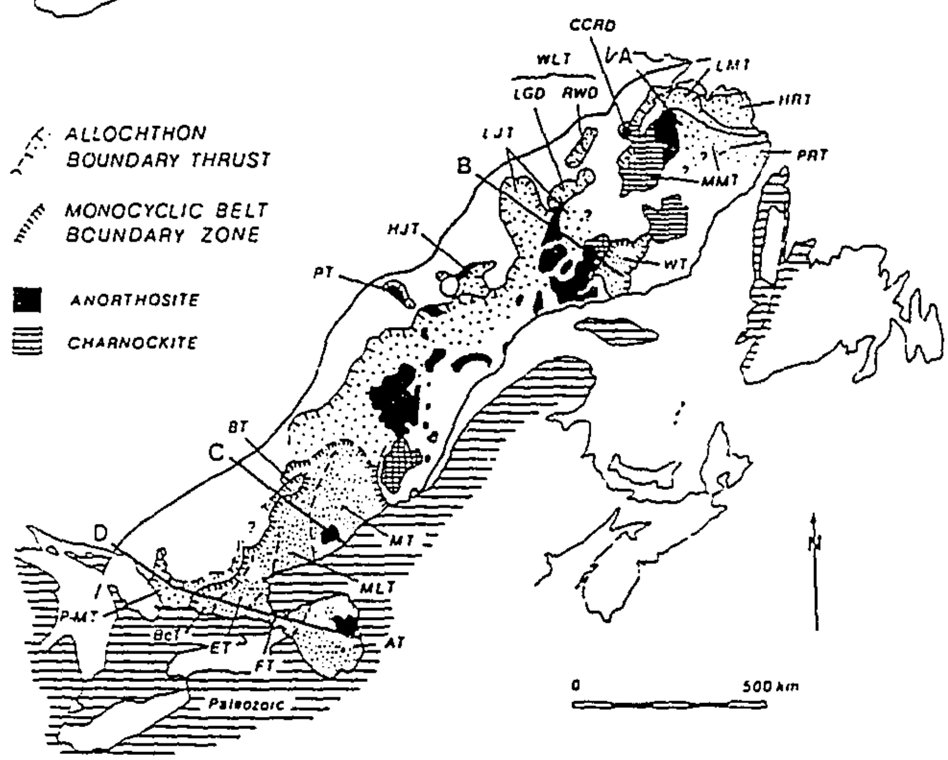
Fig. 1.1 Main tectonic divisions of the Grenville province of Wynne-Edwards (1972). CGB: the Central Gneiss Belt; CMB: the Central Metasedimentary Belt; CGT: the Central Granulite Terrane; GFTZ: the Grenville Front Tectonic Zone; MBBZ: the Monocyclic Belt Boundary Zone (Rivers et al, 1989).

Fig. 1.2 (A) Map showing the locations of the Parautochthonous Belt and the Allochthon Boundary Thrust. (B) The location of the Allochthonous Polycyclic Belt (open stipple) and the Allochthonous Monocyclic Belt (dense stipple) (from Rivers et al., 1989).

A


ALLOCHTHON
BOUNDARY THRUST
Grenville Front
GET
CFT
GT
TT
XT
RDT
TT
BST
NT

B


ALLOCHTHON
BOUNDARY THRUST
MONOCYCLIC BELT
BOUNDARY ZONE
ANORTHOSITE
CHARNOCKITE
CCRD
WLT
LGD
RWD
LMT
HRT
PRT
MMT
LJT
WT
HJT
PT
BT
MT
MLT
P-MT
BcT
ET
FT
AT
Paleozoic
0
500 km
N

Thrust was proposed to separate the Parautochthonous Belt from the Allochthonous Polycyclic Belt. In Ontario and western Quebec, the Parautochthonous Belt is spatially equal to the Grenville Front Tectonic Zone and the northern part of the Central Gneiss Belt. The Allochthonous Polycyclic Belt corresponds to the southern part of the Central Gneiss Belt, while the Allochthonous Monocyclic Belt spatially is an equivalent of the Central Metasedimentary Belt and the CGT.

In the southwest Grenville Province of Ontario, a collage of distinctive lithotectonic domains and subdomains have been recognized (Davidson, 1984, 1986), on the basis of discrepancies in lithology, metamorphic grade, structural style and geophysical signature. These tectonic units are bounded by major high grade shear zones characterized by intensively deformed rocks (straight gneisses).

K-Ar biotite geochronological studies of Stockwell (1964) indicated that the Grenville Province is characterized by postmetamorphic cooling ages of 1000-950 Ma. Timing of Grenvillian deformations have been determined based on U-Pb zircon ages obtained from pegmatites within shear zones. Deformation in the Grenville Front Tectonic Zone occurred post-1238 Ma, according to the age (Krogh et al., 1987) from the Sudbury Swarm mafic dikes. In the Central Gneiss Belt, U-Pb zircon ages from shear zones between domains suggested that deformation responsible for formation of the present imbrication of domains was initiated as early as 1180 Ma and persisted as late as 1030 Ma. Whether this deformation was a continuous process or a punctuated process peaked at 1160, 1140, 1060 and 1040 to 1030 Ma is still unknown (Easton, 1992).

Although the entire Grenville Province is affected by a major episode of deformation (Grenville orogeny) occurring at ca. 1.0-1.1 Ga, a number of U-Pb geochronological studies showed that most rocks within the provence possess a pre-Grenvillian history. For example, Archean rocks have been continually found to the south of the Grenville Front (Krogh and Davis, 1974; Krogh, 1989; Krogh et al., 1992; Gariepy et al., 1990; Joly, 1990; Childe et al., 1993). Plutonic rocks of three major ages, including 1.6-1.75 Ga, 1.4-1.5 Ga and 1.3 Ga have been also identified in the Central Gneiss Belt (Culshaw et al., 1988, 1990, 1991; Corrigan, 1990; Corrigan et al., 1990; Nadeau and van Breeman, 1990; van Breeman et al., 1986; van Breeman and Hanmer, 1986; van Breeman and Davidson, 1990; Lumbers and Vertolli, 1991). Thus, the presence of these rocks suggests that the Grenville Province represents a complex polygenetic orogen.

The presence of rocks older than ca. 1.1 Ga in the Grenville Province has been known for some time. However, crustal age structure of the Province, the distribution of Archean crust and its southern limit, and the evolution patterns of early-mid Proterozoic crust have not been clearly defined.

To solve the problems mentioned above, Dickin and McNutt (1989, 1991), Dickin et al. (1990) have applied Nd isotopic studies in the Grenville Province of Ontario. These studies have shown that:

1. the extent of Archean crust can be traced into the Central Gneiss Belt in Ontario for about 60 km from the Grenville Front.

2. the presence of a ca. 1.9 Ga arc related material, which was interpreted to represents a ca 1.9 Ga old arc developed on the southern margin of Laurentia.

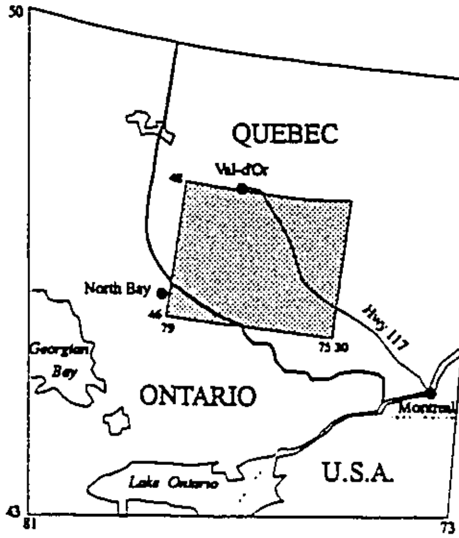
3. a suture between the 1.9 Ga arc related material and Archean crust, which formed during a collision between the arc and the Laurentian continent.

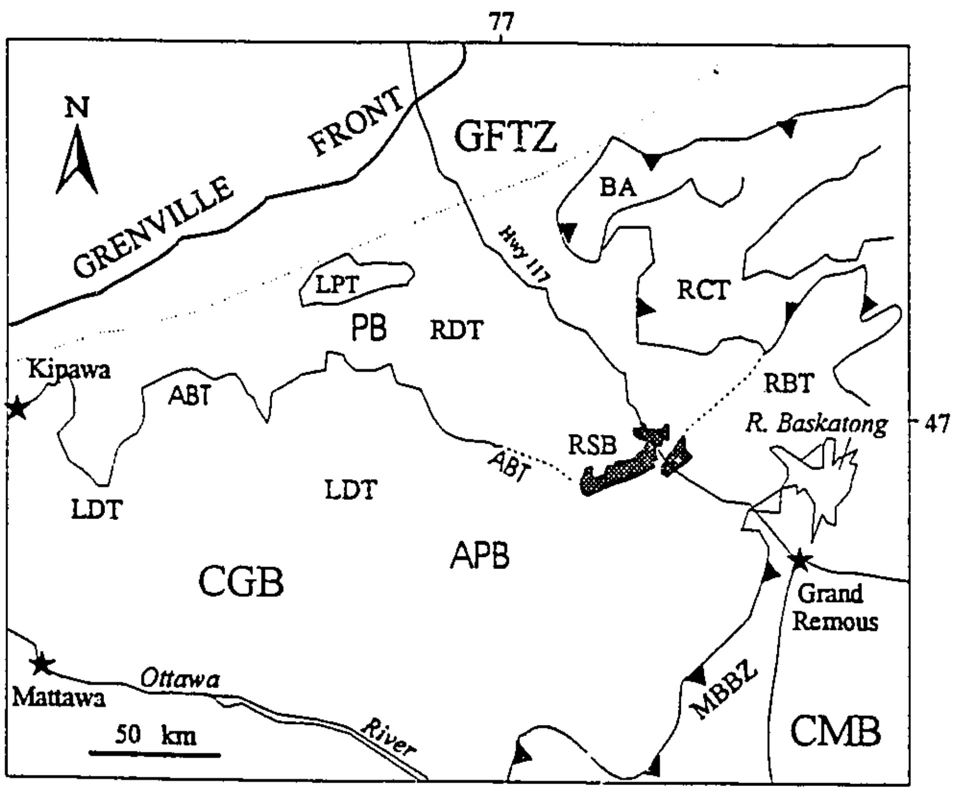
4. the internal crustal nature of the tectonic domains of Davidson et al. (1985) and Davidson (1986) in the southwest Central Gneiss Belt and establishment of the model of a long-lived Andean type continental margin.

1.2. Geological setting of the study area

The study area lies in the region between 79° and 75° 30' longitude (from the Kipawa area in the west to the Reservoir Baskatong area in the east) and between 48° and 46° latitude (the southern limit of the study area reaches approximately 150 km south from the Grenville front) in western Quebec (Fig. 1.3).

Fig. 1.3 Sketch map of the study area. CGB: the Central Gneiss Belt. CMB: the Central Metasedimentary Belt. GFTZ: the Grenville Front Tectonic Zone. PB: Parautochthonous Belt. ABT: the Allochthon Boundary Thrust. APB: the Allochthonous Polycyclic Belt. MBBZ: the Monocyclic Belt Boundary Zone. RDT: the Reservoir Dozois Terrane. RBT: the Reservoir Baskatong Terrane. LPT: the Lac Perch Terrane. RCT: the Reservoir Cabonga Terrane. RSB:The Renzy Shear Belt. LDT: the Lac Dumoine Terrane.


50
QUEBEC
Val-d'Or
48
North Bay
46
79
75 30
Hwy 117
Georgian Bay
ONTARIO
Montreal
U.S.A.
Lake Ontario
43
81
73


77
N
GRENVILLE FRONT
GFTZ
BA
Hwy 117
LPT
RCT
PB
RDT
RBT
Kipawa
ABT
RSB
R. Baskatong
47
ABT
LDT
LDT
CGB
APB
Grand Remous
Mattawa
Ottawa
River
MBBZ
CMB
50 km

As shown in Fig. 1.3, the study area lies in the Central Gneiss Belt. In terms of the tectonic subdivision of Rivers et al. (1989), the study area straddles the contact of the Parautochthonous Belt and the Allochthonous Polycyclic Belt along the proposed Allochthon Boundary Thrust.

Based on Indares and Martignole's tectonometamorphic study (1990), the Grenville Province of western Quebec is divided into a number of tectonic terranes. In the study area, these terranes are: the Reservoir Dozois Terrane (RDT), the Lac Dumoine Terrane (LDT), the Reservoir Baskatong Terrane (RBT), the Reservoir Cabonga Terrane (RCT), the Lac Perch Terrane (LPT) and the Renzy Shear Belt (RSB) (Fig. 1.3). The Reservoir Dozois Terrane belongs to the Parautochthonous Belt. The Reservoir Baskatong Terrane, a 30 Km wide wedge of quartzo-feldspathic gneisses, was assigned to the Allochthonous Polycyclic Belt. As a proposed eastern extension of the Allochthon Boundary Thrust, the Renzy Shear Belt divided the above two terranes. The Reservoir Cabonga Terrane and the Lac Dumoine Terrane were considered as allochthons. They were assigned to the Allochthonous Monocyclic Belt and the Allochthonous Polycyclic Belt, respectively. The Lac Perch Terrane was tentatively interpreted as a klippe. In a recent study, Martignole and Pouget (1993) have partially revised the above division by extending the Parautochthon to the south of the Renzy Shear Belt.

1.3. Objectives of the research

Early Proterozoic orogens were extensively developed along the margins of Laurentia at ca. 1.9 Ga, at which time Laurentia was aggregated to become a supercontinent (Hoffman, 1989). However, in the Grenville Province, the evolution pattern of early Proterozoic orogens has not been clearly defined because of the intensive overprint of the Grenvillian orogeny, which has obscured the older structures. Thus, one of the major tasks in dealing with Grenvillian geology is to reconstruct the early Proterozoic tectonic history inside the province.

To study early Proterozoic tectonics, determination of the extent of Archean crust in the Grenville Province also becomes important because this is related to the question of where early Proterozoic crust interacted with the Laurentian continent. As mentioned previously, the presence of Archean crust in the Grenville Province has been known for some time (Krogh and Davis, 1974; Krogh, 1989, 1994; Krogh et al., 1990, 1992; Joly, 1990; Childe et al., 1993). However, in comparison with the results obtained from the Nd isotopic studies in Ontario (Dickin and McNutt, 1989, 1991), the southern limit of Archean crust in the Grenville Province of western Quebec still remains unknown.

Rivers et al. (1989) identified a thrust zone termed the Allochthon Boundary Thrust (ABT, Fig. 1), which represents the limit of major northwest-directed thrust sheets (allochthons) overriding the tectonized Laurentian foreland. The ABT in western Quebec was interpreted as the southern limit of the Archean parautochthon in a number of previous studies (Indares and Martignole, 1990; Indares, 1991; Ciesielski, 1992; Ciesielski and Parent, 1992). Nevertheless, the ABT may not always coincide with the boundary between Archean and Proterozoic crust in the Grenville Province and the suggestion that it is a crustal boundary between Archean and Proterozoic crust needs to be reconsidered. In addition, there are numerous thrust zones in the Grenville Province and the limit identified by Rivers et al. (1989) may not be a unique boundary between autochthonous and allochthonous crustal slices which merits the name ABT. Hereafter I refer to this previously proposed boundary location as the "ABT".

A number of tectonic terranes have been proposed in western Quebec by Indares and Martignole (Fig.1.3, 1990). However, the crustal make-up of each terrane is still in question. This actually hampers further study of crustal evolution in this region.

Following the previous Nd isotopic studies of Dickin and McNutt (1989, 1991) and Dickin et al. (1990) in Ontario, the present research applies Nd age mapping to investigate crustal age structure in the study area. The objectives are:

1. to delimit the southern extension of Archean crust in the study area.

2. to investigate the formation age of rocks exposed to the southern limit of Archean crust, particularly the presence of the 1.9 Ga arc related material which was found in Ontario.

3. to pursue the suture between the proposed 1.9 Ga arc related material and Archean crust found in Ontario into the study area.

4. to investigate the internal crustal nature of the tectonic terranes and clarify the tectonic relationship between the terranes and the proposed Early-Mid Proterozoic continental margin.

5. to establish a synthesis model of Paleoproterozoic crustal evolution in western Quebec.

CHAPTER TWO:

GEOCHEMICAL PRINCIPLE OF THE SM-ND METHOD

2.1. Geochemistry of Sm and Nd

Samarium (Z=62) and neodymium (Z=60), both rare earth elements (REE), have very similar chemical and physical properties. This arises from the nature of REE electronic configurations.

Sm and Nd are classed as light REE (LREE, from La to Sm) and also they are lithophile in their geochemical character. In most rock forming processes, the REE are dispersed as minor or trace constituents of phases in which they are not essential components. The bulk of the Sm and Nd is often contained in the major rock-forming minerals (DePaolo, 1988), in which REE fill lattice sites in eight-fold coordination and primarily substitute for Ca (McLennan, 1989).

Both Sm and Nd behave coherently and resist fractionation during geological processes, such as weathering, erosion, transport, deposition, diagenesis and metamorphism. A study by McCulloch and Wasserburg (1978) indicates that the Sm/Nd ratios of sedimentary rocks are fairly constant and similar to the igneous and metamorphic source rocks. They suggested from this that the Sm-Nd system may remain closed during sedimentation and diagenesis. Nesbitt (1979) studied the Torronyo granite in southeastern Australia to determine the effect of weathering, and concluded that REE are primarily recycled within the weathering profile rather than transported significant distances in solution. The data presented by Banner et al. (1988) from the regionally dolomitized Mississippean carbonates indicate that REE patterns and the Nd isotopic system were not affected during diagenesis.

It is known that heavy minerals contain high REE abundances, which may have a serious effect on sediment REE patterns during sorting. However, the possibility of a dominant influence of heavy minerals in most rocks can be excluded by the examination of sediment REE patterns themselves. McLennan (1989) pointed out that most post-Archean sedimentary rocks have fairly uniform REE patterns with La_N/Yb_N <15 (with very few >20) and the heavy REE (HREE) patterns are flat with Gd_N/Yb_N ratios rarely outside the range of 1.0-2.0. This indicates little effect from sorting on REE patterns of sedimentary rocks.

The question of REE mobility during metamorphism has been debated for several decades and has not been resolved (Grauch, 1989). However, the assumption that the REE content of a metamorphic rock (assuming closed system conditions or isochemical metamorphism) directly mimics the content of the protolith has led to a great many studies of metaigneous and metasedimentary rocks. In these studies, the evolution of the protoliths were examined without specifically testing for the immobility of the REE. Grauch (1989) reviewed a series of REE studies on metabasic rocks and generalized that two major types of REE pattern, a light REE-enriched trend and a flat trend, are seemingly present in the various metamorphic grades. He thus suggested that the REE patterns of the protoliths are probably preserved throughout the spectrum of metamorphic grades.

In the Sm-Nd isotopic systematics, one of the Sm isotopes, ^{147}Sm, is radioactive and decays by alpha emission to a stable isotope daughter, ^{143}Nd. The half life of ^{147}Sm is $T_{\frac{1}{2}}=1.06\times10^{11}y$ and $\lambda=6.54\times10^{-12}y^{-1}$. This decay scheme is suitable for dating both extra-terrestrial materials and terrestrial rocks, using the equation:

$$\left(\frac{143Nd}{144Nd}\right)_R^t=\left(\frac{143Nd}{144Nd}\right)_R^m-\left(\frac{147Sm}{144Nd}\right)_R^m(e^{\lambda t}-1) \quad [2.1]$$

The ^{147}Sm-^{143}Nd decay scheme was first used as a geochronological tool in dating of extra-terrestrial materials. Lugmair et al. (1975a) determined an age of 4.56 ± 0.08 Ga with an initial $^{143}Nd/^{144}Nd$ ratio of 0.50677 ± 10 from the Juvinas achondrite. Another achondrite, Angra dos Reis, yielded a similar age, 4.55 ± 0.04 Ga and more precise initial

Nd isotope ratio of 0.50682 ± 5 (Lugmair and Marti, 1977). Ages of 4.4-3.3 Ga have been obtained on lunar rocks (e.g., Lugmair et al, 1975b and Papanastassiou et al, 1977).

Following the work of Lugmair and his co-workers on extra-terrestrial materials, the ^{147}Sm-^{143}Nd scheme has been successfully applied to the dating of terrestrial rocks and minerals.

The geochemical immobility of Sm and Nd during the geological processes previously mentioned determines the reliability of the ^{147}Sm-^{143}Nd isotopic systematics in studies of various rocks with different origins. On the other hand, this isotopic systematics is sensitive to other geological processes such as magmatic contamination, sedimentary mixing between different provenances and small volumes of partial melting. These will be discussed later in this chapter.

Since the study area lies in the Grenville province, a Precambrian orogen and since all rocks exposed in the study area are metamorphosed, by taking advantages of the Sm-Nd system, this study can "see through" the effect of metamorphism and directly deal with the original characteristics of Sm-Nd geochemistry in the rocks.

2.2. Notation of CHUR and εNd

2.2.1. Concept of CHUR

The Nd isotopic evolution in the earth is described in terms of a model called CHUR (chondrite uniform reservoir, DePaolo and Wasserburg, 1976). This model assumes that the Sm/Nd ratio of the bulk earth is equal to that of chondritic meteorites with a present-day $^{143}Nd/^{144}Nd$ ratio of 0.512638 (normalized to $^{146}Nd/^{144}Nd$=0.7219). The present $^{147}Sm/^{144}Nd$ ratio of CHUR is 0.1967. These values allow us to calculate the $^{143}Nd/^{144}Nd$ ratio of CHUR at any time t in the past by the following equation.

$$I^{t}_{CHUR}=I^{0}_{CHUR}-\left(\frac{147\,Sm}{144\,Nd}\right)^{0}_{CHUR}(e^{\lambda t}-1) \qquad [2.2]$$

Where

$I^{t}_{CHUR}=\frac{143Nd}{144Nd}$ ratio of CHUR at time t in the past;

$I^{0}_{CHUR}=\frac{143Nd}{144Nd}$ ratio of CHUR at the present time;

$\left(\frac{147Sm}{144Nd}\right)^0_{CHUR}$ - 0.1967, present value of this ratio in CHUR.

The isotopic evolution of Nd in the earth according to CHUR is expressed in Fig. 2.1. Note that magmas formed by partial melting have a lower Sm/Nd ratio than CHUR, whereas the residual solids have a higher Sm/Nd ratio. As a result, the present-day $^{143}Nd/^{144}Nd$ ratio of rock formed from silicic liquid (the continental crust) is less than that of CHUR, whereas the $^{143}Nd/^{144}Nd$ ratio of the magma derived from the residual solids (the depleted mantle) is greater.

2.2.2. Definition of εNd

In Fig. 2.1, the straight line of CHUR that represents the undisturbed bulk earth reservoir serves as a reference for the isotopic evolution of Nd in the crustal rocks.

In geological practice, people often compare the initial $^{143}Nd/^{144}Nd$ ratios (also the present-day ratio) between different geological bodies. By doing this, a further study of origin and evolution history of the bodies can be carried out. An alternative way of expressing the Nd isotope ratio which allows greater flexibility of presentation of isotopic data is the εNd notation. εNd is a measure of the deviation of a crustal sample or sample suite from the corresponding

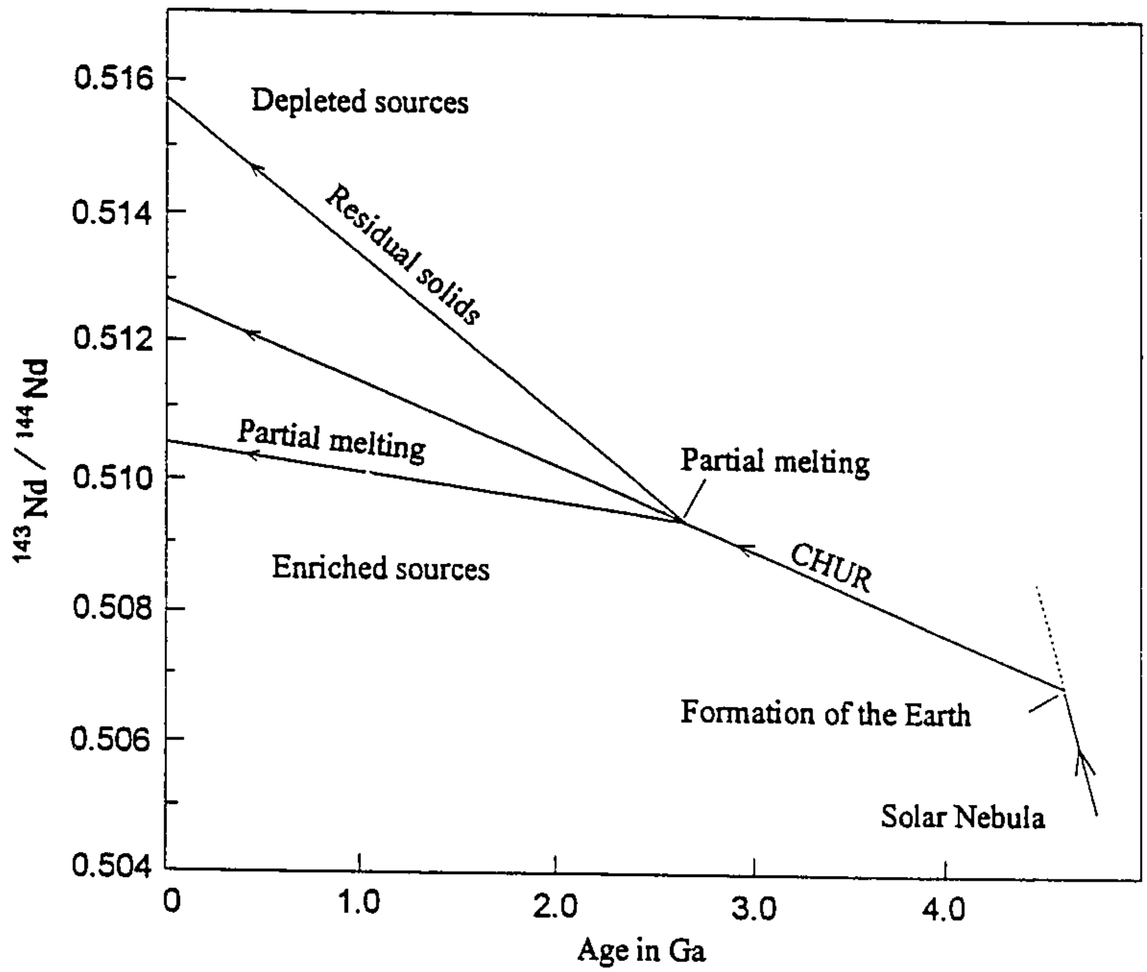


Fig. 2.1 Isotopic evolution of Nd in a chondritic uniform reservoir (CHUR). Magma formed by partial melting has a lower Sm/Nd ratio than CHUR, whereas the residual solids have a higher Sm/Nd ratio. As a result, the present-day $^{143}Nd/^{144}Nd$ ratio of the rocks formed from the partial melts (e.g., the continental crust) is less than that of CHUR, whereas the ratio for the rocks derived from the residual solid (e.g., the depleted mantle) is higher than CHUR (from Faure, 1986).

$^{143}Nd/^{144}Nd$ ratio of CHUR. εNd was introduced by DePaolo and Wasserburg (1976) and defined as

$$\varepsilon_{(t)} = \left(\frac{\left(\frac{143Nd}{144Nd}\right)_i}{I^t_{CHUR}} - 1 \right) \times 10^4 \quad [2.3]$$

$\varepsilon_{(t)}$ expresses the difference between the initial $^{143}Nd/^{144}Nd$ ratio of a rock and the corresponding value of this ratio in CHUR at the time of crystallization of the rock. Thus, like the $^{143}Nd/^{144}Nd$ of a rock with respect to that of CHUR, a positive $\varepsilon_{(t)}$ value indicates that the rock was derived from a depleted reservoir (the depleted mantle, DM), whereas a negative εNd value indicates that the rock originated from a source that had a lower Sm/Nd ratio than CHUR (the continental crust).

2.3. Model ages

A model age is a measure of the length of time a sample has been separated from its original source. Based on the source proposed, there are two commonly quoted models for calculation of model age. One is T_{CHUR} (McCulloch and Wasserburg, 1978), where the source proposed is CHUR; the other refers to the depleted mantle as source. A model age calculated relative to either CHUR or depleted mantle is the time in the past at which the sample had the same Nd isotopic composition as CHUR or depleted mantle. It is also the time at which the sample acquired a different Sm/Nd ratio from that of CHUR or depleted mantle. The meaning of the above two models is shown in Fig. 2.2.

According to equations [2.1] and [2.2], the t_{CHUR} can be calculated when [2.1] = [2.2], i.e:

$$I^0_{CHUR}-\left(\frac{147Sm}{144Nd}\right)^0_{CHUR}(e^{\lambda t}-1)=\left(\frac{143Nd}{144Nd}\right)^m_R-\left(\frac{147Sm}{144Nd}\right)^m_R(e^{\lambda t}-1)$$

This yields,

$$t=\frac{1}{\lambda}\ln\left(\frac{\left(\frac{143Nd}{144Nd}\right)^m_R-I^0_{CHUR}}{\left(\frac{147Sm}{144Nd}\right)^m_R-\left(\frac{147Sm}{144Nd}\right)^0_{CHUR}}+1\right) \quad [2.4]$$

However, studies of Nd isotopes from Precambrian rocks have shown that the mantle which supplied the continental material has evolved since the early Archean with a greater $^{143}Nd/^{144}Nd$ ratio or a positive εNd with respect to that of CHUR. In this study, rocks from a ca. 2.7 Ga Archean terrane also have εNd values greater than +3, which indicates the existence of depleted mantle in this region during the late Archean. Thus, instead of using T_{CHUR}, most Nd isotopic studies of continental rocks now adopt the depleted mantle as

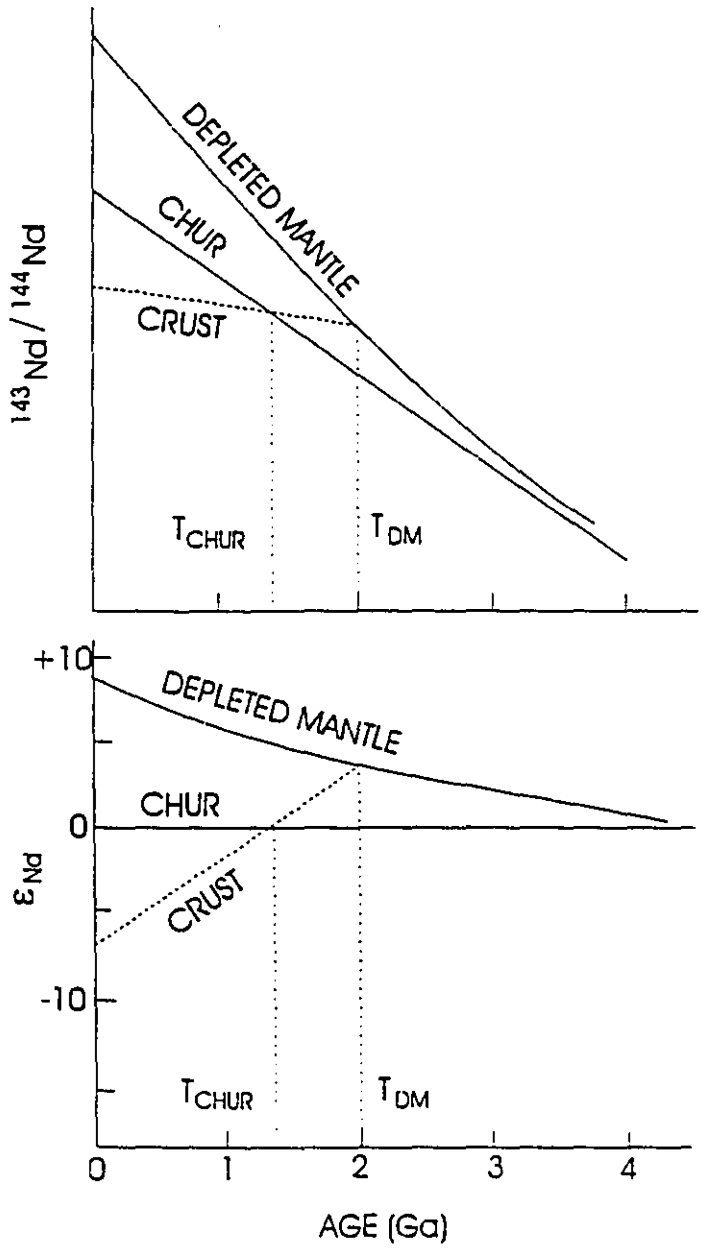


Fig. 2.2 The meaning of the T_{CHUR} and T_{DM} models (from DePaolo, 1987).

the source to calculate Nd model ages (DePaolo, 1981; Nelson and DePaolo, 1985; Patchett and Arndt, 1986; Barovich et al., 1989; Dickin and McNutt, 1989). With reference to a Nd model age calculated based on the source of depleted mantle, the T_{CHUR} underestimates the crustal formation age by about 200-400 Ma.

There are quite a few different models for description of Nd isotopic evolution of depleted mantle. Among these models, the T_{CR} model of Goldstein et al. (1984) and the T_{DM} model of DePaolo (1981) are commonly used. As shown in Fig. 2.3, the T_{CR} model expresses Nd isotope evolution in depleted mantle as a straight line (εNd=+10 for today and 0 for 4.5 Ga ago), which thus suggests the Sm/Nd ratio and Nd isotopic composition in the depleted mantle is unchanged as time elapses. The DePaolo T_{DM} uses an empirical equation to describe Nd isotope evolution in depleted mantle as follows,

$$\varepsilon Nd(t)_{DM}=0.25t^2-3t+8.5 \quad [2.5]$$

Nowadays, most Nd isotopic studies of crustal growth favour DePaolo's T_{DM} model because it represents a better approximation to be source of the continental crust. The concept for this model is that as time elapsed, the continental crust was formed by repeated extraction from the depleted mantle and thus the Sm/Nd, and in turn, the $^{143}Nd/^{144}Nd$ ratio of the depleted mantle should vary as function of time.

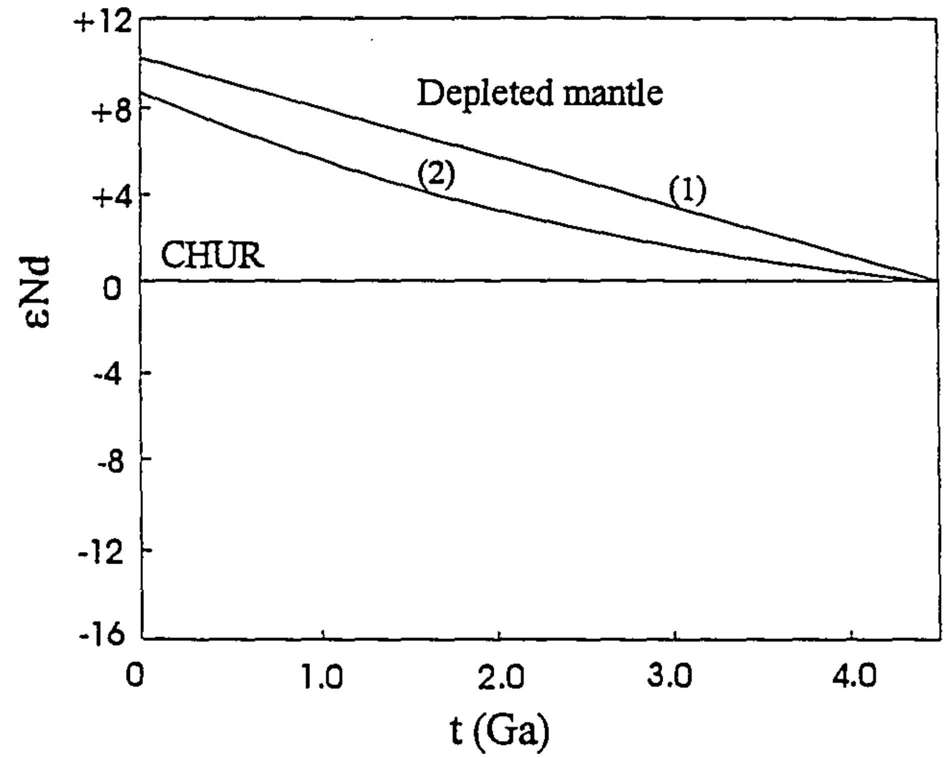


Fig. 2.3 Different Nd isotopic evolution paths of depleted mantle. Line (1): the T_{CR} model of Goldstein et al. (1984). Line (2): the T_{DM} model of DePaolo (1981).

Another major reason for general acceptance of the T_{DM} model of DePaolo is that the model was established on the basis of Nd isotopic data for island arcs. Growth of island arcs is commonly thought to be a major process for the mantle to supply material to the continental crust. In DePaolo's model, an average εNd value of +8.5 for modern island arcs was used to represent today's depleted mantle, and another value of +3.7 obtained from the Colorado gneiss was suggested for the 1.8 Ga mantle (DePaolo, 1981). The T_{DM} model was fitted through these two points and plus a zero point at 4.5 Ga ago.

According to their experiences, Dickin and McNutt (1989) argued that the model is suitable for Proterozoic subduction-related magmas because these magmas were derived from depleted mantle which has less depleted isotopic signatures than do MORB (e.g., Patchett and Bridgwater, 1984; Otherman et al., 1984). An additional advantage in using T_{DM} model age is the ease of comparison with other North American data (e.g., DePaolo, 1981; Nelson and DePaolo, 1985; Bennett and DePaolo, 1987)

When calculating model ages, the following assumptions (Arndt and Goldstein, 1987) upon which they are based have to be remembered.

1). A short time was involved for the sample between crustal emplacement and mantle extraction.

2). All material of the sample came from a single extraction event and the Sm/Nd ratio of the sample has not been modified by subsequent intracrustal events.

The second assumption is very important because several intracrustal events could modify the Nd isotopic ratios. The intracrustal events mainly include sedimentary mixing between detritus derived from different sources, crustal assimilation of a magma and crustal anatexis.

Although intracrustal events can obscure original Nd isotopic systems and make them geologically abnormal, a modified Nd isotopic system in a certain geological body can provide useful information about true materials involved in the body during an intracrustal event. Further, one can determine crustal age structure at depth (for igneous rocks) or in the source region (for sedimentary rocks), where the geological body was derived or passed through.

A typical choice for this kind of study is granitoids, which were formed either by mantle-derived magmas subjected to crustal assimilation, or crustal materials through anatexis.

A juvenile mantle-derived magma could experience crustal assimilation from older wall rocks during its ascent. This particularly happens in tectonic environments, where thick continental crust exists, such as active continental margin and continental rifts. Crustal assimilation will result in a smaller value of εNd and an obviously older Nd model age for the magmatic body with respect to εNd of the mantle source and crystallization age (Fig. 2.4). From the Nd isotopic data, combined with regional geological information,

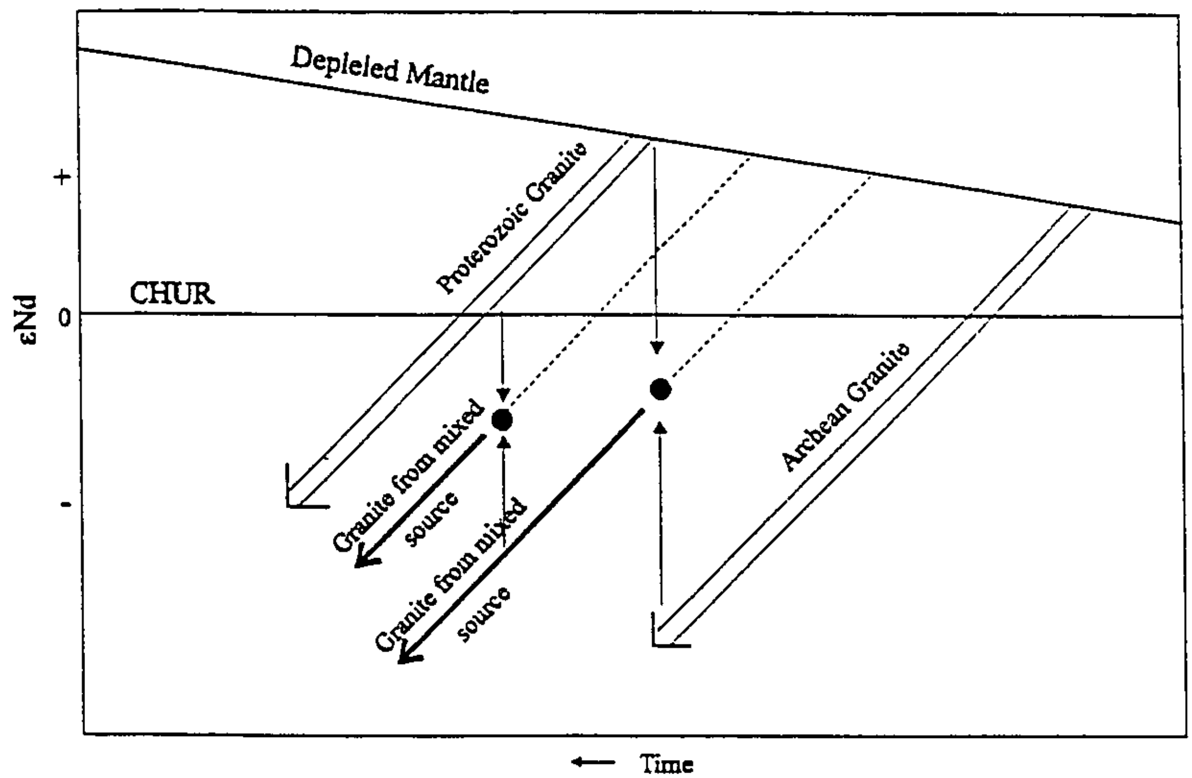


Fig. 2.4 Model ages of rocks from mixed sources do not represent crust-formation events (from Arndt and Goldstein, 1987).

one can establish crustal age structure at depth and infer the evolution history of the magmatic body.

Granitoids produced by crustal anatexis can also be used to study crustal age structure at depth and their petrogenesis. Granitoids, which are purely derived from remelting of pre-existing crust, in general yield younger model ages than those of source rocks. This is caused by fractionation between Sm and Nd during generation of magmas, while discrepancies in Nd model ages between the crustal formation and granitoids depend upon how large the time span is. Examples of Nd isotopic study of crust-derived granitoids have been given by Farm and DePaolo (1983), Nelson and DePaolo (1985) and Bennett and DePaolo (1987) in the western U.S. and Dickin and McNutt (1989, 1991), Dickin et al. (1990) in the Grenville Province of Ontario, Canada. These studies have identified the presence of the older basement under younger cover.

CHAPTER THREE:
THE SOUTHERN LIMIT OF ARCHEAN CRUST AND SIGNIFICANCE OF ROCKS WITH 1.8-1.9 GA MODEL AGES: Nd MODEL AGE MAPPING RESULTS IN THE GRAND-REMOUS AREA, THE GRENVILLE PROVINCE OF WESTERN QUEBEC

3.1. Geological setting

The Grand-Remous area lies in the Central Gneiss Belt (CGB, Wynne-Edwards, 1972) of the Grenville Province, western Quebec (Fig. 3.1). According to the tectonic subdivision of Indares and Martignole (1990), the study area straddles both the Parautochthonous Belt (PB) and the Allochthonous Polycyclic Belt (APB, Rivers et al., 1989) in the vicinity of the Renzy Shear Belt (Fig, 3.2). This belt was proposed as an eastern extension of the Allochthon Boundary Thrust and a major crustal discontinuity dividing Archean from Proterozoic crust (Indares and Martignole, 1990). However, in a recent study, Martignole and Pouget (1993) have revised the previous model of Indares and Martignole (1990) by expanding the Parautochthon to the south of the Renzy Belt.

As shown in Fig. 3.2, to the southeast and northeast, the basement of the Grand-Remous area is overlain by the Central Metasedimentary Belt (CMB) along the Monocyclic Belt

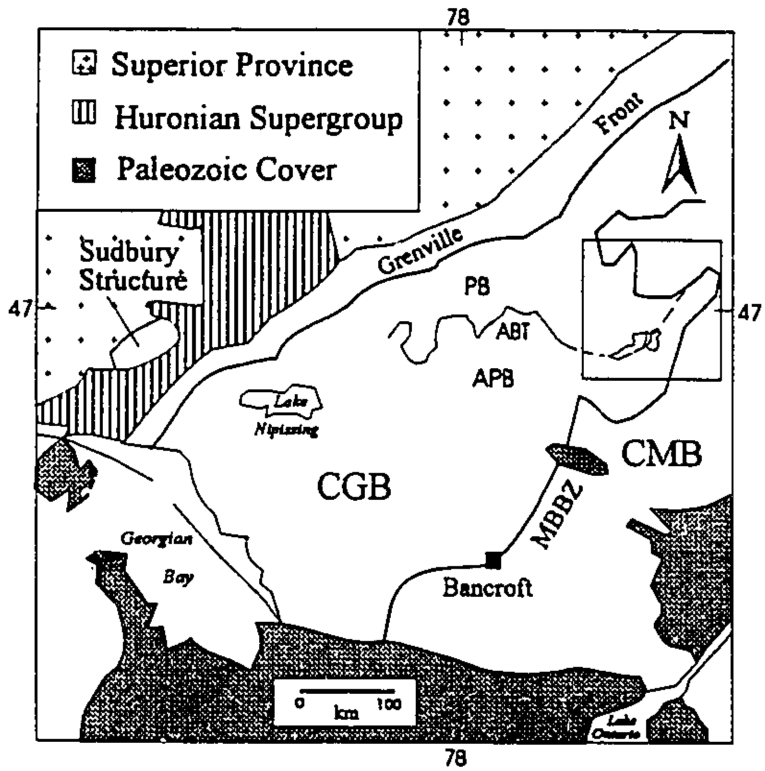
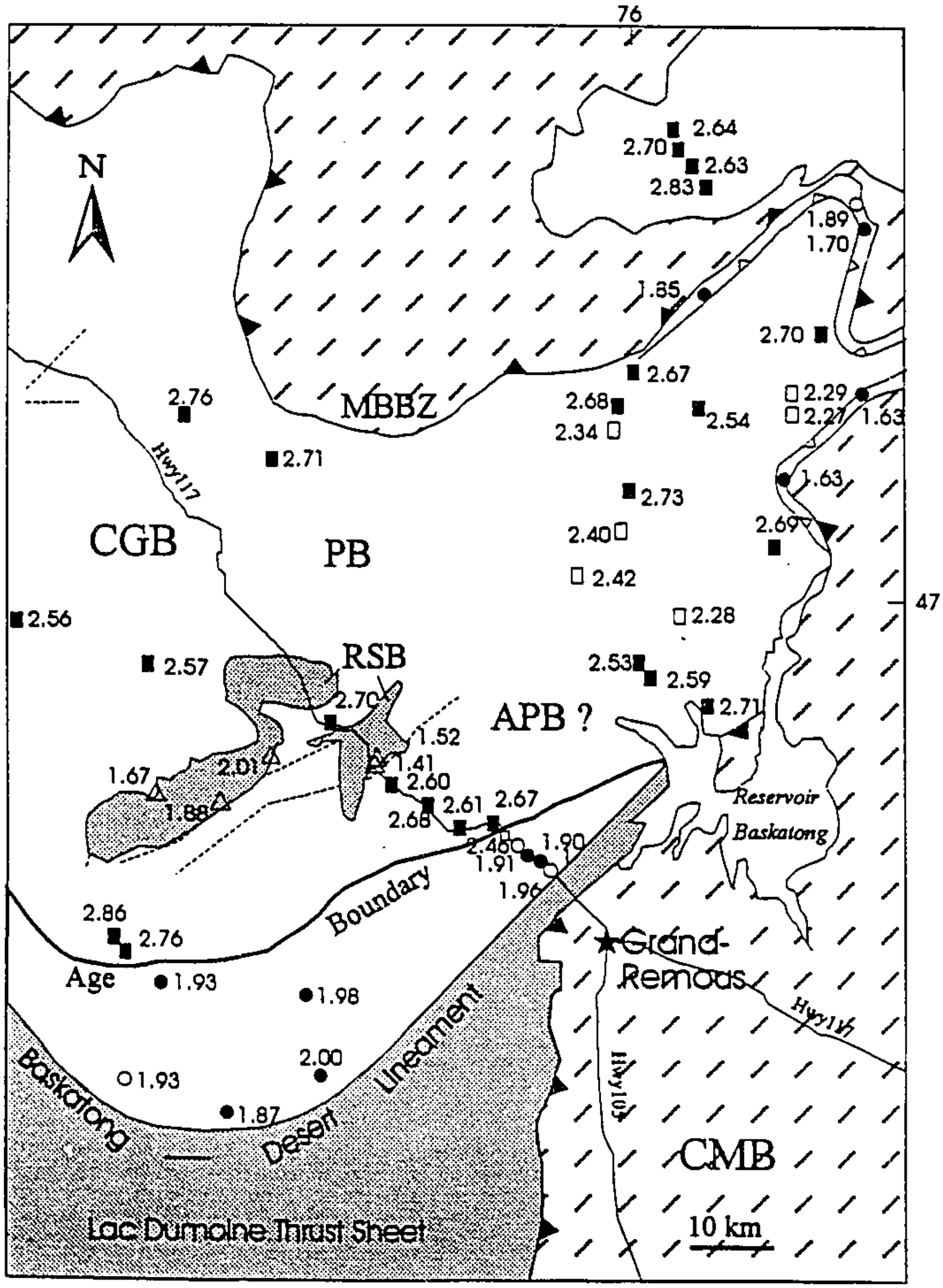


Fig. 3.1 Geological setting of the western Grenville Province. CGB: the Central Gneiss Belt. CMB: the Central Metasedimentary Belt. PB: the Parautochthonous Belt. APB: the Allochthonous Polycyclic Belt. ABT: the Allochthon Boundary Thrust. RSB: the Renzy Shear Belt (Indares and Martignole, 1990). The inset represents the study area, the Grand-Remous area.

Fig. 3.2 Map showing the Nd model age mapping results in the Grand-Remous area. MBBZ: Monocyclic Belt Boundary Zone. RSB: the Renzy Shear Belt (Indares and Martignole, 1990). Dash line: Shear zones (Martignole and Pouget, 1993). ■ and ●: samples with Archean and ca. 1.9 Ga model ages, respectively. □ and ○: plutonic rocks with model ages of 2.0-2.4 Ga and 1.8-1.9 Ga. △: samples from the RSB.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47
N
MBBZ
CGB
PB
RSB
APB ?
CMB
Hwy117
Hwy117
Hwy105
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Baskatong
Grand-
Remous
Boundary
Age
Baskatong
Desert
Lineament
Lac Dumoine Thrust Sheet
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2.70
2.63
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1.87

Boundary Zone (MBBZ). The southern limit of the study area is marked by the Baskatong-Desert Lineament, a major deformation zone defined by Sharma et al. (1992). The Lineament extends from the west where it probably connects with the ABT to northeast near the Reservoir Baskatong, where it merges with the MBBZ.

The major rock types exposed to the north of the Renzy Belt are biotite and/or hornblende quartzofeldspathic gneisses, which were recognized as grey gneiss by Doig (1977) and identified as the tonalite-trondhjemite-granodiorite (TTG) suite by Ciesielski (1992). To the south of the Renzy Belt, the lithology is similar to that exposed in the north. However, these rocks contain charnockites, which cannot be seen north of the Renzy Belt except in the X-terrane near the Grenville Front (Indares and Martignole, 1990).

Rocks with various origins were tectonically juxtaposed within the Renzy Belt. These rocks include grey gneisses, garnet amphibolites, subordinate ultramafic rocks (dunites, pyroxenites and lherzoites), charnockites and aluminous gneisses. This rock assemblage is not seen on either side of the Belt.

Based on lithological, aeromagnetic, and especially isotopic age data, including U-Pb ages of 2.60-2.74 Ga (Krogh and Davis, 1974; Krogh, 1989; Krogh et al., 1992; Joly, 1990; Childe, et al., 1993) and Rb-Sr ages of 3.0-2.06 Ga (Doig, 1977), the area to the north of the Renzy Belt is thought to be a southern extension of the Archean parautochthon (Indares and Martignole, 1990; Ciesielski, 1992). Available age data from the south of the Renzy Belt are restricted to charnockites (Rb-Sr whole rock age of 1170±44 Ma, Doig, 1977), which indicate a Grenvillian thermal event.

3.2. Results

3.2.1. Sm-Nd data

Sm-Nd isotopic data and Nd model age mapping results are shown in Table 3.1 and Fig. 3.2, respectively. As shown in Fig. 3.2, samples with Archean model ages of 2.5 -2.8 Ga were found on the NW side and the south side of the Renzy Shear Belt. To the east, the rocks with Archean model ages can be traced toward the MBBZ. Further to the northeast, beyond the MBBZ, four samples with Archean model ages of 2.63-2.83 Ga have also been identified. Eight samples to the NW side of the Renzy Belt yielded an average age value of 2.67 ± 0.09 Ga (SD = 1σ), while 15 samples to the south and east averaged a value of 2.67 ± 0.08 Ga (SD = 1σ). All samples from both sides of the Renzy Belt gave an average age value of 2.67 Ga ± 0.08 Ga (SD = 1σ).

Continuing south from the exposure of rocks with Archean model ages, a SW-NE trending strip approximately 10 km wide was mapped out. The strip consists mainly of biotite

Table 3.1 SM-ND DATA (samples with Archean model ages)

SAMPLE	AREA (Grid ref.)	Sm(ppm)	Nd(ppm)	147Sm/144Nd	143Nd/144Nd	AGE(Ga) (TDM)
THE NORTH OF THE RSB						
RB15A	VH330/490	2.24	14.28	0.0947	0.510852	2.83
RB16	VH322/513	1.80	10.75	0.1011	0.511113	2.63
RB17	VH318/519	3.01	16.72	0.1088	0.511198	2.70
RB18	VH319/526	1.30	8.09	0.0973	0.511038	2.64
M802	UH802/272	2.89	15.67	0.1113	0.511205	2.76
M886	UH886/183	2.72	15.82	0.1038	0.511098	2.72
GF4	UG750/999	1.25	9.17	0.0822	0.510882	2.57
GF6	UH618/062	8.48	59.30	0.0864	0.510927	2.56
THE SOUTH OF THE RSB						
BR3	WG261/98	5.02	29.10	0.1042	0.511233	2.53
BR9	VG399/105	9.56	65.03	0.0888	0.510853	2.69
BR12	WG319/94	1.93	10.49	0.1112	0.511237	2.71
BR13	WG281/96	1.75	27.67	0.1001	0.511125	2.59
RB6	VG063/820	1.33	9.86	0.0842	0.510807	2.61
RB7	VG037/844	9.37	55.46	0.1022	0.511094	2.68
RB8	VG012/865	1.66	10.90	0.0919	0.510973	2.60
RB11	VH253/154	1.77	10.83	0.0988	0.510998	2.73
RB13	VH263/267	2.14	13.18	0.0980	0.511021	2.68
RB14	VH267/277	3.76	20.94	0.1098	0.511275	2.67
RB21	VH334/230	0.65	4.40	0.0949	0.511052	2.57
Vol136	UG950/932	1.84	12.54	0.0884	0.510836	2.70
Vol160	UG098/830	6.32	33.70	0.1134	0.511296	2.67
LV4	UG715/720	3.08	19.64	0.9046	0.509217	2.76
LV5	UG704/735	3.07	17.95	0.1033	0.510990	2.86
ZP5	VH465/330	4.23	34.29	0.0745	0.510589	2.70

Table 3.2 SM-ND DATA (samples with model ages of <2.5 Ga)

SAMPLE	AREA Grid ref.	Sm(ppm)	Nd(ppm)	147Sm/144/Nd	143Nd/144Nd	AGE(Ga) (TDM)
Samples with 1.6-1.9 Ga (TDM)						
Biotite Gneisses						
LV2	UG935/695	7.84	41.29	0.1147	0.511737	1.98
LV3	UG761/691	6.96	37.67	0.1117	0.511754	1.93
MAW6	UG877/530	17.64	86.24	0.1238	0.511861	2.00
MAW8	UG822/543	8.18	47.65	0.1038	0.511691	1.87
Vo1632	VG130/766	13.22	75.09	0.1064	0.511658	1.91
Vol1679	VG167/766	4.27	23.5	0.1098	0.511753	1.88
RB24	VH432/180	0.59	38.34	0.1354	0.512203	1.63
ZP2	VH522/252	6.34	29.53	0.1297	0.512145	1.63
ZP9	VH154/733	6.11	34.53	0.1069	0.511740	1.85
ZP14	VH519/430	9.67	61.74	0.0946	0.511715	1.70
Plutonic rocks						
RB2	VG153/787	11.88	61.10	0.1176	0.511806	1.96
RB4	VG108/818	8.75	49.81	0.1062	0.511704	1.90
ZP12	VH116/814	5.21	30.40	0.1038	0.511664	1.89
MAW9	UG737/580	8.33	48.85	0.1031	0.511644	1.93
Samples with 2.0-2.4 Ga (TDM)						
Plutonic rocks						
BR6	VH304/035	7.84	50.02	0.0947	0.511267	2.28
RB5	VG101/830	1.01	6.84	0.0891	0.511037	2.46
RB9	VG195/063	4.42	25.57	0.1045	0.511319	2.42
RB10	VH227/092	5.78	32.9	0.1061	0.511358	2.40
RB20	VH263/258	13.13	75.74	0.1048	0.511357	2.37
RB22	VH413/248	14.06	76.10	0.1116	0.511512	2.29
RB23	VH421/232	11.15	59.55	0.1131	0.511549	2.27
Renzy Shear Belt						
Vo1439	UG985/883	8.91	44.08	0.1221	0.512195	1.41
Vo1441	UG986/883	9.63	44.74	0.1302	0.512209	1.52
X870	UG870/894	7.81	50.18	0.0941	0.511425	2.01
X803	UG803/848	7.08	64.05	0.1004	0.511646	1.88
X725	UG725/878	10.45	58.82	0.1074	0.511879	1.67

gneisses which yield ca. 1.9 Ga model ages. Between this strip and the rocks with Archean model ages to the north, a narrow age boundary (< 1 km wide) can be drawn. To its south, the strip is bounded by the Baskatong-Desert Lineament, which separates it from the Lac Dumoine Thrust Sheet, a terrane consisting of Proterozoic materials (see Chapter 5). Further northeast from the Baskatong Reservoir, samples with model ages of 1.89 - 1.63 Ga were identified in a narrow zone along the MBBZ.

Five samples taken from the Renzy Belt yielded Nd model ages ranging from 2.01 to 1.41 Ga (Table 3.1 and Fig. 3.2). These model ages are in strong contrast with the surrounding rocks that have Archean model ages.

In order to know the age structure of the crust at depth, granitoid plutons on both sides of the age boundary were analyzed (Table 3.1 and Fig. 3.2). A noticeable feature is that plutons located to the north of the age boundary have model ages greater than 2.0 Ga, whereas plutons on the south of the boundary yield model ages around 1.9 Ga. Of 6 samples with model ages of >2.0 Ga, 3 are granitic plutons and have model ages around 2.27-2.37 Ga, the others, granodioritic plutons, range from 2.40 to 2.46 Ga.

3.2.2. Petrology of Samples

Major element analyses for samples are listed in

Appendix 3. Trace element Rb, Nb, Sr, Zr and Y were analyzed in selected samples and the relevant data are listed in Table 3.3.

The major rock type of samples with Archean model ages taken from both sides of the Renzy Belt is biotite gneiss. The rocks generally contain 10-15% biotite and about 60% oligoclase as well as minor sphene and opaque minerals. Some rocks are high in biotite and/or hornblende (ca. 25%). The gneisses display weak sericitization of plagioclase and epidotization of hornblende.

When plotted on the chemical-mineralogical classification diagram (Fig. 3.3A, Debon and Le Fort, 1983), samples having Archean model ages on both sides of the Renzy Belt mostly fall in the field of tonalite (to). This result is identical with the petrological study done by Ciesielski (1992).

Samples having model ages of 2.0-2.4 Ga (RB20, RB22 and RB23) are mostly K-feldspar-rich and less foliated, apparently representing granitoid plutons. On the Q-P diagram (Fig. 3.3B), these rocks are quite variable in composition. BR6, with a negative Q value, falls below the line of Q=0 (not shown in Fig. 3.3B).

Biotite gneiss was the major rock type sampled from the 1.9 Ga (TDM) strip and the area adjacent to the MBBZ. However, compared to the biotite gneisses with Archean model ages, these rocks contain more K-feldspar (ca. 10%). This

Table 3.3 TRACE ELEMENT ANALYSES (in ppm)

Samples with Archean TDM

	RB6	RB7	RB8	RB17	RB15A	GF4	GF6
Nb	4.3	6.9	4.9	5.1	3.7	4.3	9.0
Zr	80.8	236.8	113.7	124.2	114.0	109.1	200.6
Y	3.8	13.8	3.9	10.3	5.4	3.5	8.2
Sr	500.2	364.6	516.2	675.6	364.3	498.5	640.6
Rb	40.8	111.1	39.6	24.0	36.4	37.8	82.5

Samples with 2.0-2.4 Ga TDM	RB20	RB23	Samples with 1.8-1.9 Ga TDM: LV2	LV3	RB2	RB4
Nb	14.9	14.6	12.1	10.0	32.1	17.3
Zr	294.3	235.1	247.0	188.7	430.6	295
Y	50.1	55.8	39.4	24.5	62.5	42.3
Sr	92.4	243.6	538.5	915.7	406.7	834.4
Rb	106.4	97.7	65.6	59.1	84.1	67.4

	ZP12	Vo163	Vo167	MAW8	MAW6
Nb	10.7	7.7	8.8	14.2	14.5
Zr	587.9	nd	nd	nd	nd
Y	45.9	15.8	12.5	31.1	28.4
Sr	517.6	nd	nd	nd	nd
Rb	87.7	nd	nd	nd	nd

results in their distribution in the fields of the quartz monzodiorite (mdzq), adamellite (ad) and granite (gr) in the Q-P diagram (Fig. 3.3C). Sample ZP9 taken from the area near the MBBZ contains abundant quartz and it appears to be a siliceous rock with a sedimentary origin. The majority of samples from the Renzy Belt plot in the quartz monzodiorite (mdzq) and adamellite (ad) fields (Fig. 3.3D).

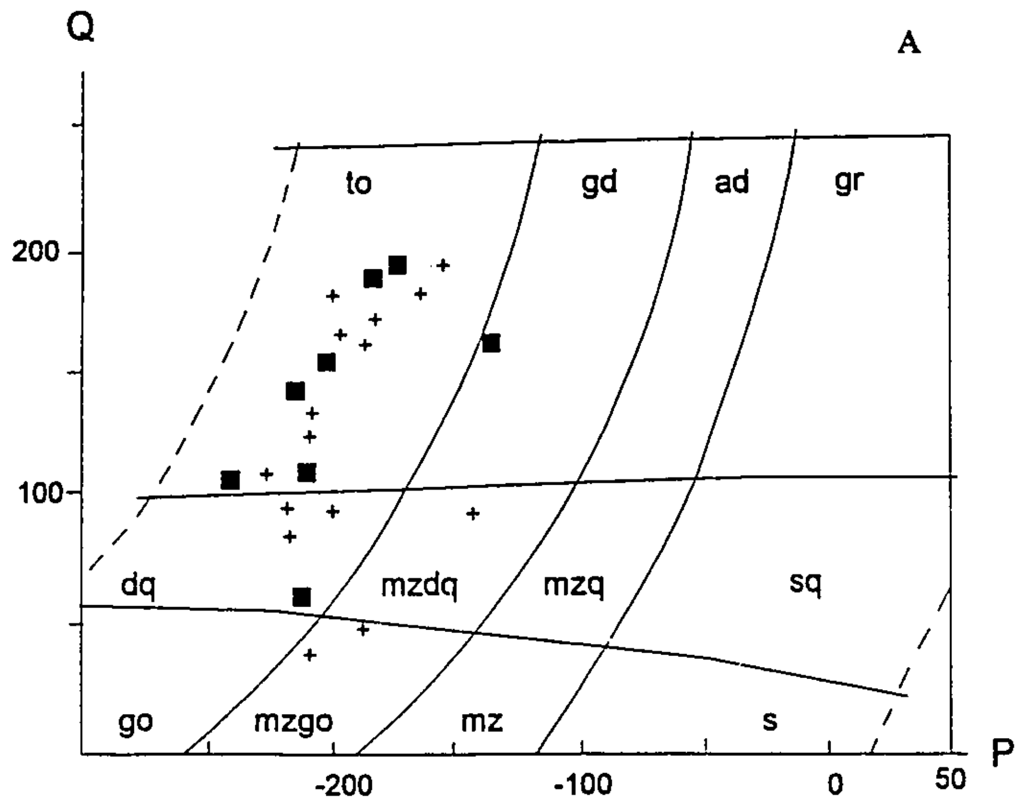
Further geochemical identification, using the Nb-Y diagram (Pearce et al., 1984), shows that rocks with Archean model ages fall in the VAG field (Fig. 3.4A). Two samples having model ages of 2.0-2.4 Ga (RB20 and RB23) plot in the WPG field (Fig. 3.4A). As shown in Fig. 3.4B, 6 samples with ca. 1.9 Ga model ages are plotted in the VGA field, and 3 (RB2, RB4 and ZP12) in the WPG (Fig. 3.4B). The samples in the WPG probably represent younger plutons formed in anorogenic settings with respect to the rocks in the VAG.

3.3 Discussion

3.3.1 Determination of Archean crust

As shown in Fig. 3.2, rocks with Archean model ages have been identified on both sides of the Renzy Shear Belt. The rocks exposed to the NW, as previously mentioned, are agreed to represent Archean crust. However, the protolith age for biotite gneisses country rocks south and east of the Renzy

Fig. 3.3 A & B Chemical-mineralogical grid. A. Biotite gneisses with Archean model age. (■): samples from the north of the Renzy Belt; (+): samples from the south of the Renzy Belt. B. Rocks with 2.0-2.4 model ages. Q = Si/3-K-Na-2Ca/3; P = K-Na-Ca. to = tonalite; gd =granodiorite; ad = adamellite; gr = granite; dq = quartz diorite; mzdq = quartz monzodiorite; mzq = quartz monzonite; sq = quartz syenite; go = gabbro; mzgo = monzogabbro; mz = monzonite; s = syenite.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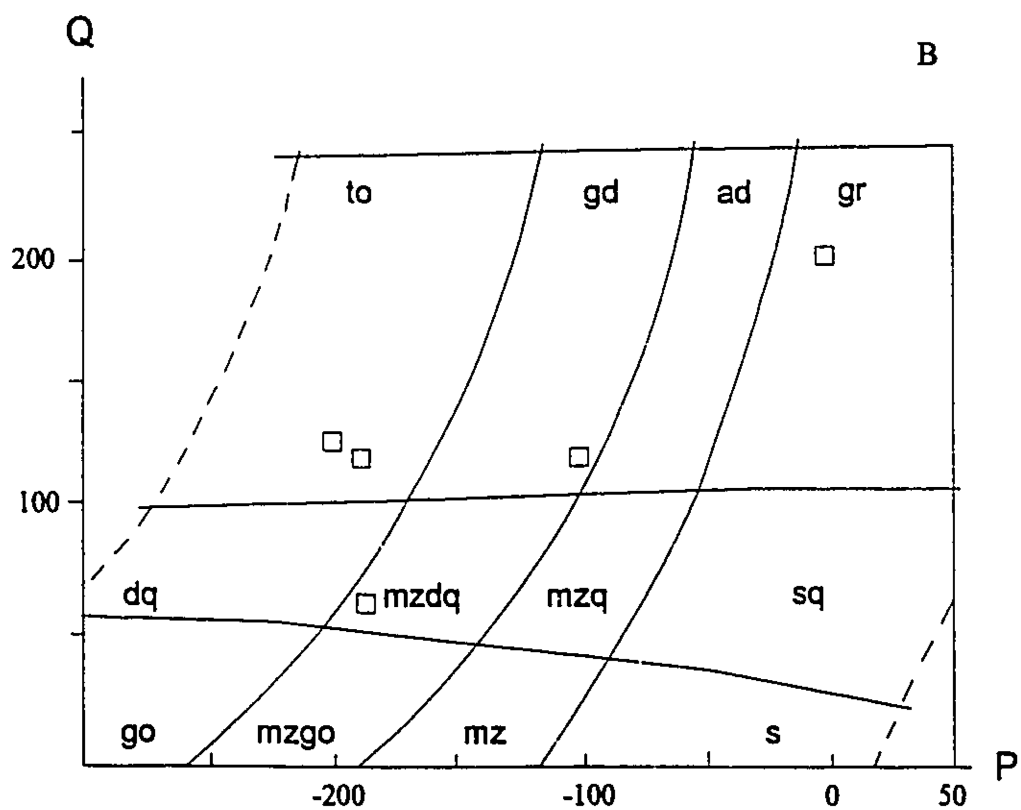
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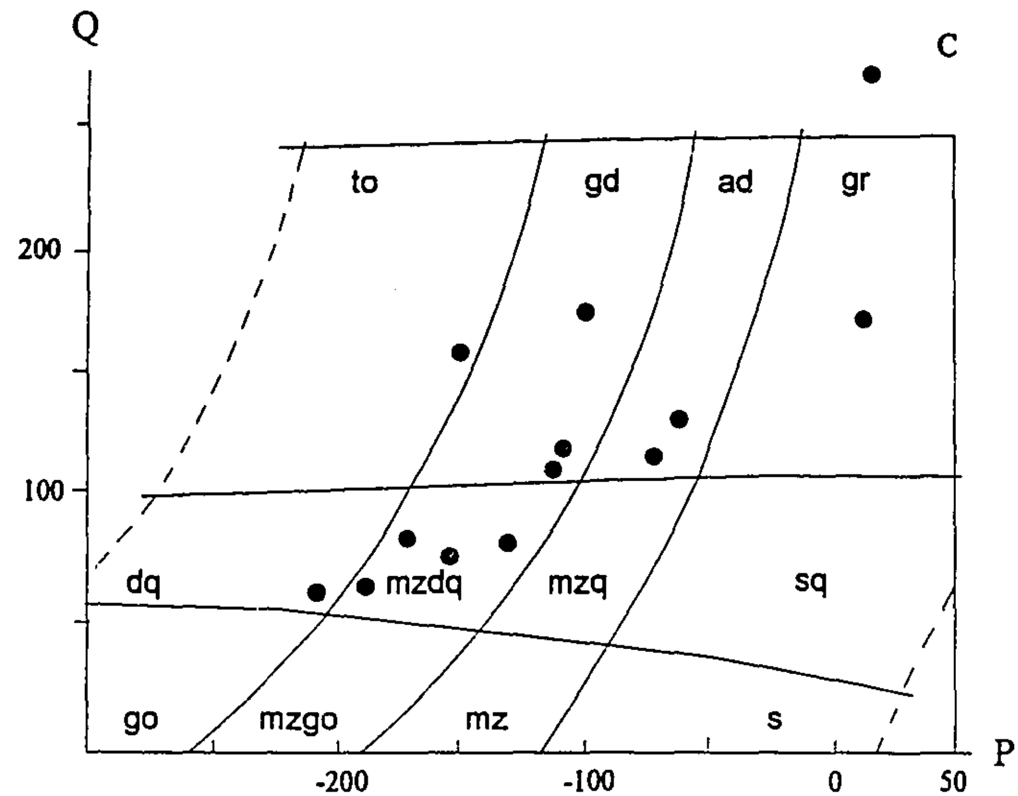
Fig. 3.3 C & D Chemical-mineralogical grid. C: Rocks with 1.8-1.9 Ga model ages. D: Rocks from the Renzy Shear Belt. Q= Si/3-K-Na-2Ca/3; P = K-Na-Ca. All terms refer to Fig. 3.3 A & B.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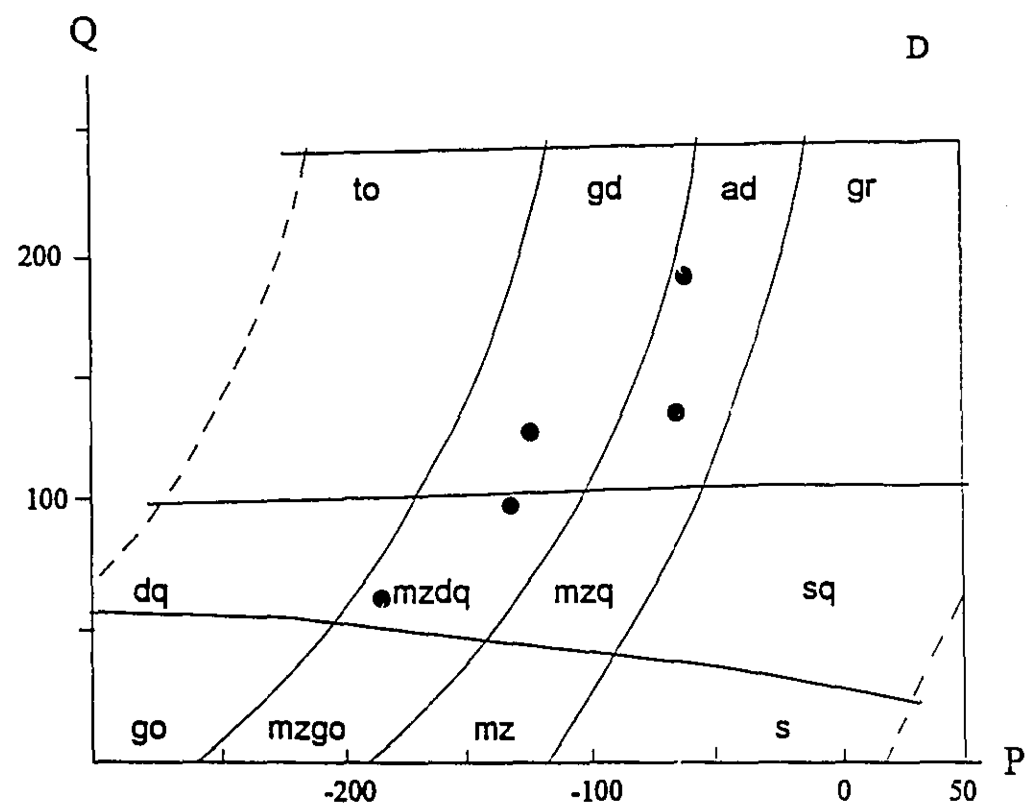
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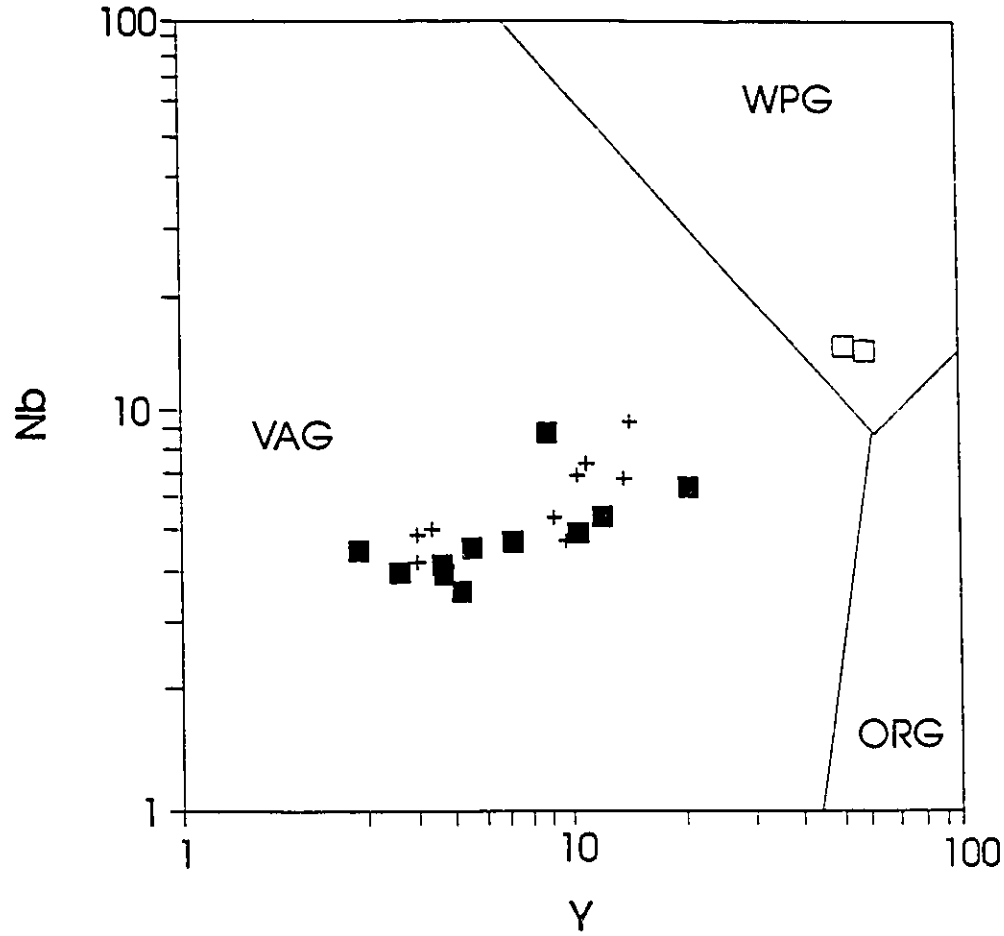


Fig. 3.4 A. Nb-Y diagram for samples with Archean model ages from both sides of the Renzy Shear Belt. (■): samples from the north of the RSB. (+): samples from the south of the RSB. (□): samples with model ages of 2.0-2.4 Ga. VAG: volcanic arc granites; WPG: within plate granites; ORG: ocean ridge granites.

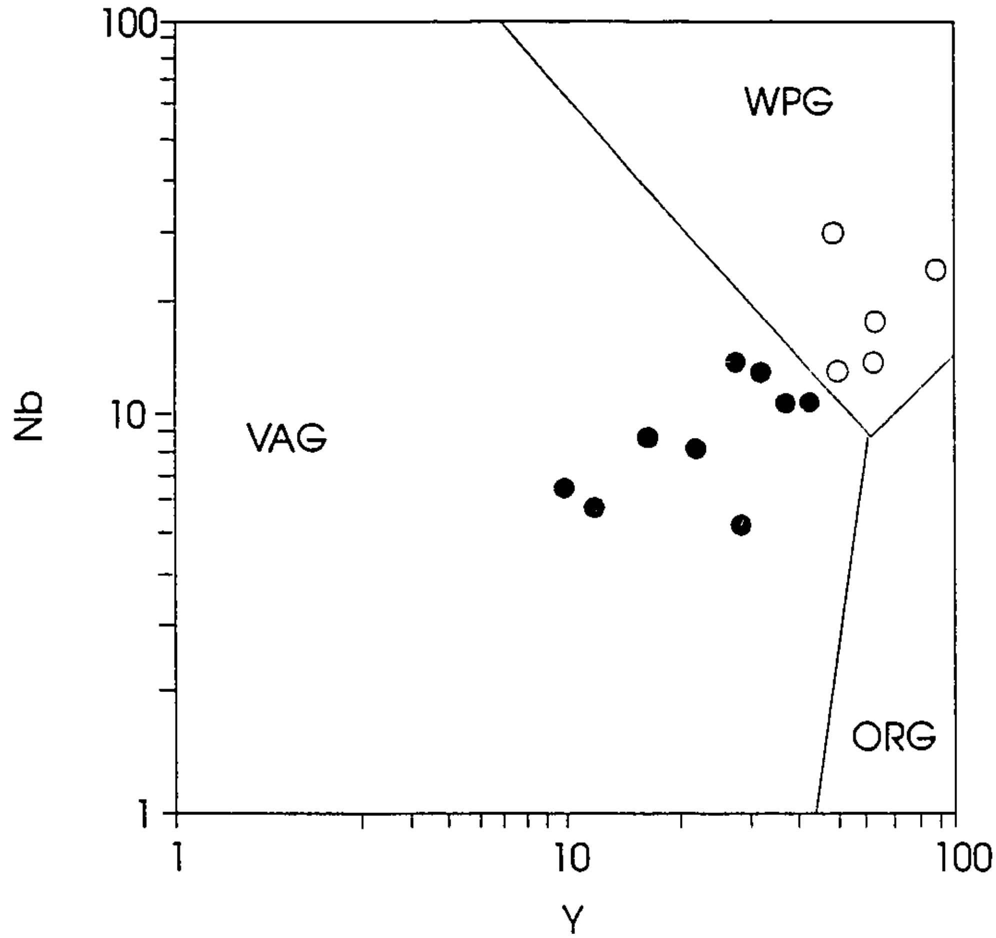


Fig. 3.4 B. Nb-Y diagram showing tectonic affinities for the biotite gneisses (●) and plutonic rocks (o) with 1.8-1.9 Ga model ages from both Grand-Remous and Kipawa-Mattawa areas (data of the Kipawa-Mattawa area are cited from Chapter 4).

Belt was unknown before the present study, although Gariépy and Verner (1989) suggested a complex pre-Grenvillian history for these gneisses. Thus, the meaning of the rocks with Archean model ages needs to be discussed. As a major feature of the PB, the uniformly low magnetic signature has been employed as an indicator of the presence of parautochthonous Archean crust in the Grenville Province (Rivers et al., 1989: Indares and Martignole, 1990; Ciesielski, 1992). As indicated by the 1:1,000,000 aeromagnetic anomaly map of the Grenville Province (Geological Survey of Canada, 1984), there is no apparent difference of magnetic signature between the two sides of the Renzy Belt and the uniformly low magnetic signature present in the north also continues to the south. Combined with the Nd isotopic evidence presented above, the low magnetic signature of the rocks exposed to the south of the Renzy Belt confirms the presence of Archean crust.

Geochemical similarities between the rocks with Archean model ages from both sides of the Renzy Belt are shown on the Q-P diagrams (Fig. 3.3A) and the Nb-Y diagram (Fig. 3.4A). These rocks display consistent tonalitic composition and an arc-related orogenic signature. The geochemical similarities indicate that the rocks from both sides of the Renzy Belt may have the same origin and belong to the same crustal formation.

From the above discussion, we suggest that the biotite gneisses with Archean model ages mapped out to the south of the Renzy Belt represent in situ Archean crust, which in turn, indicates that the Renzy Belt is not a crustal discontinuity dividing Archean from Proterozoic crust. Thus, the status of the Renzy Belt has to be clarified.

As shown in Fig. 3.2, 5 samples from the Renzy Belt yielded Nd model ages ranging from 1.41 to 2.01 Ga. The wide range of the model age value within the Belt is probably related to the complexity of the rock assemblages and isotopically reflects multiple provenances present in the Belt. These ages are in strong contrast with the surrounding gneissic rocks having Archean model ages. Similarly, gneisses and pegmatites from the Belt gave rise to Pb-Pb mineral ages of 1.1-0.98 Ga without any "Archean memory" with respect to the rocks on both sides of the Renzy Belt (Gariépy and Verner, 1989). Also, the metamorphic P-T condition (980Mpa, 750°C-850 Mpa, 690°C) for the Renzy Belt shows the difference from that recorded on both sides of the Renzy Belt (Indares and Martignole, 1990).

The distinctive characteristics of the Renzy Belt in isotopic ages, metamorphism and lithology suggest that the belt corresponds to an isolated allochthon. Based on Martignole and Friedman's study (1992) in which they suggested that NW-directed thrusting was over by about 1050 Ma in western Quebec, the emplacement of the Renzy Belt probably occurred before 1050 Ma during the Grenville orogenic cycle. As an allochthon, the Renzy Belt tectonically lies on Archean crust and the Renzy Belt itself thus does not represent the Allochthon Boundary Thrust proposed by Rivers et al. (1989) or the Allochthon Front named by Ciesielski (1992). Instead, a more prominent deformation zone to the south, the Baskatong-Desert Lineament defined by Sharma et al. (1992) probably marks the real allochthon boundary thrust in the Grand-Remous area (Fig. 3.2).

Moreover, Archean crust mapped out to the south of the Renzy Belt represents the southernmost outcrop of Archean crust in the Grand-Remous area. No evidence of any rock with Archean age (either Nd model age or crystallization age obtained from other methods) has been reported further south.

As a result, along Hwy 117 in the Grand-Remous area, Archean basement recognized by Nd model age mapping extends approximately 130 km from the Grenville Front and 20 km from the Renzy Belt, respectively, before it meets Paleoproterozoic material to its south.

3.3.2. A Paleoproterozoic arc

Previous Sm-Nd studies conducted by Dickin and McNutt (1989, 1990) have mapped out a 1.8-1.9 Ga TDM terrane in an area of over 10,000 km^2 in the Central Gneiss Belt of the Grenville Province, Ontario. In addition, a zircon age of 1.9 Ga has been determined from the Alban quartzite in the French River area, Ontario, using the Pb/Pb single zircon evaporation method (Mueller, 1991). These data imply that a Paleoproterozoic arc with 1.8-1.9 Ga Nd model ages could have been accreted to the margin of Laurentia (Hoffman, 1989).

The biotite gneisses with Nd model ages of 1.8-1.9 Ga found in the study area possess an arc affinity as indicated by Fig. 3.4B. They probably represent 1.9 Ga old arc related material. In contrast, the plutons having the same range of model ages obtained from both the strip and the Proterozoic zone near the MBBZ display an anorogenic signature (Fig. 3.4B). These plutons could have been derived from remelting of the arc material.

As seen in Fig. 3.2, the 1.9 Ga arc related material is concentrated in a NE trending strip in the Grand-Remous area. The strip makes direct contact with Archean crust to its north along the age boundary defined by this work. Based on lack of any evidence of observed Grenvillian shearing, the age boundary here can be interpreted as a suture, between the proposed Paleoproterozoic arc and Archean crust. The narrow zone with model ages of 1.89 - 1.63 Ga along the MBBZ to the east can be interpreted as Paleoproterozoic basement of the overthrusting rocks of the Central Metasedimentary Belt. This basement could have been exhumed from depth and thrust onto the CGB in the proposed Monocyclic Belt Foreland Zone (Sharma et al., 1992).

The age data of plutons from both sides of the age boundary in the study area also provide evidence for the interpretation of a suture. To the north of the age boundary, all plutons yield model ages of > 2.0 Ga and a narrow ε Nd values of -22 to -25, which are close to the values (-27 to -39) of the country rocks with Archean model ages. This is similar to the Nd isotopic studies of Dickin and McNutt (1989) and Dickin et al. (1990) in the northwest Grenville of Ontario, where all granitoid plutons intruded into a crustal section formed largely of Archean basement have Nd model ages of > 2.0 Ga. By contrast, no plutons with model ages of >2.0 Ga have been found to the south of the boundary. This implies that there may be no Archean crust present at depth beyond the age boundary and the age boundary thus probably represents a tectonic division on a crustal scale.

Although the age boundary is proposed as a suture in the study area, unlike the suture between the Wisconsin Magmatic Terrane and the Superior Province in the Penokean Orogen of the Lake Superior region (Sims et al., 1989; Barovich et al., 1989), the precise age of suturing is hard to constrain because of polycyclic orogenic activity. Despite this difficulty, based on the regional geological studies, we present a few lines of evidence to argue that a 1.7-1.8 Ga terminal collisional orogeny between the 1.9 Ga arc and Laurentian continent probably occurred in the study area. The evidence includes: 1) The prevailing Laurentia-Paleoproterozoic arc collision regime along the Laurentia continental margin during 2.0-1.8 Ga (Hoffman, 1989). 2) The structural effects of the Penokean orogeny in the Huronian Supergroup and the northwest Grenville Province (Brocoum et al., 1974; Zolnai et al., 1984; Green et al., 1988; Card, 1992). 3) A complete reset of the argon system at 1.8-1.84 Ga in the Huronian Supergroup. This event was thought to be a phase of the Penokean orogeny (Hu et al., 1991).

From the regional geological effects of the Penokean orogeny mentioned above and the Nd model age mapping results in the northwest Grenville Province in Ontario (Dickin and McNutt, 1989, 1991), the age of suturing between the Paleoproterozoic arc and the Laurentian continent is estimated to be at 1.75-1.85 Ga.

CHAPTER FOUR:

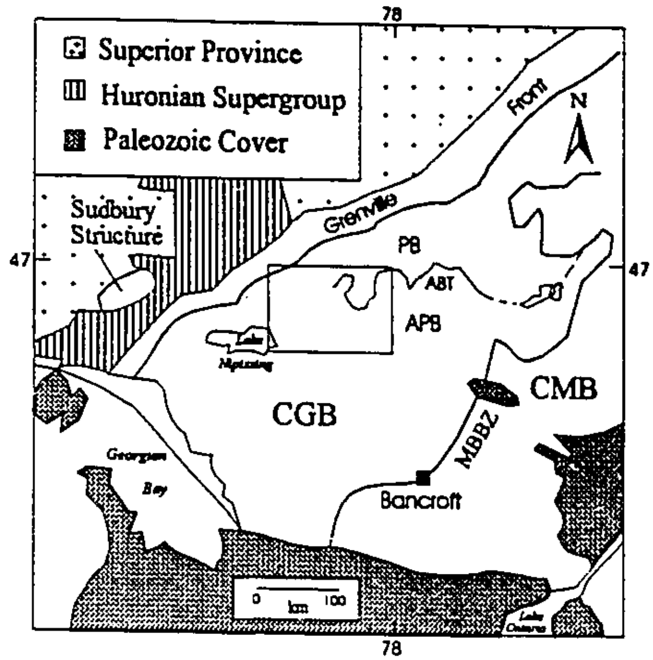
THE SOUTHERN LIMIT OF ARCHEAN CRUST AND EARLY PROTEROZOIC CRUSTAL EVOLUTION: ND ISOTOPIC EVIDENCE IN THE KIPAWA-MATTAWA AREA, GRENVILLE PROVINCE OF WESTERN QUEBEC

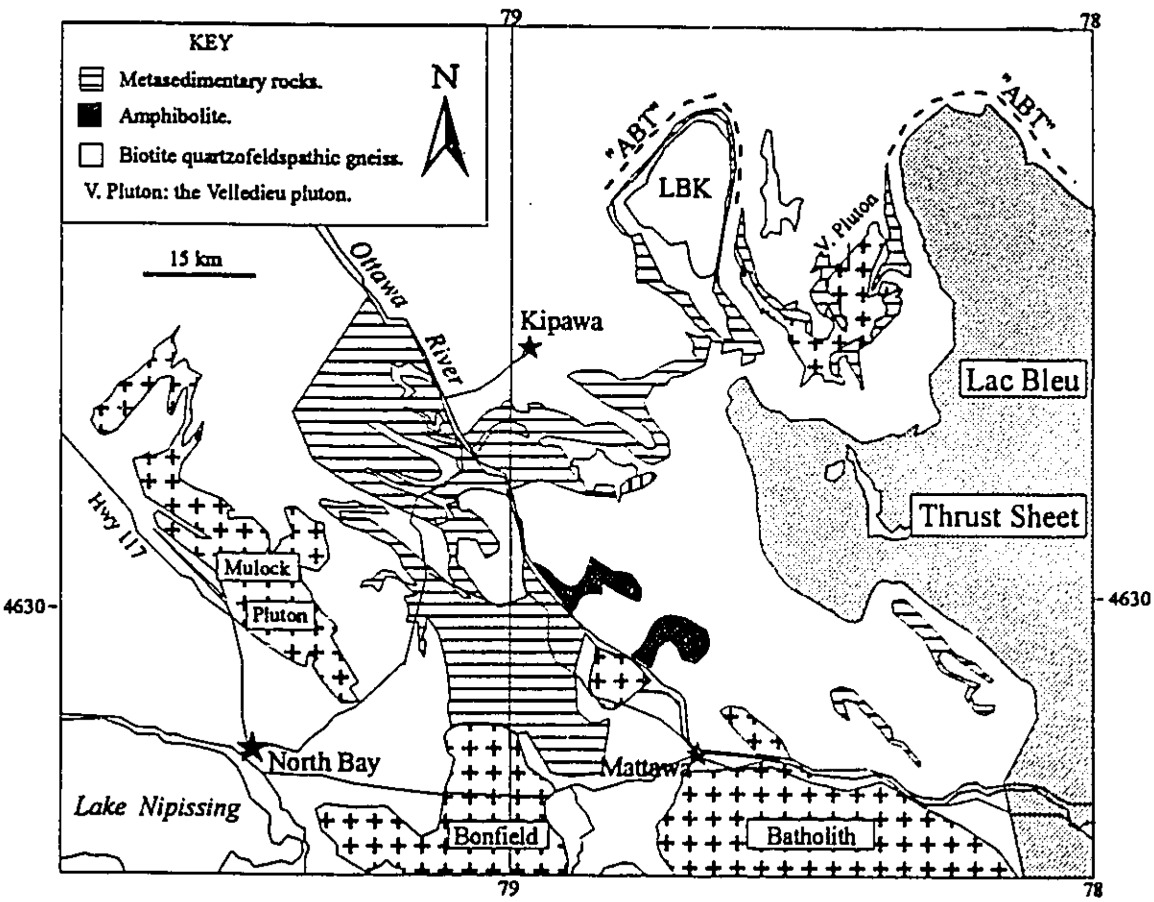
4.1. Geological setting

The study is focused on the Kipawa-Mattawa area, which lies in the Central Gneiss Belt (CGB) of Wynne-Edwards (1972) in the Grenville Province of western Quebec (Fig. 4.1). To the east, the study area is truncated by a thrust terrane which we term the Lac Bleu Thrust Sheet. To the west of 79° longitude, the geology of the North Bay and Temiscaming areas (Holmden and Dickin, 1994) is in continuity with that in the study area (Fig. 4.1).

The study area is composed of biotite gneisses, metasedimentary and plutonic rocks. Abundant biotite gneisses are exposed to the north of the "ABT". These rocks were geochemically and petrologically identified as the tonalite-trondhjemite-granodiorite suite (TTG) by Ciesielski (1992). Similar lithologies are also present to the south of the "ABT", where the gneisses are locally overlain by metasedimentary rocks characterized by muscovite quartzites, muscovite quartz schists and fragments of banded iron

Fig. 4.1 General geology of the Kipawa-Mattawa area, western Quebec, also including the North Bay area, Ontario. Dash line: the location of the ABT. PB: the Parautochthonous Belt. APB: the Allochthonous Polycyclic Belt. "ABT": the Allochthon Boundary Thrust (Rivers et al., 1989; Indares and Martignole, 1990). LBK: the Lac Booth klippe (Kellett, et al., 1994).


Superior Province
Huronian Supergroup
Paleozoic Cover
Sudbury Structure
Grenville Front
PB
ABT
APB
CGB
CMB
MBBZ
Bancroft
Georgian Bay
Lake Nipissing
78
47


KEY
Metasedimentary rocks.
Amphibolite.
Biotite quartzofeldspathic gneiss.
V. Pluton: the Velledieu pluton.
N
15 km
Ottawa River
Kipawa
"ABT"
LBK
V. Pluton
Lac Bleu
Thrust Sheet
Hwy 117
Mulock
Pluton
North Bay
Mattawa
Lake Nipissing
Bonfield
Batholith
4630
79
78

KEY

Metasediments

1.2 - 1.3 Ga plutons

Amphibolite

Samples :

Biotite gneiss (Archean model ages)

Plutonic rock (> 2.0 Ga model ages)

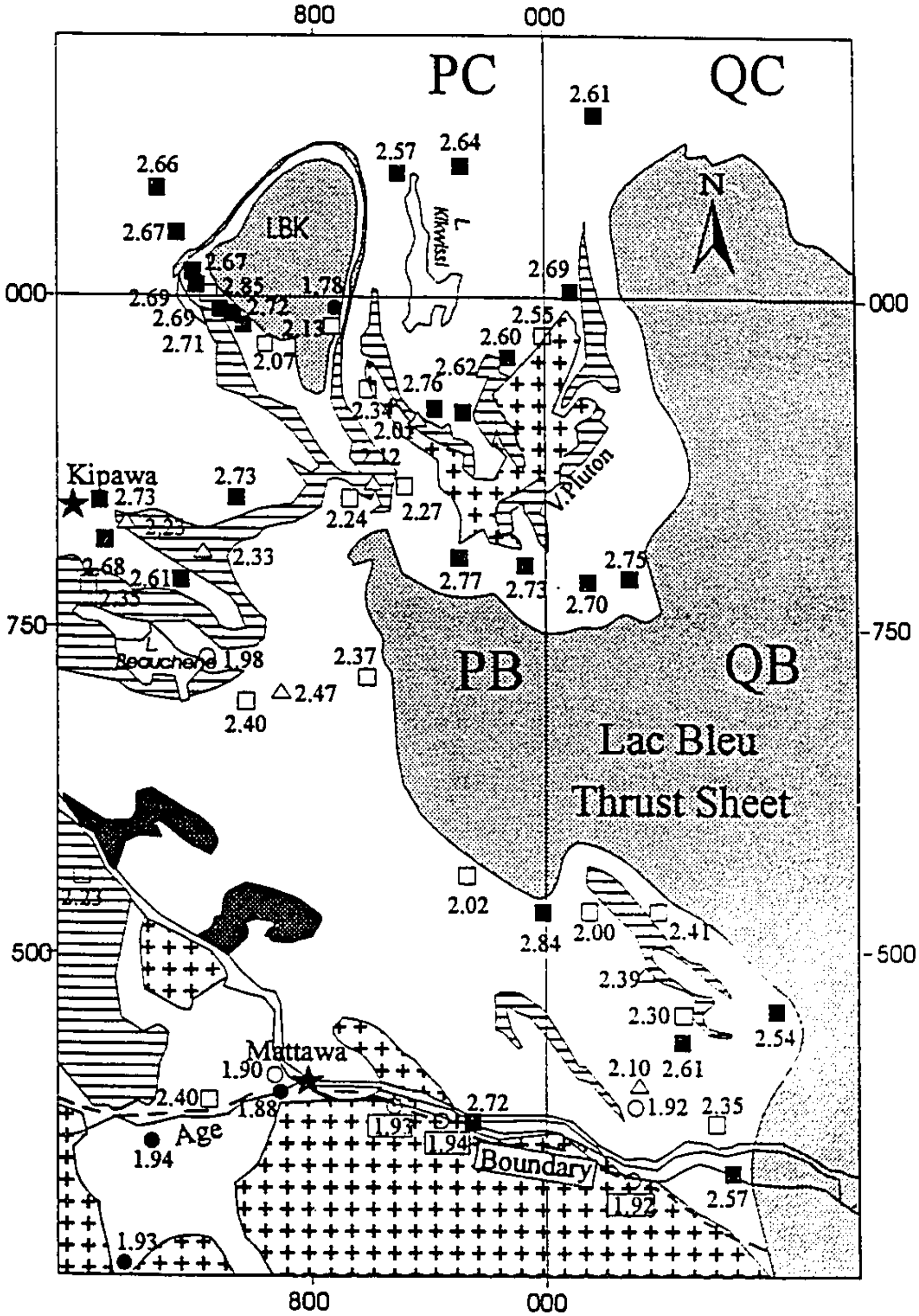
Biotie gneiss (1.8 -1.9 Ga model ages)

Plutonic rock (1.8 -1.9 Ga model ages)

Metasedimentary rock

15 km

Fig. 4.2 Map showing the Nd model age mapping result in the Kipawa-Mattawa area.


800
000
PC
QC
PB
QB
LBK
L. Kikwissi
L. Beauchene
Kipawa
Mattawa
V. Pluton
Lac Bleu
Thrust Sheet
Age
Boundary
N
750
500
2.61
2.66
2.57
2.64
2.67
2.69
1.78
2.85
2.72
2.71
2.13
2.07
2.55
2.60
2.62
2.76
2.34
2.01
2.12
2.27
2.24
2.73
2.23
2.33
2.68
2.61
2.35
2.77
2.70
2.75
1.98
2.37
2.40
2.47
2.02
2.84
2.00
2.41
2.39
2.30
2.54
2.10
1.92
2.35
1.90
1.88
2.72
1.93
1.94
2.57

formation (BIF, Geological map 31L, 1:250,000, Ministère de l'energie et des Ressources, Québec, 1980). These sedimentary rocks are also exposed in the area west of 79° longitude (Fig. 4.1, Holmden and Dickin, submitted).

In the area immediately south of the "ABT" (Figs. 4.1 and 4.2), a klippe known as the Lac Booth klippe (LBK) has been defined by the Lithoprobe seismic reflection profile Line 15 (Kallettt et al., 1994). The klippe consisting mainly of paraneisses and grey biotite gneisses extends to about 3 km depth. It is bounded by a thick shear zone and tectonically overlies grey biotite gneisses and metasedimentary rocks. Currie and van Breemen (submitted) define another allochthon which corresponds to the paragneiss portion in the central part of the Lac Booth klippe.

To the south, biotite gneisses and granitoid plutons are observed along Hwy 17. However, in contrast with the north, granitoid plutonic rocks are obviously predominant and biotite gneisses appear to be engulfed by the plutons.

Plutons intruded into the study area consist of granitic, leucocratic and mafic intrusions. Identified leucocratic plutons are confined to the area between the Ottawa River and the "ABT". Major plutons in the study area are the Bonfield batholith (1.33 Ga, Rb/Sr method, Lumbers, 1971), the Villedieu pluton (1.25 ± .0047 Ga, Pb/Pb method, Guo and Dickin, 1992) and the Mulock pluton (1.24 Ga, U/Pb method, Lumbers and Vertolli, 1991) in the North Bay area.

4.2. Results

4.2.1. Sm-Nd data

Sm-Nd isotopic data and Nd model age mapping results are shown in Tables 4.1 and 4.2 and Fig. 4.2.

As shown in Fig. 4.2, biotite gneisses with Archean formation ages have been continuously found to the north of the "ABT". Similar results were obtained in the North Bay area (Holmden and Dickin, submitted). Crossing the location of the "ABT", biotite gneisses with Archean model ages have been also identified to the south of the Villedieu pluton. Further to the south, a block with crustal formation ages of 2.54 - 2.74 Ga is exposed near the Ottawa River east of Mattawa (Fig. 4.2). In total, 27 biotite gneisses with Archean formation ages from both sides of the "ABT" yielded an average model age of 2.68 ± 0.07 Ga (SD=1σ).

Of 10 samples collected from the Lac Booth klippe, 6 biotite gneisses and 1 granite yielded Archean model ages, while 2 samples from mafic dikes and 1 mafic gneiss gave rise to 1.78, 2.13 and 2.07 Ga model ages, respectively (Fig. 4.2).

Along Hwy 17, 7 samples of biotite gneisses and plutonic rocks yielded model ages within the 1.88-1.94 Ga range. The model ages of plutonic rocks (mainly from the

Table 4.1 SM-ND DATA (samples with Archean model ages)

SAMPLE	AREA (Grid ref)	Sm(ppm)	Nd(ppm)	147Sm/144Nd	143Nd/144Nd	AGE(Ga) (TDM)
THE NORTH OF THE "ABT"						
GA4	PC835/083	4.58	27.10	0.1029	0.511187	2.57
GA8	PC924/118	0.51	3.56	0.0890	0.510892	2.64
GA9	QC025/170	2.17	10.92	0.1216	0.511478	2.61
GA13	PB869/909	1.53	7.60	0.1216	0.511393	2.76
GA14	PC003/021	1.57	7.69	0.1245	0.511481	2.69
GA17	PB945/959	0.33	1.67	0.1200	0.511455	2.60
GA19	PB895/911	1.62	9.04	0.1083	0.511241	2.62
KP1	PC605/102	2.75	17.77	0.0934	0.510945	2.66
KP3	PC627/047	2.16	10.67	0.1224	0.511455	2.67
NB54	PB651/714	1.09	6.74	0.0981	0.511118	2.61
NB57	PB553/800	2.61	17.79	0.0831	0.510756	2.69
NB65	PB698/833	1.38	6.59	0.1263	0.511494	2.73
NB66	PB540/833	2.80	16.05	0.1055	0.511117	2.73
THE SOUTH OF THE "ABT" (INCLUDING SAMPLES FROM THE LAC BOOTH KLIPPE)						
KP5	PC643/031	3.37	21.90	0.0930	0.510945	2.67
KP6	PC645/028	3.98	26.24	0.0916	0.510904	2.69
KP10	PC668/003	4.55	25.24	0.1089	0.511192	2.71
KP11A	PC657/014	2.51	15.76	0.0964	0.510985	2.69
KP12A	PC659/010	2.39	12.01	0.1204	0.511395	2.72
TM6	QB037/768	3.03	17.44	0.1051	0.511095	2.75
TM5	QB015/761	2.55	19.12	0.0808	0.510608	2.70
TM3	PB959/763	1.94	10.70	0.1096	0.511167	2.73
TM1	PB900/790	2.19	17.62	0.0751	0.510608	2.77
DR24	QB203/404	5.96	29.22	0.1232	0.511136	2.54
DR18	PB971/497	7.43	45.17	0.0994	0.510926	2.85
MT4	PB928/281	4.17	25.96	0.0971	0.510978	2.72
MT7	PB157/262	6.59	31.42	0.1268	0.511586	2.57
TA24	QB090/361	2.53	15.02	0.1017	0.511136	2.61
Granitic intrusions						
GA18	PB978/987	1.501	8.27	0.1096	0.511310	2.55
KP7	PC645/029	0.949	4.52	0.1269	0.511424	2.85

Table 4.2 SM-ND DATA (samples with model ages of < 2.5 Ga)

SAMPLE	AREA Grid ref.	Sm(ppm)	Nd(ppm)	147Sm/144Nd	143Nd/144Nd	AGE (Ga) (TDM)
Samples with 1.8-1.9 Ga (TDM)						
Biotite gneisses						
MT2	PB740/303	5.28	30.89	0.1033	0.511679	1.88
TA32	PB160/316	8.73	42.52	0.1241	0.511908	1.93
TA37	PB663/252	8.79	47.96	0.1107	0.511735	1.94
Plutonic rocks						
H533-3	PB743/342	22.32	129.51	0.1072	0.511679	1.90
MT3	PB849/305	11.89	70.79	0.1015	0.511619	1.93
MT5	OB055/257	7.01	37.84	0.1120	0.511764	1.92
NB51	PB672/687	13.66	75.19	0.1098	0.511690	1.98
TA3	PB899/293	12.51	68.64	0.1102	0.511723	1.94
TA21	OB067/308	14.95	104.29	0.0867	0.511439	1.92
Samples with 2.0-2.4 Ga (TDM)						
Metasedimentary rocks						
FA2	PB576/803	1.60	9.83	0.0982	0.511354	2.23
NB53	PB745/662	2.61	17.91	0.0819	0.510917	2.47
NB62	PB652/778	3.33	19.27	0.1038	0.511368	2.33
GA20	PB860/903	9.24	53.33	0.1048	0.511608	2.01
GA22	PB829/841	8.55	53.17	0.0972	0.511428	2.12
TA23	OB071/331	5.11	34.10	0.0906	0.511348	2.10
TA27	OB080/410	2.69	16.43	0.0991	0.511252	2.39

Table 4.2 continued

Plutonic rocks						
Leucocratic and gneissic rocks						
DR1	OB085/475	2.63	18.99	0.0838	0.510994	2.41
H176	OB140/300	1.75	14.55	0.0725	0.510875	2.35
MT1	PB663/227	1.51	8.81	0.1032	0.511312	2.40
NB52	OB714/652	0.49	3.07	0.0965	0.511202	2.40
GA23	PB800/841	8.47	54.85	0.0929	0.511270	2.24
Mafic rocks						
H533-1	PB566/499	5.65	26.84	0.1273	0.511782	2.23
DR8	OB013/476	8.29	42.49	0.1179	0.511785	2.00
NB59	PB555/745	7.01	32.69	0.1300	0.511754	2.35
Granitic rocks						
DR16	PB821/670	10.11	67.55	0.0905	0.511132	2.37
DR21	PB910/502	9.72	48.36	0.1214	0.511819	2.02
GA12	PB820/925	10.01	56.46	0.1072	0.511410	2.34
GA21	PB843/838	7.02	43.30	0.0980	0.511321	2.27
TA29	OB105/395	8.29	53.55	0.0936	0.511233	2.30
Samples from Lac Booth klippe						
KP12	PB689/988	8.74	45.44	0.1165	0.511722	2.07
GA2	PB807/997	0.85	4.47	0.1159	0.511673	2.13
GA3	PB809/999	2.63	15.51	0.1024	0.511739	1.78

Bonfield batholith) correspond well to the crustal formation ages of the remaining country rocks.

Between the Ottawa River to the south and the "ABT" to the north, 7 sedimentary and 14 plutonic samples gave rise to Nd model ages ranging from 2.01 Ga to 2.47 Ga and 2.0 to 2.41 Ga respectively (except two granites with model ages of ca.1.9 Ga, Fig. 4.2). The metasedimentary and plutonic rocks extend westward into the North Bay area, where Holmden and Dickin (submitted) determined the same range of model ages.

Based on the age data obtained from biotite gneisses and plutons, an age boundary can be drawn between the southernmost exposure of the rocks with Archean model ages and the rocks having 1.9 Ga model ages along Hwy 17 (Fig. 4.2).

4.2.2. Petrology of samples

Major element analyses for all samples are listed in Appendix 1. Trace element (Rb, Sr, Zr, Nb and Y) analyses in selected samples are listed in Table 4.3.

Biotite gneisses with Archean model ages generally contain 10-15% biotite and/or hornblende and about 60% oligoclase as well as about 15% quartz and accessory minerals. The gneisses exhibit weak sericitization of plagioclase and epidotization of hornblende.

When plotted on a chemical-mineralogy discrimination diagram (Fig. 4.3A, Debon and Le Fort, 1983), most samples

Table 4.3 TRACE ELEMENT ANALYSES (in ppm)

Samples with 1.5-1.9 Ga model ages

	H5333	NB51	TA3	TA21	MT3	TA37	MT2
Nb	26.7	29.2	18.6	14.3	14.6	11.9	10.3
Zr	669.6	411.6	365.6	404.2	377.6	686.9	164.7
Y	95.1	49.3	57.3	43.5	54.2	35.5	18.7
Sr	820.8	186.6	216.2	112.5	628.5	495	794.2
Rb	55.1	126.6	122.9	67.9	68.2	34.3	126.8

Samples with 2.0-2.4 Ga model ages

	DR16	DR21	GA12	GA23	H176	KP12
Nb	12.5	19.6	24.4	11.9	6.3	11.1
Zr	359.6	370.9	143.1	157.1	129.8	143.3
Y	32.3	57.3	45.6	21.5	5.6	40.3
Sr	96.9	583.1	61.4	284.1	1020.9	635.8
Rb	90.3	88.6	154.5	92.4	11.7	61.6

Samples with Archean model age

	DR18	GA4	GA9	GA13	GA14	GA18	KP1
Nb	5.5	6.7	4.7	4.6	4.5	15.3	4.2
Zr	186.5	147.2	129.2	97.1	88.7	174.6	153.3
Y	9.1	19.6	6.9	5.1	2.7	45.7	4.6
Sr	1353.6	1160.6	563.9	742.4	709.8	98.4	629.3
Rb	79.6	67.7	28.8	43.8	44.4	84.6	56.7

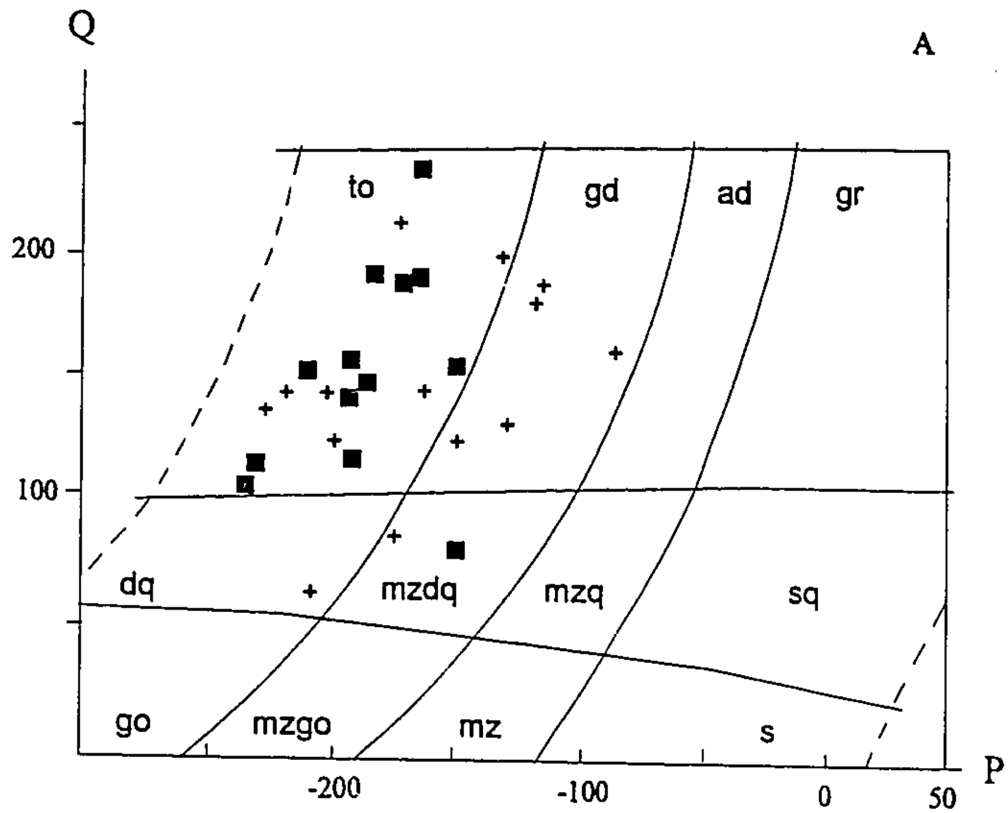
	MT4	MT7	TA24	NB65	NB66	KP5	KP12A
Nb	5.1	9.8	6.9	4.3	5.7	5	7.4
Zr	130.6	6.6	113	92.1	101.8	144.8	120.2
Y	9.8	13.8	10.3	4.4	11.4	4.2	11.4
Sr	600.8	504	262.5	846.4	287.2	359.6	310.6
Rb	47.2	135.6	51.2	61.4	63.2	76	99.9

having Archean model ages taken from both sides of the "ABT" are concentrated in the fields of tonalite and granodiorite (Fig. 4.3A). This result is in agreement with the petrological study of Ciesielski (1992).

Samples with model ages of 2.0-2.4 Ga are either metasedimentary or plutonic intrusive rocks. The plutons consist of granitic, mafic and leucocratic varieties. Granitic rocks are K-feldspar-rich and less foliated. Thus they can be easily recognized as granites in the field. On the Q-P diagram (Fig. 4.3B), these rocks are mainly defined as granite and adamellite. Mafic rocks (DR8, H533-1 and NB59) contain hornblende, biotite and plagioclase. These rocks are high in FeO and low in SiO_2 (ca. 50%), and fall in the gabbro and diorite fields (Fig. 4.3B). They probably represent mafic dikes. A trondhjemitic pluton (NB52) featured by its low content in mafic minerals is plotted in the tonalite field (Fig. 4.3B). It is difficult to distinguish some gneissic rocks (e.g., MT1, DR1 and GA23), which mainly fall in the tonalite and quartz monzodiorite fields (Fig. 4.3B), from the country rock biotite gneisses because they are similar to each other in both composition and rock structure. However, based on the lack of known magmatic intrusion ages of 2.0-2.4 Ga in this region, I tentatively assign them to young plutons.

Samples with model ages of 1.8-1.9 Ga are represented by gneissic country rocks along Hwy 17 and granitic rocks taken from the Bonfield batholith. The plutons are

Fig. 4.3 Chemical-mineralogical grid for the rocks from the study area. Q = Si/3-K-Na-2Ca/3; P = K-Na-Ca. to = tonalite; gd =granodiorite; ad = adamellite; gr = granite; dq = quartz diorite; mzdq = quartz monzodiorite; mzq = quartz monzonite; sq = quartz syenite; go = gabbro; mzgo = monzogabbro; mz = monzonite; s = syenite. (A). Samples with Archean model ages from both sides of the " ABT ". ■: biotite gneisses from the north. +: biotite gneisses from the south. (B). Metasedimentary rocks (▵) and plutonic rocks (□) with 2.0-2.4 model ages.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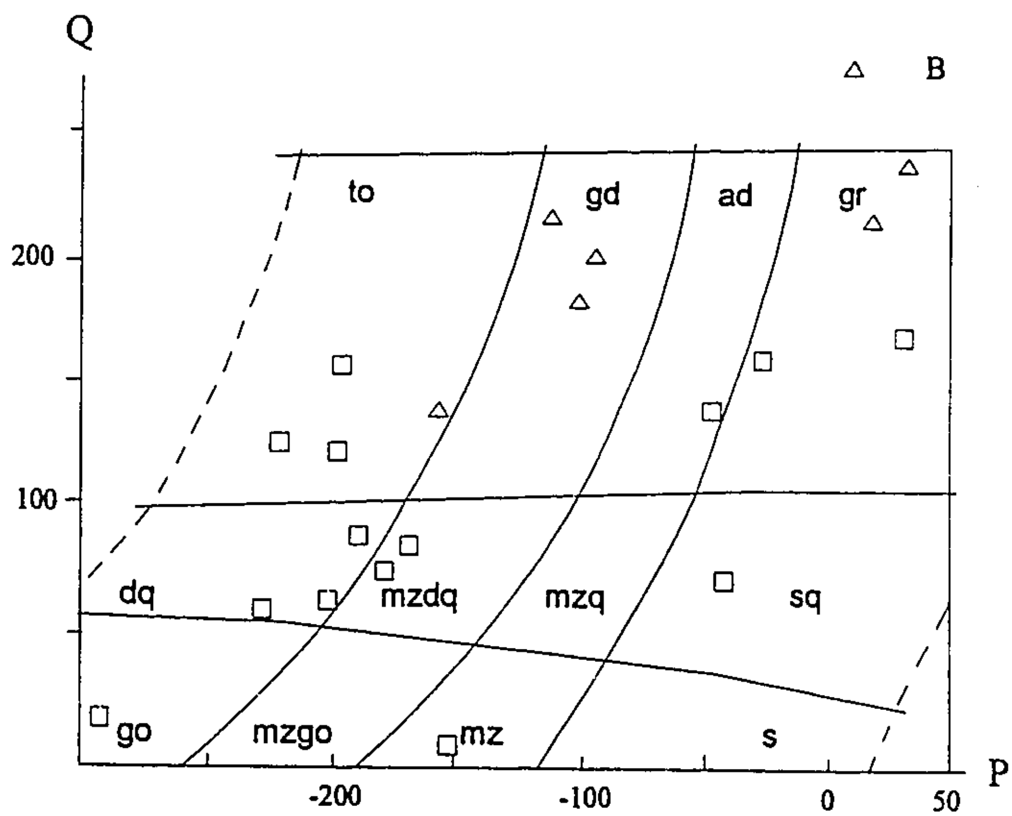
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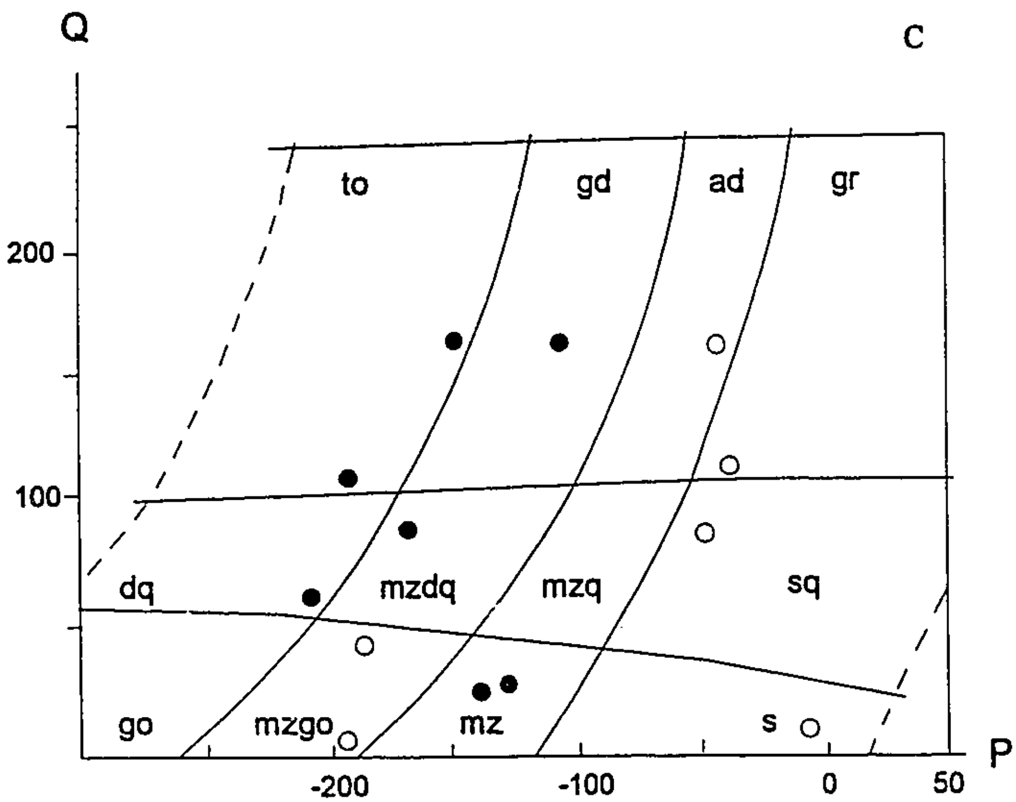

Fig. 4.3 C. Biotite gneisses (●, including samples from the Grand-Remous area, see Chapter 3) and plutonic rocks (o) with 1.8-1.9 Ga model ages.

distributed in the fields of syenite and granite when plotted on the Q-P diagram (Fig. 4.3C). The biotite gneisses (including some samples from the Grand-Remous area, Guo and Dickin, submitted) mostly fall in the fields of quartz monzodiorite and tonalite.

Further geochemical discrimination, using the Nb-Y diagram shows that samples with Archean model ages on both sides of the "ABT" consistently plot in the VAG field (Fig. 4.4A). In addition, one granite (GA18) falls in the WPG field, while 6 plutonic rocks having model ages of 2.0-2.4 Ga fall in both VAG and WPG fields (Fig. 4.4B). Two of them, plotting in the WPG field, are granitic rocks. Granitic rocks with 1.9 Ga model ages all plot in the WPG field (Fig. 4.4C), whereas the gneisses (including some samples from the Grand-Remous area, Guo and Dickin, submitted) fall in the VAG field.

4.3. Discussion

4.3.1. Determination of the southern limit of Archean crust

As shown in Fig. 4.2, rocks with Archean model ages are distributed on both sides of the "ABT". Based on U-Pb age data, the presence of Archean crust on the north side has been known for some time. Recent age determinations (Krogh et al., 1994) from the North Bay region in Ontario and Lavigne region, Quebec gave 2.67-2.68 Ga U-Pb ages. The biotite gneiss in the

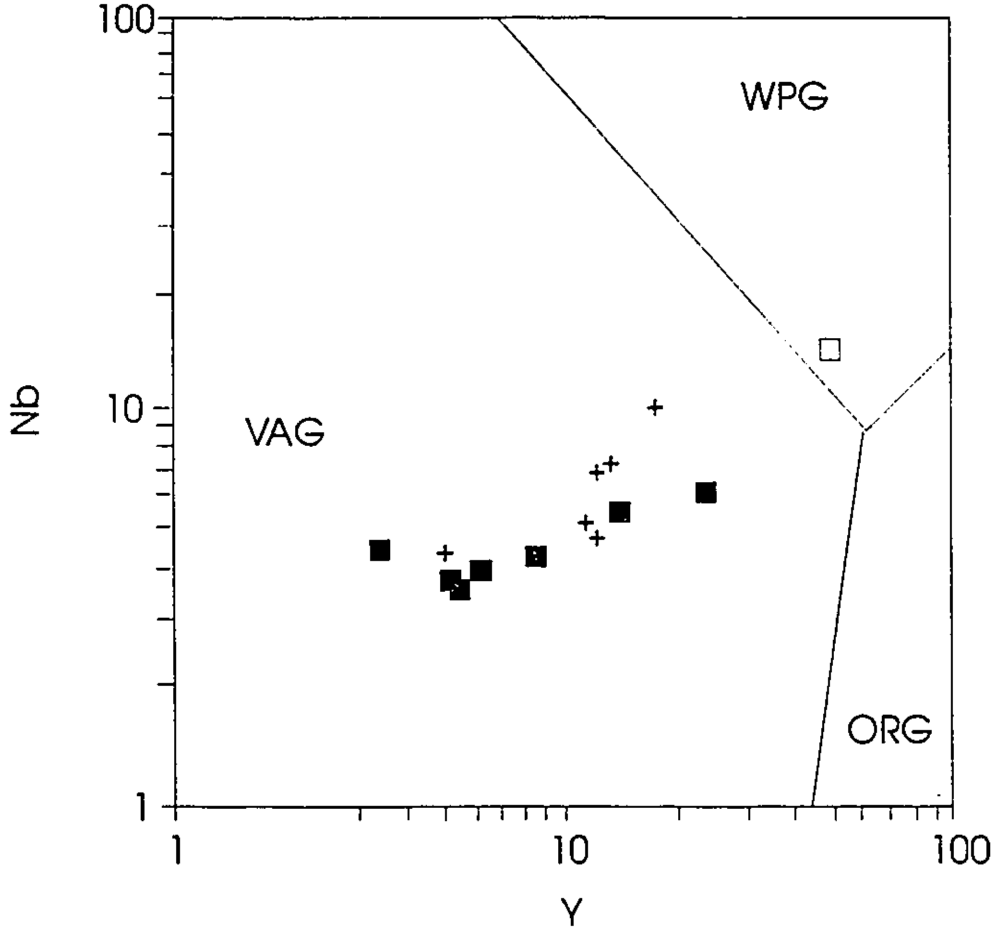

Fig. 4.4A Nb-Y diagram showing tectonic affinities for rocks with Archean model ages from both sides of the " ABT ". □: granite. Symboles refer to Fig. 4.3A.

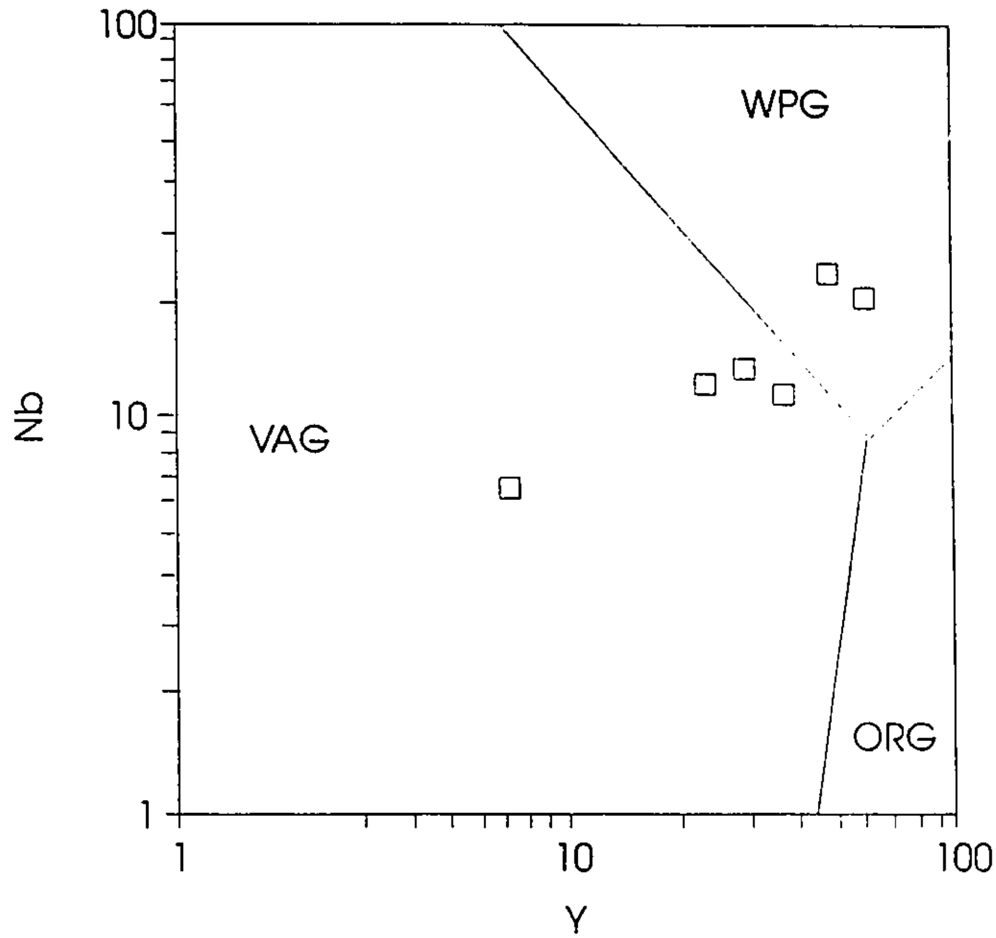

Fig. 4.4B Nb-Y diagram showing tectonic affinity for plutonic rocks with model ages of 2.0-2.4 Ga.

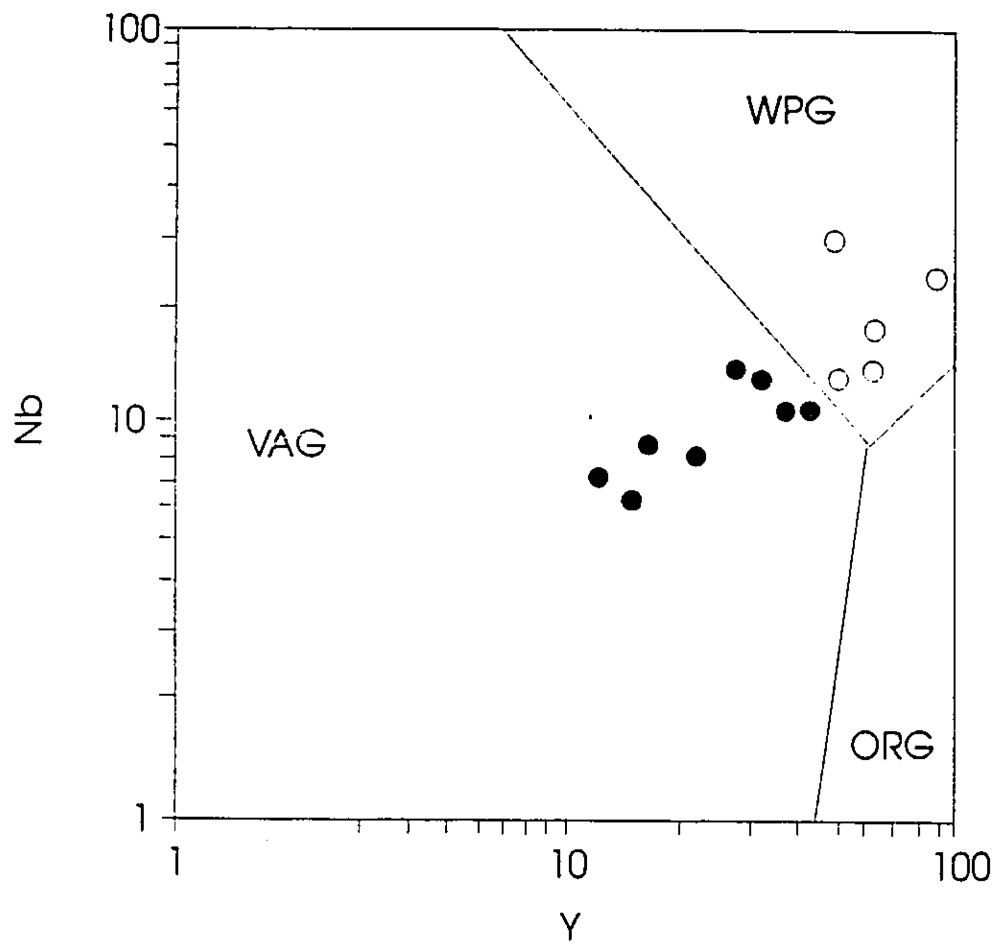

Fig. 4.4C Nb-Y diagram showing tectonic affinity for biotite gneisses (including samples from the Grand-Remous area, Chapter 3) and plutonic rocks with 1.8-1.9 Ga model ages. Symbols refer to Fig. 4.3C.

vicinity of the "ABT" yielded a U-Pb zircon age of 2.62 Ga (Joly, 1990). Childe et al. (1993) dated a U-Pb monazite age of 2.60 Ga from the northern part of Reservoir Dozois, western Quebec. Krogh and Davis (1974) and Krogh (1989) also determined U-Pb ages of 2.60-2.64 Ga for zircons and monazites from pegmatites crosscutting the gneisses in the PB, which impose the lowest limit to the formation of protoliths of the biotite gneisses. Thus, it is clear that rocks with Archean model ages in this part of the study area represent in-situ Archean crust.

As shown on both Q-P (Fig. 4.3A) and Nb-Y diagrams (Fig. 4.4A), all the biotite gneisses with Archean model ages consistently display tonalitic and granodioritic petrochemistry and arc/orogenic affinities. The geochemical similarities between the rocks with Archean model ages from both sides of the "ABT" suggest that they have the same origin and represent the same crustal formation.

According to Nd isotopic studies done by Dickin and McNutt (1989) and Dickin et al. (1990) in the northwest Grenville Province of Ontario, granitoid plutons intruded into a crustal section formed largely of Archean or reworked Archean basement all have Nd model ages of > 2.0 Ga. Thus, plutons with model ages of > 2.0 Ga can be used as an indicator of the presence of Archean crust. In the study area, most plutonic rocks intruded into the area between the Ottawa River and the location of the "ABT" yielded model ages of > 2.0 Ga (Fig. 4.2). Of the plutons, granitic ones may have a crustal origin through anatexis of Archean crust in an anorogenic setting (Fig. 4.4B). The leucocratic plutons may be derived from underplated Archean mafic bodies at the base of the continental crust in this region. These plutons imply the presence of Archean crust in this part of the study area.

From the above discussion, we suggest that the biotite gneisses with Archean model ages mapped out to the south of the "ABT" also correspond to Archean crust and the "ABT" does not represent the crustal division between of Archean and Proterozoic crust. However, the area to the south of the "ABT" was assigned to an allochthon by the previous studies (Indares and Martignole, 1990; Indares, 1991; Ciesielski and Parent, 1992).

Since no Archean crust has been reported further south of the study area, we argue that the rocks with Archean model ages exposed on the south side of the "ABT" represent the southernmost outcrop of Archean crust in this region, and that significant NW directed transport of the Archean crust did not take place during Grenvillian thrusting. Furthermore, the Villedieu pluton, whose intrusive age (1257 ± 47 Ma) is similar to the other two major plutons (the Bonfield Batholith and the Mulock pluton) in this region is older than the age of major Grenvillian thrusting (1180-1030 Ga, Easton, 1992) and cuts the location of the "ABT" (Fig. 4.2). Therefore the proposed "ABT" probably does not mark the front of a major crustal scale allochthon.

As suggested by Dickin and Guo (submitted), the ABT is probably located further south in Proterozoic crust. This major structural boundary, when extended into the study area from the south, is probably represented by the western limit of the Lac Bleu Thrust sheet (Fig. 4.2). Because the Lac Bleu Thrust sheet consists merely of Proterozoic material (see Chapter 5), in this specific portion, the main allochthon boundary (ABT) coincides with an Archean-Proterozoic boundary.

The Lac Booth klippe displays lithological and Nd isotopic similarities to the area south of the "ABT," for example, the presence of both biotite gneisses and metasediments, and determination of Archean and > 2.0 Ga model ages. Thus, it is suggested that the klippe was probably transported from the south by thrusting that involved both Archean basement and its overlying sediments. The klippe now, as a tectonically duplicated crustal profile rests on the in situ Archean crust and the overlying metasediments.

In conclusion, Archean basement recognized by Nd model age mapping probably extends more than 120 km south from the Grenville Front and reaches the Ottawa River. This Archean basement was the southern margin of the Laurentian continent during an early Proterozoic orogeny.

4.3.2. A reworked early Proterozoic arc

Previous Sm-Nd studies by Dickin and McNutt (1989, 1990) have identified a 1.8-1.9 Ga (TDM) terrane in an area of over 10,000 Km^2 in the Central Gneiss Belt of the Grenville Province of Ontario. Additionally, a Pb/Pb zircon age of 1.9 Ga has been determined from a quartzite in the French River area, Ontario, using the single zircon direct evaporation method (Mueller, 1991). The importance of these two results, in combination, is that they provide evidence for the formation of a Paleoproterozoic arc with 1.8-1.9 Ga crustal formation age, an age at which growth of juvenile crust prevailed along the margin of Laurentia (Hoffman, 1989).

As shown in Fig. 4.4A, the biotite gneisses with ca. 1.9 Ga model ages from the Kipawa-Mattawa area display orogenic affinities on the Nb-Y diagram, while the plutonic rocks with ca. 1.9 Ga model ages reflect anorogenic character. Furthermore, the biotite gneisses (average of 8 samples, including biotite gneisses from the Grand-Remous area) are poorer in a number of trace elements than the plutonic rocks (average of 7 samples, Fig. 4.5), with the exception of high concentration of Sr (this is probably caused by abundant plagioclase in the biotite gneisses, Sr acting as a compatible element in plagioclase). Also, it is noticeable in Fig. 4.5

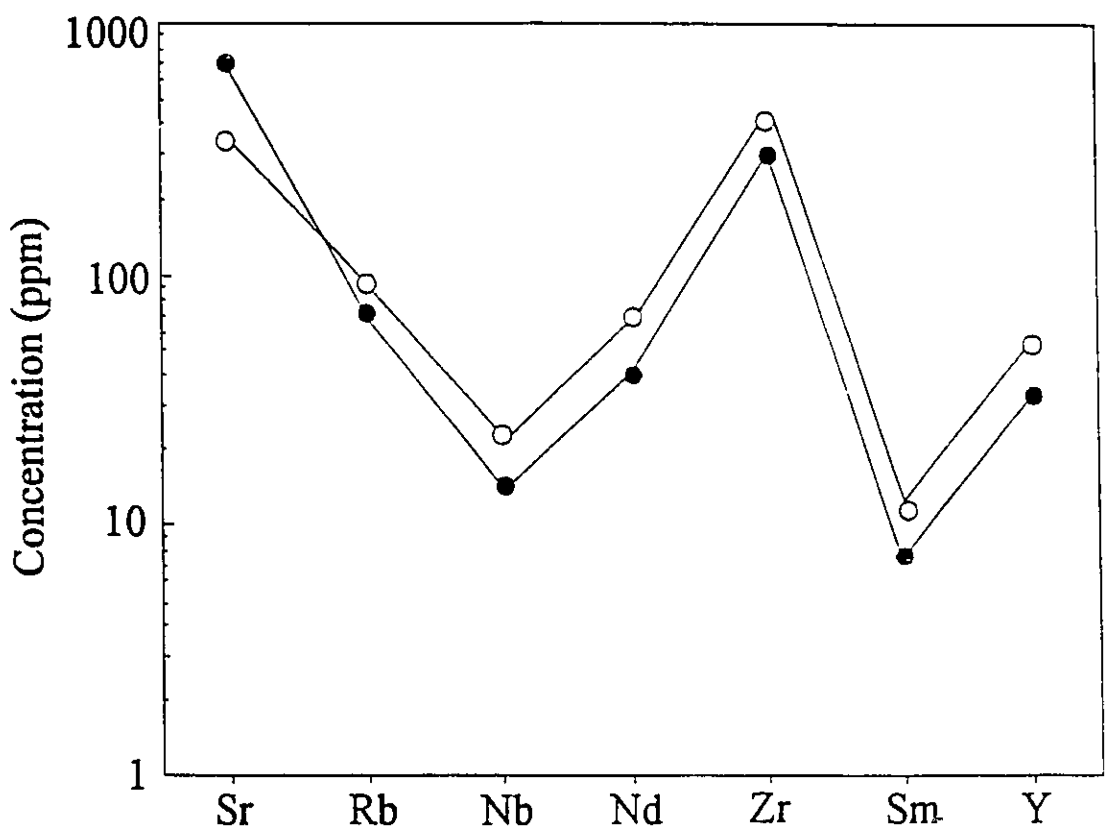

Fig. 4.5 Comparison of 1.9 Ga (TDM) biotite gneisses and plutonic rocks in trace elements. Symbols refer to Fig. 4.3C.

that the two types of rocks are parallel to each other in the trace elements.

In the light of these geochemical features, we argue that the biotite gneisses having arc/orogenic affinities probably represent juvenile 1.9 Ga arc material, while Mesoproterozoic plutonic rocks (e.g., the Bonfield batholith) were generated by anatexis of the arc-related material in an anorogenic setting.

This interpretation is in agreement with the study done by Dickin et al. (1990) in the southwest Grenville Province of Ontario. The gneissic country rocks (ca. 1.9 Ga model ages) in the area were interpreted to represent juvenile crustal accretion with clear orogenic affinities, whereas Mesoproterozoic plutons (e.g., 1.45 Ga Britt pluton and Powassan pluton, Dickin et al., 1990) with ca.1.9 Ga model ages exhibit anorogenic affinities.

As previously suggested, along Hwy 17 near Mattawa, the 1.9 Ga arc-related material is in direct contact with the Archean basement to the north and defines an age boundary (Fig. 4.2). Based on the lack of any evidence of observed Grenville-age shearing in the field, this study speculates that the age boundary here represents a suture along which the 1.9 Ga arc collided with the southern Early Proterozoic margin of the Laurentian continent.

The model age data for plutons on both sides of the age boundary also provide evidence for the interpretation of a suture. In contrast to the plutons intruded north of the age boundary, no plutons with model ages of > 2.0 Ga have been found south of the boundary. This indicates that there is no Archean crust present at depth beyond the age boundary and hence, the age boundary probably represents a tectonic division on a crustal scale.

Although I propose the age boundary as a suture in the Kipawa-Mattawa area, the precise age of suturing is hard to constrain because of polycyclic orogenic activities in the Grenville Province. Despite this difficulty, we present a few lines of evidence from regional geological studies to argue that a 1.7-1.8 Ga collisional orogeny probably occurred in the study area. 1) The prevailing Laurentia-Paleoproterozoic arc collision regime along the Laurentian continental margin during 2.0-1.8 Ga (Hoffman, 1989). 2) The structural effects of the Penokean orogeny in the Huronian Supergroup and the northwest Grenville Province (Brocoum, 1974; Zolnai et al., 1984; Green et al., 1988; Card, 1992). 3) A complete reset of the argon system at 1.8-1.84 Ga in the Huronian Supergroup. This thermal event was thought to be a phase of the Penokean orogeny (Hu et al., 1991). 4) the 1.75 Ga Killarney granite (with anorogenic affinities: Clifford, 1990) in the area adjacent to the Grenville Front and the comparable anorogenic granite-rhyolite suite in the Penokean orogen (van Breemen and Davidson, 1988; Easton, 1992) represent the earliest activity of post-Penokean magmatism in the region. This probably imposes the lowest limit for the end of the Penokean orogeny.

Based on the regional effects of the Penokean orogeny and development of the 1.7 Ga regional anorogenic magmatism, the age of suturing is estimated to be interval 1.75 - 1.85 Ga.

4.3.3. Development of a long-lived marginal basin

As shown in Fig. 4.2, the sedimentary rocks exposed in the Kipawa-Mattawa area gave rise to Nd model ages ranging from 2.0 Ga to 2.4 Ga. The lack of evidence that other provenances were available as sediment sources in this region, except Archean crust and the proposed early Proterozoic arc, leads us to conclude that sedimentary mixing of Archean source with a 1.9 Ga arc source could have happened.

When plotted on the Nd concentration vs. Nd model age diagram (Fig. 4.6), the sedimentary samples display an interesting distribution pattern. The samples with Archean model ages vary from 1 to 48 ppm Nd, with the majority lower than 30 ppm. The rocks with model ages of 1.9 Ga (orogenic) are twice as high in Nd as those having Archean model ages, whereas the sedimentary samples scatter and overlap the range of Nd contents for the rocks with Archean and 1.9 Ga model ages. As shown in Fig. 4.6, a calculated mixing envelope closely parallels the Nd contents of the sediments. The mixing lines for Nd in the sedimentary rocks

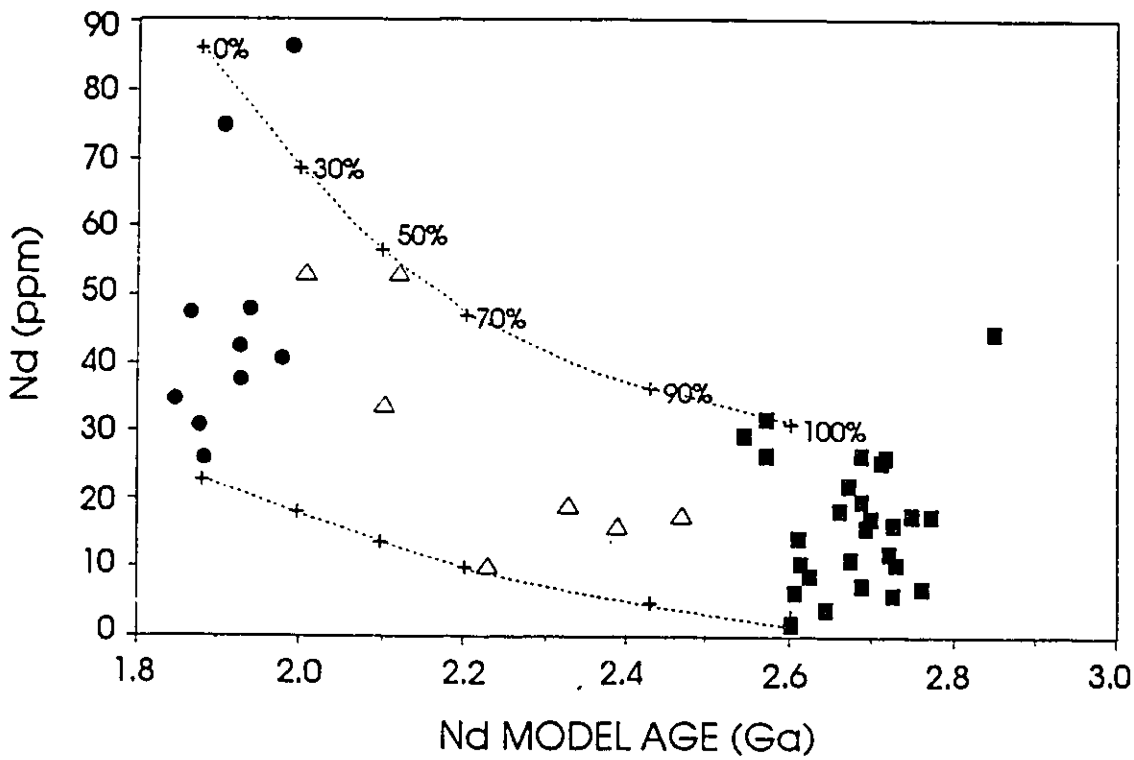

Fig. 4.6 Neodymium--model age diagram showing that the metasedimentary rocks (▵) in the Kipawa-Mattawa area could have been derived from mixing between Archean (■) and the 1.9 Ga arc (●) sources.

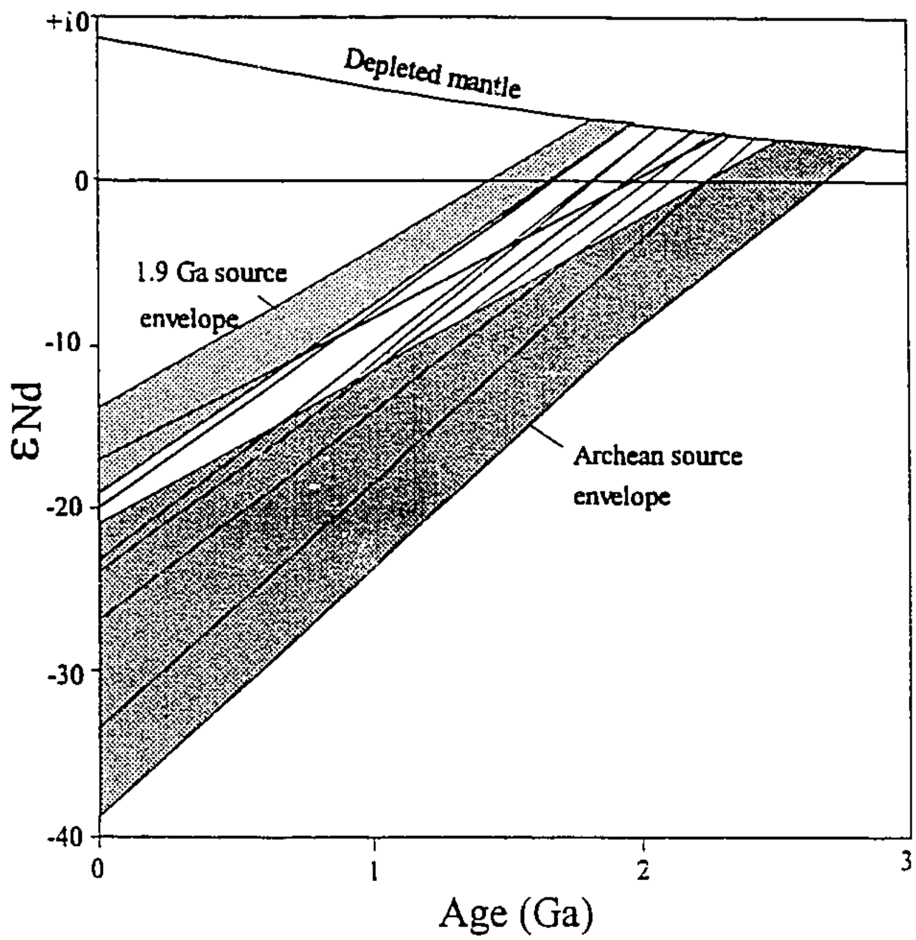

Fig. 4.7 εNd-age plot showing Nd evolution paths of sedimentary rocks (2.0-2.4 Ga model ages) and biotite gneisses with Archean and ca.1.9 Ga model ages.

were calculated for an Archean component of different percentage from 100% to 0% and for a proposed deposition age of 1.9 Ga.[4.1]

Furthermore, on the Nd vs. age plot (Fig. 4.7), samples with Archean and 1.9 Ga model ages form two envelopes of Nd evolution paths. Nd evolution paths of the metasediments are plotted between the two envelopes and overlap them to some degree, indicating an inherited Nd isotopic signature from both Archean and 1.9 Ga arc-related provenances. The Nd evolution pattern illustrated in Fig. 4.7 may also rule out the possibility of another younger juvenile provenance.

Krogh (1989) reported a 1.74 Ga detrital zircon U-Pb age from the French River area and a zircon age of 1.68 Ga

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[4.1] The calculation of the mixing lines for Nd in metasedimentary rocks was carried out using the following two equations:

(A).

$$Nd^{m}=f*[Nd]^{\alpha}+(1-f)*[Nd]^{\beta}$$

This equation was used to calculate Nd content in the sedimentary rocks, where Nd^{m} refers to the concentration of a mixture of two components. $[Nd]^{\alpha}$ and $[Nd]^{\beta}$ represent weight concentrations of Archean and 1.9 Ga arc components containing weight fractions f and (1-f), respectively. (B).

$$\varepsilon^{m}_{Nd}=\frac{f*[Nd]^{\alpha}*\varepsilon^{\alpha}_{Nd}+(1-f)*[Nd]^{\beta}*\varepsilon^{\beta}_{Nd}}{f*[Nd]^{\alpha}+(1-f)*[Nd]^{\beta}}$$

The equation (Langmuir et al, 1978; DePaolo, 1989) was used to calculate ε_{Nd} values in the sedimentary rocks for different fractions of Archean component incorporated and then ε^{m}_{Nd} are used to calculate model ages.

$\varepsilon^{\alpha}_{Nd}$ and ε^{β}_{Nd} represent ε_{Nd} in both Archean and 1.9 Ga arc components at a proposed deposition age 1.9 Ga.

from a quartzite in the Mattawa area. When these findings are combined with Mueller's 1.9 Ga and 2.7 Ga zircon data (1991), it is obvious that there must have been multi-sources with various ages supplying sediments to basins in this region.

Considering the age data above and their Nd model age mapping results, Holmden and Dickin (submitted) proposed a two-stage model to explain the early Proterozoic crustal evolution in this region. In the model, the first stage is collision between an early Proterozoic arc and the Laurentian continent, and the second one involves development of ca. 1.7 Ga active continental margin and formation of a back-arc basin. On the basis of their model, this study presents a model with two generations of basin (Fig. 4.8) where the first formed basin is thought to be a foreland basin during collision between Laurentia and an early Proterozoic arc.

We suggest that as south-dipping subduction was proceeding in this region at 1.8-1.9 Ga, a foreland basin was probably formed on the continental margin of Laurentia as a 1.9 Ga arc collided with the continent. During the collision, the two colliding counterparts contributed both Archean and 1.9 Ga juvenile materials into the proposed basin where they were physically and chemically subjected to mixing.

A typical example of an early Proterozoic foreland basin is in the Great Lakes region. The Upper Marquette Range Supergroup was formed when sediments filled a foreland basin developed between the Superior craton and the Penokean

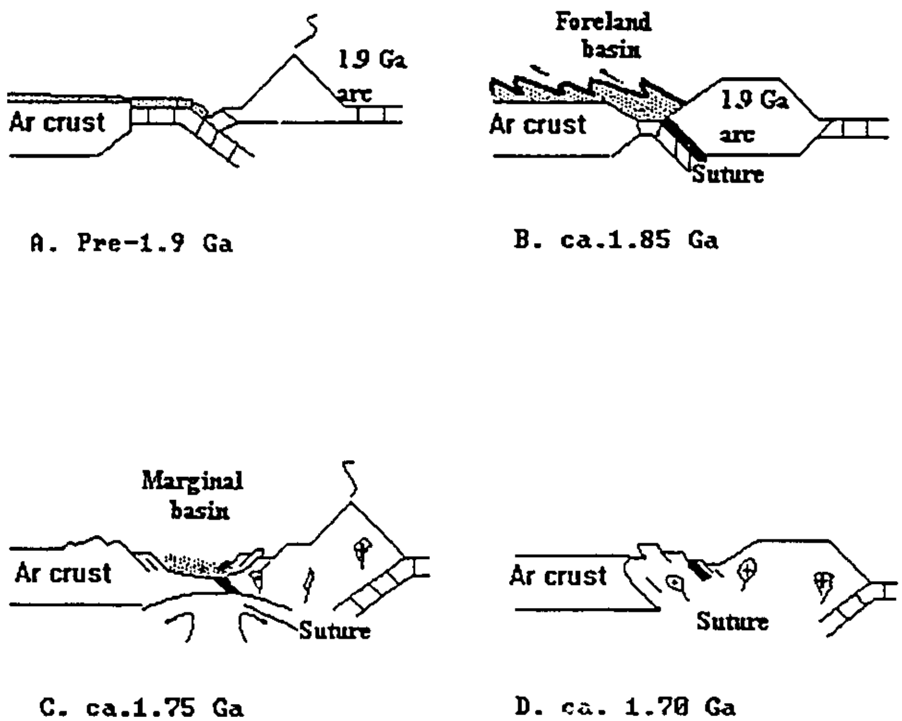


Fig. 4.8 An evolution model of early Proterozoic crust in the study area.

foldbelt in northern Michigan and Minnesota (Hoffman, 1987). The stratigraphic sequence inside the basin consists of a basal shallow-shelf quartzite which passes upward into BIF, overlain by shales and turbidites. A similar example was also studied in Finland (Huhma, 1987). In comparison, the rock assemblage observed in the study area is similar to that in the Upper Marquette Range Supergroup. The orthoquartzite, BIF, muscovite quartz schist exposed in the study area could correspond to a middle section of the original sequence.

If the subduction direction reversed from south-dipping beneath the 1.9 Ga arc to north-dipping beneath the newly formed 1.9 Ga orogen, an extensional regime could have initiated a marginal basin. The basin may have been spatially superimposed the preexisting basin formed under the compressional regime in the Kipawa-Mattawa and Temiscaming areas on the basement of the 1.9 Ga orogen, behind the 1.9 Ga continental margin. This basin would probably be similar to retroarc basins observed in the Andes and Rocky Mountain regions (Dickinson, 1974), where the basins developed in epicontinental seas along elongate pericratonic belts between continental margin arcs and cratons. Some retroarc basins may be successor basins in the sense that they are presently resting upon previously deformed terranes. The sedimentary record of the basins includes fluvial, deltaic, and marine deposits.

Accompanying the extension, anorogenic silicic magmatism may have been induced, similar to that documented in Michigan and Wisconsin, where a 1.7 Ga anorogenic granite/rhyolite suite formed in early Proterozoic crust of the Penokean orogen (Hoffman, 1989). Since no rocks with ca. 1.7 Ga model ages have been found in the study area, we conclude that: 1) plutons providing ca. 1.7 Ga zircons may not represent 1.7 Ga juvenile material. The plutons could have been derived from remelting of older crust or contaminated mantle-derived magmas; 2) the rocks with ca. 1.7 Ga model ages observed in the Huntsville area probably represent juvenile material (Dickin and McNutt, 1990) formed on an active southern margin of the 1.9 Ga continent at ca.1.7 Ga. However, the juvenile 1.7 Ga material was probably not transported to the basin from the margin.

There are no data available to constrain the closure age of the basin. However, the zircon age of 1.68 Ga could be a reference for the closure since no younger detrital zircons have been found in the study area.

CHAPTER FIVE:
Nd MODEL AGE MAPPING IN THE LAC BLEU AND LAC DUMOINE AREAS AND TECTONIC IMPLICATIONS

5.1. Regional Geology

This study focuses on the Lac Bleu and Lac Dumoine areas, which lie in the Central Gneiss Belt of the Grenville Province of western Quebec (Figs. 5.1 and 5.2). Indares and Martignole (1990) suggested these two areas to be an allochthon named the Lac Dumoine Terrane (LDT). In terms of the tectonic subdivision proposed by Rivers et al. (1989), the major parts of the above two areas fall in the Allochthonous Polycyclic Belt, which is separated by the proposed location of the Allochthon Boundary Thrust (Indares and Martignole, 1990) from the Parautochthonous Belt to the north. The presence of Archean crust in some portions of the Parautochthonous Belt has been known for some time, whereas detailed Nd model age mapping in the Kipawa-Mattawa and Grand-Remous areas of western Quebec (Guo and Dickin, submitted) has further determined the southern extent of Archean crust (Fig. 5.2).

To the west, the Lac Bleu area is in contact with Archean crust exposed in the Mattawa area. The boundary drawn

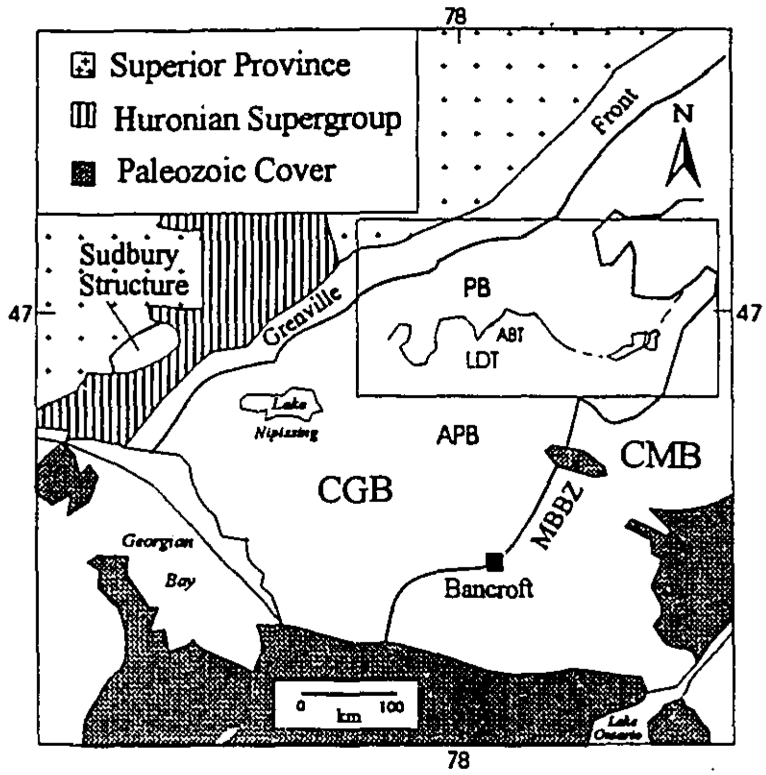
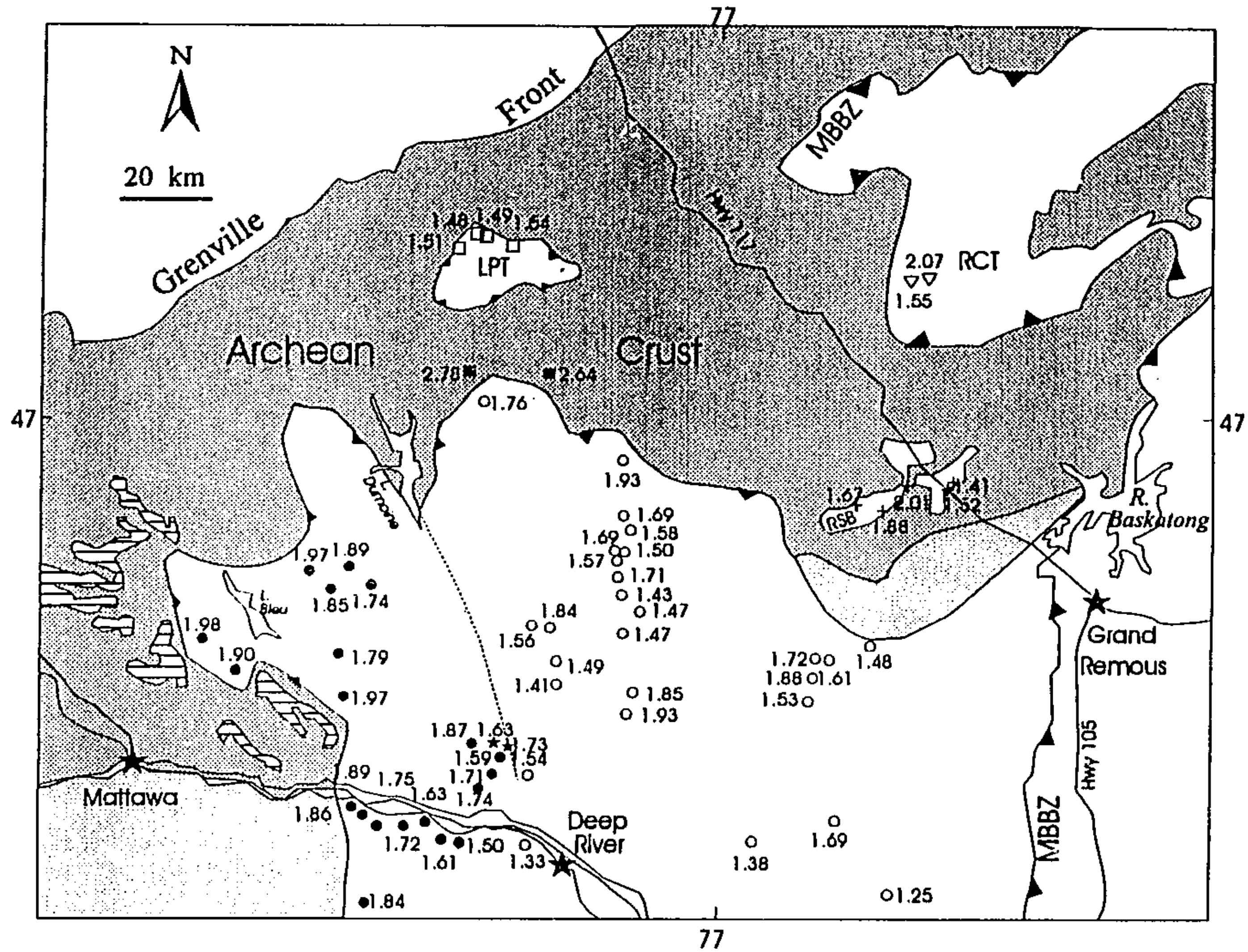


Fig. 5.1 Sketch map showing the location of the study area. LPT: the Lac Perch Terrane (Indares and Martignole, 1990).

Fig. 5.2 Nd model age distribution map. ●: samples from the Lac Bleu area. O: samples from the Lac Dumoine area. □: samples from the Lac Perch Terrane (LPT). ▿: samples from the Cabonga Terrane (RCT). +: samples from the Renzy Shear Belt (RSB). ★: outcrop of straight gneisses, represented by samples ZC2 and ZC3. Dashed line: an inferred thrust boundary between the Lac Bleu and Lac Dumoine areas.



Metasediments (2.0-2.4 Ga model ages) ca. 1.9 Ga arc related material between the study area and Archean crust in the Mattawa area is based on lithological differences on the Geological map 31L (Minístère de l'Énergie et des Ressources Québec, 1980. Scale 1:250,000).

The Lac Dumoine area is truncated by the Central Metasedimentary Belt along the Monocyclic Belt Boundary Zone to its southeast and east, while to the northeast, the area tectonically overlies a narrow strip with ca. 1.9 Ga model ages (Guo and Dickin, submitted) along the Baskatong-Desert Lineament (Sharma et al., 1992). To the south of both Lac Bleu and Lac Dumoine areas, rocks with Nd model ages ranging from 1.4 to 1.8 Ga have been identified in the Algonquin Park area by Martin (1992).

This study also includes rocks from the Lac Perch Terrane and the Reservoir Cabonga Terrane (Fig. 5.2, Indares and Martignole, 1990). The Lac Perch Terrane is located 20 km north of the Lac Dumoine area, and consists mainly of biotite gneisses. The terrane is bounded by a major shear zone and thus Indares and Martignole (1990) interpreted the terrane as a klippe. Nd isotopic study in the Grand-Remous area shows that the Lac Perch Terrane tectonically rests upon Archean crust (Guo and Dickin, submitted). The Reservoir Cabonga Terrane, an allochthon proposed by Indares and Martignole (1990) and Martignole and Pouget (1993), is situated 70 km northeast of the Lac Dumoine area. The western limit of the terrane is marked by a set of shear zones, that also involved

Archean gneisses from the basement onto which the terrane was thrust.

5.2. Results

5.2.1. Sm-Nd data

Sm-Nd isotopic data from the two areas, including the Lac Perch Terrane and the Cabonga Terrane, are listed in Tables 5.1 and 5.2, respectively. Nd model age mapping results are shown in Fig. 5.2.

As illustrated in Fig. 5.2, 2 biotite gneisses from the north of the proposed location of the Allochthon Boundary Thrust yielded Archean model ages of 2.64 Ga and 2.78 Ga, respectively.

Four biotite gneisses taken from the Lac Perch Terrane gave rise to consistent model ages of 1.48-1.54 Ga, and 2 samples from the Reservoir Cabonga Terrane yielded a 1.55 Ga and 2.07 Ga model ages. In the Lac Bleu area, 23 samples yielded Nd model ages ranging from 1.50-1.98 Ga (Fig. 5.2), while rocks from the Lac Dumoine area produced Nd model ages of 1.25-1.93 Ga.

Comparing Nd mapping results with aeromagnetic data in the Lac Dumoine area, rocks with variable model ages of up to 1.9 Ga are associated with high magnetic relief (Fig. 5.3). In contrast, rocks with more homogeneous 1.4-1.5 Ga model ages

Table 5.1 SM-ND DATA (samples from the Lac Bleu thrust sheet)

SAMPLE	AREA Grid ref.	ROCK TYPE	Sm(ppm)	Nd(ppm)	147Sm/144/Nd	143Nd/144Nd	AGE(Ga) (TDM)
Samples with 1.8-1.9 Ga (TDM)							
DR25	QB194/433	S	6.06	32.42	0.1130	0.511744	1.97
TA12	TG899/393	S	5.51	35.18	0.0947	0.511580	1.87
TM8	QB167/766	O	4.27	23.50	0.1098	0.511753	1.89
TN4	QB154/733	O	6.11	34.53	0.1069	0.511740	1.86
TM7	QB130/766	O	13.22	75.09	0.1064	0.511658	1.97
AU4	QB230/053	O	5.49	34.47	0.0955	0.511612	1.84
DR12	PB952/541	S	7.06	43.70	0.0977	0.511593	1.90
DR14	PB880/627	S	9.78	52.99	0.1116	0.511718	1.98
H171	OB174/252	P	9.69	70.94	0.0826	0.511417	1.89
TA4	QB179/249	O	8.26	48.77	0.1024	0.511684	1.86
Samples with 1.6-1.7 Ga (TDM)							
MT9	TG700/212	S	8.69	42.31	0.1242	0.512086	1.63
TA8	TG935/303	O	3.94	20.70	0.1149	0.511935	1.71
TM13	TG741/741	O	9.22	59.95	0.0930	0.511661	1.74
DR28	QB250/053	O	8.30	32.73	0.1263	0.512017	1.79
MT8	QB283/221	O	11.11	61.33	0.1095	0.511863	1.72
MT10	TG776/203	P	8.67	45.78	0.1144	0.511990	1.61
TA5	QB235/256	S	13.82	68.91	0.1213	0.511983	1.75
TA7	TG922/272	S	7.53	43.67	0.1043	0.511760	1.74
TM10	QB234/732	O	7.92	55.65	0.8607	0.511613	1.71
ZC2	TG974/348	O	7.01	38.65	0.1097	0.511928	1.63
ZC3	TG973/348	O	7.32	37.31	0.1186	0.511964	1.73
Samples with 1.4-1.5 Ga (TDM)							
MT11	TG852/169	O	7.38	43.80	0.1018	0.511940	1.50
TA13	TG940/320	S	4.13	21.28	0.1174	0.512035	1.59

NOTE: S: paragneiss.
P: plutonic rocks
O: orthogneiss.

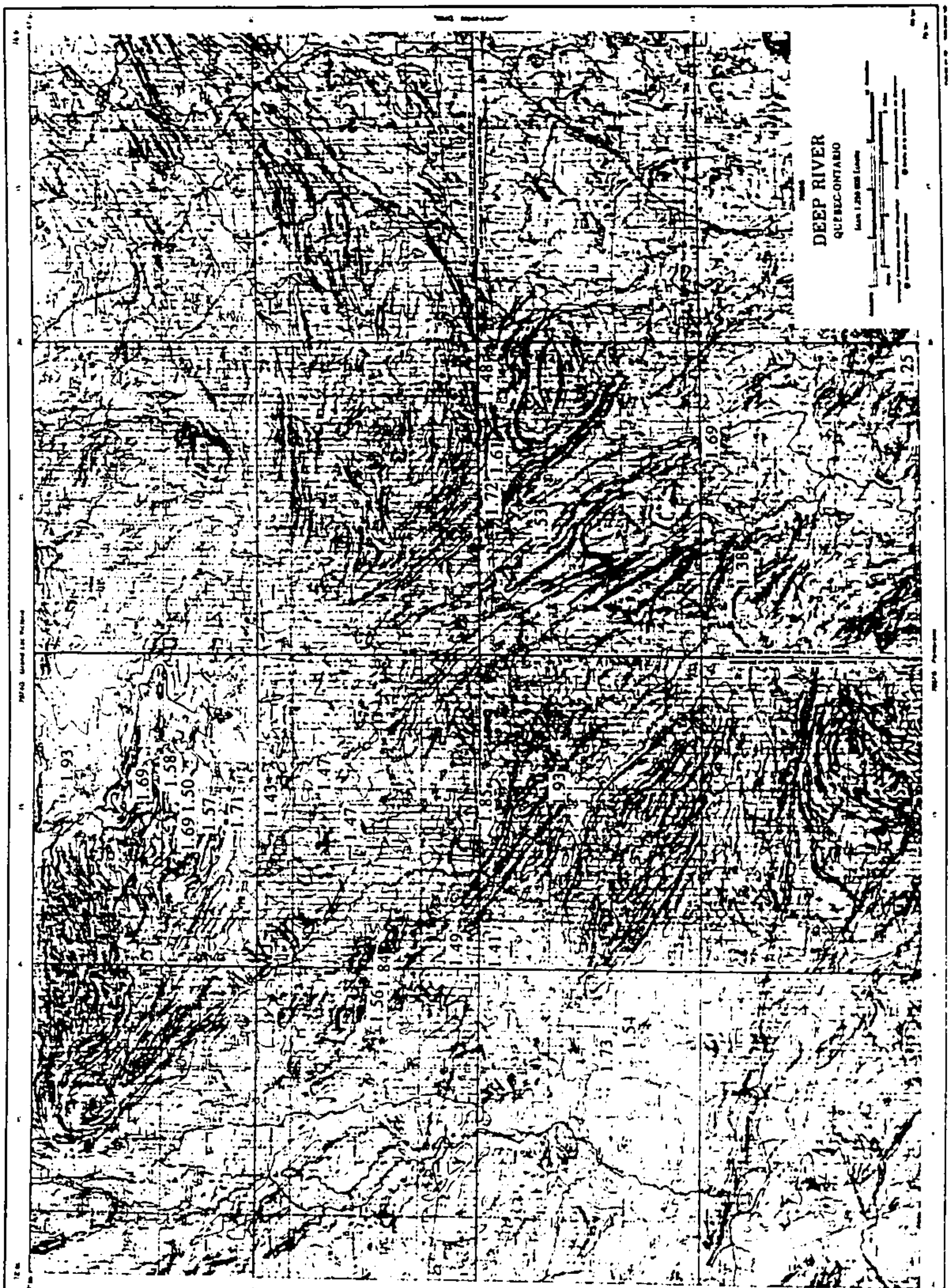
Table 5.2 SM-ND DATA (samples from the Lac Dumoine area and the Lac Perch and Cabonga terranes)

SAMPLE	AREA Grid ref.	ROCK TYPE	Sm(ppm)	Nd(ppm)	147Sm/144/Nd	143Nd/144Nd	AGE(Ga) (TDM)
Samples with 1.8-1.9 Ga (TDM)							
DU4	UG088/645	O	13.71	75.82	0.1093	0.511784	1.84
GF8	UH340/048	O	4.95	29.17	0.1025	0.511638	1.93
LN13	UG252/518	S	105.83	567.91	0.1126	0.511820	1.85
LN15	UG310/412	O	6.22	26.26	0.1431	0.512148	1.93
OT9	UG646/466	S	4.23	34.29	0.1254	0.511950	1.88
Samples with 1.6-1.7 Ga (TDM)							
DU10	UG312/940	O	2.78	14.73	0.1142	0.511937	1.69
OL3	UG732/218	O	8.80	47.32	0.1124	0.511920	1.69
OT10	UG665/476	S	1.67	8.20	0.1128	0.512018	1.72
OT11	UG675/476	S?	4.12	15.95	0.1248	0.512100	1.61
DU20	TH985/135	S	4.23	25.34	0.1009	0.511740	1.76
LN10	UG253/827	S	6.74	33.61	0.1212	0.512006	1.71
LN12	UG271/869	P	4.75	23.71	0.1201	0.512015	1.69
Samples with 1.4-1.5 Ga (TDM)							
DU2	UG037/656	S	16.78	68.79	0.1474	0.512361	1.56
LN4	UG255/677	S	7.45	36.69	0.1227	0.512166	1.47
LN7	UG312/171	P	16.11	80.49	0.121	0.512147	1.47
LN9	UG285/750	O	5.02	28.03	0.1082	0.512051	1.43
LN11	UG255/844	O	7.98	37.49	0.1286	0.512163	1.57
OT7	UG612/432	S	6.94	35.92	0.1167	0.512069	1.53
OT14	UG503/806	O	3.67	16.62	0.1335	0.512244	1.48
TA18	UG102/551	O	1.39	24.09	0.1102	0.512030	1.49
TA17	UG081/518	O	5.06	27.69	0.1015	0.512089	1.41

Table 5.2 (continued)

DU7	UG300/883	S?	9.07	40.23	0.1364	0.512281	1.5
DU9	UG326/903	O	7.04	35.83	0.1184	0.512059	1.58
ZC6	UG980/343	O	10.46	46.27	0.1367	0.512265	1.54
Samples with 1.2-1.3 Ga (TDM)							
LN19	UG519/197	O	2.88	13.27	0.1314	0.512298	1.38
MT13	UG301/136	O	5.64	26.87	0.1269	0.512275	1.33
OT1	UF817/959	S	5.81	30.13	0.1166	0.512247	1.25
The Lac Perch Terrane							
RD3	TH990/543	O	2.97	16.69	0.1074	0.510055	1.54
RD4	TH969/544	O	2.91	17.42	0.1010	0.511936	1.49
RD5	TH952/546	O	3.24	18.08	0.1084	0.512018	1.48
RD6	TH919/538	O	4.77	25.70	0.1122	0.512035	1.51
The Cabonga Terrane							
X754	UH754/383	O	2.45	10.52	0.1406	0.512299	1.55
BC312	UH	S	13.21	69.29	0.1154	0.511708	2.07

Fig. 5.3 Combination map of aeromagnetic anomaly data and model age mapping results in the Lac Dumoine area. The aeromagnetic anomaly map (31K, scale 1:250,000) was published by Geological Survey of Canada in 1981.


DEEP RIVER
QUEBEC-ONTARIO

occupy a NE-SW trending zone of flat aeromagnetic response between high magnetic relief on both sides (Fig. 5.3).

Nd model age data obtained on both sides of the Allochthon Boundary Thrust are in agreement with the location of the "ABT" in the Lac Bleu and Lac Dumoine areas. Two samples with Archean model ages to the north of the ABT represent Archean crust, which connects with the Archean crust mapped out in both Grand-Remous and Kipawa-Mattawa areas (Fig. 5.2), whereas to the south of the ABT, unlike the adjacent Kipawa-Mattawa and the Grand-Remous areas, no rocks having model ages of > 2.0 Ga have been identified. To the west of the Lac Bleu area, an age boundary, which coincides with a lithological boundary shown on the geological map 31L, can be drawn. The boundary separates rocks with model ages of 1.5-1.9 Ga in the Lac Bleu area from Archean crust identified in the Mattawa area (Guo and Dickin, submitted). As previously discussed in Chapter 4, the age boundary defined here probably represents a major structural limit which corresponds to the ABT in this specific portion.

5.2.2. Petrology of Samples

Major element analyses for all samples are listed in Appendix 3. Trace element Rb, Nb, Sr, Zr and Y were analyzed in selected samples and the data are listed in Table 5.3.

For discrimination of paragneiss and orthogneiss, this

Table 5.3 TRACE ELEMENT ANALYSES (in ppm)

The Lac Bleu area

Samples with 1.8-1.9 Ga model ages							
	DR12	DR25	TA12	TM8	TN4	DR14	H171
Nb	13.5	13.0	8.3	7.6	12.2	17.7	22.2
Zr	196.4	223.1	161.9	nd	238.2	236.0	nd
Y	25.9	34.1	20.6	13.6	32.5	52.4	60.3
Sr	411.2	500.0	404.6	nd	716.1	241.6	nd
Rb	121.3	87.6	121.2	nd	97.4	106.4	nd

Samples with 1.6-1.7Ga model ages				Samples from the LPT and RCT			
	MT9	TA8	TM13	RD3	RD4	RD5	X754
Nb	9.3	12.6	10.8	6.6	5.9	5.6	3.9
Zr	207.5	188.0	165.4	118.4	145.6	129.6	44.6
Y	28.2	23.0	30.9	13.5	9.0	11.1	10.6
Sr	339.9	206.2	565.6	608.1	969.6	1068.5	773.8
Rb	146.8	71.7	84.7	43.2	27.7	35.1	6.9

The Lac Dumoine area

Samples with 1.8-1.9 Ga model ages				Samples with 1.6-1.7 Ga model ages	
	LN13	LN15	OT9	DU10	OT10
Nb	14.6	17.4	6.0	12.2	6.5
Zr	346.5	171.9	101.6	83.6	83.0
Y	40.8	38.8	17.1	19.6	11.7
Sr	595.0	246.9	919.0	1094.4	349.4
Rb	95.0	125.8	141.8	20.1	34.5

Samples with 1.4-1.5 Ga model ages						
	LN4	LN7	LN9	LN11	OT7	OT14
Nb	13.2	8.2	7.0	10.1	13.3	4.8
Zr	268.2	111.3	156.3	229.8	415.8	69.8
Y	41..0	21.9	21.6	43.3	31.3	24.7
Sr	171.6	68.0	679.2	515.3	297.2	471.0
Rb	111.9	92.0	60.8	65.0	106.0	18.1

study adopts the method of Dickin and McNutt (1989), using three normative minerals: corundum, quartz and diopside to distinguish them from each other. Paragneisses were identified by their high normative corundum and quartz. Of 56 samples in the study, 20 samples are probably sedimentary in their origin (Tables 5.1 and 5.2). The rest of rocks (except apparently intrusive plutons with undisturbed massive structure), characterized by zero to low normative corundum, low to high quartz and zero to high diopside, are assigned to orthogneisses. These rocks are mostly represented by biotite gneisses and granitic and mafic gneisses.

In the Lac Bleu and Lac Dumoine areas, the major rock type is biotite gneiss which generally contains 10-20% biotite and/or hornblende, 50-60% plagioclase and 10-20% quartz, and these minerals display a medium-coarse grained, granoblastic mosaic texture. However, some biotite gneisses with model ages of 1.4-1.5 Ga in the Lac Dumoine area differ from the biotite gneisses described above. They are fine-grained (about 1 mm in size) and finely layered (one single layer is about 2-3 mm in thickness). These rocks may represent equivalents of straight gneisses. Similarly, samples from the Lac Perch Terrane also show fine-grained texture.

Plutons with different model ages in the Lac Bleu and Lac Dumoine areas include both granitic and mafic varieties. These plutons are easily recognized in the field because they are either K-feldspar or mafic mineral rich and less foliated, which may imply that they are postkinematic intrusions.

When plotted on the chemical-mineralogical discrimination diagram (Fig. 5.4, Debon and Le Fort, 1983), orthogneisses from the study area (including the Lac Perch and Cabonga Terranes as well as the Renzy Shear Belt) are distributed in most fields but display a general trend from gabbro to granite.

In Fig. 5.5, a plot of K_2O versus SiO_2, most orthogneisses from the study area fall in both high K and medium K fields, and occupy the same field as the plutonic rocks from the Arequipa and Lima segments of the Coastal Batholith of Peru (Wilson, 1989).

On the AFM diagrams (Figs. 5.6A and B), orthogneisses and plutonic rocks from both Lac Bleu and Lac Dumoine areas and the other terranes show a calc-alkaline trend. Also, most rocks fall in the field defined by the Coastal Batholith of Peru, displaying an orogenic affinity. Samples lying outside the field are either granitic (e.g., H171) or mafic (e.g., LN12 and LN7) plutons, which were probably formed in a late anorogenic setting. Similarily, most orthogneiss samples from the Lac Bleu area, Lac Dumoine area, and the Lac Perch Terrane and the Cabonga Terrane display an orogenic character on the Nb-Y diagram (Fig. 5.7).

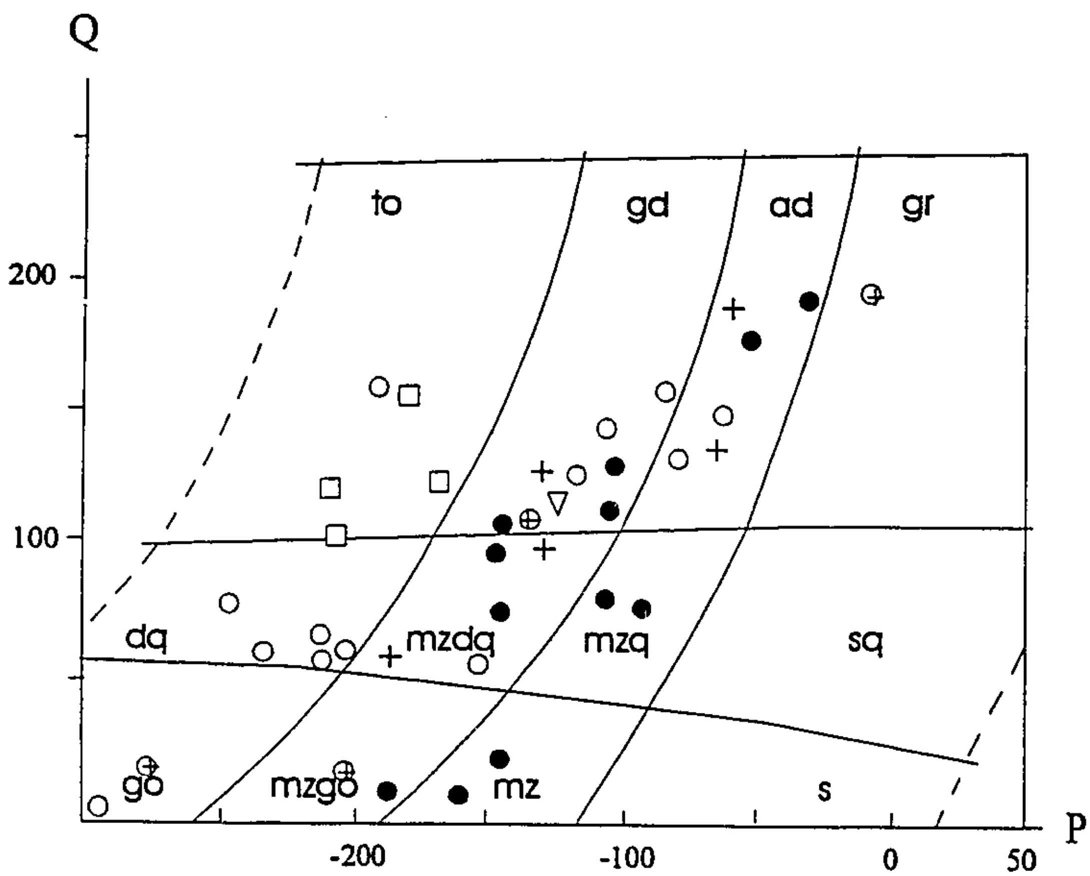


Fig. 5.4 Chemical-mineralogical grid for orthogneisses and plutonic rocks from the study area. ●: samples from the Lac Bleu area. O: samples from the Lac Dumoine area. □: samples from the Lac Perch Terrane. ▽: sample from the Cabonga Terrane. +: samples from the Renzy Shear Belt. ⊕: plutonic rocks.

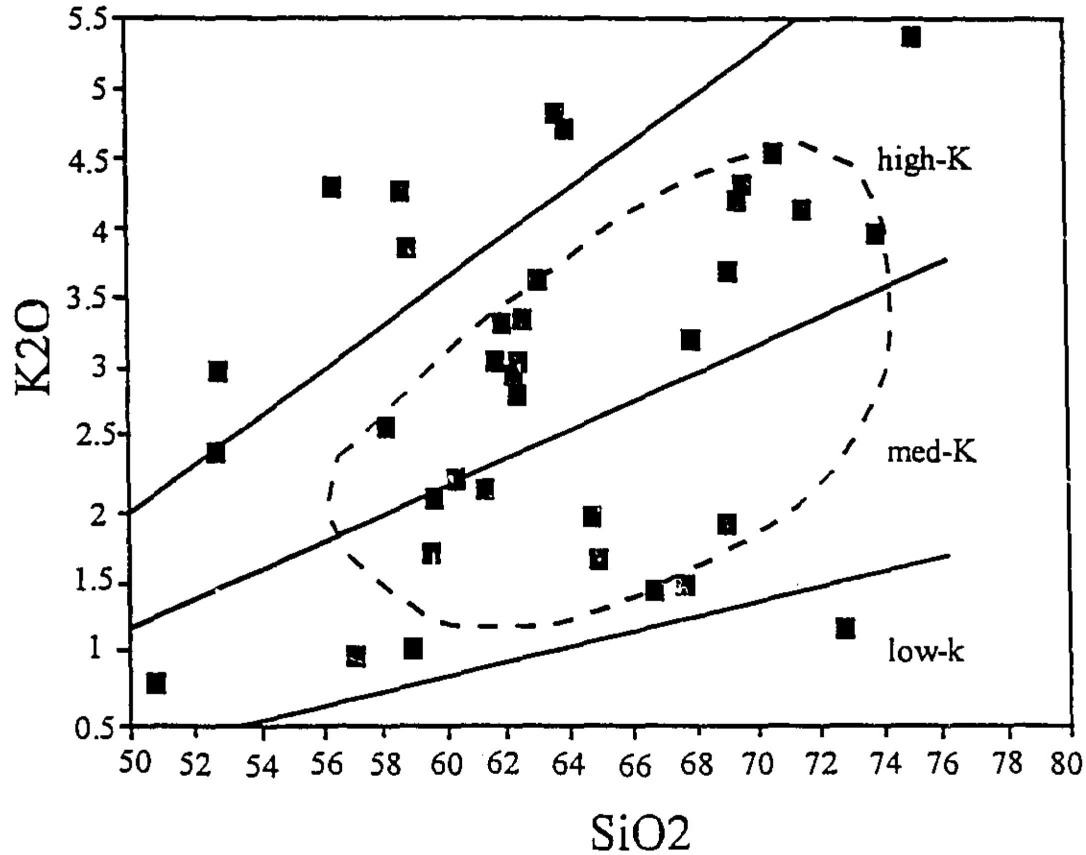


Fig. 5.5 Plot $\%K_2O$ versus $\%SiO_2$ for orthogneisses from the study area. The boundaries between the high-, medium- and low-K fields are those of Peccerillo and Taylor (1976). The dash line marks the field of plutonic rocks from the Lima and Arequipa segments of the Coastal Batholith of Peru (after Wilson, 1989).

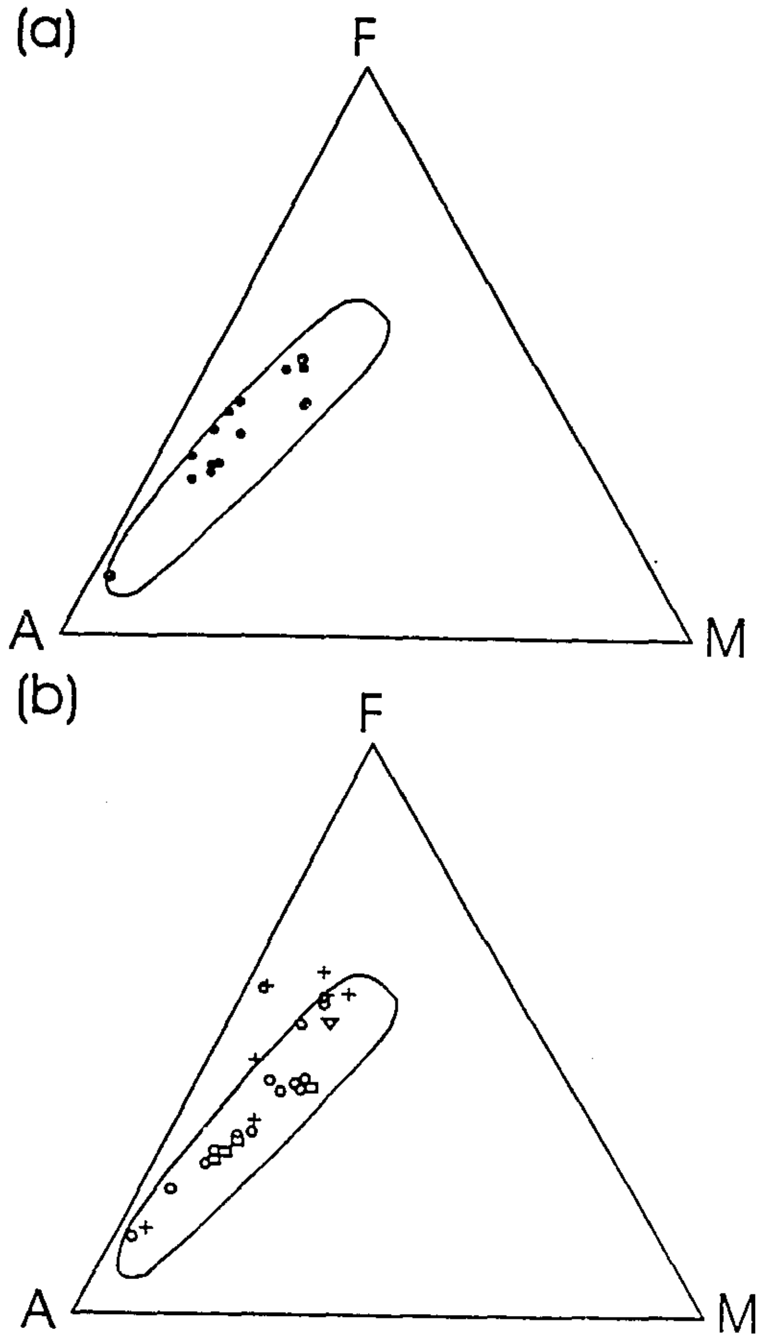


Fig. 5.6 AFM diagram for orthogneisses from (a) the Lac Bleu area and (b) the Lac Dumoine area. Symbols in (b) refer to Fig. 5.4. The field represents the Coastal Batholith of Peru showing an orogenic trend (after Dickin and McNutt, 1991).

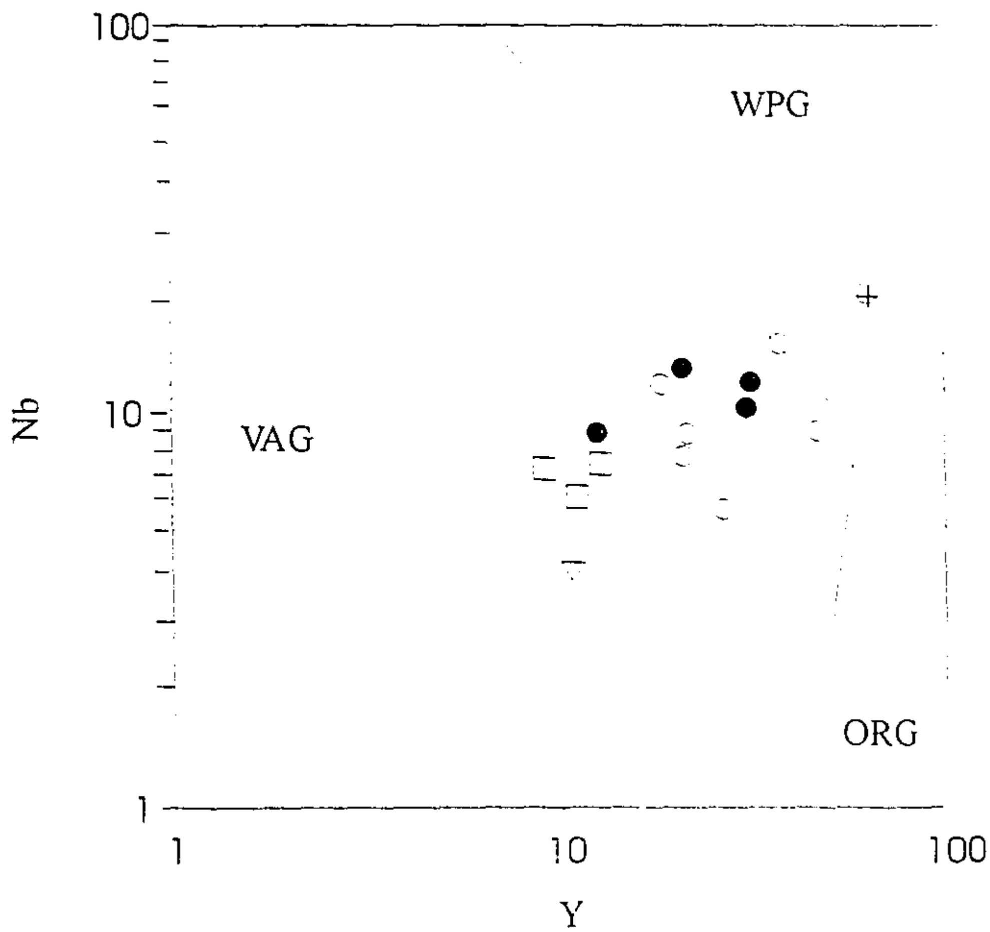


Fig. 5.7 Nb-Y diagram showing tectonic affinity for the orthogneisses in the study area. All symbols refer to Fig. 5.4.

5.3. Discussion

5.3.1. A Paleo-Mesoproterozoic Andean-type continental margin

As shown in Tables 5.1 and 5.2 and Fig. 5.2, post-Archean model age values are distributed in a wide range (1.2-1.9 Ga). Also, the spatial distribution of model ages lacks an obvious southerly decreasing trend. Both temporal and spatial scattering of model ages, can be interpreted to reflect characteristics of a long-lived Andean-type continental margin, which has probably undergone multi-episodic orogenies.

Orthogneisses in the study area show lithological and petrochemical similarities to plutonic rocks from the Coastal Batholith of Peru in the Central Andes (Figs. 5.4, 5.5, 5.6). These similarities provide evidence for the interpretation that the rocks in the study area represent products of an Andean-type continental margin. The rocks display a wide lithological spectrum from gabbro to granite (Fig. 5.4). This is much like the Coastal Batholith of Peru, which comprises 16%, by volume, gabbro and diorite, 58% tonalite and granodiorite, 25.5% adamellite and 0.5% granite (Hughes, 1992).

Regional Nd model age mapping results presented by

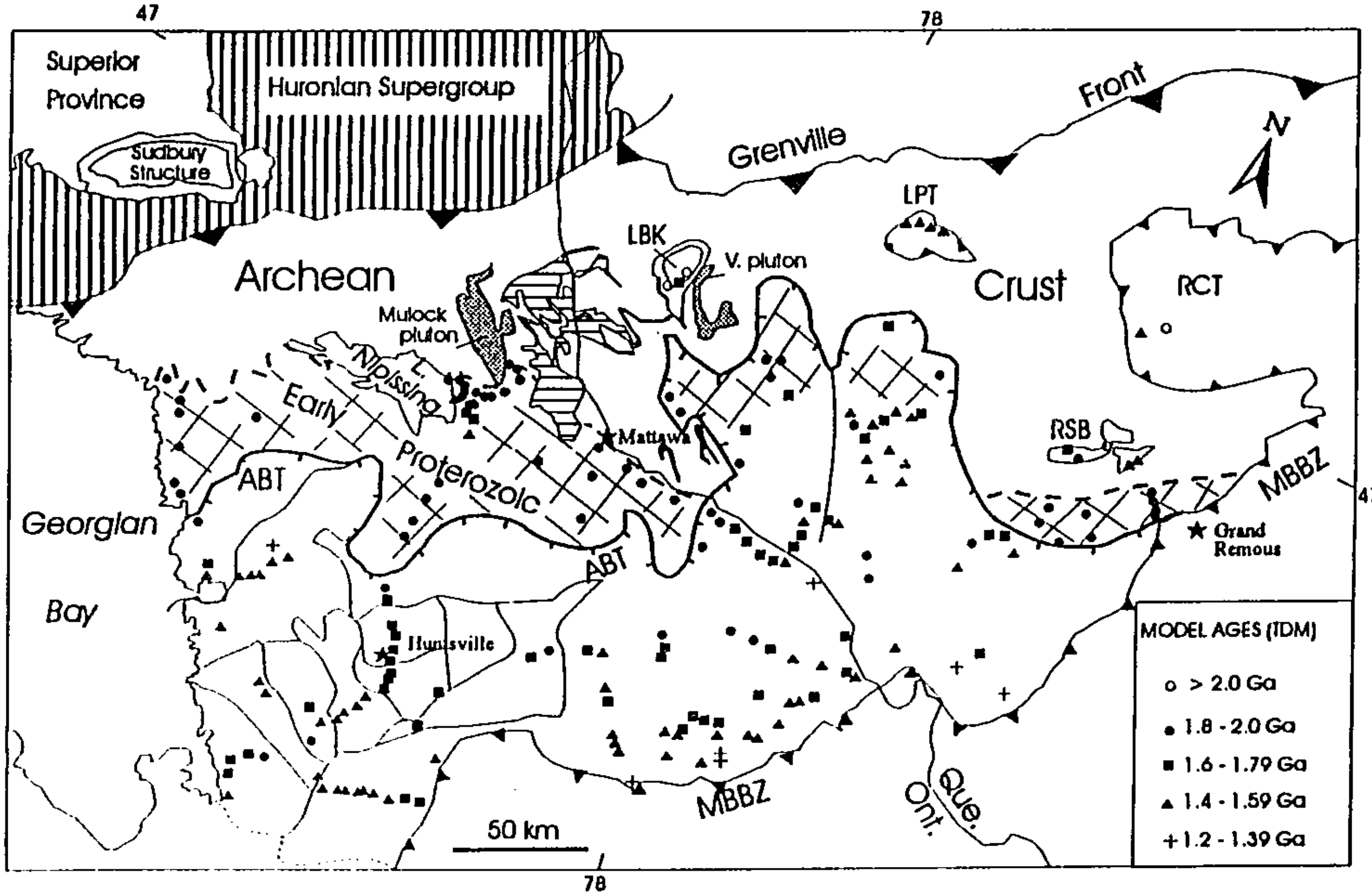
Dickin and McNutt (1989, 1991), Holmden and Dickin (submitted) and Martin (1993), in an area of approximately 30,000 km^2 in the Central Gneiss Belt of Ontario, provide strong evidence in favour of the interpretation of a continental margin. As shown in Fig. 5.8, a compilation map of Nd model age data for Ontario and western Quebec, rocks with a range of 1.3-1.9 Ga Nd model age were identified by the above studies. The rocks include grey gneisses having a orogenic signature and young plutons with an anorogenic chemistry. The model age data and geochemical evidence together suggest the existence of a prolonged active continental margin with Killarnean (1.75 Ga) and Mesoproterozoic (1.55-1.35 Ga) arc - back-arc associations on the Paleoproterozoic - Archean foreland.

It is obvious from Fig. 5.8 that both Lac Bleu and Lac Dumoine areas show a similar crustal age structure to that in the Central Gneiss Belt of Ontario. Therefore, it can be suggested that both Lac Bleu and Lac Dumoine areas, also the Lac Perch and the Cabonga Terranes as well as the Renzy Shear Belt probably represent crustal slices of the proposed long-lived continental margin in the south-southwest Central Gneiss Belt of Ontario.

5.3.2. Structural implications

A regional comparison between model age mapping results of Ontario and western Quebec (including the Kipawa-

Fig. 5.8 Compilation map of Nd model age mapping results in Ontario and western Quebec. The lined area: metasedimentary unit in the North Bay and Kipawa areas. The cross-lined area: ca.1.9 Ga arc-related material. The model age data in Ontario are cited from Dickin and McNutt (1991); Holmden and Dickin (submitted); Martin (1993).


47
78
Superior Province
Huronian Supergroup
Sudbury Structure
Grenville
Front
N
LPT
LBK
V. pluton
Archean
Crust
RCT
Mulock pluton
L. Nipissing
Early
Proterozoic
Mattawa
RSB
MBBZ
47
ABT
Georgian
Bay
Grand Remous
ABT
Huntsville
MODEL AGES (TDM)
o > 2.0 Ga
• 1.8 - 2.0 Ga
■ 1.6 - 1.79 Ga
▲ 1.4 - 1.59 Ga
+ 1.2 - 1.39 Ga
MBBZ
Que.
Ont.
50 km
78

Mattawa and Grand-Remous areas, see Chapters 3 and 4) further confirms the suggestion that the Lac Bleu and Lac Dumoine are allochthonous in nature (Indares and Martignole, 1990).

As shown in Fig. 5.8, 1.9 Ga arc-related material is located further south in the Grand-Remous area and the Mattawa area in western Quebec, and in the area south of the Lake Nipissing and adjacent to the Georgian Bay in Ontario. The 1.9 Ga arc-related material has been suggested to be parautochthonous crust crust (Dickin and McNutt, 1989; Dickin and Guo, submitted; Guo and Dickin, submitted) and represents the northern limit of Early Proterozoic crust. With reference to the exposure of the 1.9 Ga crust, rocks with ca. 1.9 Ga model ages exposed in the north Lac Bleu and Lac Dumoine areas have been probably moved at least 50 km to the north. It is also clear in Fig. 5.8 that without the effect of thrusting in the Lac Bleu and Lac Dumoine areas, the 1.9 Ga material exposed in the above areas would constitute an E-W trending unbroken belt from the Grand-Remous area in the east to the Georgian Bay area in the west.

Moreover, no rocks with model ages of 1.6-1.7 Ga have been found in the lateral Kipawa-Mattawa and Grand-Remous areas. These rocks are commonly exposed in the Huntsville area and the area near the Central Metasedimetnary Belt in Ontario (Fig. 5.8). As a result of NW directed transport of the Proterozoic material, Archean crust is buried in both Lac Bleu and Lac Dumoine areas and the exposure of Archean crust retreats greater than 80 km to the north with respect to the extent of in situ Archean crust in both Kipawa-Mattawa and Grand-Remous areas.

Although Archean crust can exist underneath the allochthon, no plutons with model ages of > 2.0 Ga are found in both Lac Bleu and Lac Dumoine areas (Fig. 5.2). This is unlike the NW Grenville Province of Ontario (Dickin and McNutt, 1989) and both Kipawa-Mattawa and Grand-Remous areas, where plutons with model ages of > 2.0 Ga serve as an indication of the presence of Archean basement (Guo and Dickin, submitted). The reason for the lack of plutons with model ages of > 2.0 Ga could be attributed to the fact that magmas derived from Archean crust were contaminated by the tectonically overlying Proterozoic material during their ascent.

Both Lac Bleu and Lac Dumoine areas, as a whole, were proposed as an allochthon (LDT) by Indares and Martignole (1990). However, based on geology and Nd model age mapping results obtained from this study, two separated thrust sheets, which I will refer to as the Lac Bleu thrust sheet and Lac Dumoine thrust sheet, can be defined. A few lines of reason for this division are:

1) From the 1:250,000 aeromagnetic anomaly map (Geological Survey of Canada, 1981), the Lac Dumoine area exhibits stronger and more complex magnetic anomalies than those in the Lac Bleu area.

2) An Archean crustal salient projects to the south between the two areas near Lac Dumoine (Fig. 5.2). This can be interpreted to indicate the presence of two separated thrust sheets.

3) Straight gneisses with north-striking and east-dipping (40-85°, dipping angle is 60°) gneissosity have been observed in the area 40 km northwest of Deep River (Fig. 5.2 and Plate 5.1). These straight gneisses probably represent a high grade shear zone between the two areas and indicate a displacement sense in which the Lac Dumoine thrust sheet was thrust onto the Lac Bleu thrust sheet from the southeast.

Accordingly, a proposed boundary (shear zone) can be drawn through the tip of the Archean crustal salient and the outcrop of the straight gneisses found in the central part of the study area (Fig. 5.2).

As shown in a combination map of model age mapping results and aeromagnetic anomaly data (Fig. 5.3) in the Lac Dumoine thrust sheet, most rocks with 1.4-1.5 Ga model ages are associated with a NE-SW trending zone of low magnetic relief. The zone is in surrounding rocks with model ages ranging from 1.6-1.9 Ga and strong magnetic anomalies. Although the aeromagnetic anomaly data lack a detailed structural interpretation, coupled with the isotopic model ages, they may imply that the Lac Dumoine thrust sheet comprises different terranes with distinctive crustal components.

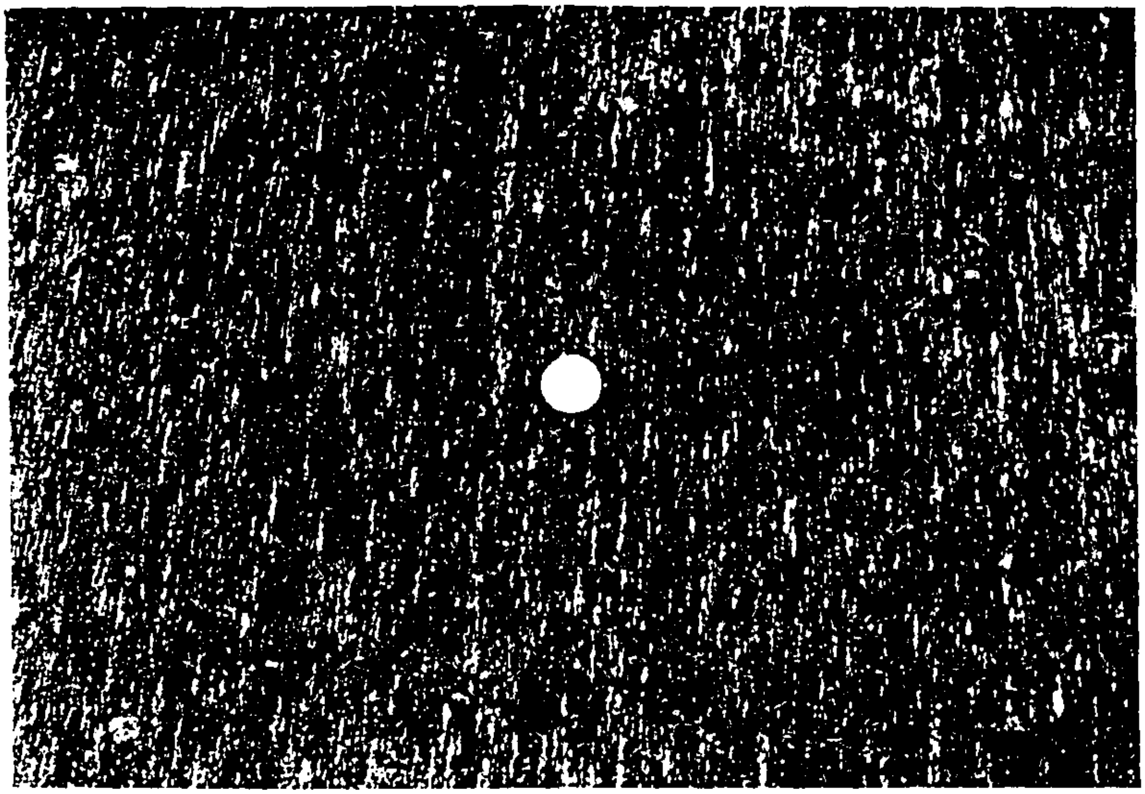


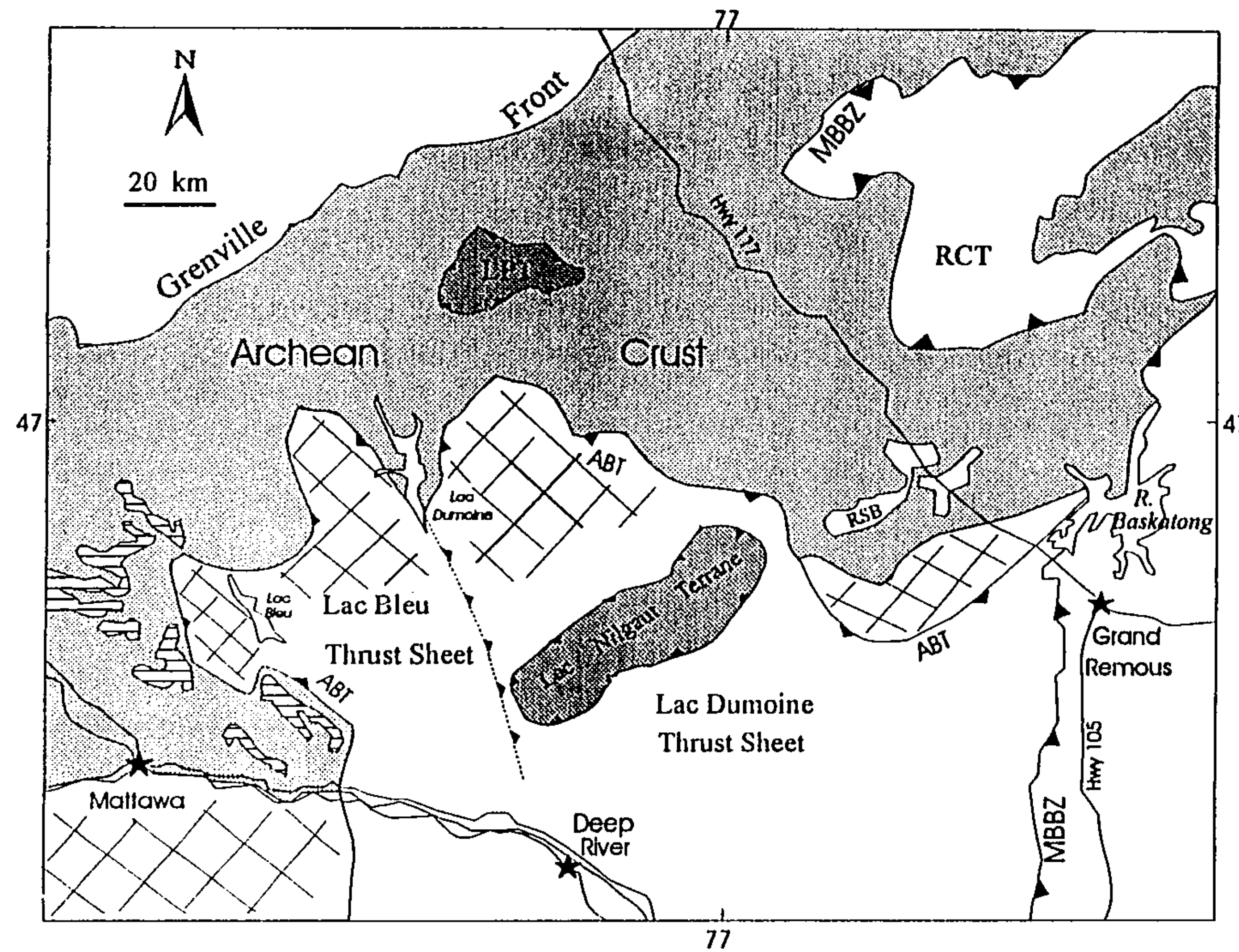
Plate 5.1 an outcrop of straight gneisses observed in the central study area about 40 km northwest of Deep River (the sampling positions are marked as stars in Fig. 5.2).

To the north of the Lac Dumoine thrust sheet, 1.4-1.5 Ga model ages associated with biotite gneisses are also determined in the Lac Perch Terrane, which is tectonically allochthonous and completely rests on Archean crust as a klippe. From the allochthonous status of the Lac Perch Terrane, it is reasonable to make inference that the rocks having 1.4-1.5 Ga model ages associated with the low magnetic relief zone in the Lac Dumoine thrust sheet also represent a thrust mass. The thrust mass, tentatively named the Lac Nilgaut Terrane by this study (Fig. 5.9), probably corresponds to a klippe which tectonically overlies the surrounding rocks with model ages of 1.6-1.9 Ga. Since rocks with 1.6-1.9 Ga model ages can be traced into the area to the south, they may constitute a nappe still attached to the root zone.

Although the above inference needs further structural study to confirm, an early phase of folds with NE-trending axes in the Lac Dumoine area was recognized (Katz, 1976). This NE-trending structure may have controlled the distribution of the Proterozoic material. A set of NE trending folds were also found by Harris et al. (1986), using remotely sensed data, to the northeast of the Lac Dumoine area.

The northern and western limit of the two thrust sheets could represent a major thrust boundary and possess the significance of the ABT in the study area because no major thrust boundaries have been found to the north and west of both Lac Bleu and Lac Dumoine areas (Fig. 5.9). As shown by

Fig. 5.9 Structural interpretation of the Nd model age data (see detail in text). The cross-lined area: ca. 1.9 Ga arc-related material.


77
N
20 km
Grenville
Front
MBBZ
Hwy 117
RCT
LPT
Archean
Crust
47
47
ABT
Lac Dumoine
RSB
R. Baskatong
Lac Nilgaut Terrane
Lac Bleu
Lac Bleu
Thrust Sheet
ABT
ABT
Grand
Remous
Lac Dumoine
Thrust Sheet
Hwy 105
MBBZ
Mattawa
Deep
River
77

the model age mapping results from this study, the thrust limit also serves as a crustal boundary between Archean crust and Paleoproterozoic material.

A structural analogue can be found in the SW Central Gneiss Belt in the Grenville Province of Ontario, where a number of thrust-bounded domains and subdomains are stacked together (Davidson et al., 1985; Davidson, 1986). Among these structural domains, the Huntsville and Novar subdomains of Algonquin domain and the Rosseau and Go Home subdomains are thought to be the lowermost thrust sequences. The Parry Sound domain, as a klippe, is thrust over the above domains. Overlying the Parry Sound domain are thrust sheets of the Moon River and Seguin subdomains which attach to their root in the Muskoka domain.

CHAPTER SIX:

CONCLUSION

Detailed Nd model age mapping, combined with lithological and geochemical studies in this work, has successfully achieved in the following two aspects:

1. Determination of crustal constitutions in the Grenville Province of western Quebec.

2. Identification of structural terranes.

Determination of crustal constitution:

1) extent of Archean crust and its southern limit.

Archean model ages identified from grey gneisses in the Kipawa-Mattawa and the Grand-Remous areas represent a southern extension of the Archean parautochthon. Thus, Archean crust recognized by this study extends 120 km and 130 km south from the Grenville Front, and 70 km and 20 km from the previously proposed location of the southern limit ("ABT") of the Archean parautochthon in the two areas, respectively.

2) 1.8-1.9 Ga arc-related juvenile crust.

To the south of the Archean parautochthon, biotite gneisses with model ages of 1.8-1.9 Ga represent a reworked Paleoproterozoic arc, which was developed along the southern margin of the Laurentian continent and collided with the continent at 1.75 - 1.85 Ga. The 1.9 Ga arc related material identified in the study area, together with the rocks having similar model ages in the Central Gneiss Belt of Ontario, formed a belt along the southern margin of Laurentia within the Grenville Province. This belt extends from the Grand-Remous area of Quebec to the east of Georgian Bay area of Ontario in the west (except a portion in the Lac Bleu and Lac Dumoine areas which were thrust to the north), with a variable width of 10-70 km.

An age boundary mapped out between the Archean crust and the 1.9 Ga arc related material can be interpreted as a cryptic suture, along which Paleoproterozoic arc(s) converged with the Laurentian continent. As an ancient suture, the lack of any evidence of shearing can be attributed to the effect of metamorphism, which could have welded the suture.

Metasediments overlying Archean crust in the Kipawa-Mattawa area represent mixing deposits in a proposed foreland basin developed during a collision between the early Proterozoic arc and Laurentia. The foreland basin may have evolved to a late marginal basin formed on the basement of a ca.1.8 Ga orogen, accompanying a north-dipping subduction that reversed from the previous south-dipping direction.

3) A long-lived active continental margin.

In the central study area, rocks with model ages of 1.3 Ga -1.7 Ga from the Lac Bleu and Lac Dumoine thrusts probably represent materials generated from a long-lived continental margin. These rocks connect with the similar tectono-lithological terrane in the Grenville Province of Ontario, defined by Dickin and McNutt (1991).

Identification of structural terranes and boundaries:

1) nappes. An apparent nappe defined by this study is located in the Lac Bleu and Lac Dumoine thrust sheets and characterized by rocks with 1.8-1.9 Ga model ages. With respect to its original position, the terrane has been moved 60-80 km to the north and it is now still attached its root zone.

2) kllipen. A number of kllipen have been identified in the study area. These kllipen includes those tectonically resting on Archean crust, such as the LPT, RSB and LBK, and those overlying 1.8-1.9 Ga crust, fro example, the LNT.

3) relocation of the ABT. The Allochthonous Boundary Thrust (ABT) is located to the south of the Kipawa-Mattawa area, where it cuts Proterozoic crust (Dickin and Guo, submitted). This major thrust boundary, when extended into the study area from the south, is represented by the western and northern limits of the Lac Bleu and Lac Dumoine thrust sheets. Since the two thrust sheets consist merely of Proterozoic material, the ABT in this specific portion coincides with an Archean-Proterozoic boundary and thus serves as both structural and crustal boundaries. The feature, being both a crustal and a structural boundary, is changed when the boundary extends into the Grand-Remous area, where it, represented by the Baskatong-Desert Lineament, cuts through

Early Proterozoic material.

Future study on structure is needed to confirm the structural interpretation in this work. Further zircon age dating for the biotite gneisses having different Nd model ages is also desirable.

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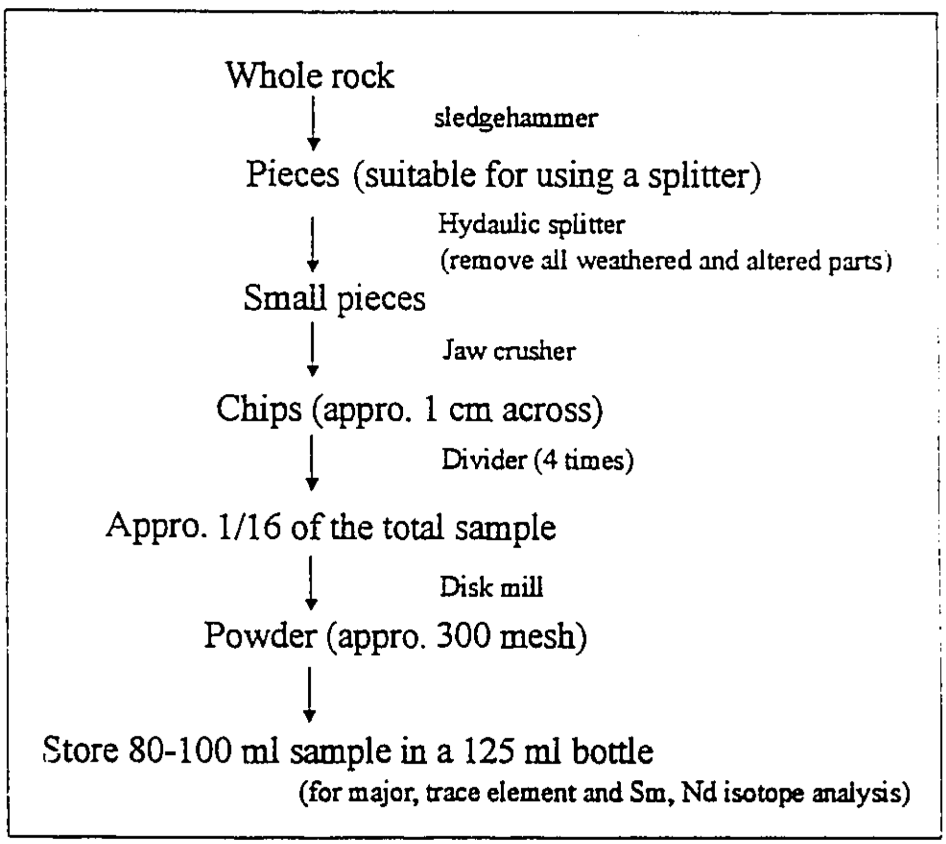
APPENDIX 1: ANALYTICAL PROCEDURES

1. Sample preparations

1) Sampling and crushing

Each sample weighing, each about 5 to 10 kg, was collected at outcrops in the field. Special precautions were taken to achieve homogeneity and representation of the samples in the collection at all sites.

The samples were processed by the following procedures in the rock crushing laboratory at McMaster University.



The following steps were performed to prevent contamination during crushing of samples:

A. Before using the jaw crusher, the crusher was pre-contaminated with small portion of the sample, that then was discarded.

B. Between each sample preparation, all pieces of equipment and working surfaces were throughout cleaned first with a vacuum and then wiped with paper towels. The jaw crusher were cleaned by wire brush and vacuum.

2) Chemical dissolution and separation

75 to 150 mg of each sample was weighed into a clean Teflon bomb. Before weighing, the Teflon bombs were freed of static electricity. The empty bombs were usually weighed several time to ensure they were static free (if reading difference was smaller than 0.1 mg between two consecutive weighings, the previous reading could be acceptable).

Approximately 10 ml of concentrate HF (48%) was then added to each bomb. The bomb was sealed and put in a Teflon jacket which was placed into an oven at 120° C for three days.

After removing the bomb from the oven, the sample solution was evaporated on a hot plate. When the sample was dry, another 5 ml of 16N HNO_3 was added and evaporated to dryness. 5 ml of 6N HCl was added and the bomb was returned to the oven overnight.

The sample solution was diluted by adding 5 ml of Milli-Q water (triple-distilled and disionized water) and the solution was subsequently split into two aliquots in two 15 ml beakers. 150 to 250 mg of mixed $^{149}Sm/^{150}Nd$ spike was then added into one aliquot for isotope dilution analysis. Both spiked and unspiked fractions were evaporated to dryness and then added 2 ml of 2.5N HCl, and poured into clean polystyrene tubes. A 10-minute centrifugation of the solutions was then performed.

Chemical separation and purification of Sm and Nd were done by eluting through a two stage of cation exchange. The first stage separated major elements and some trace elements (e.g., Sr and Ba) from bulk rare earth elements, using cation exchanging column. The second stage involved separation of Sm and Nd by REE exchanging column.

A. Extraction of bulk REE

Sample solutions in 1 ml of 2.5N HCl were loaded onto quartz column (195mm × ϕ10mm) packed with 125 mm high (15 ml?) Dowex Bio-Rad AG 50W 200-400 mesh resin. Major elements and Sr were removed by an elution of 2.5 N HCl. Before collecting the REE with 7.5 N HNO_3, Ba was washed off from the REE cut by 30 ml 2N HNO_3.

The REE solutions were evaporated to dryness and subsequently redissolved in 1 ml of 0.2 N HCl.

B. Separation of Sm and Nd

Quartz columns (195mm × ϕ10mm), packed with 100-200 mesh teflon powder coated with a HDEHP (Di-2-ethyl-hexyl-orthophosphoric acid) resin (85 mm high), were used for separation of Sm and Nd.

The reverse phase ion exchange method (since LREE are eluted first, while other cation exchange method HREE come out first) was used in the REE exchange column. Three different solutions were collected through this method: unspiked Nd sample was collected from the previously unspiked fraction of a sample with 0.2 N HCl after eluting 0.2 N HCl. Spiked Nd sample from the previously spiked fraction of the sample for isotope dilution determination was collected in 0.2N HCl with an elution of 0.2 N HCl first. An elution of 0.5N HCl was carried out in the same fraction and spiked Sm sample for isotope dilution analysis was collected in 0.5N HCl.

Finally, all three samples were evaporated to dryness and redissolved in 2 drops of mixed 3 N HNO_3 and 0.3M H_3PO_4 (in a mixing rate: 100: 1.3).

2. Mass spectrometry

For mass spectrometric determination, Sm and Nd samples in approximately 1 μg of 0.3M H_3PO_4 (for both isotope dilution and Nd isotopic ratio analyses) were loaded onto the Tantalum side filament of a double filament bead respectively (Rhenium center filament) and then were heat to dry using 1.5-2.0 amps.

Sm and Nd dilution and Nd isotopes analyses were performed on a VG ISOMASS 354 mass spectrometer with 27 cm radius and 90° magnetic sector. Nd isotopic ratios were obtained by using a 4-collector multidynamic mode. Nd isotopic fractionation was corrected against $^{146}Nd/^{144}Nd$ ratio of 0.7219. A total of 81 runs of the La Jolla standard (Table A 3.1) through the course of this study produced an average value of 0.51185 ± 0.00002 (2 σ, population), which is comparable with the recommended value of 0.511860. Average within-run precision (standard error) of samples was ± 0.0022% (2 σ). Sm and Nd contents and $^{147}Sm/^{144}Nd$ ratios were determined by isotope dilution analysis in the single collector mode. Analysis of BCR-1 yielded a Sm/Nd ratio of 0.228. Based on duplicate analyses of dissolutions of unknowns, $^{147}Sm/^{144}Nd$ can be reproduced within 0.5%, correlated

Table A1.1 La Jolla Standard Analyses (143Nd/144Nd, Sept.1989-Jan.1993)

	143Nd/144Nd	Standard error(/mil. 1)		143Nd/144Nd	Standard error (/mil. 1)
1.	0.511849	0.004	41.	0.511844	0.025
2.	0.511841	0.005	42.	0.511853	0.007
3.	0.511846	0.003	43.	0.511876	0.006
4.	0.511840	0.004	44.	0.511841	0.010
5.	0.511825	0.004	45.	0.511855	0.011
6.	0.511837	0.004	46.	0.511875	0.011
7.	0.511825	0.008	47.	0.511820	0.005
8.	0.511830	0.010	48.	0.511856	0.006
9.	0.511844	0.008	49.	0.511871	0.016
10.	0.511842	0.013	50.	0.511824	0.006
11.	0.511823	0.006	51.	0.511853	0.011
12.	0.511833	0.006	52.	0.511877	0.010
13.	0.511825	0.005	53.	0.511846	0.010
14.	0.511836	0.004	54.	0.511852	0.010
15.	0.511837	0.006	55.	0.511874	0.013
16.	0.511846	0.005	56.	0.511831	0.006
17.	0.511855	0.004	57.	0.511845	0.007
18.	0.511838	0.006	58.	0.511883	0.011
19.	0.511829	0.005	59.	0.511876	0.011
20.	0.511853	0.004	60.	0.511820	0.005
21.	0.511835	0.005	61.	0.511868	0.009
22.	0.511853	0.005	62.	0.511832	0.006
23.	0.511858	0.006	63.	0.511851	0.007
24.	0.511861	0.005	64.	0.511832	0.007
25.	0.511852	0.005	65.	0.511860	0.010
26.	0.511849	0.013	66.	0.511849	0.009
27.	0.511840	0.005	67.	0.511842	0.008
28.	0.511841	0.005	68.	0.511905	0.013
29.	0.511850	0.005	69.	0.511841	0.005
30.	0.511820	0.006	70.	0.511897	0.015
31.	0.511858	0.005	71.	0.511828	0.008
32.	0.511830	0.004	72.	0.511852	0.006
33.	0.511855	0.006	73.	0.511862	0.008
34.	0.511855	0.004	74.	0.511828	0.008
35.	0.511850	0.005	75.	0.511832	0.011
36.	0.511837	0.005	76.	0.511838	0.005
37.	0.511820	0.010	77.	0.511856	0.009
38.	0.511895	0.011	78.	0.511822	0.007
39.	0.511846	0.006	79.	0.511835	0.010
40.	0.511889	0.011			

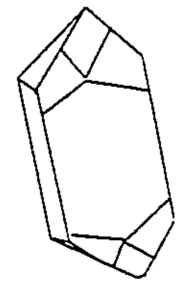
Average value of 143Nd/144Nd ratios: 0.511847±0.000019 (2σ, population).

with $^{143}Nd/^{144}Nd$, which leads to about ± 20 Ma errors (2 σ) in model age. All samples were run in a vacuum condition better than 2×10^{-7} mBars (1.5×10^{-7} Torr).

The level of background contamination for Nd was measured three times at values of 0.2 ng, 0.36 ng and 0.02 ng respectively. Nd blanks for the former two measurements were prepared from the first stage of sample weighing through the chromatography procedure. The latter was prepared after the whole chemical procedure.

APPENDIX 2: SINGLE ZIRCON PB-PB AGE DATA OF THE VELLIDIEU PLUTON

1.Method: the Pb-Pb single zircon evaporation method is applied by this study.
The method is described in detail by Kober (1986) and Mueller (1991).



2. Description of zircon: GA12(2)

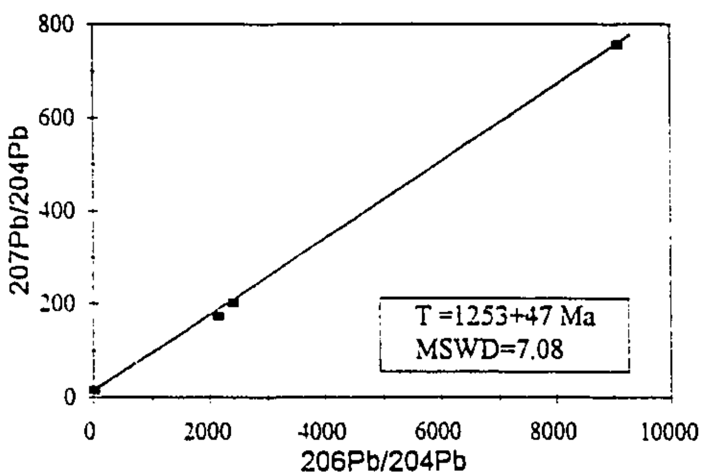
Euhedral crystal, yellownish colour and clear. Size: 0.02 * 0.04 mm.

3. Experimental condition: the zrcon was determined at the side filament evaporation current of 4.0 amp in 10 minutes and the centre filament ionisation current of 3.8 amp.

4. Pb-Pb data

Sample	Runs	207Pb/204Pb	(St.Err. %)	206Pb/204Pb	204Pb/206Pb	(St. Err. %)	207Pb/206Pb	(St. Err. %)
GA12(2)	1	756.43	81%	9090.91	.0001100	74%	.082668	.69%
	2	203.31	24%	2400.38	.0004166	22%	.083876	.47%
	3	174.11	54%	2146.38	.0004659	57%	.082814	1.4%
Common lead (at 1.26 Ga)		15.4		16.4			.0939	

5. 207Pb/204 Pb-- 206Pb/204Pb isochron



APPENDIX 3: MAJOR ELEMENT ANALYSES

The Grand-Remous area

	GF4	GF6	LV4	LV5	RB6	RB7	RB8	RB11	RB13	RB14	RB15A	RB16	RB17
SiO2	70.18	62.92	66.04	69.89	70.49	67.55	69.73	69.58	67.77	60.78	72.80	71.44	66.22
TiO2	0.31	0.68	0.51	0.37	0.25	0.48	0.32	0.44	0.32	0.68	0.25	0.34	0.46
Al2O3	16.91	17.65	16.34	15.78	16.31	16.80	16.35	16.91	17.09	17.31	15.28	15.24	16.21
Fe2O3	2.04	3.99	3.99	2.99	2.40	2.96	2.77	2.54	2.64	6.27	2.08	2.71	3.79
MnO	0.03	0.04	0.05	0.03	0.01	0.01	0.01	0.01	0.01	0.04	0.01	0.01	0.01
MgO	0.73	2.55	1.91	1.10	1.24	1.45	0.77	0.64	1.05	2.99	0.55	1.04	1.75
CaO	3.30	3.26	4.28	3.60	3.23	1.73	3.46	3.57	4.31	5.61	2.81	3.30	4.69
Na2O	5.33	6.22	5.42	4.85	4.65	4.15	5.16	4.96	5.48	4.70	5.19	4.62	5.72
K2O	1.10	2.25	1.33	1.24	1.30	4.75	1.31	1.19	1.18	1.37	1.03	1.20	0.95
P2O5	0.07	0.45	0.13	0.15	0.12	0.12	0.12	0.16	0.14	0.24	0.10	0.10	0.19
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Na2O/K2O	4.8	2.8	4.1	3.9	3.6	0.87	3.9	4.2	4.6	3.8	5	3.9	6
Di	nd	nd	3.49	nd	nd	nd	nd	nd	1.65	3.76	nd	nd	5.43
C	1.44	0.15	nd	0.28	1.73	2.07	0.46	1.40	nd	nd	0.78	0.61	nd
Q	26.20	6.29	16.55	26.84	29.27	18.41	25.31	27.08	20.07	9.46	31.33	30.74	16.43
A	68.26	100.00	51.53	57.93	60.37	65.25	62.71	64.00	62.56	37.88	68.48	58.98	52.86
M	7.73	16.53	14.59	10.42	12.55	10.60	7.45	6.63	9.84	18.63	6.06	10.56	13.83
F	24.01	28.67	33.88	31.66	27.09	24.14	29.84	29.36	27.60	43.49	25.48	30.46	33.30
Q*	155	62.01	112	162	175	120	151	158	123	90	181	183	107
P	-207	-211	-222	-195	-180	-64	-200	-198	-229	-222	-196	-182	-248
TDM (Ga)	2.57	2.56	2.76	2.86	2.61	2.68	2.60	2.73	2.68	2.67	2.83	2.63	2.70

Q*=Si/3-K-Na-2Ca/3 P=K-Na-Ca

Di: normative diopside; C: normative corundum; Q:normative quarzt.

	RB18	RB21	BR3	BR9	BR12	BR13	Vol136	Vol160	802	886	ZP5	BR6	RB5
SiO2	71.72	72.03	60.18	56.72	64.81	61.09	71.96	56.75	65.39	66.83	67.76	56.71	68.56
TiO2	0.01	0.27	0.45	0.58	0.36	0.44	0.23	0.73	0.42	0.43	0.41	0.45	0.16
Al2O3	16.00	15.76	19.75	20.36	19.19	19.28	14.84	15.52	16.95	16.49	18.07	22.24	17.4
Fe2O3	1.63	1.76	4.42	5.13	2.81	4.81	2.69	8.85	4.49	3.74	2.94	4.12	1.78
MnO	0.01	0.01	0.05	0.06	0.03	0.05	0.03	0.15	0.07	0.05	0.03	0.05	0.02
MgO	0.56	1.35	2.00	2.83	1.47	1.82	0.92	5.34	1.60	1.73	1.26	1.21	1.24
CaO	2.41	2.95	4.31	4.44	3.49	3.62	2.30	7.36	4.68	4.62	2.46	2.80	3.45
Na2O	4.92	4.39	5.98	6.70	6.17	5.77	5.86	3.32	5.11	5.00	5.51	5.93	5.7
K2O	2.63	1.40	2.66	2.81	1.54	2.88	0.67	1.34	1.10	0.91	3.37	6.27	1.59
P2O5	0.12	0.09	0.21	0.38	0.12	0.23	0.12	0.25	0.17	0.21	0.21	0.23	0.1
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Na2O/K2C	1.9	3.1	2.2	2.4	4	2	8.7	2.5	4.6	5.5	1.63		
Di	nd	nd	0.74	1.97	nd	nd	nd	10.74	1.77	1.45	nd	nd	nd
C	0.99	1.92	nd	nd	1.35	0.69	0.60	nd	nd	nd	1.44	1.15	0.28
Q	26.67	32.73	0.56	nd	12.12	3.32	28.41	5.75	17.49	20.01	12.69	nd	19.61
A	76.11	63.68	55.57	52.71	62.70	54.69	62.62	23.55	48.54	50.11	66.23	67.82	69.35
M	5.67	14.82	12.83	15.69	11.92	11.53	8.82	26.98	12.48	14.64	9.38	6.75	11.83
F	18.22	21.50	31.59	31.61	25.39	33.78	28.56	49.47	38.99	35.25	24.39	25.43	18.81
Q*	155	193	33	-13	86	48	169	92	119	135	86	-43	122
P	-146	-165	-213	-235	-228	-189	-217	-211	-225	-224	-150	-108	-211.77
TDM (Ga)	2.64	2.57	2.53	2.69	2.71	2.59	2.70	2.67	2.76	2.72	2.70	2.28	2.46

	RB9	RB10	RB20	RB23	RB22	LV2	LV3	RB2	RB4	MAW6	MAW8	MAW9	Vol632
SiO2	63.85	60.70	74.60	64.19	Granite	63.13	56.45	65.72	59.99	67.68	68.48	71.53	59.55
TiO2	0.50	0.65	0.36	1.05		0.60	0.92	1.10	0.80	0.39	0.57	0.42	0.67
Al2O3	16.99	15.96	13.00	14.56		17.33	16.81	14.30	18.09	17.12	16.27	15.39	17.75
Fe2O3	5.35	6.84	2.84	7.00		5.76	8.71	6.84	6.78	3.03	2.96	1.97	6.64
MnO	0.08	0.08	0.01	0.09		0.13	0.17	0.23	0.21	0.07	0.07	0.09	0.11
MgO	2.28	2.92	0.48	2.48		1.12	3.77	0.74	1.84	0.69	0.66	0.40	2.79
CaO	4.53	5.03	0.66	3.71		3.31	6.72	3.74	4.69	2.25	2.47	1.80	5.77
Na2O	4.59	4.68	3.33	3.33		5.24	4.03	3.64	4.86	4.10	3.64	2.60	4.03
K2O	1.59	2.87	4.66	3.34		3.12	2.13	3.58	2.36	4.55	4.75	5.73	2.4
P2O5	0.24	0.28	0.05	0.25		0.26	0.30	0.35	0.38	0.13	0.13	0.07	0.29
Total	100	100	100	100		100	100	100	100	100	100	100	100
Di	nd	8.07	nd	1.63		0.12	9.04	2.46	0.15	nd	nd	nd	3.09
C	0.07	nd	1.43	nd		nd	nd	nd	nd	1.71	1.00	1.83	nd
Q	15.77	5.44	34.39	18.05		9.05	1.55	20.29	6.54	19.40	21.93	29.49	7.72
A	42.90	41.80	68.71	39.35		52.63	31.43	46.41	43.53	68.08	67.94	76.32	38.7
M	15.83	16.17	4.14	14.68		7.08	19.21	4.76	11.08	5.43	5.38	3.63	16.8
F	41.27	42.03	27.15	45.97		40.30	49.37	48.83	45.39	26.51	26.68	20.05	44.49
Q*	118	65	199	134		76	58	130	70	120	132	170	80.98
P	-195	-180	-20	-103		-162	-204	-104	-190	-76	-60	6	-181.92
TDM (Ga)	2.42	2.40	2.37	2.27	2.29	1.98	1.93	1.96	1.90	2.00	1.87	1.93	1.91

	Vol679	RB24	ZP2	ZP9	ZP12	ZP14	Vol439	Vol441	X870	X803	X725
SiO2	68.89	67.20	63.39	70.75	60.22	63.82	58.70	67.16	74.35	61.66	58.24
TiO2	0.47	1.35	0.46	0.87	0.57	0.94	1.77	0.79	1.02	1.43	1.25
Al2O3	15.60	14.55	18.03	12.16	20.89	16.49	16.83	14.01	13.61	18.11	15.57
Fe2O3	4.17	5.31	4.98	7.74	3.56	6.05	11.14	6.21	1.61	4.75	10.28
MnO	0.07	0.08	0.05	0.10	0.06	0.07	0.09	0.09	0.02	0.09	0.14
MgO	1.13	1.89	1.09	3.09	0.71	2.13	2.47	1.08	0.31	1.85	3.73
CaO	2.85	3.36	3.16	2.93	1.89	3.06	2.82	3.06	1.61	3.91	4.71
Na2O	3.55	4.17	5.02	0.06	6.24	3.93	3.65	3.36	3.82	5.53	3.27
K2O	3.06	1.98	3.62	2.23	5.71	3.25	2.39	4.03	3.65	2.44	2.59
P2O5	0.19	0.11	0.19	0.08	0.14	0.24	0.14	0.21	nd	0.23	0.22
Total	100	100	100	100	100	100	100	100	100	100	100
Di	nd	0.73	nd	nd	nd	nd	nd	2.08	nd	0.47	1.66
C	1.81	nd	0.59	4.99	1.37	1.63	3.90	nd	0.45	nd	nd
Q	27.53	23.83	9.27	50.44	nd	16.41	12.86	19.42	34.03	7.32	8.25
A	53.39	44.12	56.63	16.36	71.92	44.78	28.89	48.08	78.09	52.80	27.89
M	9.15	13.55	7.13	22.11	4.26	13.29	11.82	7.03	3.21	12.27	17.74
F	37.45	42.32	36.23	61.54	23.82	41.93	59.29	44.90	18.70	34.93	54.37
Q*	169	156	75	309	-11	122	124	142	193	65	107
P	-100	-153	-141	-7	-114	-112	-117	-77	-75	-196	-134
TDM (Ga)	11.88	1.63	1.63	1.95	1.89	1.70	1.41	1.52	2.01	1.88	1.67

The Kipawa-Mattawa area

	GA4	GA8	GA9	GA13	GA14	GA17	GA18	GA19	NB54	NB57	NB65	NB66	KP1
SiO2	57.88	74.66	67.66	71.13	70.31	72.74	63.02	72.50	69.16	70.48	69.81	63.47	71.67
TiO2	0.73	0.20	0.42	0.24	0.22	0.15	0.62	0.18	0.27	0.28	0.22	0.51	0.28
Al2O3	19.30	14.84	17.14	16.26	16.57	16.74	16.22	16.03	15.01	15.58	16.47	16.43	15.37
Fe2O3	7.24	2.03	3.49	1.82	1.72	1.28	7.97	1.55	2.40	2.04	1.76	5.62	2.35
MnO	0.14	0.02	0.06	0.01	0.01	0.01	0.26	0.01	0.02	0.01	0.01	0.08	0.02
MgO	2.47	0.32	1.27	0.72	1.28	0.34	0.41	0.40	3.14	1.73	0.69	3.28	0.75
CaO	4.97	2.82	4.09	2.69	2.58	2.02	1.70	2.50	2.55	2.30	3.03	4.23	2.82
Na2O	3.96	4.14	4.67	5.38	5.40	5.43	4.71	4.97	5.51	5.02	6.41	4.74	4.95
K2O	2.80	0.92	1.06	1.66	1.84	1.20	5.01	1.77	1.64	2.35	1.45	1.50	1.11
P2O5	0.52	0.05	0.13	0.09	0.06	0.08	0.08	0.08	0.10	0.11	0.11	0.14	0.15
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Na2O/K2C	1.4	4.5	4.4	3.2	2.9	4.5	0.9	2.8	3.4	2.1	4.4	3.2	5.6
DI	nd	nd	nd	nd	nd		nd	nd	0.56	nd	2.08	0.84	nd
C	2.15	2.07	1.22	0.95	1.19		0.15	1.60	nd	1.01	nd	nd	0.73
Q	6.50	40.06	24.64	26.22	24.00		6.84	30.50	20.41	24.53	19.32	13.73	29.05
A	39.12	66.27	52.70	71.96	69.38		51.20	76.07	55.18	64.77	74.57	39.55	66.15
M	14.29	4.21	11.65	7.39	12.28		2.16	4.53	24.23	15.24	6.59	20.82	7.59
F	46.59	29.56	35.65	20.65	18.34		46.64	19.40	20.58	19.99	18.88	39.63	26.26
Q*	74	226	153	154	146	178	70.99	174	141	152	113	117	170
P	-157	-164	-201	-186	-181	-185	-76.22	-168	-188	-153	-230	-197	-175
TDM (Ga)	2.57	2.64	2.61	2.76	2.69	2.60	2.55	2.62	2.61	2.69	2.73	2.73	2.66

	KP3	KP5	KP6	KP7	KP10	KP11A	KP12A	TM1	TM3	TM5	TM6	DR24	DR18
SiO2	66.38	69.98	67.46	75.42	63.73	72.95	65.60	65.74	69.97	69.66	67.42	55.73	63.08
TiO2	1.18	0.33	0.41	0.09	0.58	0.32	1.32	0.24	0.34	0.33	0.50	0.95	0.67
Al2O3	17.34	16.43	16.94	14.10	15.96	14.07	15.56	18.86	16.05	16.45	15.95	18.64	19.29
Fe2O3	2.98	2.55	3.19	0.76	6.14	3.18	5.30	2.15	2.73	2.90	3.71	8.42	3.50
MnO	0.03	0.03	0.05	0.05	0.09	0.05	0.08	0.03	0.03	0.03	0.05	0.08	0.04
MgO	1.43	0.94	1.37	0.13	3.06	0.59	3.24	0.73	0.87	0.96	1.92	3.56	1.49
CaO	3.21	3.00	3.01	0.72	3.78	3.31	3.33	6.26	3.09	3.49	4.02	6.10	3.70
Na2O	5.99	3.92	5.68	4.29	3.87	4.30	3.46	3.05	5.63	5.44	4.77	4.34	5.25
K2O	1.36	2.62	1.65	4.35	2.55	1.11	2.05	2.82	1.14	1.09	1.46	1.98	2.62
P2O5	0.09	0.20	0.24	0.09	0.09	0.14	0.05	0.11	0.15	0.18	0.21	0.20	0.37
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Na2O/K2C	4.4	1.5	4.3	1.0	1.5	3.9	1.7	1.1	4.9	5	3.3	2.2	2
DI	nd	nd	nd	nd	nd	nd	nd	0.71	nd	0.14	0.69	3.41	nd
C	0.40	2.24	0.92	1.27	0.62	0.11	1.87	nd	0.31	nd	nd	nd	2.06
Q	16.57	28.98	18.73	32.07	16.33	35.00	24.17	22.19	24.21	23.44	21.81	nd	11.58
A	60.79	63.37	59.88	89.87	39.39	56.69	37.63	65.24	63.44	60.81	50.75	32.86	59.42
M	11.86	9.16	11.17	1.38	18.77	6.21	22.12	8.16	8.14	8.98	15.64	18.51	11.24
F	27.35	27.48	28.94	8.75	41.84	37.10	40.24	26.60	28.42	30.22	33.61	48.63	29.34
Q*	108	170	120	179	130	203	187	132	146	146	141	54	81
P	-221	-124	-202	-59	-138	-174	-140	-150	-212	-215	-194	-207	-179
TDM (Ga)	2.67	2.67	2.69	2.85	2.71	2.69	2.72	2.77	2.73	2.70	2.75	2.54	2.85

	MT4	MT7	TA24	GA20	GA22	NB53	NB62	TA23	TA27	GA2	DR1	DR8	MT1
SiO2	63.44	68.92	70.52	73.72	74.89	71.59	72.54	76.13	65.29	53.10	68.43	48.93	62.43
TiO2	1.37	1.11	0.39	0.52	0.51	0.13	0.37	0.24	0.52	0.32	0.25	1.41	1.41
Al2O3	15.75	15.35	15.21	14.04	14.70	15.53	14.46	13.26	17.42	24.35	17.86	22.76	17.95
Fe2O3	6.04	2.97	3.59	3.51	3.55	1.31	2.30	1.16	4.94	4.62	2.26	8.91	4.61
MnO	0.07	0.05	0.06	0.02	0.01	0.01	0.02	0.02	0.09	0.07	0.03	0.04	0.08
MgO	3.83	1.71	1.05	0.27	0.19	2.19	1.18	0.21	1.65	1.94	0.89	2.70	1.95
CaO	3.91	2.99	3.16	1.90	0.42	2.03	2.14	1.01	4.17	9.47	2.56	7.33	4.06
Na2O	4.03	3.55	3.87	4.13	1.34	4.41	3.98	2.13	3.96	4.27	5.74	6.08	4.80
K2O	1.46	3.31	2.05	1.83	4.37	2.72	2.86	5.82	1.77	1.80	1.93	1.21	2.55
P2O5	0.09	0.04	0.10	0.07	0.03	0.07	0.15	0.03	0.19	0.07	0.11	0.62	0.15
total	100	100	100	100	100	100	100	100	100	100	100	100	100
Na2O/K2C	2.8	1.2	1.9										
Di	nd	nd	nd	nd	nd	nd	nd	nd	nd	3.75	nd	0.90	nd
C	0.71	0.61	1.17	2.07	7.31	1.87	1.33	1.72	1.98	nd	1.99	nd	0.29
Q	18.17	26.06	30.78	37.28	48.36	28.04	31.91	38.78	22.32	nd	20.01	nd	11.43
A	34.25	57.83	53.99	58.73	58.01	66.10	64.68	84.10	44.52	46.16	69.29	36.67	50.94
M	23.87	14.36	9.61	2.68	1.96	20.36	11.19	2.25	12.84	14.75	8.00	13.57	13.52
F	41.88	27.81	36.40	38.59	40.03	13.54	24.13	13.64	42.64	39.09	22.70	49.77	35.54
Q*	144	162	185	215	274	173	188	218	147	6	123	-38	89
P	-168	-97	-137	-128	42	-121	-106	37	-164	-268	-190	-301	-173
TDM (Ga)	2.72	2.57	2.61	2.01	2.12	2.47	2.33	2.10	2.39	2.13	2.41	2.00	2.40

	H533(1)	NB52	NB59	H176	DR16	DR21	GA12	GA21	GA23	TA29	MT2	MT3	MT5
SiO2	50.83	72.31	51.14	68.39	68.43	60.56	74.72	72.04	63.54	73.31	61.35	61.09	51.34
TiO2	1.72	0.07	2.24	0.25	0.25	0.72	0.21	0.36	0.51	0.30	1.39	1.52	1.14
Al2O3	20.27	17.07	12.86	17.57	16.48	19.82	13.79	14.37	17.72	14.19	17.05	18.52	18.70
Fe2O3	9.60	0.66	16.84	2.29	2.40	4.28	1.56	2.73	5.72	1.17	5.62	4.63	10.20
MnO	0.14	0.01	0.33	0.03	0.03	0.03	0.01	0.08	0.21	0.02	0.08	0.10	0.21
MgO	4.37	0.50	4.62	0.59	0.20	1.12	0.32	0.38	1.09	0.03	3.38	1.64	4.24
CaO	8.95	2.47	7.32	4.09	0.89	2.49	0.67	1.31	2.64	0.49	4.84	3.35	7.57
Na2O	3.06	5.57	3.12	5.57	5.15	6.32	4.02	4.12	5.69	3.41	3.89	6.08	4.75
K2O	0.87	1.27	1.16	1.09	6.11	4.40	4.66	4.53	2.67	6.05	2.25	2.88	1.36
P2O5	0.19	0.07	0.36	0.15	0.04	0.26	0.03	0.09	0.19	0.02	0.13	0.19	0.51
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Di	3.80	nd	15.33	nd	0.29	nd	nd	nd	nd	nd	0.66	0.54	7.13
C	nd	2.23	nd	0.17	nd	0.74	0.99	0.55	1.19	1.20	nd	nd	nd
Q	nd	29.05	nd	21.55	11.57	nd	31.09	26.43	9.68	29.85	12.56	3.29	nd
A	20.74	84.67	15.49	67.96	79.66	64.58	80.88	71.67	52.88	87.71	39.01	56.87	28.20
M	23.03	6.22	16.73	6.05	1.44	6.76	3.00	3.16	6.91	0.26	21.44	10.42	19.53
F	56.23	9.12	67.78	25.99	18.90	28.66	16.12	25.16	40.20	12.03	39.56	32.71	52.27
Q*	58	165	71	128	73	9	178	155	81	168	109	42	12
P	-240	-197	-200	-229	-52	-155	-43	-60	-174	10	-196	-195	-12
TDM (Ga)	2.23	2.40	2.35	2.35	2.37	2.02	2.34	2.27	2.24	2.30	1.88	1.93	1.92

The Lac Bleu thrust sheet

	TA21	TA3	TA32	TA37	HI33(3)	NB51	KP12	GA3	DR14	DR25	TA4	TA12	TM7
SiO2	68.37	67.66	61.09	62.33	54.98	69.12	59.64	53.13	65.64	62.11	64.09	72.01	63.05
TiO2	0.52	0.58	0.64	0.90	2.25	0.61	0.88	0.50	0.58	0.45	0.51	0.34	0.79
Al2O3	16.97	16.49	18.03	18.29	18.41	14.07	17.14	23.90	17.14	17.20	18.32	14.25	16.60
Fe2O3	2.35	3.32	6.23	4.17	8.18	4.90	7.49	4.97	4.41	7.83	3.66	2.42	5.09
MnO	0.11	0.06	0.12	0.13	0.22	0.11	0.17	0.07	0.08	0.05	0.05	0.05	0.14
MgO	0.29	0.56	0.38	0.95	2.34	1.98	2.61	2.10	0.94	0.87	1.02	0.82	1.86
CaO	0.89	1.42	3.45	2.39	4.29	1.24	5.13	9.87	1.84	2.16	2.53	1.79	3.65
Na2O	5.01	4.39	5.47	6.16	5.42	3.70	4.40	4.07	5.99	4.95	4.93	3.46	4.99
K2O	7.00	5.34	4.32	4.27	3.26	4.16	2.03	1.27	3.14	4.17	4.69	4.70	3.65
P2O5	0.07	0.18	0.26	0.40	0.65	0.11	0.51	0.06	0.23	0.19	0.19	0.16	0.18
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Di	nd	nd	2.95	nd	0.67	nd	1.00	4.20	nd	nd	nd	nd	4.16
C	1.44	1.38	nd	0.15	nd	1.60	nd	nd	1.15	1.15	1.04	0.62	nd
Q	15.11	16.61	1.80	2.03	nd	24.33	8.35	nd	11.47	6.51	8.85	28.14	7.83
A	78.23	69.59	57.23	65.11	43.15	51.40	37.02	41.16	61.00	48.78	65.41	69.95	53.48
M	2.20	4.00	2.24	5.95	11.66	12.95	15.05	16.20	6.26	4.67	6.92	7.00	11.53
F	19.57	26.40	40.53	28.94	45.19	35.65	47.93	42.64	32.75	46.55	27.66	23.05	35.00
Q*	91	104	30	28	10	161	85	19	62	70	67	167	68
P	-63	-54	-146	-151	-182	-53	-190	-280	-159	-110	-104	-44	-149
TDM (Ga)	1.92	1.94	1.93	1.94	1.90	1.98	2.07	1.78	1.98	1.97	1.86	1.87	1.97

	TM8	TN4	AU4	DR12	DR28	MT8	MT9	MT10	TA5	TA7	TA8	TM10	TM13
SiO2	61.52	62.27	63.85	69.92	53.00	71.62	60.84	52.72	63.49	69.89	67.84	69.58	62.37
TiO2	0.63	0.64	0.36	0.30	0.98	1.20	1.92	2.15	0.89	0.25	0.48	0.37	0.87
Al2O3	16.11	15.69	17.95	17.51	19.65	14.08	16.36	20.03	16.48	16.54	16.22	14.91	15.50
Fe2O3	6.04	6.07	3.78	1.59	9.06	3.10	8.16	8.41	6.81	1.87	4.44	3.44	7.45
MnO	0.10	0.10	0.05	0.03	0.12	0.06	0.13	0.14	0.07	0.03	0.06	0.05	0.15
MgO	3.27	3.23	1.53	0.34	3.39	0.61	1.90	2.95	0.74	0.57	0.86	1.19	2.43
CaO	5.40	5.16	3.22	1.56	5.62	2.13	4.19	5.92	2.74	1.73	2.27	2.70	3.70
Na2O	3.57	3.55	4.36	3.49	4.89	2.96	3.37	4.75	3.55	3.88	4.53	3.28	3.81
K2O	3.11	3.05	4.76	5.19	3.02	4.17	2.78	2.44	4.97	5.18	3.18	4.29	3.34
P2O5	0.26	0.24	0.15	0.06	0.26	0.06	0.34	0.50	0.28	0.19	0.13	0.19	0.37
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
DI	5.75	5.56	nd	nd	2.89	nd	nd	0.0022	nd	nd	nd	nd	0.55
C	nd	nd	0.16	3.51	nd	0.99	1.10	nd	1.00	1.65	1.58	0.43	nd
Q	10.80	12.50	9.20	25.40	nd	32.30	15.83	nd	22.29	22.29	21.29	25.63	12.73
A	40.10	39.81	61.39	80.49	37.03	63.75	35.92	36.91	50.63	77.38	57.11	60.18	40.02
M	19.63	19.50	10.32	3.13	15.87	5.45	11.12	15.13	4.42	4.90	6.38	9.42	13.62
F	40.27	40.69	28.29	16.38	47.10	30.80	52.96	47.96	44.96	17.72	36.50	30.40	46.36
Q*	96	105	74	146	5	188	120	17	99	132	136	157	108
P	-146	-142	-97	-30	-194	-45	-124	-207	-58	-46	-119	-63	-118
TDM (Ga)	1.89	1.86	1.84	1.90	1.79	1.72	1.63	1.61	1.75	1.74	1.71	1.71	1.74

	H171	ZC2	ZC3	MT11	TA13
SiO2	75.02	56.64	58.50	58.81	77.38
TiO2	0.15	0.99	0.93	1.52	0.17
Al2O3	13.91	19.98	19.40	20.68	13.04
Fe2O3	0.91	6.61	6.02	4.38	0.40
MnO	0.01	0.13	0.11	0.08	0.03
MgO	0.26	1.44	1.32	1.44	0.04
CaO	0.91	4.62	4.30	3.18	0.57
Na2O	3.37	4.94	4.78	5.84	3.35
K2O	5.35	4.28	4.30	3.87	4.99
P2O5	0.11	0.36	0.34	0.19	0.02
Total	100	100	100	100	100
Di	nd	0.71	0.26	nd	nd
C	1.20	nd	nd	1.59	1.14
Q	32.65	nd	nd	nd	37.48
A	87.24	51.21	53.13	60.61	94.50
M	2.59	8.01	7.72	9.00	0.44
F	27.47	40.78	39.15	30.39	5.08
Q*	183	9	28	18	208
P	-12	-151	-140	-163	-12
TDM (Ga)	1.89	1.63	1.73	1.50	1.59

The Lac Dumoine thrust sheet

	DU4	GF8	LN13	LN15	OT9	DU10	OT10
SiO2	73.85	69.19	65.65	62.15	63.85	67.66	72.91
TiO2	0.40	0.55	0.97	0.80	0.52	0.41	0.18
Al2O3	13.92	15.46	17.46	16.59	17.67	15.75	14.54
Fe2O3	1.76	3.07	3.66	7.38	6.21	4.25	3.73
MnO	0.09	0.90	0.07	0.12	0.06	0.08	0.03
MgO	0.30	0.94	0.81	2.15	1.84	1.59	0.68
CaO	0.69	2.41	2.36	4.39	3.42	4.37	2.71
Na2O	4.91	4.39	4.57	3.25	4.01	4.23	3.98
K2O	3.99	3.68	4.29	3.01	2.26	1.47	1.21
P2O5	0.10	0.21	0.16	0.17	0.16	0.20	0.02
Total	100	100	100	100	100	100	100
Di	nd	nd	nd	nd	nd	0.63	nd
C	0.52	0.40	1.45	0.45	3.03	nd	1.89
Q	27.72	22.25	15.12	15.56	19.05	24.54	37.05
A	79.80	64.94	64.49	37.66	41.76	47.41	51.80
M	2.67	7.60	5.80	12.97	12.29	13.28	6.84
F	17.53	27.47	29.63	49.37	45.95	39.31	41.36
Q*	159	135	98	124	136	156	218
P	-86	-106	-99	-119	-142	-183	-151
TDM (Ga)	1.84	1.93	1.85	1.93	1.88	1.69	1.72

	OT11	LN10	LN12	DU20	LN4	LN7	LN9	LN11	OT7	OT14	TA18	TA17	ZC6
SiO2	60.50	72.14	50.75	73.06	66.02	62.36	61.57	60.32	69.62	57.28	59.55	62.00	69.39
TiO2	0.46	0.73	1.45	0.40	0.73	1.11	0.84	0.91	0.68	0.57	0.73	0.56	0.52
Al2O3	19.68	13.25	22.71	13.98	16.08	15.21	16.26	18.92	15.69	18.12	18.36	18.03	15.04
Fe2O3	5.86	4.63	8.08	4.66	5.79	9.62	5.90	5.84	3.26	8.17	5.92	4.81	3.45
MnO	0.06	0.06	0.11	0.08	0.12	0.19	0.10	0.13	0.04	0.09	0.06	0.05	0.08
MgO	1.50	1.31	2.45	0.27	1.96	0.80	2.57	1.58	0.89	2.80	3.04	2.06	0.87
CaO	5.23	1.85	8.87	1.37	1.80	3.35	5.12	4.42	2.39	6.42	4.59	3.61	2.14
Na2O	4.92	2.36	4.35	2.33	3.54	4.29	5.24	5.32	3.11	4.82	5.43	5.37	4.08
K2O	1.58	3.53	0.77	3.73	3.81	2.85	2.18	2.27	4.17	0.99	2.09	3.34	4.20
P2O5	0.22	0.14	0.46	0.13	0.16	0.22	0.21	0.28	0.15	0.19	0.24	0.18	0.22
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Di	nd	nd	0.67	nd	nd	1.17	8.49	nd	nd	5.23	1.44	1.36	nd
C	1.00	2.64	nd	4.10	3.50	nd	nd	0.38	2.15	nd	nd	nd	0.46
Q	13.65	38.10	nd	40.61	21.91	13.24	6.79	5.97	28.38	2.96	2.62	4.79	22.79
A	50.63	47.67	30.91	47.41	46.65	38.31	44.84	48.47	61.73	31.77	43.89	54.08	63.72
M	4.42	10.63	14.83	13.28	12.44	4.32	15.53	10.08	7.55	15.33	17.73	12.75	6.72
F	44.96	41.70	54.26	39.31	40.91	57.38	39.63	41.45	30.72	52.91	38.38	33.17	29.55
Q*	81	3	19	235	150	107	65	62	169	65	56	57	139
P	-218	-34	-282	-20	-65	-138	-214	-202	-54	-249	-213	-167	-80
TDM (Ga)	1.61	1.71	1.69	1.76	1.47	1.47	1.43	1.57	1.53	1.48	1.49	1.41	1.54

	DU2	DU7	DU9	LN19	MT13	OT1	RD3	RD4	RD5	RD6	X754	BC311
SiO2	68.83	67.81	70.88	58.96	59.21	70.26	69.17	66.74	64.97	64.71	58.24	43.84
TiO2	0.60	0.69	0.43	0.61	1.60	0.18	0.38	0.51	0.52	0.72	1.25	2.74
Al2O3	15.05	13.83	14.74	21.23	17.98	13.99	16.51	17.32	18.02	16.04	15.57	26.10
Fe2O3	4.75	7.17	2.67	4.23	6.16	2.95	2.94	3.23	3.55	4.87	10.28	19.56
MnO	0.04	0.19	0.06	0.05	0.08	0.02	0.04	0.06	0.06	0.07	0.14	0.12
MgO	0.80	0.47	0.65	1.47	2.92	2.28	0.88	1.10	1.31	2.55	3.73	2.65
CaO	2.08	2.43	1.80	5.22	4.64	0.39	2.94	3.72	4.31	4.58	4.71	1.64
Na2O	4.56	2.77	4.04	7.01	5.61	1.32	5.03	5.58	5.37	4.20	3.27	0.62
K2O	3.07	4.44	4.56	1.02	1.63	8.59	1.90	1.47	1.63	2.00	2.59	2.61
P2O5	0.21	0.20	0.22	0.21	0.16	0.01	0.21	0.27	0.27	0.27	0.22	0.12
Total	100	100	100	100	100	100	100	100	100	100	100	100
Di	nd	nd	nd	0.87	2.63	nd	nd	nd	nd	1.78	1.66	nd
C	1.00	2.15	0.34	nd	nd	1.94	1.38	0.47	0.24	nd	nd	24.14
Q	23.28	28.38	24.53	nd	3.55	24.44	24.36	18.30	15.24	17.85	8.25	11.64
A	55.62	61.73	70.41	56.52	42.56	64.06	62.53	60.06	57.11	43.81	27.89	11.70
M	5.85	7.55	5.29	10.34	17.18	14.72	7.97	9.34	10.72	17.99	17.74	9.59
F	38.53	30.72	24.30	33.14	40.25	21.22	29.51	30.59	32.17	38.20	54.37	78.71
Q*	145	164	145	17	58	160	146	115	101	126	107	148
P	-119	-38	-66	-298	-229	130	-174	-215	-215	-175	-134	6
TDM (Ga)	1.56	1.50	1.58	1.38	1.33	1.25	1.54	1.49	1.48	1.51	1.55	2.07