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EARLY PROTEROZOIC EVOLUTION OF THE GRENVILLE BELT: EVIDENCE FROM NEODYMIUM ISOTOPIC MAPPING, NORTH BAY, ONTARIO

EARLY PROTEROZOIC EVOLUTION OF THE GRENVILLE BELT: EVIDENCE FROM Nd ISOTOPIC MAPPING, NORTH BAY, ONTARIO

by

Christopher Holmden

A Thesis

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TITLE: Early Proterozoic Evolution of the Grenville Belt: Evidence from Neodymium Isotopic Mapping, North Bay Ontario

AUTHOR: Christopher Holmden

SUPERVISOR: Professor A. P. Dickin

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Abstract

Detailed Nd isotopic mapping in the southwestern Grenville Province between North Bay, Ontario, and Temiscaming, Quebec has revealed the precise trend of the proposed Penokean-aged suture discovered during reconnaissance isotopic mapping by Dickin and McNutt (1989).

Lithotectonic domains proposed by Easton (1989) for the greater North Bay area are cross-cut by the suture. As presently located, the Tilden-Tomiko domain boundary effects no apparent offset of the suture which would be expected during low angle differential Grenville thrusting. Although a lack of apparent offset suggests these domains are not significant Grenville structures a definitive answer must await more precise mapping of their boundaries. There appears to be some potential for unravelling aspects of Grenville tectonism through such cross-cutting relationships.

In the North Bay-Temiscaming area the full model age transition from ca 1.90 Ga to ca 2.70 Ga is negotiated in stepwise fashion through metasediments of intermediate Nd model age spanning an area from a few kilometers to a few tens of kilometers in width. This suggests the suture boundary is better described as a suture zone. Presently two groups of intermediate aged metasediments are recognized (1) a 2.00-2.39 Ga group and (2) a 2.40-2.60 Ga group. These age groups

correspond to rocks of two different lithologies separated along strike of the suture in the Temiscaming and North Bay areas respectively. Although the ages of metasediments comprising the suture zone more or less spans the entire interval between 1.90 and 2.70 Ga, there is no well defined transect wherein the whole range of intermediate aged crust is recorded within a single rock type. Therefore a 'splitting' rather than 'lumping' approach is deemed justified for the intermediate aged crust until provenance studies using zircons can be undertaken to show in a definitive manner whether or not the two groups are related in a genetic sense.

The absence of plutonism with crystallization ages between 2.00 and 2.60 Ga in the North Bay-Temiscaming area suggests that metasediments of the suture zone acquired their model age from sedimentological mixing between crust of Archean (ca 2.70 Ga) and Proterozoic (ca 1.90 Ga) provenance. The arrangement of mixed provenance metasediments coincident with the suture suggests a genetic relationship. It is proposed that the mixed provenance metasediments are part of a foreland basin assemblage which formed in response to down-loading of the cratonal edge by the combined effect of an overriding island arc and the attempted subduction of the Superior craton.

Major element analyses show that mixed provenance and arc derived sediments of the proposed foreland basin display a wide range in their maturity. This is consistent with the foreland basin environment where sediments can be reworked to varying degrees in response to tectonically controlled local sea level fluctuations. Contrasting the dynamic environment of the foreland basin the belt of Archean crust north of the suture with model ages of ca 2.72 Ga shows a very restricted range of reworking implying a uniform depositionary environment e.g., deep water passive margin.

North of the field area a lobe of Archean crust extends into the Grenville Province, anchored by the Pontiac Group on the northern margin of the Grenville Front (GF), and consisting in part of the parautocthonous Red Cedar Lake Gneiss south of the GF. The full expression of the Archean lobe within the Grenville Province and north of the North Bay-Temiscaming field area is unknown, however, preliminary results from Nd isotopic mapping suggest that Archean crust between the suture and the Grenville Front Tectonic Zone (GFTZ) may be **part of**, or, **derived from** this Archean parautocthonous lobe. Archean provenance crust north of the field area defines a relatively homogeneous belt of crust with ca 2.72 Ga model ages and a whole rock Sm-Nd isochron age of 2.77 Ga. This is in sharp contrast to the heterogeneity of model ages displayed by Archean crust further west, between the suture (French River area) and the Grenville Front near Sudbury, Ontario (Dickin et al., 1989). Here, the Archean foreland may owe its peculiar heterogeneity to mixing between 2.72 Ga crust and 2.4 Ga Huronian volcanics and/or 1.7 Ga

Kilarnian juvenile crust (Dickin et al., 1990). Evidence for the presence of these crustal endmembers in the North Bay-Temiscaming area is lacking.

Finally, the presence of a suture zone consisting of mixed provenance metasediments is the best evidence yet in support of the suture hypothesis explanation for the model age transition as opposed to juxtaposition of two crustal age domains by Grenville thrusting.

This work is dedicated with love to the memory of my sister Karen Annette Holmden

ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. Alan P. Dickin for suggesting this research project. I would also like to extend thanks to Catharina Jaeger for support in the clean lab and to Otto Murdoch for his XRF analyses.

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And finally, I'd like to extend a very special thankyou to Cathrin Hagey, for without her support and encouragement to re-enter university, I might still be waiting on tables (p.s. in the future I'll try to come up with new words for such things as 'samples' and 'thesis').

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CHAPTER 1

INTRODUCTION

1.1.0 Objectives

While carrying out a study to characterize the crustal formation ages of the southwestern Grenville province a significant step in model age was discovered approximately 60 km south of the Grenville front on northward traverses along highways 11 and 69. Model ages increased abruptly from ca 1.90 Ga to ca 2.70 Ga defining a line that was traced west to Georgian Bay and east as far as the town of Temiscaming. The model age transition was tentatively identified as a collisional suture between the Archean foreland to the northwest and a Proterozoic island arc of Penokean age to the southeast (Dickin & McNutt, 1989) (Fig. 1.1).

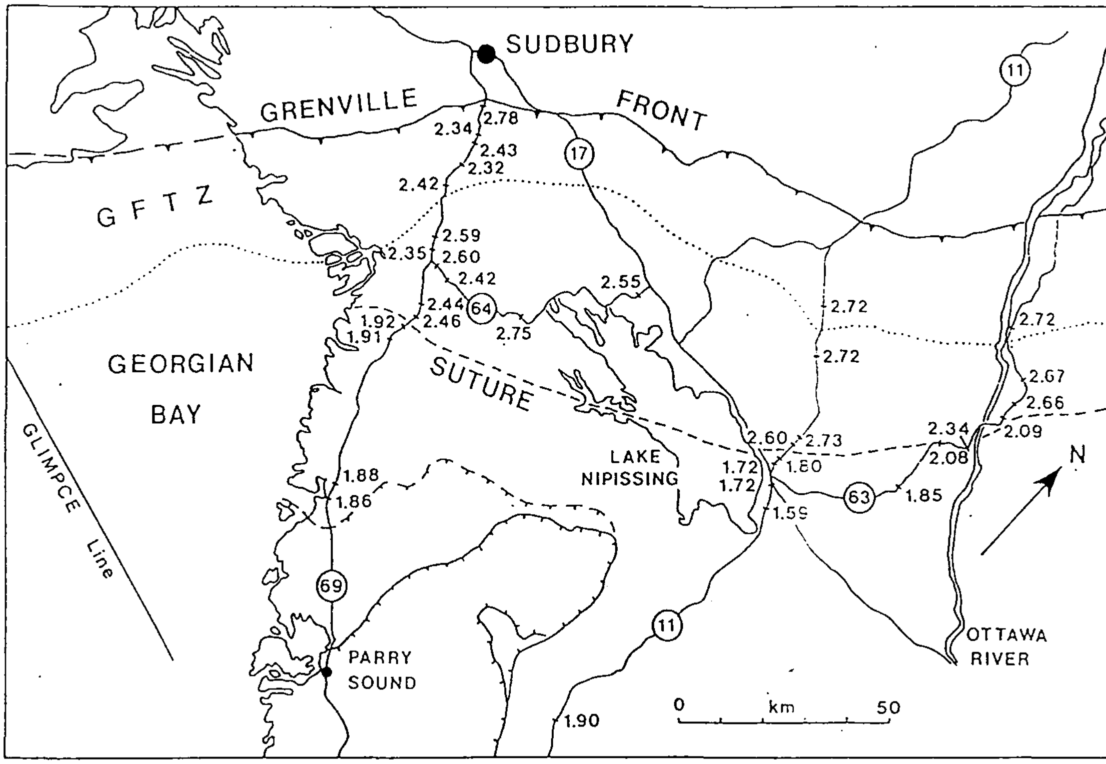
The proposed suture was identified (to reconnaissance standards) as passing through the North Bay area of Ontario. It was recognized that this area posed some problems with regard to the magnitude of the step in model ages. Rather than a clear break between ca 1.90 and ca 2.70 Ga gneisses, a number of intermediate aged gneisses were encountered straddling the transition zone (Fig 1.1).

The objective of this work was 3-fold:

1. To Locate as precisely as possible by isotopic mapping the trend of the proposed suture through the study area.

Fig. 1.1 Reconnaissance scale mapping of the step in model ages discovered within the CGB by Dickin & McNutt (1989) and interpreted by them as a Penokean aged suture (1.85-1.90 Ga) juxtaposing an allocthonous terrane, identified as an early Proterozoic island arc, and the edge of the Archean foreland. (Fig. 1., Dickin et al., 1989)

Fig. 1.2 Map of the hypothetical shelf edge of Laurentia at 2000 Ma. In the Great Lakes Region the edge of the Archean craton is constrained to lie at some point south of the supracrustal successions, namely, the Animike Supergroup (ANIM), the Marquette Range Supergroup (MAR) and the Huronian Supergroup (HUR). From the Niagara Fault Zone (NFZ) which has been proposed as a collisional Penokean suture boundary (Cambray, 1978; Schulz et al., 1987b) the ancient cratonal margin is projected into the Grenville province where in principle it should have existed 1000 Ma prior to Grenville tectonism (Anderson and Burke, 1983). The location and trend of the suture boundary of Dickin et al. (1989) is in remarkable agreement with the hypothesized boundary of Anderson and Burke despite Grenville reworking. (Fig. 7., Anderson & Burke, 1983)


SUDBURY
GRENVILLE
FRONT
G F T Z
GEORGIAN
BAY
SUTURE
GLIMPCE
Line
LAKE
NIPISSING
PARRY
SOUND
OTTAWA
RIVER
N
0 km 50
11
17
64
69
63
11
2.34
2.78
2.43
2.32
2.42
2.59
2.60
2.35
2.42
2.44
2.46
1.92
1.91
2.75
2.55
2.72
2.72
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2.67
2.66
2.34
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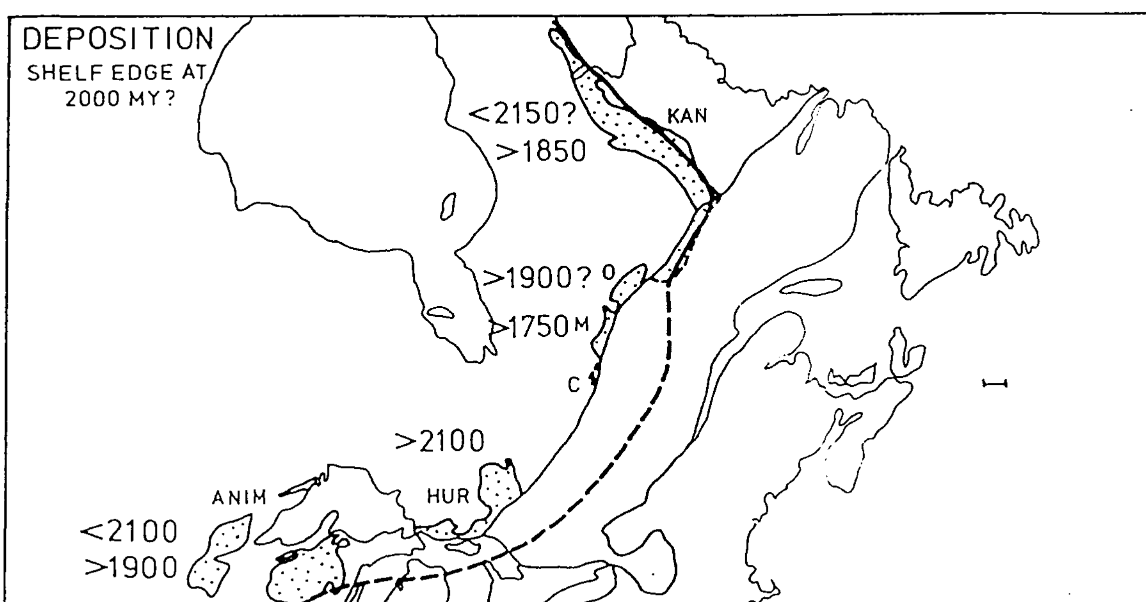
1.88
1.86
1.90


DEPOSITION
SHELF EDGE AT
2000 MY?
<2150?
>1850
KAN
>1900? O
>1750 M
C
>2100
ANIM
HUR
<2100
>1900

2. To characterize the nature of the proposed suture and model age transitions.

3. To Use the Sm-Nd isotopic data along with major and selected trace elements from the Archean and Proterozoic segments to corroborate the original contention by Dickin and McNutt (1989) that the Proterozoic segment is an island arc sutured to the Archean foreland.

1.2.0 The Field Area: North Bay/Temiscaming

The field area is approximately 6000 km^2 and located within the Central Gneiss Belt (CGB) of the Grenville Province, between the city of North Bay, Ontario and the town of Temiscaming, Quebec.

The North Bay area was last mapped extensively by Lumbers (1971), which resulted in the production of a geological map with a scale of 1 inch to 2 miles (OGS Map 2216). Lumbers described the exposed lithologies in considerable detail and also studied the economic and structural geology of the area.

The field area is dominantly underlain by high grade para and orthogneiss with scattered younger intrusions ranging in size from small lenses to batholith in scale. A Nd model age study of the major plutons in the area has been published recently (Dickin, A.P., McNutt, R.H., and Clifford, P.M., 1990). The Mulock batholith is the major intrusive in the field area with a crystallization age of 1240 Ma (pers. comm., Heaman, 1989) and a Nd model age of 2.40 Ga (Dickin et al., 1990).

The field area is by and large underlain by vast exposures of paragneiss. Based on the work of Lumbers (1971) four categories of metasediment can be inferred, (1) Biotite gneiss (2) Feldspathic Gneiss (3) Amphibolite gneiss, and (4) Muscovite-quartzose gneiss. From these categories two major facies were proposed.

1. **Miogeoclinal Facies:** represented by the feldspathic gneiss (2), and the muscovite-quartzose gneiss (4), referred to for the remainder of this text as the muscovite-quartzofeldspathic gneiss.

2. **Eugeoclinal Facies:** represented by the biotite gneiss (1), and the amphibolite gneiss (2). For the remainder of this paper gneiss of Proterozoic provenance is referred to as biotite(hornblende) gneiss while gneiss of Archean provenance is referred to as biotite gneiss.

The eugeoclinal facies greatly predominates over the miogeoclinal facies but Lumbers reports that in the area northeast of North Bay both facies are intercalated and suggested that the miogeoclinal deposits were equivalent to reworked eugeoclinal deposits. Lumbers concurs with a proposal by Dietz & Holden (1966) that this area of the CGB represents the eugeoclinal facies complimentary to the miogeoclinal Huronian Supergroup. Some changes to this model are suggested by this work.

In keeping with the suture hypothesis eugeoclinal sediments are relegated to two domains (1) of Proterozoic provenance, or (2) of Archean provenance, representing deposits of the island arc and the Archean foreland respectively. The contention by Dietz and Holden (1966), supported by Lumbers (1971), that the eugeoclinal deposits of Archean provenance represent a deep water clastic prism of the Huronian is not supported by this work. In the North Bay-Temiscaming area Nd isotopic mapping of the belt of Archean terrane between the suture and the Grenville Front Tectonic Zone (GFTZ) suggest that this crust may be related to the Pontiac Group which is Archean in age. Therefore, eugeoclinal metasediments north of the suture may be considered as part of the Archean craton 'proper', and, having stabilized ca 2.70 Ga may have avoided Huronian events entirely.

Finally, rather than the Grenville Front (Dietz and Holden, 1966) the trend of the suture becomes the locus of the edge of the Archean craton at 2000 Ma (Dickin et al., 1989) (Fig. 1.2).

CHAPTER 2

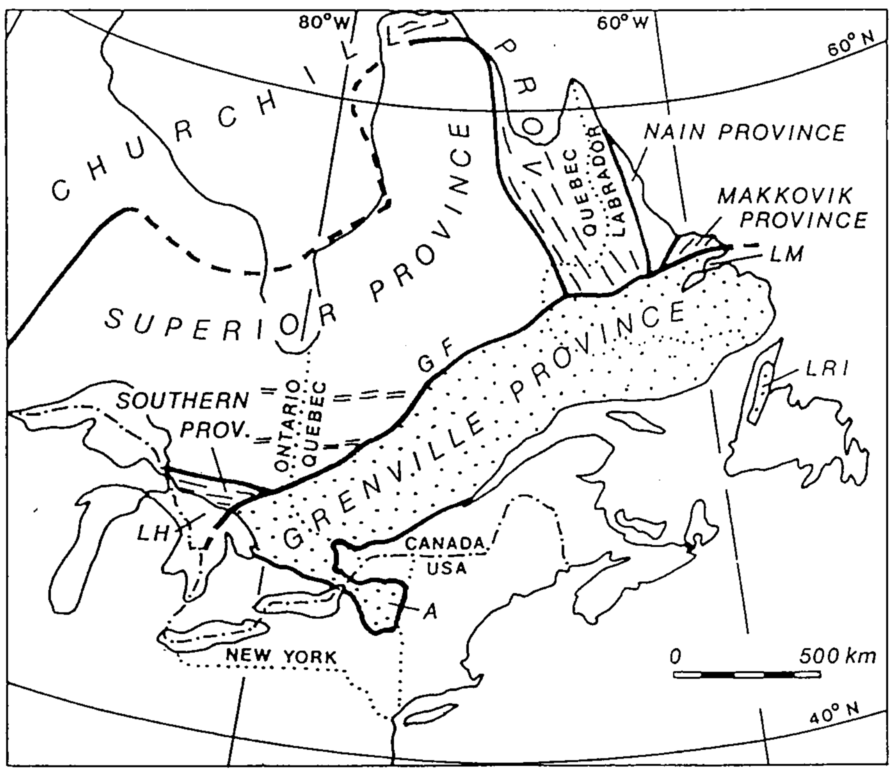
TECTONIC SETTING: THE GRENVILLE AND PENOKEAN OROGENIES

2.1.0 The Grenville Province

The Grenville Province is the youngest orogen of the Canadian Shield, affecting an area more than 2000 km long and 500 km wide and flanking the southeast margin of the Superior province (Fig. 2.1). Isotopic, isobaric and structural evidence agree that the Grenville crust was shortened and thickened during a major compressional/thermal event 950 ± 150 Ma (K/Ar cooling age after Stockwell, 1964). Major Andean style plutonic emplacement is not a major feature of the Grenville belt; therefore models of Grenville evolution have tended to invoke a Himalayan style continent/continent collision. In addition, such models account for the pervasiveness of imbricated Grenville crust and concomitant crustal thickening. Kinematic indicators along the Grenville Front and more recently within the shear boundaries of Davidson's lithotectonic domains resolve that compression was directed from the southeast, resulting in northwest-directed overthrusting of deep crustal slices.

Current thinking on the origin and evolution of the Grenville Province centers around the heterogeneity in ages of its structural components. U-Pb zircons and in some cases Rb-Sr isochrons can be used to 'see through' Grenvillian

Fig. 2.1 The geographical location of the Grenville Strucural Province. (Fig. 1., from Rivers, Martignole, Gower and Davidson, 1989)


80°W
60°W
60°N
40°N
CHURCHILL PROV
SUPERIOR PROVINCE
QUEBEC
LABRADOR
NAIN PROVINCE
MAKKOVIK PROVINCE
LM
GF
GRENVILLE PROVINCE
LRI
SOUTHERN PROV.
ONTARIO
QUEBEC
LH
CANADA
USA
A
NEW YORK
0
500 km

metamorphism and date igneous crystallization ages of pre-Grenvillian orogenies. Precise U-Pb ages on zircons from a compilation by Easton (1986) of Grenville ages up to May 1985, show ages ranging from typical Grenville (ca 1000 Ma) to events as far back as 2700 Ma. The demonstration of significantly older terranes within the province indicates that the Grenville Orogeny effected considerable reworking of crustal elements that were emplaced prior to ca 1000 Ma in a plate tectonic setting.

Identifying coherent bodies of pre-Grenvillian accretionary terranes is actively being pursued in the Grenville by a number of workers with various approaches. The work at McMaster University in the CGB, of which this work is a part, has used Nd model ages of country rock gneisses to define crustal residence ages of pre-Grenvillian terranes. This approach perhaps more than any other has revealed the deeper history of the Grenville crust in a simple and elegant way. However, all methods of discerning coherent pre-Grenvillian blocks and their boundaries (sutures) have been frustrated by superimposed Grenville structures resulting from severe crustal shortening and metamorphic overprinting. Differential movement of thrust slices during the Grenville orogeny may juxtapose crustal elements that are not related in time as they may presently appear. Telescoping of crustal slices may favour exposure of one block over another block which is perhaps more fundamental to the accretionary history.

Shear boundaries between pre-Grenvillian accreted terranes and other structural lineaments have been mercilessly erased and replaced by Grenville structures.

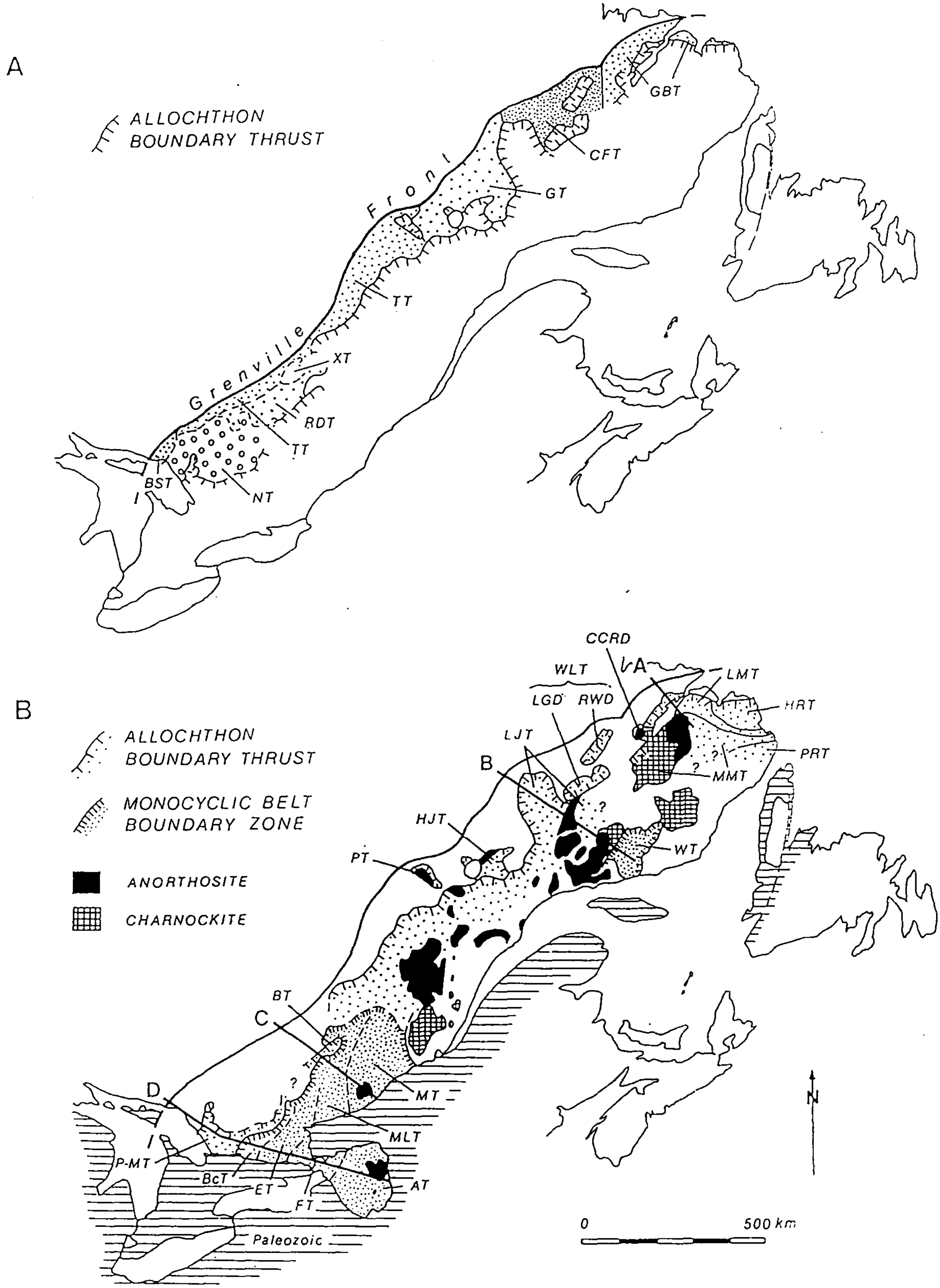
Rivers and Chown (1986) and Rivers et al. (1989) have developed a new tectonic framework for the Grenville that is purported to be an improvement over the long-standing tectonic division of Wynne-Edwards (1972). The new divisions are based on geological, geophysical and geochronological data, and define three 'first order' longitudinal belts separated by three first order tectonic boundaries. However, <u>within</u> the first order belts second order domains may be present.

Grenville Front: first order boundary marking the most northward expression of Grenville thrusting. Several studies have traced lithologic units of Archean age north of the GF, to tectonized equivalents south of the GF.

Parautochthonous Belt: located between the GF and the Allochthon Boundary Thrust to the south. Geophysically this belt is distinguished over much of the northeastern part of the province by a negative Bouger anomaly and a distinctive aeromagnetic pattern. Terranes ranging in age from Archean to middle Proterozoic are present and separated by second order boundaries.

Allochthon Boundary Thrust: first order boundary between the parautochthonous belt and the allochthonous polycyclic belt to the south. Defined in the northwest Grenville

Fig. 2.2 New tectonic divisions of the Grenville Province divide it into longitudinal belts. The divisions were developed as an aid to categorizing aspects of Grenville tectonism and so the early Proterozoic evolution of the Grenville Belt is not considered outside this reference frame. Presently the suture falls within the Parautocthonous Belt and serves to separate this belt into two major terranes, one of Proterozoic provenance and one of Archean provenance, and locates the edge of the Archean foreland as it may have appeared 2000 Ma. (Fig. 4, from Rivers et al., 1989)


A
ALLOCHTHON BOUNDARY THRUST
Grenville Front
GBT
CFT
GT
TT
XT
RDT
TT
BST
NT
B
ALLOCHTHON BOUNDARY THRUST
MONOCYCLIC BELT BOUNDARY ZONE
ANORTHOSITE
CHARNOCKITE
CCRD
WLT
LGD
RWD
LJT
A
LMT
HRT
PRT
MMT
B
HJT
PT
WT
BT
C
MT
D
MLT
P-MT
BcT
ET
FT
AT
Paleozoic
N
0
500 km

by low angle mylonites with kinematic indicators revealing northwest directed thrusting. Has also been shown in some cases to mark a metamorphic grade inversion and/or chronologic transition as revealed by radiometric dating.

Allochthonous Polycyclic Belt: consists of exotic terranes tectonically juxtaposed, overlapping the parautochthonous belt, and representing pre-Grenvillian accretionary events or orogenies. The Grenville Orogeny served to imbricate these terranes, thrusting the more southerly terranes northwards to double the crustal thickness of the Grenville.

Monocyclic Belt Boundary Zone: tectonic boundary between the allochthonous polycyclic belt and the allochthonous monocyclic belt to the south.

Allochthonous Monocyclic Belt: terranes composing this belt have been affected by the Grenville event only. In the southwestern Grenville this belt is represented by the Central Metasedimentary Belt.

2.2.0 The Central Gneiss Belt (CGB)

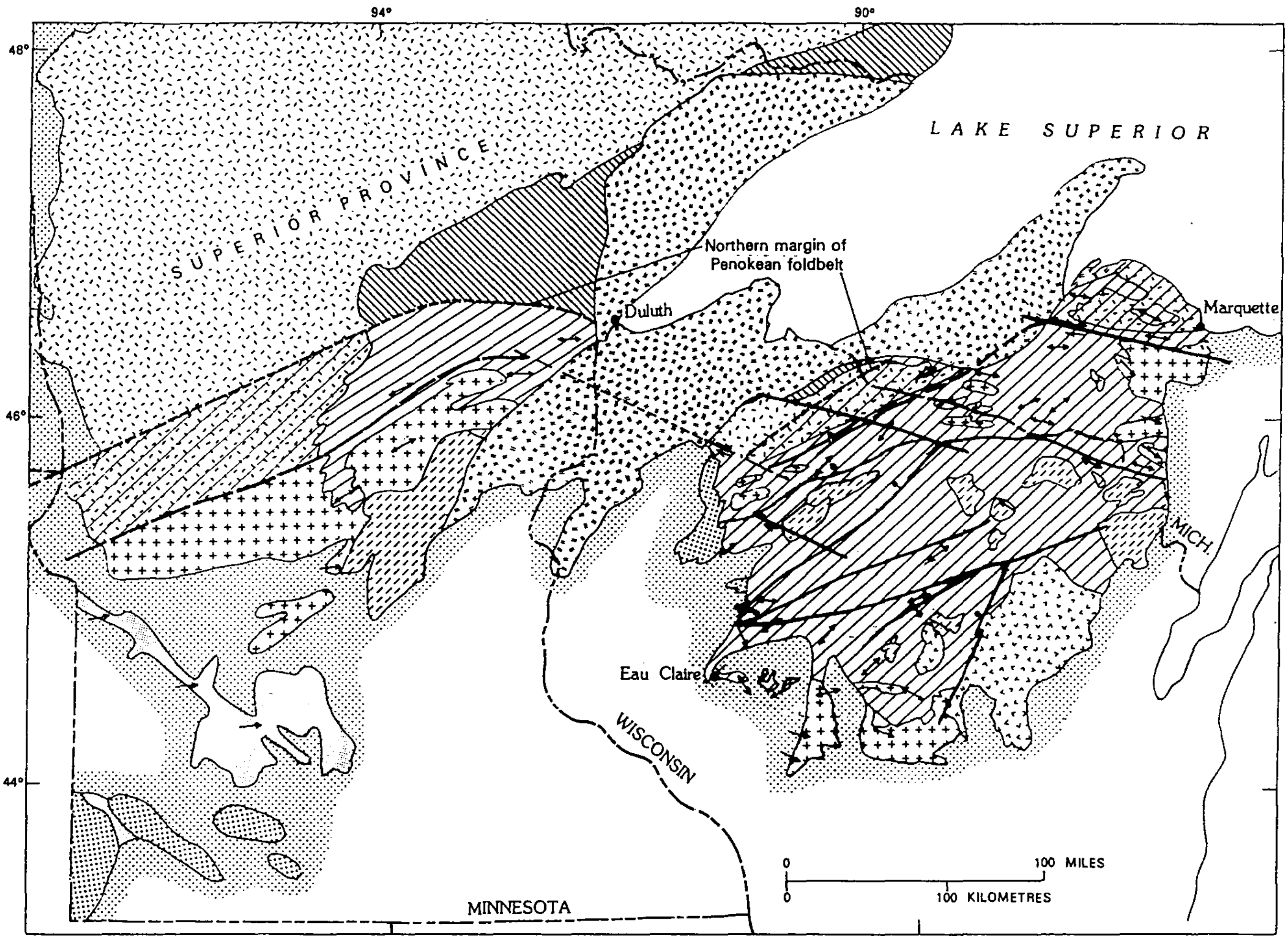
The Central Gneiss Belt, described as a 'vast sea of gneisses,' is sandwiched between two unrelated sets of supracrustals, the Huronian metasediments of the Superior foreland to the north and the Grenville Supergroup of the Central Metasedimentary Belt to the south. In the central gneiss belt Davidson (1986) has defined a number of domains based on lithology, internal structure, geophysical signature and metamorphic grade. These domains and subdomains are separated by shear zones with kinematic indicators revealing typical Grenville northwest-directed overthrusting. Davidson suggests the CGB represents, "a segment of crust formerly thickened by a process of northwest directed stacking of large blocks and slices along inclined ductile shear zones."

The origin and evolution of the CGB has been a question of long standing in Grenvillian geology.

2.3.0 The Penokean Orogeny

The Penokean foldbelt is a 250 km wide northeast-southwest trending zone of deformed and metamorphosed early Proterozoic and Archean rocks straddling the southern margin of the Superior craton in Wisconsin, Michigan and Minnesota (Sims and Peterman, 1983). The age of the orogen is dated by zircons between 1.83-1.89 Ga (Van Schmus, 1980) and consists of two provinces: (1) a passive margin clastic prism to the north, called the Marquette Range Supergroup, and (2) a belt of calc-alkaline volcanics and intrusives to the south called the Wisconsin Magmatic Terrane. The Wisconsin Magmatic Terrane is interpreted as an allochthonous terrane accreted to the passive margin sediments of the Marquette Range Supergroup with the termination of south-dipping subduction along the Niagara Fault Suture Zone (Cambray, 1978; Schulz et

Fig 2.3 Map of the geographical location of the Penokean Orogeny in the Great Lakes Region. (after Sims, 1981)



EXPLANATION

- Phanerozoic platform rocks
- Late Proterozoic (~1,100 M.Y.) rocks of midcontinent rift system
- Thin platform quartzite, weakly deformed
- Anorogenic granitic rocks (~1,500 M.Y.)
- Granitoid plutons (1,850-1,760 M.Y.)
- Early Proterozoic sedimentary rocks, little deformed and metamorphosed
- Early Proterozoic sedimentary and volcanic rocks, highly deformed and variably metamorphosed ; includes some older rocks in central Wisconsin
- Archean greenstone-granite complexes subjected to Penokean deformation and retrograde metamorphism
- Archean greenstone-granite complexes (2,750-2,600 M.Y.)
- Archean gneiss, amphibolite, and granitoid rocks (3,500-2,600 M.Y.) reactivated during Penokean
- Archean gneiss, amphibolite, and granitoid rocks, little deformed and metamorphosed during Penokean orogeny
- Boundary between Archean basement terranes
- Strike-slip fault
- Dip-slip fault, ball on downthrown side
- Trend of Penokean folds
- Trend of Archean folds (Gneiss terrane only)

al., 1987b).

The Penokean orogeny has long been associated with folding of the Huronian Supergroup deposited between 2.1 and 2.5 Ga (Van Schmus et al., 1965). Although attempts have been made at correlating the Huronian Supergroup with the Marquette Range Supergroup results have been met with skepticism (Card, 1978a; Young, 1983). Deposition of the Marquette Range Supergroup is bracketed between 1850 and 1950 Ma and is therefore younger than the Huronian strata (Van Schmus et al., 1981).

Zolnai et al. (1984) attributed Huronian deformation and metamorphism to collision with an allocthonous terrane from the south which overrode and depressed the Huronian strata to midcrustal levels. They linked the timing of the collision with the Penokean orogeny in Wisconsin and postulated that a Penokean allochthonous slice may still lie south of the Manitoulin Island Discontinuity, buried within the Grenville. Dickin et al. (1989) proposed that the step in model ages discovered approximately 60 kms south of the Grenville Front in the CGB represents the collisional suture predicted by Zolnai and others. They also correlate the suture with the Niagara Fault Zone in Wisconsin. Deep seismic reflection profiling across the Grenville Front by Green et al. (1988) picked up what they interpreted as an expression of the decollement of the Penokean Orogeny.

CHAPTER 3

Nd MODEL AGE SYSTEMATICS:
APPLICATIONS AND PREVIOUS WORK

3.1.0 Nd Model Ages

To calculate the radiometric age of a rock three quantities must be known: (1) the abundance of the parent isotope (2) the present day abundance of the daughter isotope and (3) the initial abundance of the daughter isotope. The parent and daughter abundances can be measured easily by routine mass spectrometry, however, instrumentally, there is no way to distinguish between the daughter isotope produced radiogenically over the 'life' of the rock and that incorporated initially as the stable element itself. One method developed to overcome this problem is the familiar isochron plot, however, another way is to model the isotopic evolution of the rock-forming reservoir.

On Earth, the continental crust has been built up over geological time by 'melting off' the lighter elements, or Large Ion Lithophiles (LIL), of the Earth's mantle. The lower specific gravity of these fractions makes them more buoyant than the mantle residuum, enabling them to resist subduction and accumulate in masses referred to as continents. If the mantle can be treated as a homogeneous reservoir, or at least that part of the mantle responsible for crust formation, then, with an estimate for the initial ratio of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$, the evolution of mantle $^{143}Nd/^{144}Nd$ may be modelled with respect to time. The ratio of $^{143}Nd/^{144}Nd$ in the mantle reservoir is a monotonically increasing function of time, therefore, the initial ratio of $(^{143}Nd/^{144}Nd)_o$ in a new addition of continental crust will have the same ratio as the mantle reservoir at the time of extraction.

On a plot of E_{Nd} vs Time the evolution of the mantle reservoir with respect to Nd isotopic composition appears as a linear or curvilinear trend. The slope of this trend is model dependent. Juvenile magma, produced by partial melting of the mantle reservoir, is preferentially enriched in Nd over Sm. This deviation from the mantle Sm/Nd ratio defines a new evolutionary trend for this new crustal package. Where the new crustal trend intersects with the mantle trend, i.e., at the time of crustal extraction, the initial $(^{143}Nd/^{144}Nd)_o$ is defined.

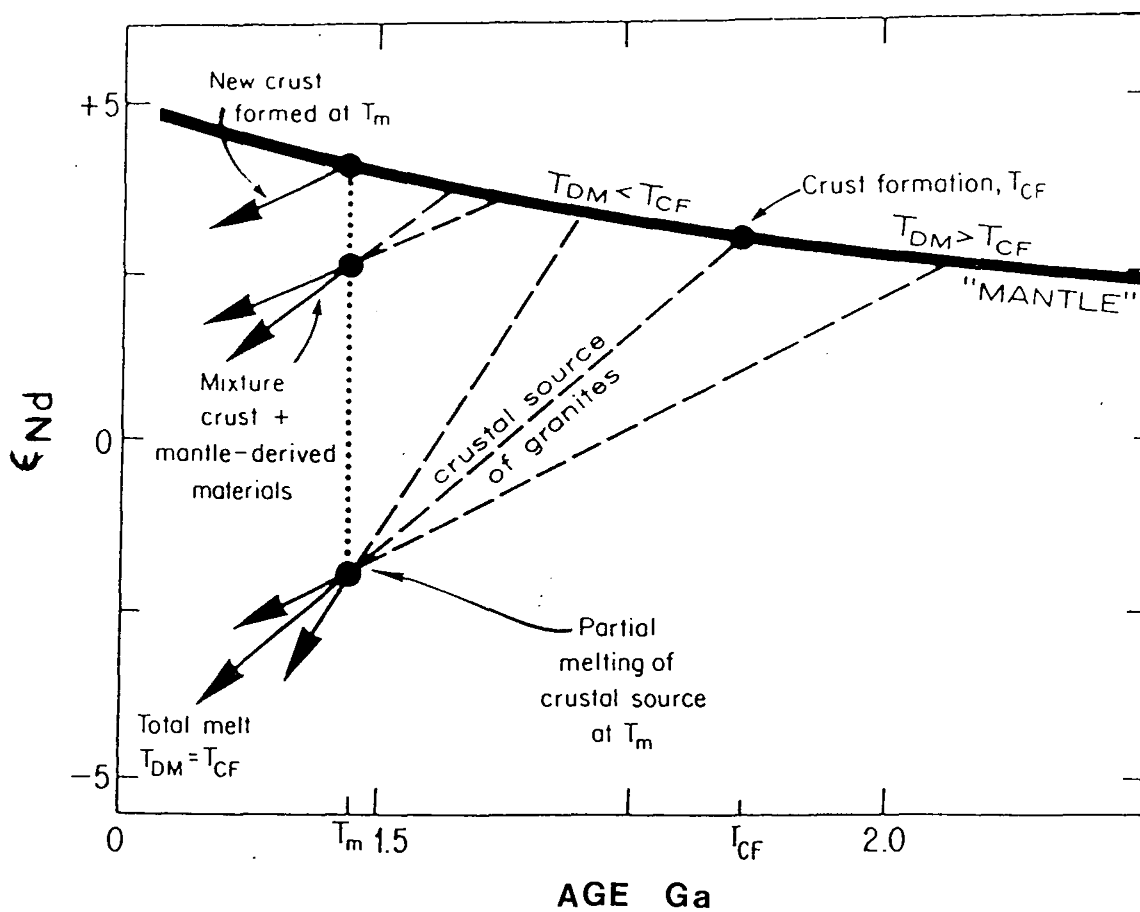
Arndt (1987) reminds us of the assumptions upon which the model age is based:

1. Isotopic evolution of the mantle reservoir responsible for crust formation is precisely known.

2. The interval of time between formation of the melt in the mantle domain and its subsequent incorporation into the crustal domain is short.

3. The Sm/Nd ratio of the resultant crustal package has not been modified since crustal extraction.

Fig. 3.1 The heavy black line represents the depleted mantle curve of DePaolo (1981c). Magma generated by partial melting of the depleted mantle fractionates Sm with respect to Nd, altering the Sm/Nd ratio of the new crustal addition by about 50% at T_{CF}. After fractionation, the new crustal addition is constrained to follow a new evolution line denoted 'crustal source of granites.' Along this line intracrustal differentiation produces the more evolved suites of igneous rocks. At time T_m the effects of partial melting and mixing of old and young crust on the model age is examined. Although partial melting within the crust is not thought to significantly affect the crustal evolution line, small fractionations of the Sm/Nd ratio can significantly alter the crustal evolution line, which when back-extrapolated to the depleted mantle curve no longer defines the true crustal extraction age. New crust that is derived from mixtures of old and young crust also has a ratio of Sm/Nd that does not give the true crustal extraction age. The model age of a sample derived by mixing lies between the model ages of the endmembers. (Fig. 2., from Nelson & DePaolo, 1985)



+5
0
−5
ε Nd
0
Tm 1.5
TCF
2.0
AGE Ga
New crust
formed at Tm
TDM < TCF
Crust formation, TCF
TDM > TCF
"MANTLE"
Mixture
crust +
mantle-derived
materials
crustal source
of granites
Partial
melting of
crustal source
at Tm
Total melt
TDM = TCF

For orogenically derived crustal terranes 2.70 Ga or younger, the depleted mantle model of DePaolo (1981c) is preferred to the CHUR (CHondritic Uniform Reservoir) model which is based on the evolution of Nd and Sm in chondritic meteorites. As with the CHUR evolution curve the Depleted Mantle curve increases monotonically with time and is called T_{DM} for Time dependent Depleted Mantle curve. Evidence accumulated over the past seven years from a variety of researchers working in terranes 2700 Ma or younger, has supported the depleted mantle curve for this time interval. The depleted mantle curve is empirically derived. DePaolo (1981c) based his derivation on 1.8 Ga island arcs with ENd= +3.7 and modern island arcs which cluster around ENd= +8.5. The depleted mantle curve is fitted to these two points.

Packets of new crust with initial $(^{143}Nd/^{144}Nd)_{o}$ identical to the depleted reservoir, and with a distinctly fractionated Sm/Nd ratio, face a wide range of future intra-crustal differentiation events and sedimentary episodes that could further fractionate Nd with respect to Sm. If the Sm/Nd ratio of a sample has been altered, back-extrapolation to the depleted mantle reservoir will not give the correct crust formation age. Experience and modelling have shown that intracrustal differentiation has for the most part a negligible effect on the model age (Nelson & DePaolo, 1985).

3.2.0 Nd Model Age Mapping

Nd Model Age mapping is an ideal tool for characterizing crustal formation ages in multiply metamorphosed terranes (DePaolo, 1980; Nelson & DePaolo, 1985; Farmer & DePaolo, 1983, 1984). This is based on a growing volume of evidence which suggests Sm and Nd are not significantly fractionated on a 'large' whole-rock scale during metamorphism, anatexsis and sedimentation. Therefore once new crustal material is emplaced it will maintain the Nd isotopic composition and f Sm/Nd inherited from the depleted mantle. As long as the assumptions outlined by Arndt (1987) in section 3.1.0 are upheld, the model age can be measured irrespective of the present configuration of the crustal package, be it ortho or paragneiss, young granite or sediment. The model age 'sees through' the reworking and defines the average crustal extraction age of the material.

The episodicity of major crust forming events in Earth history significantly simplifies the interpretation of crustal extraction ages. For 800 Ma, between 2.70 Ga and 1.90 Ga, geochronometers show very little new crust being formed. Therefore model ages that lie outside recognized crust-forming episodes must be treated with suspicion. They may be due to two kinds of mixing processes:

1. a) Anatexsis with assimilation of older or younger crust.
   b) Sediment subduction of old crust contaminating new

juvenile additions in an orogenic setting.

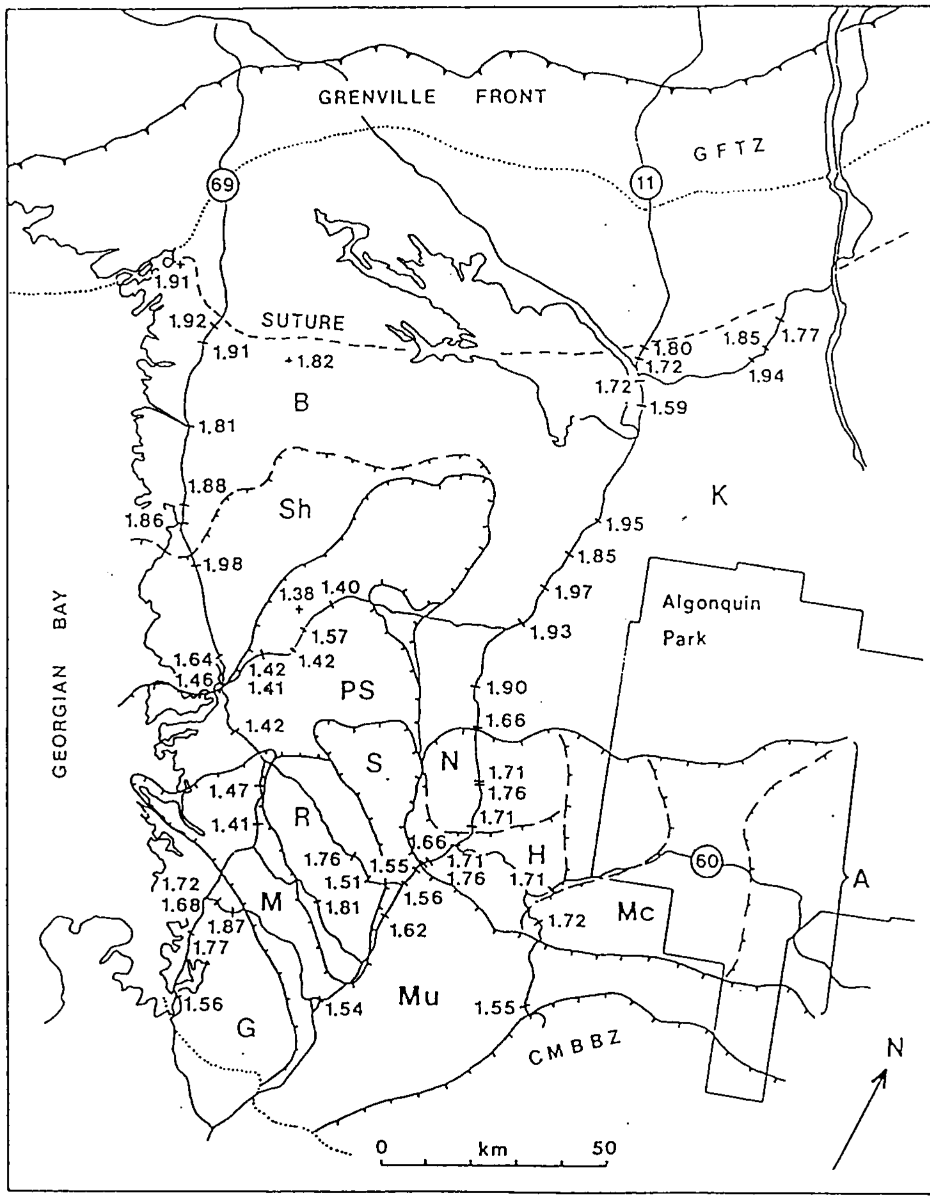
2. A mixed provenance paragneiss consisting of contributions from old and young sediment sources.

When interpreting model ages these possibilities must be considered. If mixing of different crustal packages has occurred, then the model age no longer dates the unique time of crustal extraction and should be referred to as a crustal residence age (Fig. 3.1). The crustal residence age gives an 'average' estimate of the age of the crust rather than the time of extraction from the mantle.

3.3.0 Model Age Mapping In the Grenville Province, Ontario

The Grenville Province is ideally suited for study by model age mapping. The Grenville is a multiply metamorphosed exhumed orogeny consisting of smaller terranes of older crustal material. This older material ranges in age from 2700 Ma near the Grenville Front to ca 1000 Ma further south, where eventually the province slips beneath Paleozoic cover. The Grenville Orogeny effected severe shortening and thickening of these terranes by northwest- directed thrust/stacking. The Orogeny was also accompanied by pervasive thermal metamorphism that reset or partially opened many of the standard geochronometers. Although the Grenville event has hampered traditional geological mapping of its older blocks, Nd model ages may be used to map the boundaries of these blocks. Hidden within the Grenville's veil of metamorphism may be a

Fig. 3.2 This study by Dickin and McNutt (1990) demonstrates the potential of Nd isotopic mapping for characterizing crustal domains within the Grenville Province. The suture is shown near the top of the map. The domains are B=Britt (Sh=Shawanaga), K=Kiosk, PS=Parry Sound, G=Go Home, R=Rosseau, Mu=Muskoka (M=Moon River, S=Sequin), A=Algonquin (N=Novar, H=Hunstville, MC=McLintock). CMBZ=Central Metasedimentary Belt Boundary Zone. Ticks indicate down dip direction. (Fig, 1., from Dickin & McNutt, 1990)



GRENVILLE FRONT
GFTZ
69
11
SUTURE
B
K
Sh
PS
S
N
R
H
M
Mc
Mu
G
A
60
Algonquin Park
GEORGIAN BAY
CMBBZ
N
0 km 50
1.91
1.92
1.91
1.82
1.81
1.88
1.86
1.98
1.38
1.40
1.57
1.42
1.64
1.46
1.42
1.41
1.42
1.47
1.41
1.76
1.51
1.81
1.55
1.66
1.71
1.76
1.71
1.72
1.68
1.87
1.77
1.56
1.54
1.62
1.56
1.55
1.72
1.71
1.76
1.71
1.66
1.90
1.93
1.97
1.85
1.95
1.80
1.72
1.72
1.59
1.85
1.77
1.94

preserved synopsis of the history of orogeny and accretion dating from 2700 Ma to 900 Ma, and compacted within 200 kms of exposed crust.

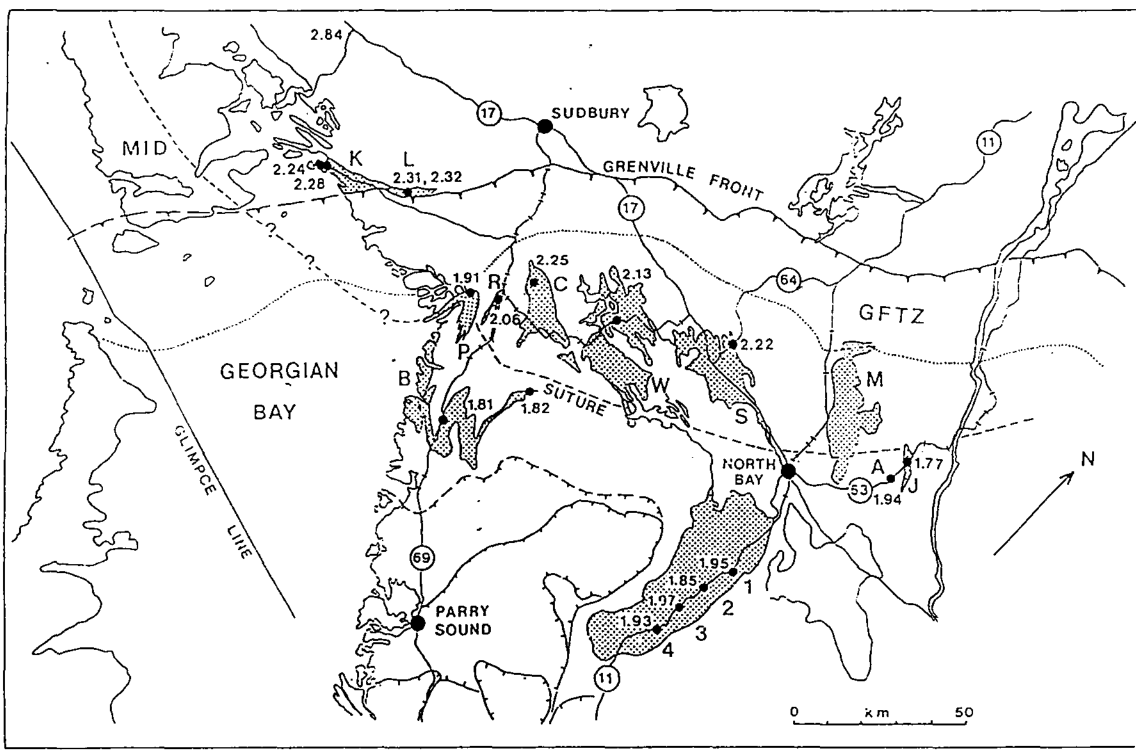
3.3.1 Lithotectonic Domains of the Central Gneiss Belt:

The crustal formation ages of Davidson's lithotectonic domains were characterized by (Dickin & McNutt, 1990). The results are consistent with a structural model proposed by Davidson which interpreted the Parry Sound Domain as an allochthonous klippe thrust over the Moon River and Sequin subdomains, which are themselves autochthonously attached to their Muskoka Domain root zone. Two major sets of model ages are distinguished. The Muskoka root zone, along with the Moon River and Sequin Subdomains have model ages between 1.40-1.60 Ga. The Parry Sound Klippe shows the same range in model ages but has a distinctly different lithology. The Go Home and Rosseau Domains have model ages ranging between 1.56-1.81 Ga. Dickin and McNutt (1990) interpreted these terranes as representing part of a "single lower Proterozoic basement" more fully developed in the Britt and Kiosk Domains. The termination of this Proterozoic basement against metasediments derived from the Archean foreland marks the suture discovered by Dickin and McNutt (1989).

3.3.2 Penokean Aged Suture in the Central Gneiss Belt:

As already mentioned in the introduction, reconnaissance style Nd isotopic mapping in the CGB revealed a significant

Fig. 3.3 Nd model age study of plutons on both sides of the suture boundary. Plutons emplaced on the Archean side have model ages >2.0 Ga while plutons emplaced on the Proterozoic side have model ages <2.0 Ga. The low model ages of plutons north of the suture may be resolved by invoking a wedge of Proterozoic crust at depth on the Archean side. Model ages of plutons on the Proterozoic side are tightly clustered and indicate an origin dominated by crustal anatexsis. There does not appear to be any Archean crust at depth south of the suture, supporting the contention by Dickin & McNutt (1989) that the suture marks the edge of the Archean foreland at ca 2000 Ma. Plutons to the north of the suture: K=Killarney, L=Bell Lake, R=Rutter, C=Cosby, W=West Bay, S=Sturgeon Falls, M=Mulock, and, to the south of the suture: B=Britt, 1,2,3,4=Powasson, A=Balsam Creek, J=Jocko and P=Pickerel Complex. MID=Manitoulin Island Discontinuity. (Dickin, McNutt & Clifford, 1990)


2.84
SUDBURY
17
MID
K
L
2.24
2.28
2.31, 2.32
GRENVILLE FRONT
11
17
2.25
2.13
64
1.91
R
C
GFTZ
2.06
2.22
GEORGIAN
BAY
B
P
M
1.81
1.82
SUTURE
W
S
GLIMPCE LINE
NORTH BAY
A
1.77
J
53
1.94
N
69
1.95
1.85
1.97
1.93
1
2
3
4
PARRY SOUND
11
0 km 50

step in model ages from ca 1.90 Ga to ca 2.70 Ga, tentatively interpreted as a 1.90 Ga crustal suture between the Superior craton and an accreted 1.90 Ga Proterozoic island arc (Dickin & McNutt, 1989). The Proterozoic mobile belt falls within the Britt and Kiosk Domains which is bounded by the Grenville Front Tectonic Zone (GFTZ) to the north. The suture can remain <u>within</u> these Grenville-age domains provided it was not reactivated by Grenville tectonism. A model of southerly-dipping subduction is consistent with the lack of plutonism of this age on the Archean foreland.

Nd model ages of plutons on opposite sides of the suture fall into two distinct provinces. Plutons to the north of the suture are compatible with a dominantly Archean source, T_{DM} age >2 Byrs, and, plutons to the south of the suture have T_{DM} age <2 Byrs (Dickin, McNutt, and Clifford, 1990). The Britt and Powassan Batholiths on the Proterozoic side are consistent with a model of crustal anatexsis with little or no juvenile component necessary. Model ages for plutons on the Archean side like the Killarney and Sturgeon Falls Batholiths averaging 2.26 and 2.22 Ga respectively require an admixture of younger crustal material. There are three possible candidates for this younger endmember (1) tectonic mixing with 1.70-1.90 Ga juvenile component (2) Sedimentological mixing with 2.40 Ga Huronian volcanics and (3) Sedimentological mixing between 2.70 and 1.90 Ga protoliths (Dickin, McNutt and Clifford, 1990).

Dickin et al. (1990) proposed that a midcrustal level delamination of the Penokean arc may protrude at midcrustal level beneath the surface expression of the suture. Assimilation of this younger component during anatexsis could account for the model age data north of the suture. In one sense this concurs with Green et al. (1988) who during seismic reflection profiling across the Grenville Front picked up a mid-crustal reflector that they interpreted as an expression of the decollement resulting from Penokean tectonism. Perhaps the most significant aspect of this study is the lack of Archean signature south of the suture, supporting the hypothesis that the suture represents the edge of the continental crust ca 2000 Ma.

CHAPTER 4

ANALYTICAL PROCEDURE

4.1.0 Introduction

Analytical procedures for Sm/Nd geochronology at McMaster University are routine procedures and will be described in the same order that they are encountered in practice.

1. Rock crushing
2. Dissolution and cation chromatography
3. Mass spectrometry

4.2.0 Sampling and Rock Crushing

Samples chosen in the field were homogeneous and representative of the outcrop as a whole. Wherever possible samples were chosen that would yield at least 5 kg of pristine material from which to work in the lab. Weathering rinds and other alteration structures (e.g., hydrothermal fracture-filling) were removed. Large samples were chosen to ensure closure with respect to Sm and Nd through Grenvillian regional metamorphism (amphibolite to granulite grade) which post-dates the emplacement of these rocks. All of the samples collected were gneissic and every effort was made to avoid extensive banding since banding is indicative of element migration during metamorphism and could compromise closure at the sample size collected.

In the lab, with a hammer and the aid of a hydraulic splitter, samples were broken up into handsample size pieces.

The sample was then processed with a jaw crusher into gravel of less than about 1 cm equivalent diameter. The gravel aliquot was reduced in size methodically with a table-top-divider to a sample size small enough to be loaded into a tungsten carbide disc mill for powdering with a shatterbox.

The milling process was executed in two steps. The first step requires the mill to be filled to just over capacity and run for approximately 3 minutes to produce a fine sand size fraction. The whole sample is removed from the mill and poured onto a clean piece of paper. From this material approximately 150 ml of sample is returned to the disc mill and crushed to less than 300 mesh. The two-step procedure yields optimal sample homogenization at all stages of the procedure. About 100 ml is transferred to a 125 ml glass jar ready for dissolution.

All equipment and working surfaces were meticulously cleaned with a vacuum, equipped with a soft bristled brush, between samples. The jaw crusher plate assembly was dismantled between samples so that plates could be cleaned adequately with a wire brush, and grit vacuumed up. Polyethylene gloves were used when handling the disc mill and puck to keep grit-attracting skin oils off the apparatus and to facilitate visual inspection of cleanliness. After cleaning, the jaw crusher, table-top-splitter and sample containers were precontaminated with a handsample size portion of the next sample.

4.3.0 Dissolution and Cation Chromatography

Between 70 and 150 mg of powder was weighed and transferred to a teflon bomb of known weight. Approximately 10 mL of concentrated HF (42 %) was added, the lid tightly secured, and the bomb placed in a teflon safety jacket. The whole assembly was placed in an oven at 140 degrees celsius for 3 days. In the oven dissolution of acid-resistant minerals like zircon and monazite were enhanced by elevated pressure and temperature.

In three days the bomb was removed from the oven, allowed to cool and the lid removed. The HF was evaporated on a hotplate within a laminar flow hood. To curtail the formation of acid-resistant insoluble fluorides, 5 mL of 16 M HNO_3 was added when the sample was close to dryness and also evaporated. The residue was taken up into solution with 5 mL of 6 M HCl the bomb sealed and replaced in the oven (with jacket) for 1 day. The next day, after allowing the sample to cool, 5 mL of milli-Q was used to dilute the HCl solution in preparation for splitting and spiking.

The sample was split into two and a mixed REE spike, isotopically enriched in Sm and Nd, was added to an aliquot of known weight. Both solutions were evaporated, redissolved in 2 mL of 2.5 M HCl, and transferred to polystyrene test tubes for centrifugation. Centrifugation prevents undissolved material from contaminating the columns. With a pipette 1 mL of solution was loaded onto cation exchange columns filled with Dowex Bio-Rad AG50W (200-400 mesh).

For accurate isotope ratios Sm and Nd must be isolated from one another and concentrated, by solution chromatography. This is necessary due to isobaric interferences (e.g., ^{144}Sm and ^{144}Nd) and matrix effects (e.g., Ba suppresses ionization of rare earths). To this end a two step process was used:

1. Most major elements were eluted using 2.5 M HCl (e.g., Na, K, Ca) followed by 2 M HNO_3 (e.g., Ba & Sr) on a polystyrene sulphonic acid resin. Rare earths were retained on the column and eluted as a group with 7.5 M HNO_3.

2. The rare earths were separated in a Hexyl di-ethyl hydrogen phosphate medium in quartz columns. Light rare earths were eluted using 0.2 M HCl followed by Sm using 0.5 M HCl. This method is called "reverse phase" for the Nd is collected before the Sm, as opposed to first, which is the more conventional order of elution in two other methods of REE collection (Richard et al., 1978).

Columns were calibrated in the lab on test runs of eluent by ICP-MS.

From the columns three solutions were collected for each original sample, one for precision analysis of Nd isotope ratio (^{143}Nd/^{144}Nd), one containing heavy REE for isotope dilution analysis of Sm and one containing light REE for isotope dilution analysis of Nd.

Samples were evaporated and three drops of 3 M HNO_3 acid containing 1.3 % H_3PO_4 (.3 M) was added and evaporated again.

This has the effect of softening the crystal residue, facilitating redissolution in 0.3 M H_3PO_4 for sample loading onto a tantalum ribbon for mass spectrometric analysis.

4.4.0 Thermal Ionization Mass Spectrometry

Samples were taken into solution with approximately 1/2 microlitre of 0.3 M H_3PO_4 acid and transferred with a one microlitre pipette to the side tantalum filament of a double rhenium/tantalum filament bead assembly. A current of up to 2.5 amps was passed through the side filament, evaporating the acid and securing the sample residue.

Nd isotope ratios and Nd and Sm isotope dilution analyses were performed on a VG 354, 5-collector, solid-source mass spectrometer. Analyses were started when the pressure in the source chamber was below 2×10^{-7} bars. Isotope dilution analyses of Sm and Nd were measured in single collector mode using a mixed REE spike (^{149}Sm-^{150}Nd). Spike calibration was tested on BCR-1 and yielded a $^{147}SM/^{144}Nd$ ratio of .2280 +/- 2 in agreement with Thirlwall (1982). Repeat dissolutions of samples within the McMaster Geochronology Lab show an average variation in $^{147}Sm/^{144}Nd$ of < 0.5%, correlated with $^{143}Nd/^{144}Nd$. This generally translates into a 20 Myr uncertainty in model age.

Column blanks for Sm and Nd, spiked prior to column chemistry, yielded 0.37 and 0.38 ng respectively. These blanks are higher than normal which may partially reflect loss of spike during column chemistry. The blanks translate to about 0.7 ppm and will have the most detrimental effect on Archean samples with low Nd and Sm, e.g., sample NB0; Nd=8.03 ppm, Sm=1.22 ppm, T_{DM}=2.69 Ga; although the concentrations are low the model age is essentially identical to the ca 2.70 Ga age typical of this material i.e., consider sample NB9; Nd=113.63 ppm, Sm=16.86 ppm, T_{DM}=2.71 Ga; concentrations of Nd and Sm are considerably higher yet the model age is similar. The above blanks represent only four columns out of a total of 30 and may not be representative of the other columns as a whole. The blanks quoted above represent a maximum amount of contamination expected. One repeat dissolution was performed for CH19 with a T_{DM} model age of 1.79 Ga and repeat age of 1.78 Ga.

Nd isotope ratios were measured by general peak jumping in 4 collector mode. Measured ratios were normalized against a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Average within run precision was 0.000012 (2sigma mean).

CHAPTER 5

RESULTS

5.1.0 Model Age Mapping: North Bay-Temiscaming Area

For the area falling between North Bay, Ontario and Temiscaming, Quebec, 46 new Nd model ages (Tb. 5.1) were added to the 12 previously determined by Dickin et al. (1989). To best display the distribution of the data, 3 maps were constructed, a compilation map of the whole field area (Fig. 5.1), a detailed map of the Temiscaming area (Fig. 5.2) and, a detailed map of the North Bay area (Fig. 5.3).

From the compilation map it is readily seen that the suture is well defined in the immediate vicinity of the city of North Bay and the town of Temiscaming, however, on the East side of the Mulock pluton and northwest of Temiscaming there is a large area of drift with almost no exposed outcrop. Model age results from the Temiscaming area west of the Ottawa River indicate that the trend of the suture is located somewhere within the areal extent of the drift. A dashed line is used to indicate that in this area only the '1st order' trend of the suture is known. A solid line indicates where the suture is precisely located, often picking up '2nd order' variation with a more sinuous character.

Because the rocks underlying the field area have been subjected to amphibolite grade metamorphism at ca 1000 Ma, distinguishing units of paragneiss from orthogneiss, for rocks

Table 5.1 Nd Model ages and other isotopic data for mapped samples in the North Bay-Temiscaming area. Also, fingerprinting for para or orthogneissic affinity of samples.

Table 5.1 Sm & Nd Data for Gneissic and Plutonic Rocks

Sample Number	Normative* corundum	Normative* quartz	Rock Type	Nd ppm	Sm ppm	147Sm/144Nd	143Nd/144Nd	TDM Model Age
North Bay Area								
Archean: ca 2.70 Ga								
NB9	1.19	12.03	P	113.63	16.86	0.0897	0.510855	2.71
NB11	2.86	26.08	P	36.67	5.39	0.0886	0.510846	2.69
NBO	2.93	34.82	P	8.03	1.22	0.0913	0.510910	2.69
NB15	2.20	26.52	P	8.33	1.37	0.0997	0.511063	2.66
MR23.3+	2.20	31.10	P	29.90	3.19	0.0645	0.510395	2.72
MR35.2+	1.50	26.70	P	23.20	4.01	0.1044	0.511110	2.72
MR56.6+	1.40	27.40	P	9.17	1.57	0.1034	0.511080	2.73
Intermediate (Archean): 2.40-2.60 Ga								
NB17	1.94	28.75	P	54.17	9.19	0.1026	0.511310	2.39
CH22	0.56	9.68	?P	35.66	6.08	0.1030	0.511265	2.46
CH26	1.28	22.56	P	15.02	2.62	0.1057	0.511294	2.48
NB14	2.42	22.98	P	41.97	6.79	0.0976	0.511205	2.42
CH29	1.95	27.42	P	38.09	6.57	0.1042	0.511277	2.47
CH44	2.46	33.67	P	12.24	1.74	0.0858	0.510891	2.58
MPR-6+	-0.61	21.62	O	n/d	n/d	0.0981	0.511260	2.36
Proterozoic: ca 1.90 Ga								
NB12	-0.33	22.62	?O	121.53	20.76	0.1033	0.511648	1.93
NB4	-4.14	3.27	O	29.72	5.66	0.1151	0.512031	1.56
NB6	0.85	17.61	?P	59.94	12.1	0.1219	0.511869	1.95
CH28	1.10	26.88	P	93.19	17.06	0.1106	0.511749	1.91
NB19	0.95	31.74	P	41.26	7.74	0.1134	0.511789	1.91
NB20	0.06	19.4	?P	64.08	12.37	0.1166	0.511808	1.95
CH41	0.70	25.81	?P	65.79	12.79	0.1177	0.511792	1.99
CH19	-1.61	19.31	O	130.13	20.52	0.0953	0.511648	1.79
CH19	repeat			n/d	n/d	0.0962	0.511672	1.78
NB8	-1.53	12.29	O	107.02	21.06	0.1188	0.511871	1.88
NB13a	0.93	32.92	P	140.58	24.75	0.1063	0.511744	1.84
MR71.2+	2.06	29.10	P	98.30	18.63	0.1146	0.511923	1.72
MR155.2+	-0.50	12.40	O	51.25	9.02	0.1063	0.511706	1.90

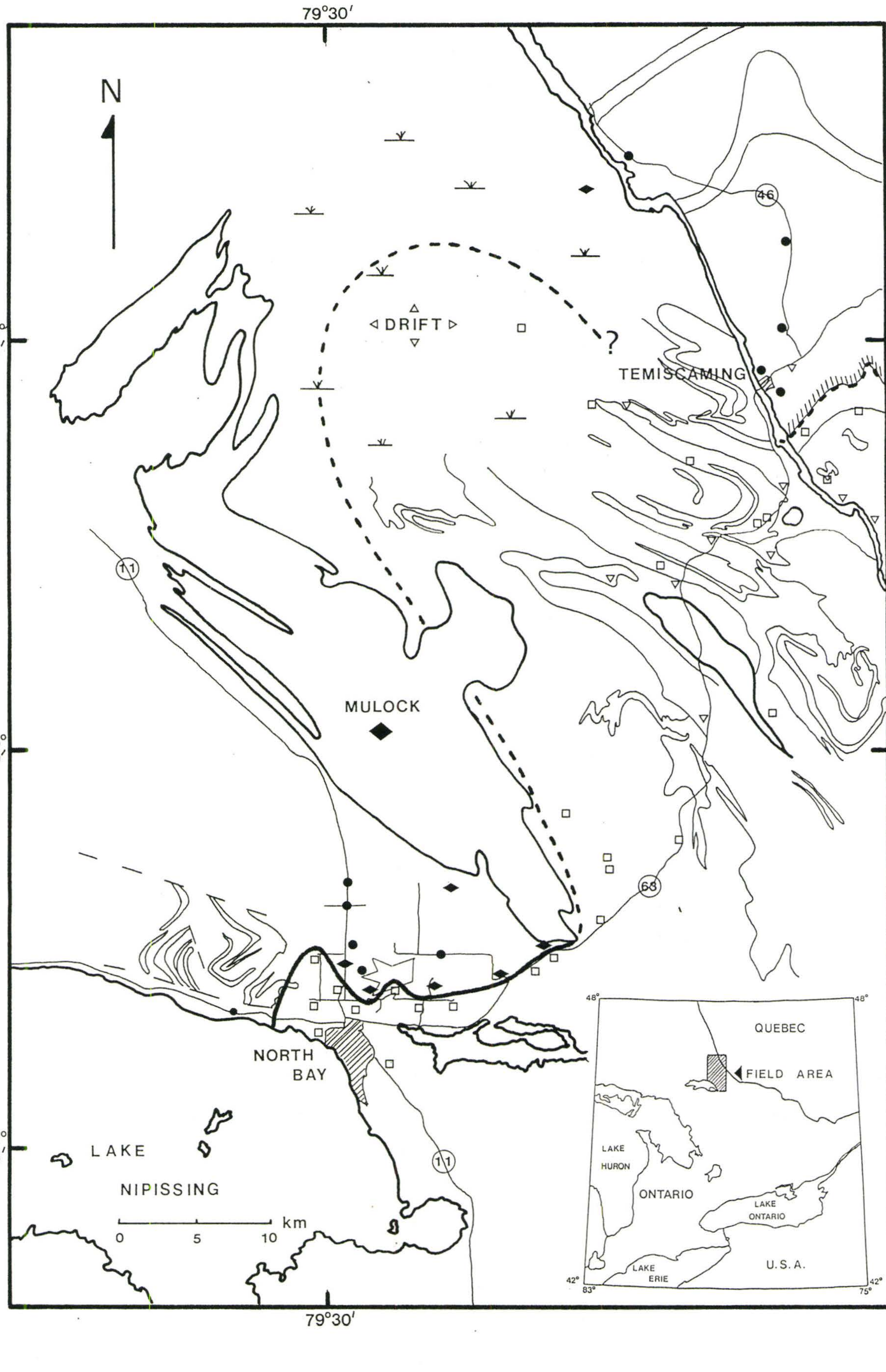
*Norms calculated assuming FeO/Total Fe = 0.9.
Negative values of normative corundum - normative diopside
n/d = not determined
O = Orthogneiss; P = Paragneiss; ? = uncertain affinity
147-Sm/144-Nd average reproducibility is 0.1% (1 sigma)
143-Nd/144-Nd average within-run precision is 0.000012 (2 sigma)
+analyzed by Dickin et al. (1989)
MPR-6=Mulock Pluton T020.9=Jocko Pluton

Table 5.1 Continued from previous page

Table 5.1 (continued)

Sample Number	Normative* corundum	Normative* quartz	Rock Type	Nd ppm	Sm ppm	147Sm 144Nd	143Nd 144Nd	TDM Model Age
Temiscaming Area								
Archean: ca 2.70 Ga								
TQ16.2+	0.75	21.50	?P	3.05	0.578	0.1146	0.511323	2.67
TQ9.5+	1.45	26.00	P	1.86	0.355	0.1162	0.511356	2.66
TQ30+	-3.40	4.30	O	27.03	4.60	0.1029	0.511082	2.72
CH11	1.75	27.70	P	39.47	4.75	0.0727	0.510521	2.75
CH7	2.13	28.98	P	33.56	4.79	0.0861	0.510797	2.71
Intermediate (Archean): 2.40-2.60 Ga								
CH3	3.3	31.89	P	4.06	0.66	0.0986	0.511145	2.53
Intermediate (Proterozoic): 2.00-2.39 Ga								
NB28	2.50	59.4	P	33.03	5.75	0.1051	0.511429	2.27
NB37	2.91	27.57	P	55.63	9.37	0.1017	0.511426	2.20
CHO	-2.05	33.75	?O	115.82	23.18	0.1211	0.511730	2.16
NB45A	4.04	45.24	P	39.32	6.61	0.1014	0.511454	2.16
CH17	0.41	13.98	?P	45.46	7.64	0.1015	0.511557	2.02
CH10	3.20	49.23	P	28.84	4.92	0.1032	0.511544	2.07
NB36	1.03	69.10	P	19.32	3.40	0.1065	0.511593	2.06
CH4	0.43	26.95	?P	38.07	7.37	0.1170	0.511638	2.22
TO7.2+	0.25	68.00	P	21.74	3.60	0.1000	0.511300	2.34
TO14.7+	0.50	44.70	P	29.73	5.41	0.1099	0.511625	2.08
TQ6.2+	3.70	23.10	P	37.14	6.60	0.1075	0.511592	2.08
TO20.9+	-2.1	n/d	O	156.2	23.74	0.0920	0.511626	1.77
Proterozoic: ca 1.90 Ga								
NB33	5.39	34.03	P	51.66	8.70	0.1018	0.511651	1.90
NB26	-0.12	33.85	?O	108.75	17.52	0.0975	0.511644	1.83
NB29	2.83	32.28	P	44.00	7.47	0.1026	0.511631	1.94
NB22	0.72	28.62	?P	158.35	28.03	0.1072	0.511741	1.86
NB32	0.85	26.24	?P	63.40	11.41	0.1088	0.511704	1.97
CH46	0.60	31.64	?P			0.1024	0.511632	1.93
CH51	1.89	35.20	P	89.08	16.21	0.1103	0.511751	1.90
CH15	-1.04	24.98	?O	84.60	15.77	0.1126	0.511833	1.82
CH14	0.96	24.20	?P	81.32	15.93	0.1183	0.511847	1.91
CH1	1.37	18.27	P	34.88	6.03	0.1044	0.511655	1.94
CH2	3.20	37.76	P	46.79	8.02	0.1036	0.511659	1.92
NB40	3.61	77.39	P	13.58	1.95	0.0868	0.511437	1.93
NB43	0.94	3.78	?P	46.24	8.36	0.1093	0.511685	1.98
NB38	2.67	49.63	P	31.84	5.17	0.0982	0.511575	1.94
TO29.7+	-.80	44.00	P	33.60	6.05	0.1088	0.511769	1.85

Fig. 5.1 Map showing localities of dated samples. All data are represented, including 12 samples from the original paper by Dickin & McNutt (1989). Solid symbols represent gneisses with Archean model ages composing part of the Archean foreland; open symbols represent gneisses with Proterozoic model ages composing part of the allocthonous island arc terrane. In the Proterozoic open squares represent ages <2.00 Ga; open inverted triangles represent ages between 2.00 & 2.34 Ga. In the Archean, solid circles represent ages >2.60 Ga; solid diamonds represent ages between 2.40 & 2.60 Ga. The suture is denoted by a solid line (2nd order:precise) and a dashed line (1st order: approx.). Notice the large area of 'No Exposure' in the Temiscaming area northeast of the Mulock pluton. This was not mapped by Lumbers (1971).


79°30′
N
DRIFT
?
46° 45′
TEMISCAMING
46
11
MULOCK
46° 30′
63
NORTH BAY
46° 15′
LAKE
NIPISSING
0 5 10 km
11
79°30′
48°
48°
QUEBEC
FIELD AREA
LAKE HURON
ONTARIO
LAKE ONTARIO
LAKE ERIE
U.S.A.
42° 83°
42° 75°

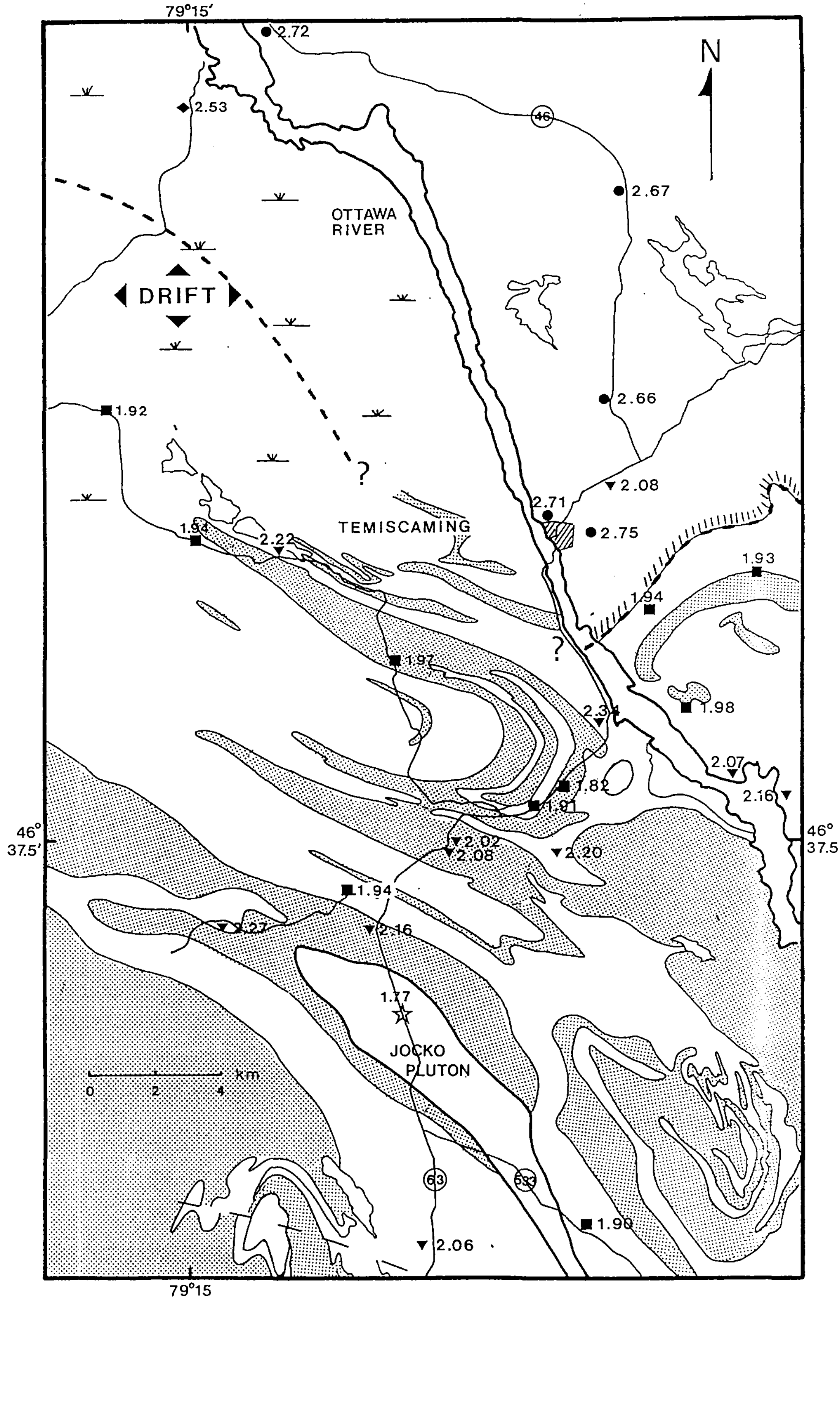
emplaced 800-1400 Ma earlier, is a difficult task. A geochemical criterion is used here to distinguish between rocks with or without obvious affinities to sediments, based on the normative quartz and normative corundum abundances in the sample. Samples of paragneiss are distinguished by their high normative quartz and high normative corundum content from samples of orthogneiss which are low in these minerals and high in normative diopside. This chemical fingerprinting is useful but not without ambiguity, particularly where a sample has both low normative quartz and low normative corundum. When the distinction isn't clear a question mark (?) is entered for the ortho or paragneissic affinity of that sample (Tb. 5.1).

5.1.1 Temiscaming Area:

The 'Temiscaming area' refers to that part of the field area east and northeast of the Mulock pluton (Fig.5.2) including that area east of the Ottawa River in Quebec. West of the Ottawa River the 1st order trend of the suture is constrained between the only sample of Archean provenance, 2.53 Ga, and the most northerly sample of Proterozoic provenance, 1.92 Ga (top left of Fig. 5.2). Approximately 10 km separates these two data points. However on the East side of the Ottawa river, beginning north of Temiscaming, a well defined block of Archean material of ca 2.70 Ga in age stretches to just south of Temiscaming. Tracing the suture west to east, from the area of poor exposure in Ontario to connection with the suture south of Temiscaming, requires the suture to negotiate a fairly steep southeasterly plunge. On the Quebec side of the Ottawa River, south of Temiscaming, the suture appears to be well defined by a mapped unit of ca 1.95 Ga muscovite-quartzofeldspathic gneiss that winds its way through Quebec for many 10's of km's beyond the area covered by this study. The northern extent of this unit east of the Ottawa River marks a transition to ca 2.72 Ga Archean gneiss. Since this unit continues into Quebec for some distance it is likely the trend of the suture is coincident with it for some distance. Assuming this is true, the muscovite-quartzofeldspathic gneiss has a roughly east-northeasterly trend and is lobate or sinuous. The sinuosity displayed by the unit is in excellent agreement with the steep southeasterly dip the suture must negotiate coming out of the drift west of the Ottawa River. Therefore since the suture appears to be lobate or sinuous along strike suggesting that the large lobe negotiated by the suture in the Temiscaming area east of the Mulock Pluton is not out of character for the suture as a whole (Fig. 5.1).

North of the suture and East of the town of Temiscaming, Quebec, a sample with a model age of 2.08 Ga was recovered during the initial reconnaissance isotopic mapping of Dickin et al. (1989). More detailed work from this study has revealed that the lithology of the 2.08 Ga sample is atypical

Fig. 5.2 The gray stippled lithology is biotite(amphibole) gneiss; the white lithology below the suture is muscovite-quartzofeldspathic gneiss. In the Temiscaming area the suture is defined on the Quebec side of the Ottawa River by a mappable unit of quartzofeldspathic gneiss. West of the Ottawa River the suture is less well defined due to a large area of no exposure. From the area of no exposure the suture must curve sharply to the southeast to connect with a better defined section exposed in Quebec south of Temiscaming. Due to the sinuosity displayed by the muscovite-quartzofeldspathic unit further into Quebec (not shown here), such undulations of the suture appear normal. The 2.08 Ga sample east of Temiscaming on the Archean side of the suture is not representative of other model ages in the area as a whole and may owe its present position to Penokean or Grenville tectonics (see text for discussion). Symbol shapes are as described in Fig. 5.1.



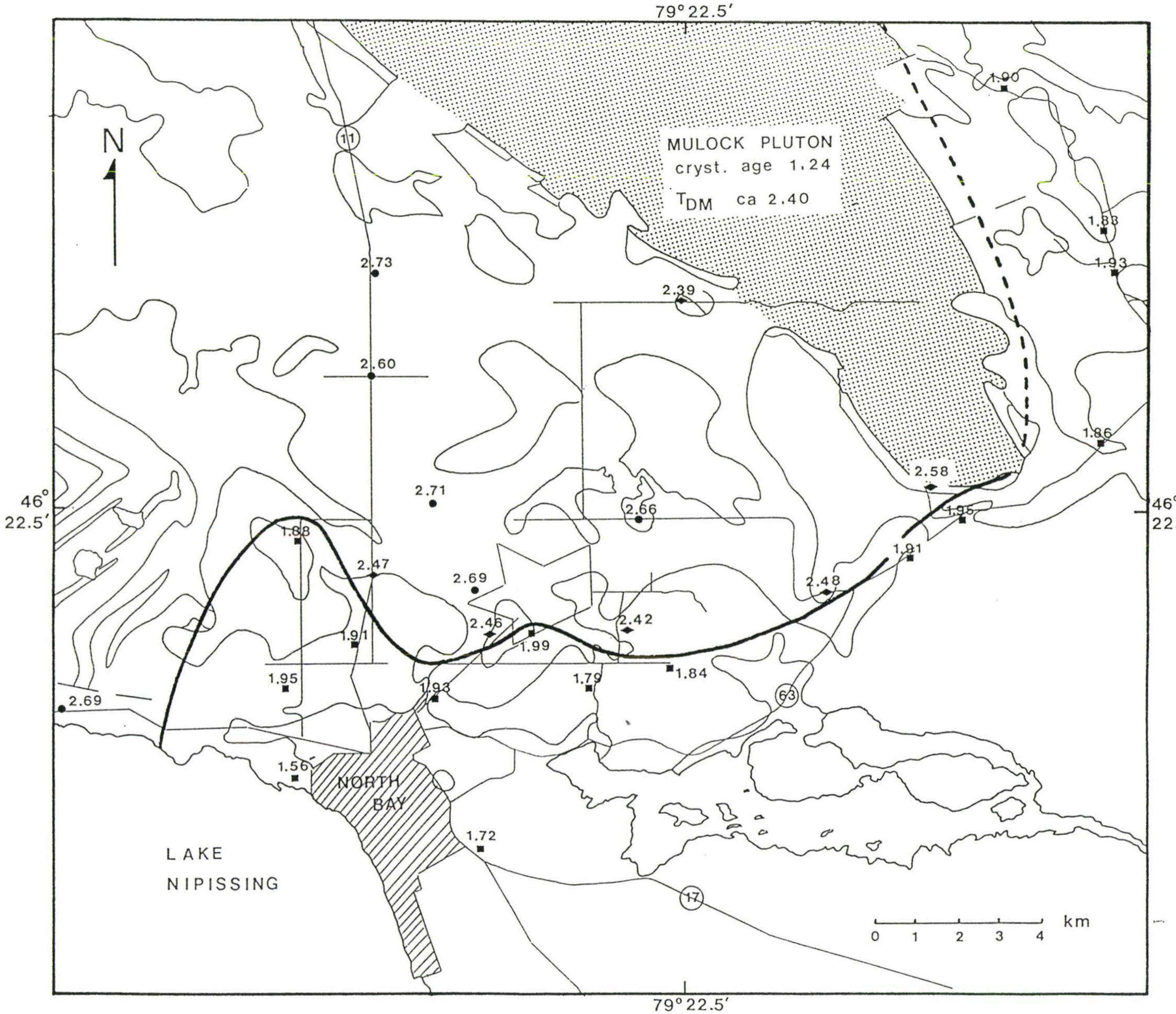
79°15'
N
2.72
2.53
2.67
46
OTTAWA
RIVER
DRIFT
2.66
1.92
?
2.08
2.71
TEMISCAMING
2.75
1.94
2.22
1.93
1.94
?
1.97
1.98
2.34
2.07
1.82
2.16
1.81
46°
37.5'
2.02
2.08
2.20
46°
37.5'
1.94
2.27
2.16
1.77
JOCKO
PLUTON
0
2
4
km
63
533
1.90
2.06
79°15

of the surrounding lithology, with model ages firmly established around 2.72 Ga. The suture could be extended north to account for this sample but such an extension does not seem justified at present. Closer scrutiny of this area in the future will determine if the 2.08 Ga sample is a true outlier or not. However, until that time the presence of this 'outlier' within what seems to be predominately an Archean terrane may indicate that such outliers, as lenses, are possible within the opposing terrane. If more outliers are discovered in the future it will be of considerable interest to determine if their emplacement is due to Penokean or Grenvillian tectonism.

5.1.2 North Bay Area:

In the North Bay area the trend of the suture is very well defined, in two areas its location is known to within a few hundred meters (Fig. 5.3). Since almost every exposed outcrop in the area of the suture has been sampled in the North Bay area it appears that the suture has been eroded slightly more than the country rock on either side. However, now that a very precise trend has been established, it will be easier to locate any outcrops containing the suture that may be identified by lithological contacts. Presently, on the Proterozoic side of the suture, the lithology is by and large a gray biotite gneiss sometimes containing abundant hornblende. The Archean lithology encountered immediately

Fig. 5.3 On this map the 2nd order sinuosity displayed by the trend of the suture in the North Bay area is well demonstrated. Although a single outcrop containing the suture has not been found, future work in this area will undoubtedly produce examples of such contacts. A band of intermediate ages on the Archean side (2.40-2.60 Ga) may represent mixing between 2.70 Ga Archean sediments, exposed a few kms further north, and 1.90 Ga Proterozoic sediments. The Mulock pluton with a crystallization age of 1.24 Ga, has a Nd model age of 2.40 Ga, indicating that the crust at depth in this area is largely Archean north of the suture. Symbol shapes are as in Figure 5.1.



79° 22.5′
MULOCK PLUTON
cryst. age 1.24
T_{DM} ca 2.40
N
1.90
1.83
1.93
2.73
2.39
2.60
1.86
2.58
2.71
2.66
1.95
46°
22.5′
1.88
1.91
2.47
2.69
2.48
2.46
2.42
1.99
1.91
1.95
1.79
1.84
1.93
2.69
63
1.56
NORTH
BAY
1.72
LAKE
NIPISSING
17
0
1
2
3
4
km
11

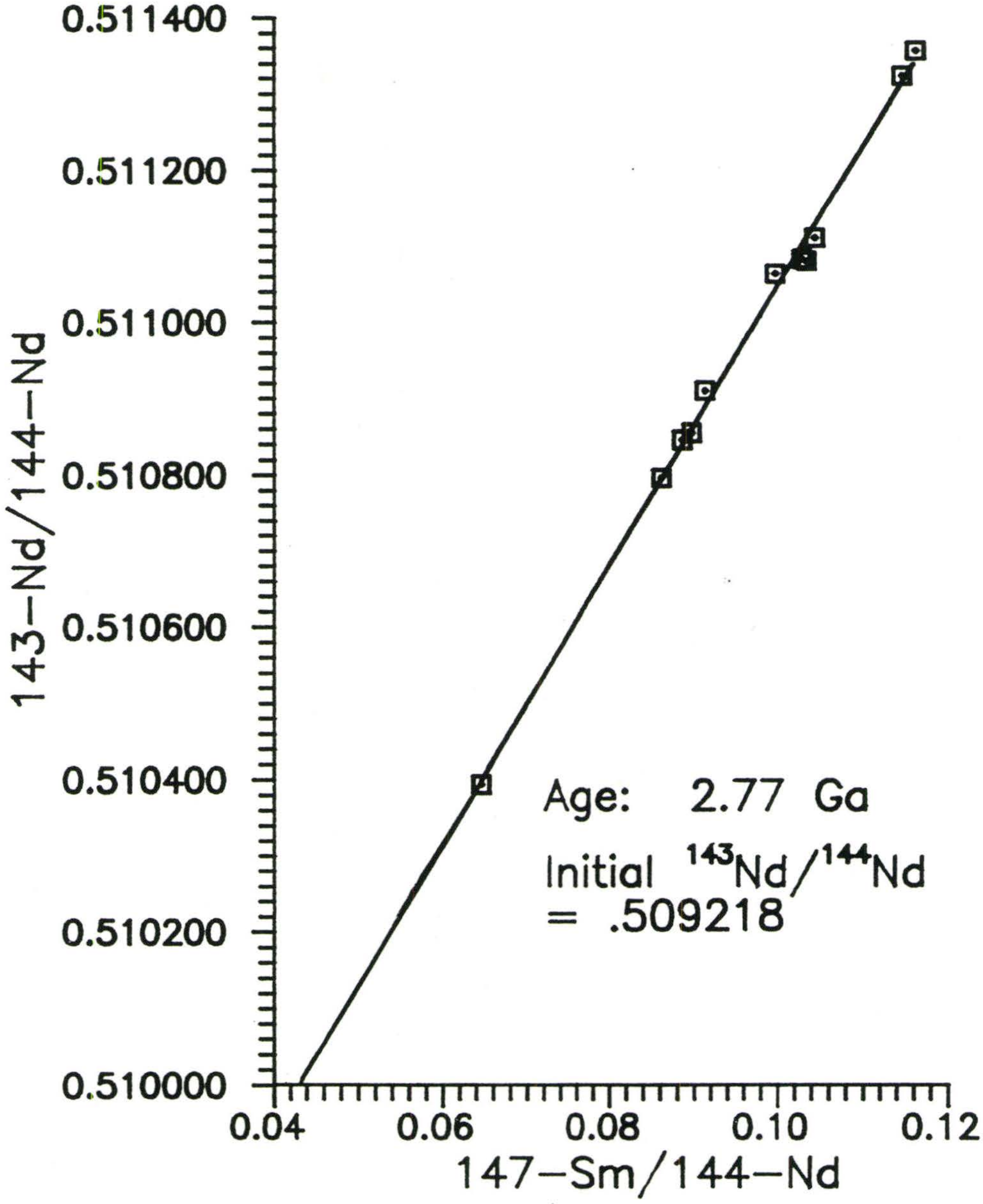
north of the suture is a lighter colored orange/pink feldspathic gneiss with abundant biotite and often visible fracture-fillings. This changes to more typical biotite gneiss with distance north of the suture. The units defining these lithologies appear on Lumber's map (Map 2216) ; however, they do not show a good correlation with the suture overall, and so Lumber's map can not be used as a reliable indicator of the location of the suture, based on lithology.

Model age transitions across the suture in the North Bay area do not traverse the whole 800 Ma from 1.90-2.70 Ga's in one step. On the Archean side there appears to be a transitional step with crust of between 2.40 and 2.60 Ga rising to ca 2.70 Ga quickly thereafter. Although a lack of adequate sample density on the Archean side prohibits a more precise estimate of the distance from the suture before evidence of the ca 2.70 Ga material, a maximum estimate based on the data in hand is approximately 2-4 km's. One sample at 2.39 Ga lies approximately 8 km's from the suture within the Archean Domain but is only a few 10's of meters from contact with the Mulock pluton with essentially the same model age (2.40 Ga) suggesting that this sample may have been metasomatized upon emplacement of the pluton at 1.24 Ga.

5.1.2. An Archean Isochron

One of the tests for the correctness of the mantle model used to calculate model ages is to compare the model age of the sample with a Sm-Nd isochron constructed from the same sample or cogenetic suite. The model age may also be confirmed by other geochronometers. Within the study area the Archean provenance crust has Nd model ages of ca 2720 Myrs. A whole-rock isochron constructed from these samples yields an age of 2770 +/-107 Myrs (2 sigma): This is slightly older, but within error. The excellent agreement between model age and isochron age is justification for the correctness of DePaolo's derivation of the depleted mantle as a model of the crust forming reservoir for the Superior Province about 2.7 Ga.

Fig. 5.4 An isochron for the Archean gneisses representing the age of the Archean crust north of the suture. Model ages for these samples are ca 2.72 Ga. The isochron age is 2770 +/-107 Ma (2 sigma) which approaches the model ages within error. The good agreement between the isochron age and the model ages supports the use of DePaolo's depleted mantle curve for crust as old as 2.7 Ga.


0.511400
0.511200
0.511000
0.510800
0.510600
0.510400
0.510200
0.510000
143—Nd/144—Nd
0.04
0.06
0.08
0.10
0.12
147—Sm/144—Nd
Age: 2.77 Ga
Initial 143Nd/144Nd
= .509218

CHAPTER 6

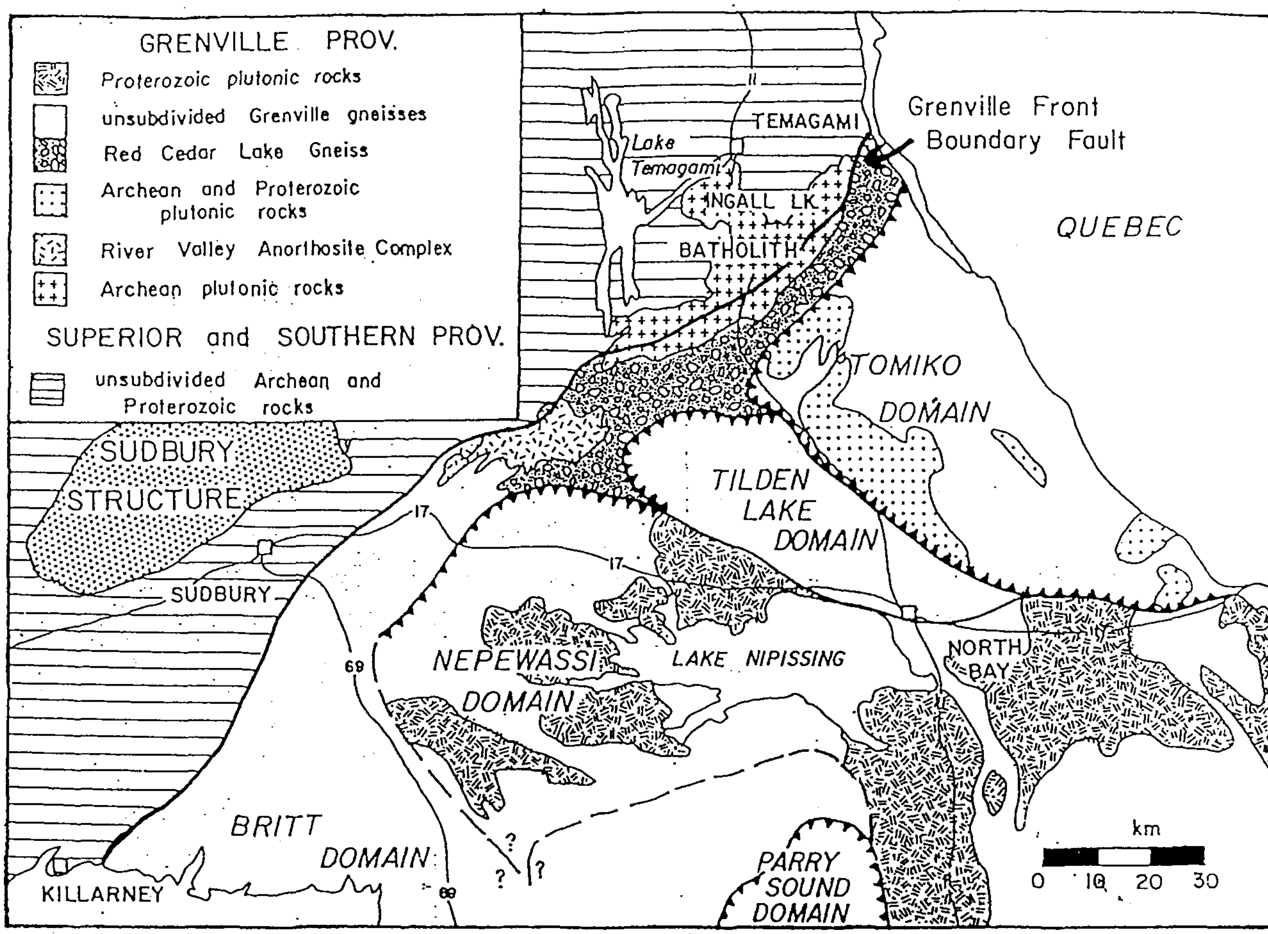
DISCUSSION AND CONCLUSIONS

6.1.0 Lithotectonic Domains in the North Bay Area

Following the work of Davidson (1986) in the Parry Sound area of Ontario, Easton (1989) has proposed three new lithotectonic domains for the North Bay area; moving from west to east these are, the Nepewassi, Tilden and Tomiko structural domains (Fig. 6.1). Lithotectonic domains are interpreted as Grenville thrust structures displaced both laterally and vertically northwest along inclined ductile shear zones during the Grenville Orogeny. They are generally bounded by shear zones and distinguished from one another by differences in lithology, internal structure, metamorphic grade, isotopic signature and geophysical signature (Davidson ,1986). Domains may be truly allocthonous, as in the separation of a fold nappe from its root, e.g., Parry Sound Domain, or comprise uniform packages of crust decoupled from one another due to differential thrusting in both a temporal and geometrical sense.

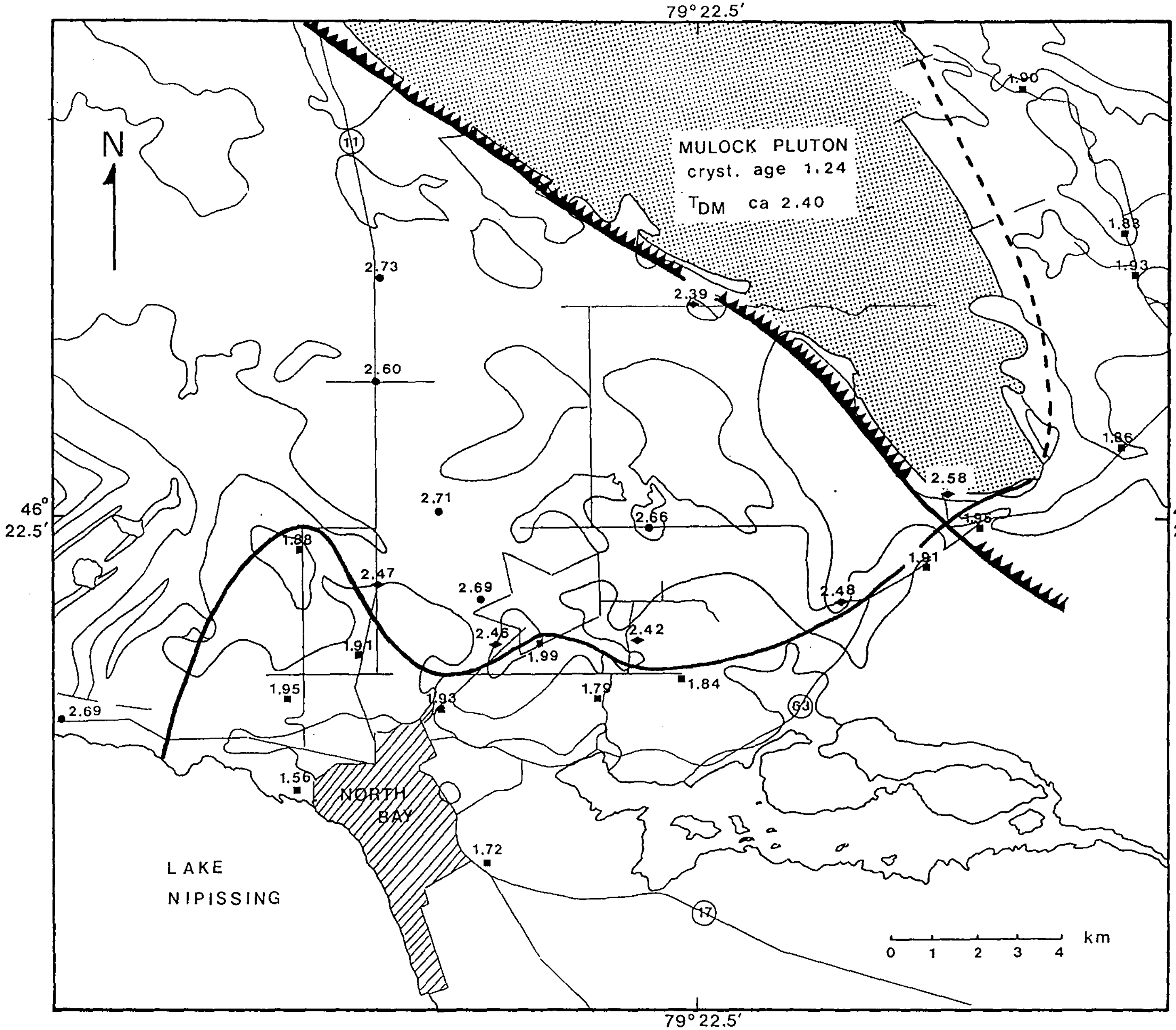
East of the city of North Bay the suture intersects the proposed Tilden-Tomiko Domain boundary southwest of the southern tip of the Mulock pluton (Fig. 6.2). Since the suture is the older structure it would be expected that differential thrusting of these domains (some 700-1000 Ma

Fig. 6.1 Tentative lithotectonic domain boundaries proposed by Easton (1989) for the North Bay area. (Fig. 43.2, Easton, 1989)



GRENVILLE PROV.
Proterozoic plutonic rocks
unsubdivided Grenville gneisses
Red Cedar Lake Gneiss
Archean and Proterozoic plutonic rocks
River Valley Anorthosite Complex
Archean plutonic rocks
SUPERIOR and SOUTHERN PROV.
unsubdivided Archean and Proterozoic rocks
TEMAGAMI
Lake Temagami
INGALL LK BATHOLITH
Grenville Front Boundary Fault
QUEBEC
TOMIKO DOMAIN
TILDEN LAKE DOMAIN
SUDBURY STRUCTURE
SUDBURY
NEPEWASSI DOMAIN
LAKE NIPISSING
NORTH BAY
BRITT DOMAIN
PARRY SOUND DOMAIN
KILLARNEY
km
0 10 20 30

Fig. 6.2 Map of the North Bay area highlighting the intersection of the Penokean aged suture with the proposed Grenville lithotectonic domain boundary of Easton (1989). Differential thrusting of the Tilden Domain relative to the Tomiko Domain should effect a significant offset of the trend of the suture, which is proposed to be the older structure. If Easton's boundary between the Tomiko and Tilden domain is accurately mapped, the domains are probably not significant Grenville structures, for the suture shows no displacement as it crosses the boundary. However interpretation is complicated as the suture is constrained to bend abruptly north as it rounds the Mulock pluton. Since access problems prohibited sampling the East margin of the Mulock pluton for Archean provenance material, nothing unequivocal about this domain boundary can be said until Archean provenance material is shown to be present or absent from the east margin of the Mulock, and, until the domain boundaries are more precisely defined.


79°22.5'
MULOCK PLUTON
cryst. age 1.24
T_{DM} ca 2.40
N
46°
22.5'
46°
22.5'
11
63
17
NORTH
BAY
LAKE
NIPISSING
2.73
2.60
2.71
2.39
2.66
2.58
1.90
1.88
1.93
1.86
1.96
1.91
1.88
2.47
2.69
2.48
2.46
1.99
2.42
1.91
1.95
1.93
1.79
1.84
2.69
1.56
1.72
0
1
2
3
4
km
79°22.5'

later) would result in a significant displacement of the suture across their boundaries. For the Tilden/Tomiko domain boundary this does not appear to be the case. Well defined Archean and Proterozoic ages straddle the proposed domain boundary without any apparent offset. However, the proximity of the intersection point to the nose of the Mulock pluton complicates the interpretation, for following the suture east it appears to swing around the pluton rather abruptly, where poor exposure of country rock gneisses along the east margin of the Mulock has prohibited adequate sampling of this important area for Archean aged terrane. Demonstrating the existence of Archean aged gneisses in this crucial area would indicate that Easton's domains are not significant Grenville structures. However, if contact with the Archean is terminated at the nose of the Mulock and can be shown to appear at some point further up the east margin of the Mulock this may signify an offset. Until Easton's domain boundaries are verified by better mapping, the question of lithotectonic domains in the North Bay area will remain unresolved. However, an important potential for unravelling Grenville tectonism through consideration of such cross-cutting relationships is demonstrated.

6.2.0 The Suture Zone

The full model age transition separating ca 2.70 Ga Archean provenance material from ca 1.90 Ga Proterozoic material is 800 Ma. However, the data presented here suggest that the suture may be better thought of as a 'suture zone' of typically a few km's to a few 10's of km's width which is characterized by a band of intermediate model aged metasediments. From the present data-set metasediments of intermediate age can be subdivided into two age groups (1) a 2.00-2.39 Ga group, and (2) a 2.40-2.60 Ga group.

The basis for this grouping is both geographical and lithological. In the North Bay area the suture is marked by a transition from gray biotite(hornblende) gneiss (ca 1.90 Ga) to biotite containing feldspathic gneiss (2.40-2.60 Ga). However, the model age quickly rises to ca 2.72 Ga and the lithology becomes a typical gray biotite gneiss within a few kilometers of the suture boundary which is taken at the 1.90/2.40-2.60 Ga transition. The the lithological contact marking the transition between feldspathic gneiss and gray biotite gneiss was not identified as part of this work.

In the Temiscaming area the suture is marked by transitions from gray biotite(hornblende) gneiss (ca 1.90 Ga) to muscovite-quartzofeldspathic gneiss (1.90-2.34 Ga) to feldspathic gneiss (2.53-2.75 Ga; CH3 and CH7 & CH11 respectively). Genetic relationships between restricted units of feldspathic gneiss, e.g., those from the North Bay area compared with those from the Temiscaming area, will require detailed thin section work and provenance studies with zircons to help establish if such a realtionship exists. However, it is instructive to note that model ages ranging from old Archean at 2.75 Ga down to intermediate ages as low as 2.39 Ga characterize this lithological type.

2.40-2.60 Ga:

The most continuous exposure of this group of intermediate aged gneiss occurs immediately northeast of the city of North Bay where the transition from ca 1.90 Ga gneiss involves a 2.40-2.60 Ga step of a few kilometers width before encountering typical Archean gneisses of ca 2.72 Ga. In the Temiscaming area, west of the Ottawa River one Archean sample of feldspathic gneiss with a Nd model age of 2.53 Ga was recovered suggesting that ages between 2.40 and 2.60 Ga are encountered further east. However, a large area of no exposure (Fig. 5.2) limited recovery of Archean provenance samples to just one. Within the bounds of the field area east of the Ottawa River (Fig. 5.2) no samples with model ages in this range were recovered but unpublished data for samples further east into Quebec indicate that gneisses with model ages falling into this group exist (Guo, unpublished data).

2.00-2.39 Ga:

The 2.00-2.39 Byr group of intermediate ages is also coincident with the suture boundary. Gneisses with model ages falling in this group are absent in the North Bay area but well represented in the Temiscaming area where the lithology is a pink/white muscovitic and quartzose gneiss with lenses of a more feldspathic gneiss together intercalated with gray biotite(hornblende) gneiss. In general, the muscovite-quartzofeldspathic and gray biotite(hornblende) gneisses represent part of Lumber's (1971) miogeoclinal and eugeoclinal facies respectively. The range of model age for the muscovite-quartzofeldspathic gneiss is from 1.90-2.34 Ga and for those lenses of gray biotite(hornblende) gneiss that are clearly similar in lithology to gneisses further south i.e., in the North Bay area, the model age is always <2.00 Ga (CH1, NB43, CH15, NB32). Although Fig. 5.2 discriminates between the two lithologies (after Card & Lumbers 1974-75; OGS Map 2361) rocks that appear to be mixtures between the two are present; an observation which is supported by the range of model ages such rocks display.

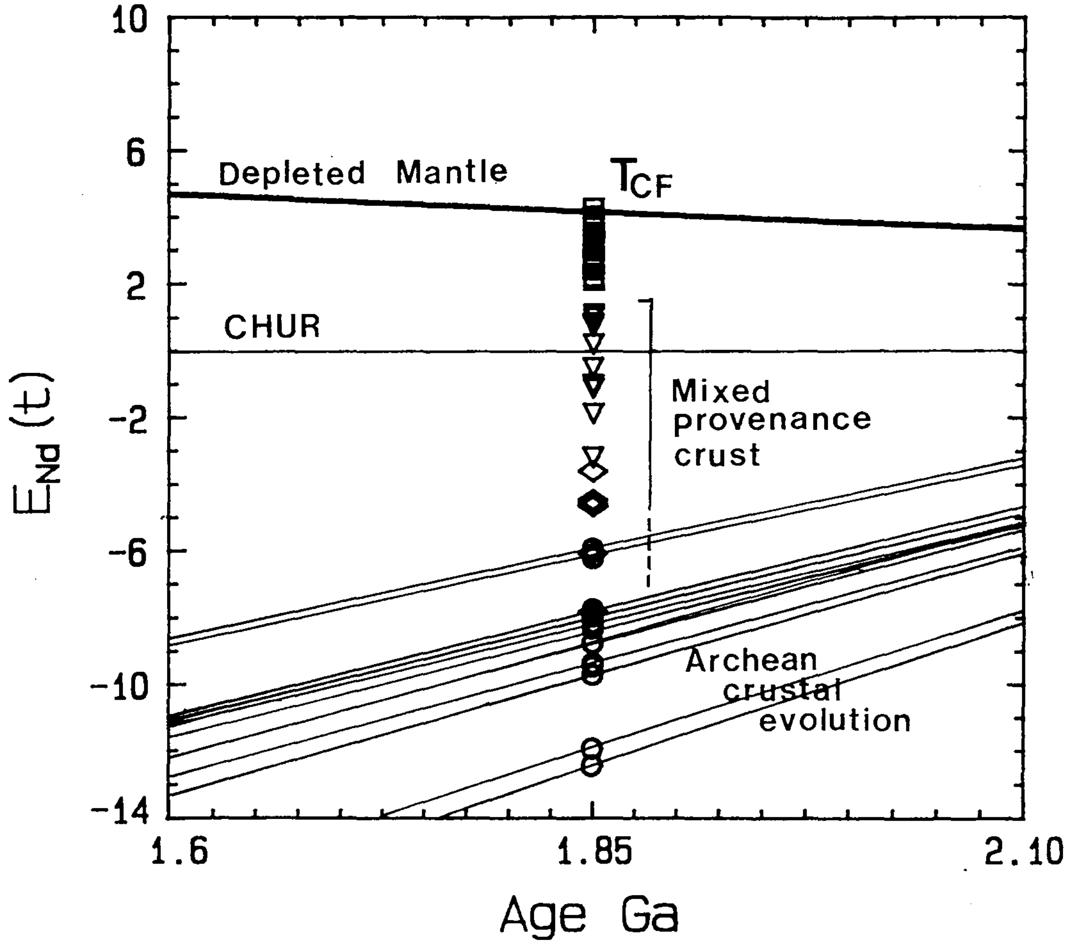
For the suture as a whole, these groupings of intermediate ages are provisional, having been based on the model age distribution with respect to lithology in the North Bay-Temiscaming area and outlined here to provide a basis for further study. It may be that such a delineation is not warranted and that gneisses of intermediate model age are genetically related and together span the entire 2.00-2.60 Ga range. However, because the groups as outlined do not appear together in one location it is premature, lacking direct evidence, to suggest that a more or less complete belt of intermediate ages spans the entire 800 Ma model age transition. What is clear however is that upon closer inspection the 800 Ma age transition from 1.90-2.70 Ga crust is negotiated in one or more steps which may be discrete (as above) or relatively continuous. If continuous, such apparent groupings of intermediate ages may be of local significance only; from a larger perspective the suture zone may be a relatively continuous belt of mature miogeoclinal-type metasediments.

Presently, where a clear 1.90-2.70 Ga transition does not occur, the suture is drawn along the northerly extent of the 2.00-2.39 Ga group or the most southerly extent of the 2.40-2.60 Ga group.

6.2.1 The Suture Zone and Mixed Provenance Ages

The Nd model age of a sample represents a unique crustal extraction age only if the criteria outlined in section 3.1.0 are met. The only way to ensure that the ratio of Sm/Nd in a sample has not been altered during intracrustal evolution is to compare the model age to well -documented orogenic events in Earth history, particulary those orogenies that added a significant amount of new crustal material to the continents. The episodic nature of continental crust formation normally makes interpretation of Nd model ages fairly straight forward. For example, geochronometers show

Fig. **6.3** Plot of E_{Nd} against Time showing evolution of the depleted mantle and Archean crust. Values of $E_{Nd}(t)$, where t=1.85 Ga, were calculated for all samples. It is readily seen how the intermediate aged samples can be modelled as mixtures of ca 1.90 Ga depleted mantle and 2.70 Ga Archean crust. Symbols are as follows: squares, ca 1.90 Ga; inverted triangles, 2.00-2.39 Ga; diamonds, 2.40-2.60 Ga and circles, ca 2.70 Ga.



Depleted Mantle
T_{CF}
CHUR
Mixed provenance crust
Archean crustal evolution
E_{Nd} (t)
Age Ga
10
6
2
-2
-6
-10
-14
1.6
1.85
2.10

a relative quiescence of tectonic activity between ca 2.70 Ga and 1.90 Ga, i.e., between the Kenoran and Penokean orogenies respectively. Both of these orogenies effected the transfer of large amounts of mantle- derived material to the continental crust with only minor additions in between. Hence the vast majority of continental crust spanning this time range has a Nd model age of one, or, the other end-member.

Samples with Nd model ages that do not correspond to crust-forming episodes must have had their original ratio of Sm/Nd altered during intracrustal differentiation or by mixing between endmembers with different model ages. Such samples are referred to as being of mixed provenance for their intermediate model age is a result of mixing between two crustal provinces. Figure 6.3 shows pictorially how the E_{Nd} of a mixed provenance sample can be accounted for by mixing, in this case, ca 2.70 Ga Archean crust and 1.85 Ga depleted mantle.

6.2.2 The Character of Archean Provenance Crust and models for the origin of the 2.40-2.60 Ga crust:

In the French River area, north of the suture, crust with Archean model ages between 2.34 and 2.78 Ga are outcropped along a traverse following Hw. 69 north from the suture to the Grenville Front (Dickin & McNutt, 1989). There appears to be no increase in model age with distance from the suture towards the Grenville Front, in fact, the distribution of Archean model ages in this area is decidedly heterogeneous. Dickin et al. (1990) isolated 3 possible mechanisms to account for the model age data, (1) sedimentological mixing between ca 2.70 Ga Archean provenance crust and 2.40 Ga Huronian volcanics (2) tectonic mixing between older crustal sources and 1.7 Ga juvenile material, or (3) sedimentological mixing between 2.70 and 1.90 Ga provenance material.

The heterogeneity of model ages characterizing the Archean crust north of French River is contrasted by the apparent 2.72 Ga homogeneity of Archean crust north of the suture in the North Bay-Temiscaming area. Intermediate aged crust (2.40-2.60 Ga) in the North Bay-Temiscaming area is restricted to a zone a few kilometers wide north of the suture boundary after which the model age of the crust rises quickly to ca 2.72 Ga (Fig. 5.3). Although intermediate ages within the belt of Archean crust in the French River area overlap with intermediate ages in the North Bay-Temiscaming area, they may not be genetically related, e.g., admixtures of Huronian volcanics and Kilarnian crust with ca 2.70 Ga Archean crust may be responsible for the heterogeneity in model ages north of French River, but there is no evidence of either Huronian or Kilarnian crust in the Archean terrane of the North Bay-Temiscaming area. In addition, the 2.40-2.60 Ga crust in the North Bay-Temiscaming area, unlike similar aged terrane in the French River area, is coincident with the suture and confined to a few kilometers width.

With respect to model ages the character of the belt of Archean crust north of the suture and south of the GF, from Georgian Bay to the Ottawa River, changes from heterogeneous in the west to relatively homogeneous in the east. The dominance of old Archean crust (ca 2.72 Ga) north of the suture in the North Bay-Temiscaming area may be related to a parautocthonous segment of the Archean craton 'proper' exposed within the Grenville Province, south of the Grenville Front (GF) and north of the field area.

It has been proposed that the metagraywackes of the Pontiac group, exposed north of the field area on the northern margin of the GF, are genetically related to the compositionally similar Red Cedar Lake gneiss exposed along the south margin of the GF (Rive, 1976a; Davidson, 1979). Hence, the Red Cedar Lake gneiss may represent an exhumed parautochtonous crustal section of the Archean craton still anchored to the Pontiac Group which remains in situ on the northern margin of the Grenville Front.

Recent work by Krogh (1989) supports the existence of an in situ cratonal segment of Archean age south of the GF and north of the North Bay-Temiscaming field area. In one study a pegmatite cutting through a major agglomerate unit (Red Cedar Lake Gneiss?) 16 Km south of the GF and north of the city of North Bay yields a monazite age of 2642 +/- 2.4 Ma. By the principle of cross-cutting relationships the agglomerate unit is constrained to be older making the Red

Cedar Lake Gneiss an Archean deposit. In another study northwest of the city of North Bay, about 22 Km south of the GF near Hagar, a tonalite gneiss has a zircon age of 2737 Ma (Krogh, 1989).

The Red Cedar Lake gneiss has not been previously recognized south of the Grenville Front Tectonic Zone (GFTZ), however, this work, and the work by Dickin et al. (1989) for the North Bay-Temiscaming area, suggests that the homogeneous 2.72 Ga belt of model ages between the GFTZ and the suture may be part of, or, derived from a parautocthonous Archean segment extending into the Grenville Province perhaps as far south as the suture boundary. Further work is needed to distinguish between Archean terrane that is 'in situ', that is, deposited or emplaced ca 2.70 Ga, from terrane derived thereof but deposited later during Proterozoic time. Some of this material may have been uplifted and redeposited in the Penokean as a result of collision with the island arc (Fig. 6.5). An easy check on this hypothesis would be to analyze Archean crust close to the suture for 1.90 Ga zircons, particularly intermediate aged crust with model ages between 2.40 and 2.60 Ga. Summarizing, in the North Bay-Temiscaming area Archean provenance crust between the suture and the GFTZ may be part of an in situ segment of the Archean craton represented in part by the Pontiac Group and Red Cedar Lake gneiss and deposited in late Archean time.

Zircon studies of the Archean intermediate-aged crust are needed to define crustal endmembers and constrain mixing models, e.g., for the 2.40-2.60 Ga gneisses sampled along the suture near the city North Bay (Fig. 5.3) a lack of zircons with U-Pb or Pb-Pb ages of ca 1.90 Ga would suggest that sedimentological mixing between 2.70 and 1.90 Ga provenance material is not a viable mixing model to account for these intermediate model ages. Hence some other mechanism would be needed to account for their intermediate ages.

6.2.3 The Suture Zone and 2.00-2.39 Ga Mixed Provenance Ages:

In the Temiscaming area, as noted earlier, the suture is marked along its length by the presence of a band of muscovite-quartzofeldspathic gneiss (white in Fig.5.2) intercalated with biotite-amphibole gneiss (gray in Fig. 5.2). The muscovite-quartzofeldspathic gneiss has a range of model age from 1.90-2.34 Ga, suggesting that some of these metasediments are of mixed provenance. A mixed provenance hypothesis involving 1.90 and 2.70 Ga material is more certain than for the 2.40-2.60 Ga group because (1) geochronometers show an absence of mantle-derived material with ages between 2.00 and 2.39 Ga (2) Muscovite-quartzofeldspathic gneiss (1.90-2.34 Ga) is interlayered with gray biotite(hornblende) gneiss (<1.98 Ga) suggesting basinal sedimentation from at least two distinct sources and, (3) the 2.00-2.39 Ga age group is far more voluminous, requiring a formational mechanism of some significance.

Therefore, it is proposed that a genetic link exists between tectonic processes operative in suturing the Proterozoic island arc to the Archean foreland and the mixed provenance metasediments with model ages between 2.00-2.39 Ga.

6.3.0 The Mixing Model:

It is proposed that the 2.00-2.39 Ga group of intermediate ages represents sediments formed by mixing between ca 2.70 and ca 1.90 Ga provenance material in a foreland basin formed in response to suturing of the island arc to the Archean foreland (Fig. 6.4). The island arc, rafted in over south-dipping subduction, overrode the edge of the Superior craton which was itself depressed in response to a failed subduction. Depressing the cratonal edge created a foreland basin which was fed by both Archean and Proterozoic source sediments. Mixing between arc sediments and sediments derived in some manner from the Archean foreland are responsible for the 2.00-2.39 Ga group and perhaps as well for the 2.40-2.60 group of intermediate aged metasediments.

Based on the evidence in hand, details concerning the collision and subsequent formation of the foreland basin are conjectural; the important result is that mixed provenance model ages comprising the suture zone require a basin more or less coincident with the edge of the ancient craton to accumulate sediments of mixed provenance. That the suture zone is largely composed of metasediments with a miogeoclinal affinity is coherent with the foreland basin model. Sea level changes in the foreland basin, particularly surrounding formation and destruction of the basin, can account for the maturity of the muscovite-quartzofeldspathic metasediments. These mature sediments display a range of model age from 1.90 Ga to 2.34 Ga, suggesting that input to the basin from an Archean source was variable. Lenses of intercalated gray biotite(hornblende) gneiss with model ages <2.00 Ga may represent a deeper water (eugeoclinal) facies and suggest that a link existed between Archean input to the basin and basinal tectonics. The miogeoclinal persuasion of the 2.40-2.60 Ga feldspathic gneiss exposed along the suture, particularly as represented in the North Bay area supports their inclusion as deposits in the foreland setting.

The major element data support a dynamic depositionary environment in the foreland basin. Figure 6.5 shows two plots relating model age of the sample to (1) wt.% SiO_2 and (2) the ratio of Al_2O_3/SiO_2, both similar representations of the degree of reworking. The clumping of data distributed along the ordinate is an artifact of grouping the data according to model age. A wide range in the distribution of data along the abscissa is suggestive of a large variation in the degree of reworking, particulary where the data is skewed towards high wt.% SiO_2 or low ratios of Al_2O_3/SiO_2. The Archean data in both plots are abruptly truncated at an Al_2O_3/SiO_2 ratio of

Fig. 6.4 Cartoon displaying collision of a 1.90 Ga old island arc with the edge of the Superior craton: (A) shows the edge of the Superior craton with schematic representation of the Pontiac Group; understood to include the Red Cedar Lake gneiss and the rest of the belt of Archean crust with model ages of ca 2.72 Ga exposed north of the suture in the North Bay-Temiscaming area (B) shows the island arc being rafted in towards the Archean craton over south dipping subduction and tectonizing the Archean foreland (C) shows development of the foreland basin, failed subduction of the cratonal margin and deposition of mixed provenance sediments (D) collision is terminated: the suture is characterized by a zone of mixed provenance crust.

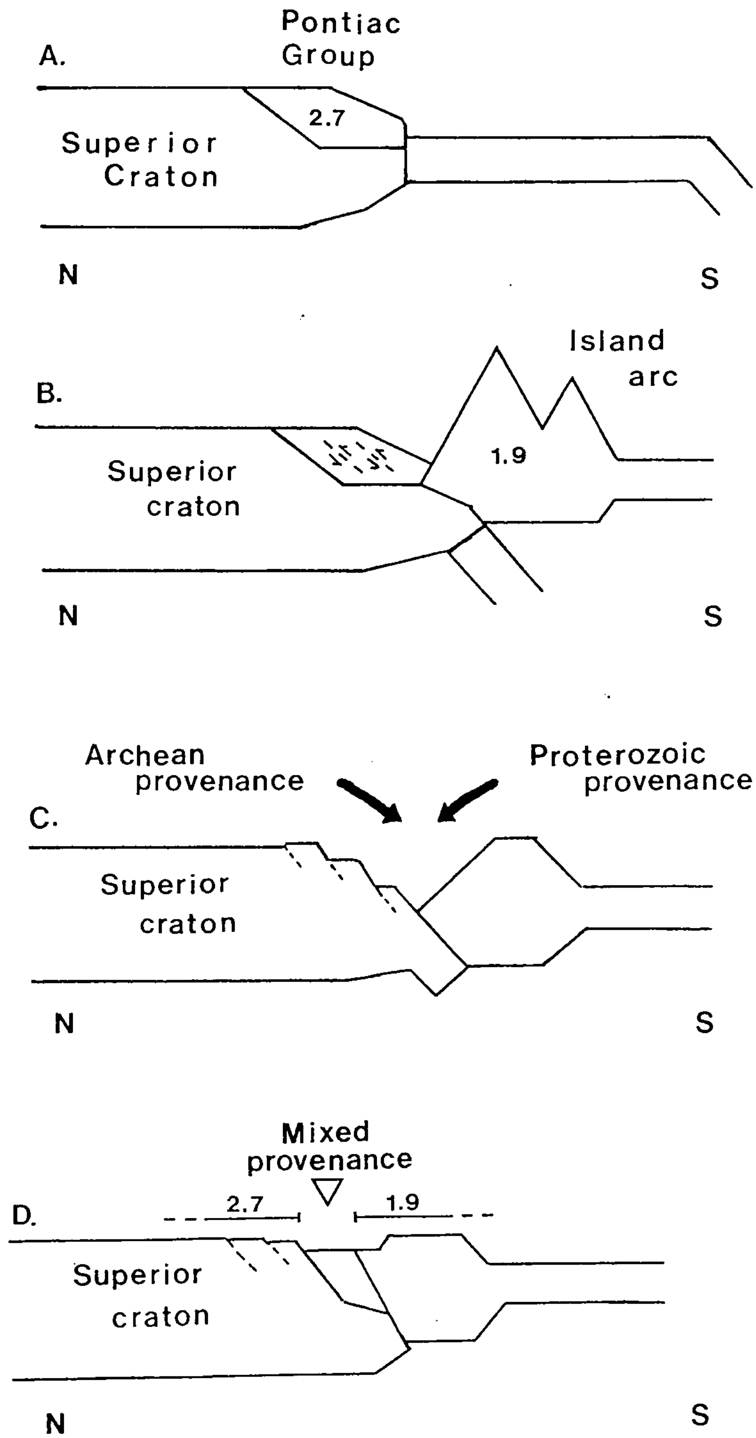
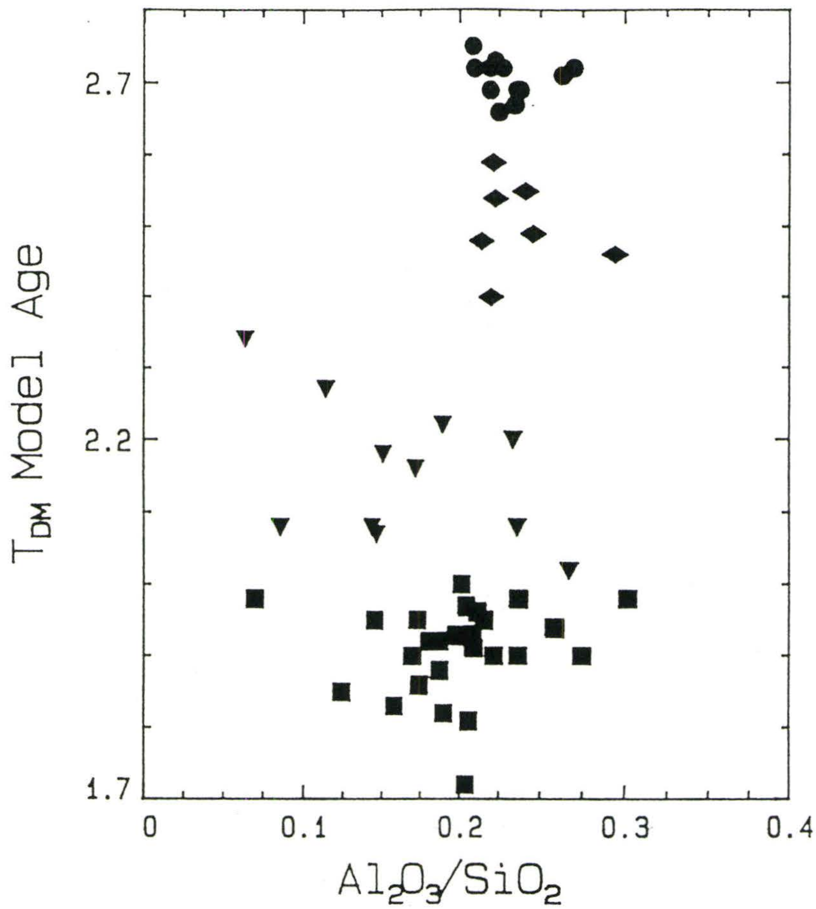
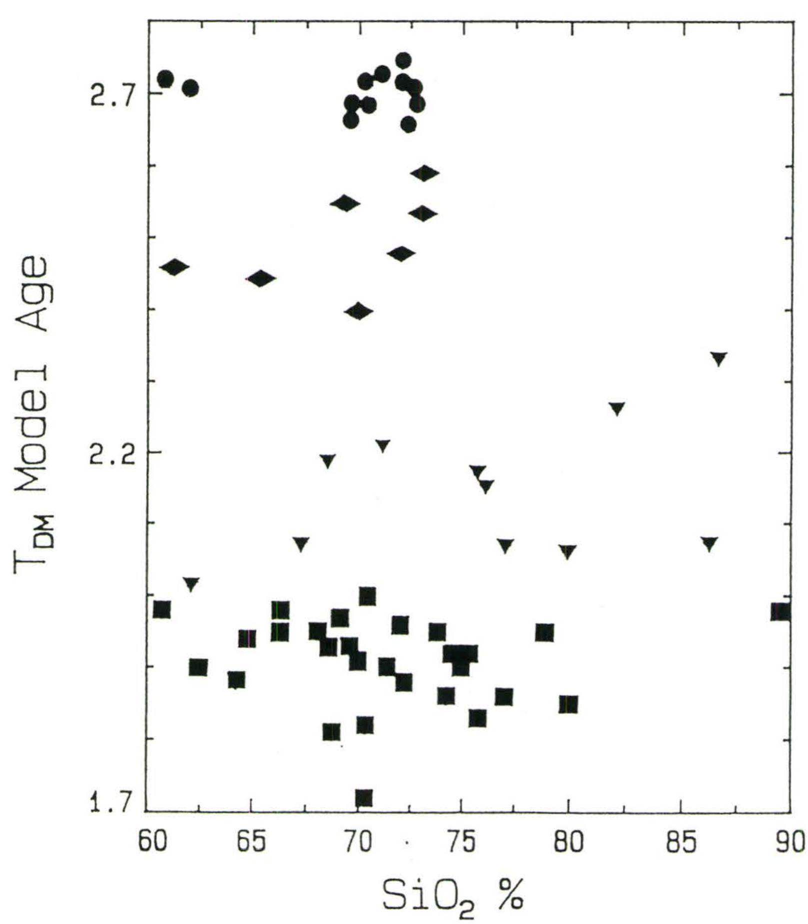

A.
Pontiac Group
2.7
Superior Craton
N
S
B.
Island arc
1.9
Superior craton
N
S
C.
Archean provenance
Proterozoic provenance
Superior craton
N
S
D.
Mixed provenance
2.7
1.9
Superior craton
N
S

Fig. 6.5 T_{DM} model age is plotted against both the wt.% SiO_2 and the ratio of Al_2O_3/SiO_2 to discriminate between degrees of sedimentary reworking. Archean aged metasediments are truncated abruptly at an Al_2O_3/SiO_2 ratio of 0.2 and a wt.% SiO_2 of about 72. This is evidence that the Archean sediments were deposited within a uniform sedimentary regime. Contrasted with the Archean metasediments, the Proterozoic aged metasediments show a wide range in their degree of reworking. This is consistent with deposition of Proterozoic and intermediate aged metasediments in the more dynamic foreland basin environment (Symbols as in Fig. 6.3).



T_{DM} Model Age
2.7
2.2
1.7
0
0.1
0.2
0.3
0.4
Al_2O_3/SiO_2



T_{DM} Model Age
2.7
2.2
1.7
60
65
70
75
80
85
90
SiO_2 %

about 0.21 and a wt. % SiO_2 of about 72%. This suggests that the Archean metasediments were eroded and deposited under a uniform sedimentary regime. Note that the 2.40-2.60 Ga (diamonds) group of gneisses appears to follow the older Archean (circles) gneisses with respect to their degree of reworking. If this group represents a foreland basin assemblage it consists mostly of Archean provenance sediments with a measure or two Proterozoic derived material to support the lower model age. With respect to the geometry of the foreland basin such sediments might characterize deposits closer to the northern shore of the basin and/or represent pockets within the basin of Archean source dominated sedimentation. Contrasting the Archean or near Archean metasediments, metasediments with Proterozoic and mixed provenance ages show a wide range in their degree of reworking which is consistent with deposition in a relatively shallow water foreland basin.

6.4.0 Conclusions

Nd model age mapping in the North Bay area of Ontario supports the proposal by Dickin & McNutt (1989) that the model age transition represent a collisional suture formed by the termination of south-dipping subduction 1.90 Ga as a Penokean aged island arc was accreted to the Archean foreland. This model is in agreement with tectonic models proposed for the Penokean Foldbelt (Cambray, 1978; Sims, 1983; Schulz,1987b;

Hoffman,1988) in Wisconsin and Northern Michigan and also in agreement with the allocthonous terrane invoked by Zolnai et al. (1984) to account for folding of the Huronian further west. The Penokean Orogeny and its equivalents in Europe constitute a global event and the first major vehicle for new crustal additions to the Laurentian margin ca 1.90 Ga. Much of this new material seems to have been accreted in the form of island arcs.

The suture is very well defined in the North Bay area and south of the town of Temiscaming. There is no place within the study area where it is not possible to draw a line, clearly separating Proterozoic from Archean Provenance crust.

In the North Bay-Temiscaming area the full model age transition from ca 1.90 Ga to ca 2.70 Ga is negotiated in stepwise fashion through crust of intermediate model age which constitutes the 'suture zone'. In the North Bay-Temiscaming area the suture zone consists of two packages of intermediate aged crust separated along strike of the suture; the 2.40-2.60 Ga group in the North Bay area and the 2.00-2.39 Ga group in the Temiscaming area. Until zircon studies are performed, the relationship between groups of lithologically distinct intermediate aged metasediments remains equivocal, therfore, it is deemed better that the groups are maintained as a basis for further study. However, it is suggested that the overall character of the suture zone is that of a more or less continuous band of intermediate aged crust with a miogeoclinal affinity spanning the entire range of model ages between 1.90 and 2.70 Ga. In principle the foreland basin mixing model is perfectly compatible with such an hypothesis.

That the model age transition is correlated with metasediments whose model age signature can be easily understood in terms of mixing between 2.70 and 1.90 Ga crust constitutes strong evidence for a suture as an explanation of the model age transition. If the model age transition remains correlated with the 2.00-2.39 Ga band of muscovite-quartzofeldspathic gneiss further east into Quebec, interpretation of the suture as a major Grenville imbrication seems still more unlikely. Although this work supports the contention that the suture is not a Grenville thrust structure, this does not preclude Grenville tectonism shaping its present exposure or of effecting significant offsets along its length. In fact truncation of the suture and displacement to the north would go a long way in support of the 'suture hypothesis' particularly if the 2.00-2.39 Ga band of mixed provenance metasediments is present and also displaced by the same amount.

To the north of the field area a parautocthonous segment of Archean crust extends into the Grenville Province, anchored by the in situ Pontiac Group on the northern margin of the Grenville Front and consisting in part of the Red Cedar Lake gneiss south of the Grenville Front. In the North Bay-Temiscaming area the ca 2.72 Ga model age homogeneity of

Archean gneisses north of the suture and south of the Grenville Front Tectonic Zone suggest that this belt of Archean crust may be part of, or, derived from the parautocthonous segment. If this is true, it should be possible to map within the Grenville Province the boundary of this parautocthonous segment by Nd isotopic mapping.

Finally, a systematic age study of zircon populations within the mixed provenance metasediments is the crucial test of the proposed mixing model and suture hypothesis.

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APPENDIX

MAJOR AND SELECTED TRACE ELEMENTS

	CH0	CH7	CH11	CH19	CH22	CH26	CH44	NB6
SIO2	75.58	72.54	72.14	68.75	61.90	65.07	72.92	66.31
TIO2	0.29	0.16	0.21	0.45	0.58	0.45	0.17	0.62
AL2O3	11.40	15.20	15.05	14.17	17.93	16.00	16.14	15.71
FE2O3	3.22	1.46	1.68	5.37	5.38	6.74	1.47	6.04
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.02	0.01	0.01	0.09	0.08	0.05	0.02	0.10
MGO	0.09	0.29	0.65	0.10	1.86	2.04	0.36	0.22
CAO	0.68	1.07	1.20	1.42	3.97	4.01	2.64	1.95
NA2O	3.24	3.19	3.29	3.87	4.79	4.02	4.81	3.62
K2O	5.35	5.55	5.46	5.51	2.75	1.14	1.03	5.17
H2O+	0.12	0.47	0.23	0.26	0.48	0.34	0.37	0.18
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.01	0.06	0.08	0.01	0.28	0.14	0.07	0.08
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Rb	102.10	154	144	65.40	66.20	39.30	23.50	74.10
Sr	15.40	221	552	50.80	728	275	624	154
Y	56.30	13.10	9.90	42.40	12.60	9.60	1.20	32.30
Zr	526	193	258	640	217	158	214	593
Nb	39.40	14.60	14.90	36.80	14.20	14.20	12.60	26.90
AL/SI	.15083	.20954	.20862	.20611	.28966	.24589	.22134	.23692

	NB11	NB12	NB14	NB15	NB17	NB20	NB22	NB26
SIO2	69.79	69.53	69.00	70.47	69.86	68.06	72.17	75.73
TIO2	0.24	0.49	0.46	0.20	0.38	0.46	0.36	0.20
AL2O3	16.48	13.75	16.64	16.77	15.38	14.69	13.53	11.99
FE2O3	2.41	5.43	2.79	2.17	4.77	4.88	4.18	2.70
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.01	0.08	0.07	0.01	0.01	0.09	0.06	0.01
MGO	0.83	0.36	0.71	0.79	0.61	0.29	0.01	0.03
CAO	1.93	1.35	1.82	2.49	2.55	1.46	0.96	0.45
NA2O	3.86	3.67	4.24	5.29	4.58	3.98	3.39	3.51
K2O	3.81	5.10	3.90	1.42	1.52	5.13	5.12	5.06
H2O+	0.49	0.19	0.26	0.31	0.21	0.91	0.21	0.31
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.15	0.05	0.11	0.08	0.13	0.05	0.01	0.01
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Rb	101.90	111	85.20	36.30	31.30	76.00	113	173
Sr	498	53.40	356	571	451	121	25.10	15.60
Y	5.70	56.30	17.40	.50000	21.20	36.90	59.40	49.60
Zr	225	561	262	210	526	511	517	463
Nb	13.70	35.70	15.60	10.40	15.20	30.60	38.60	34.80
AL/SI	.23614	.19776	.24116	.23797	.22015	.21584	.18747	.15833

	CH29	CH28	NB19	CH41	CH4	CH17	CH15	CH3
SIO2	71.88	68.54	74.56	70.43	71.19	61.97	70.32	72.80
TIO2	0.37	0.64	0.21	0.47	0.42	0.72	0.44	0.15
AL2O3	15.39	14.31	13.46	14.19	13.47	16.56	13.36	16.22
FE2O3	2.06	5.72	2.22	4.60	4.38	6.10	5.13	1.45
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.01	0.10	0.02	0.07	0.08	0.07	0.07	0.01
MGO	0.11	0.31	0.08	0.13	0.15	1.82	0.02	0.40
CAO	1.12	2.21	0.67	1.41	1.09	4.10	1.41	1.66
NA2O	3.60	2.90	3.45	3.18	3.42	3.95	3.44	4.40
K2O	5.13	4.44	5.22	5.38	5.15	2.92	5.20	2.55
H2O+	0.30	0.70	0.10	0.10	0.60	1.40	0.60	0.30
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.03	0.13	0.01	0.04	0.05	0.39	0.01	0.06
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Rb	99.70	70.00	96.10	89.50	107.90	79.10	120	92.70
Sr	160	173	53.40	144	83.80	504	58.10	309
Y	14.00	42.10	22.70	38.00	13.60	16.40	48.70	3.10
Zr	238	479	222	507	113	214	583	141
Nb	14.40	27.30	23.90	27.70	16.00	14.60	36.70	11.90
AL/SI	.21411	.20878	.18053	.20148	.18921	.26723	.18999	.22280

	CH14	CH51	CH46	CH10	NB38	MR23.3	MR35.2	MR56.6
SIO2	69.96	74.98	73.82	79.82	78.88	72.06	70.37	71.07
TIO2	0.40	0.25	0.31	0.17	0.16	0.15	0.27	0.21
AL2O3	14.65	12.79	12.78	11.69	11.46	15.82	16.01	15.83
FE2O3	4.63	2.91	3.73	1.27	1.95	1.72	2.73	1.97
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.07	0.01	0.02	0.01	0.01	nd	0.06	0.21
MGO	0.12	0.11	0.08	0.09	0.17	0.63	0.78	0.51
CAO	1.36	0.20	0.68	0.32	0.97	2.32	2.60	2.28
NA2O	3.55	3.33	3.37	2.09	1.86	3.89	5.03	5.25
K2O	5.11	4.71	5.01	4.12	3.78	2.97	1.70	1.69
H2O+	0.10	0.70	0.20	0.40	0.70	0.35	0.33	1.08
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.05	0.01	nd	0.02	0.06	0.08	0.12	0.07
TOTAL	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.17
Rb	142	129	112	116	96.10	88.30	45.70	42.10
Sr	124	11.90	15.00	131	226	3054	610	534
Y	64.40	47.30	52.90	18.70	15.10	5.80	9.80	2.00
Zr	470	526	548	179	138	3.00	97.60	91.00
Nb	43.00	38.10	33.30	17.00	17.90	9.20	11.30	7.50
AL/SI	.20941	.17058	.17312	.14645	.14528	.21954	.22751	.22274

	NB32	NB33	NB36	NB37	NB40	NB43	NB45A	NB13a
SIO2	69.12	71.40	86.24	68.28	89.50	60.70	76.19	74.23
TIO2	0.63	0.43	0.11	0.57	0.10	0.63	0.33	0.23
AL2O3	14.13	15.85	7.37	15.95	6.24	18.33	13.11	12.96
FE2O3	4.86	2.76	1.34	4.28	0.71	5.93	2.06	3.39
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.06	0.05	0.06	0.06	0.01	0.10	0.01	0.03
MGO	0.61	0.30	0.22	1.19	0.35	1.42	0.52	0.02
CAO	1.95	0.62	1.53	2.58	0.02	2.74	0.98	0.73
NA2O	3.00	1.98	1.89	3.95	0.26	4.99	2.17	3.27
K2O	4.80	5.56	0.51	2.23	1.93	4.22	3.48	4.94
H2O+	0.69	1.01	0.69	0.70	0.87	0.81	1.10	0.20
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.15	0.04	0.04	0.21	0.01	0.13	0.05	nd
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Rb	137	140	3.70	53.40	59.70	119	73.70	86.30
Sr	188	149	114	590	19.40	217	273	52.60
Y	36.70	17.20	14.80	18.40	7.20	30.30	17.10	60.10
Zr	300	251	209	261	219	229	239	506
Nb	26.50	17.30	15.40	17.40	13.80	17.20	17.30	39.00
AL/SI	.20443	.22199	.08546	.23360	.06972	.30198	.17207	.17459

	CH2	CH1	MR71.2	MR155.	NB13b	NB0	NB9	NB29
SIO2	75.37	64.78	70.37	62.41	72.28	72.74	61.94	72.04
TIO2	0.35	0.54	0.51	0.71	0.15	0.20	1.04	0.33
AL2O3	14.13	16.76	14.34	17.15	16.46	15.97	16.31	15.26
FE2O3	1.82	4.78	3.22	5.44	2.01	2.02	6.28	2.50
FEO	nd	nd	nd	nd	nd	nd	nd	nd
MNO	0.01	0.09	0.04	0.12	0.02	0.01	0.06	0.06
MGO	0.32	1.76	1.06	1.81	0.56	0.39	1.99	0.66
CAO	0.78	3.38	1.39	4.30	2.37	2.53	2.99	1.69
NA2O	3.77	3.47	2.50	3.93	4.39	3.98	3.53	3.49
K2O	3.11	3.75	5.38	3.39	1.39	1.89	4.62	3.45
H2O+	0.30	0.50	1.11	0.49	0.30	0.20	0.80	0.47
H2O-	nd	nd	nd	nd	nd	nd	nd	nd
P2O5	0.04	0.19	0.06	0.25	0.07	0.07	0.44	0.05
TOTAL	100.00	100.00	99.98	100.00	100.00	100.00	100.00	100.00
Rb	96.10	121	147	85.70	35.80	64.50	93.60	85.20
Sr	159	419	223	518	551	345	578	309
Y	37.10	28.50	58.60	31.70	3.00	6.80	26.40	26.80
Zr	309	175	337	341	139	138	567	306
Nb	23.30	19.40	15.30	9.40	12.60	14.80	22.60	22.30
AL/SI	.18748	.25872	.20378	.27480	.22773	.21955	.26332	.21183

	NB28	NB8
SIO2	82.06	64.21
TIO2	0.32	0.71
AL2O3	9.35	15.21
FE2O3	2.30	7.57
FEO	nd	nd
MNO	0.05	0.16
MGO	0.64	0.40
CAO	1.00	2.30
NA2O	1.83	3.95
K2O	1.94	5.06
H2O+	0.48	0.31
H2O-	nd	nd
P2O5	0.03	0.12
TOTAL	100.00	100.00
Rb	50.00	133
Sr	172	168
Y	14.70	74.20
Zr	249	627
Nb	17.10	49.10
AL/SI	.11394	.23688