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Compilation of Sm-Nd Isotope Analyses of Igneous Suites, Western Churchill Province

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2010

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Peterson, T.D. Pehrsson, S., Skulski, T., Sandeman, H. 2010. Compilation of Sm-Nd Isotope Analyses of Igneous Suites, Western Churchill Province; Geological Survey of Canada, Open File 6439.

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Compilation of Sm-Nd Isotope Analyses of Igneous Suites, Western Churchill Province

Abstract

A compilation has been made of 523 analyses of Sm-Nd isotope ratios of intrusive and extrusive rocks, and presumed orthogneisses, within the western Churchill Province. The data indicate that the region is dominated by juvenile crust extracted from the upper mantle at 2.7-2.8 Ga, emplaced over older crustal domains with extraction ages clustering at 2.9-3.1 Ga, 3.3 Ga, and possibly 3.5-3.6 Ga. Despite extensive Proterozoic igneous activity within the region, there is very little evidence for emplacement of juvenile magmas younger than 2.6 Ga.

Introduction

The table (CSV format) of 523 Sm-Nd isotope analyses accompanying this report (Fig. 1) was compiled primarily as an aid to identifying and characterizing crustal blocks within a portion of the Western Churchill Province (WCP) (Fig. 2), and to constraining tectonic models for their assembly. It only contains data for intrusive and extrusive igneous rocks, and pre-2.8 Ga rocks interpreted as orthogneisses. Such rocks will typically be sourced from older rocks immediately around or beneath

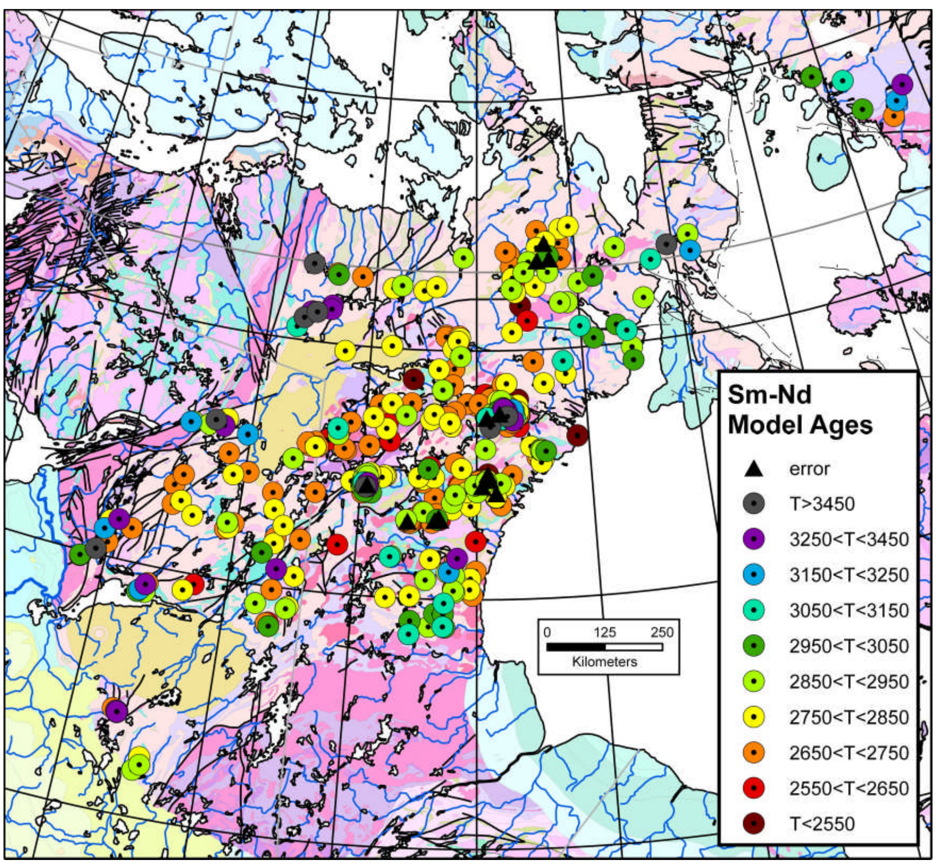


Figure 1. *Locations of all Sm-Nd analyses in the database. Model ages in millions of years. 'Error' indicates model ages older than 3.45 Ga, or which cannot be calculated. The base geology map is that of Wheeler et al. (1996).*

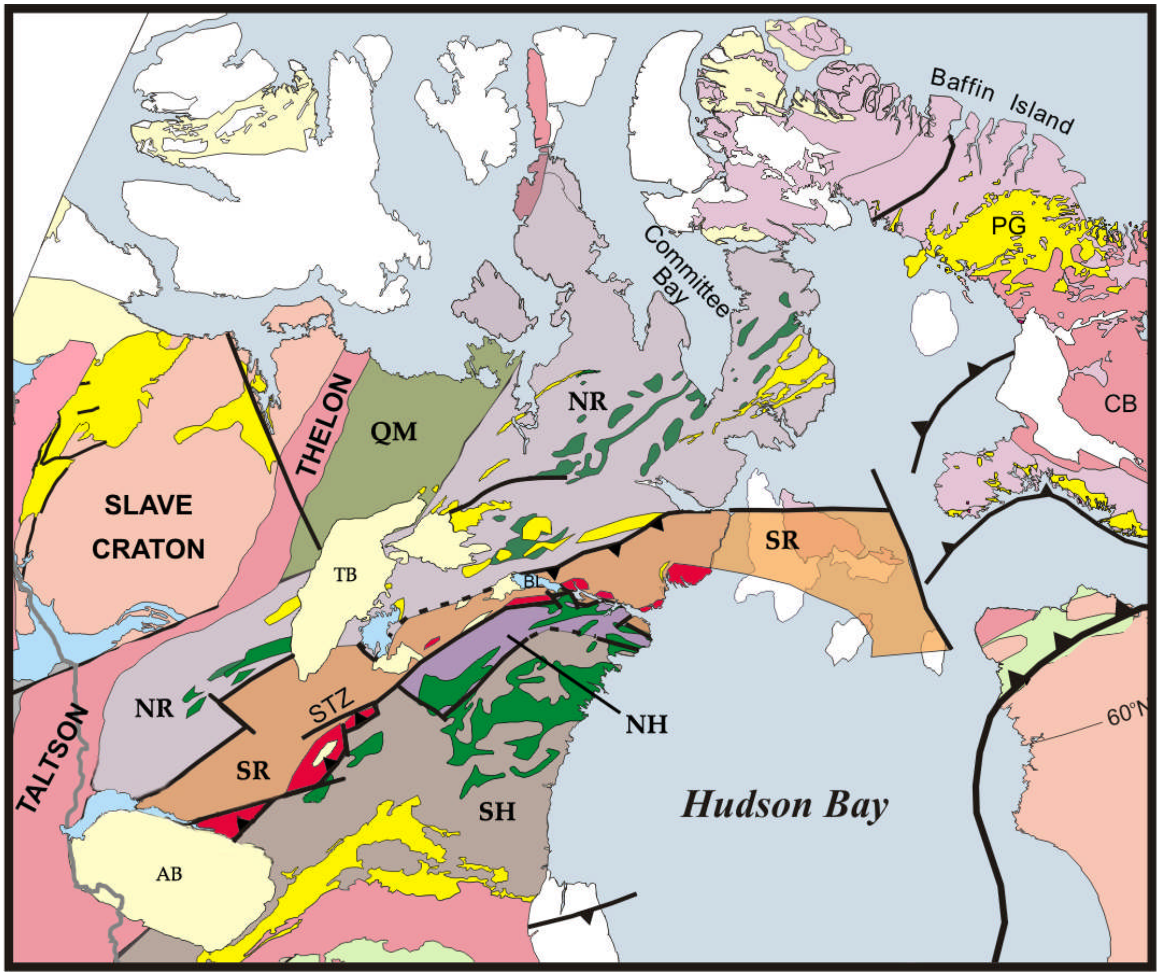


Figure 2. *Tectonic domains in the Western Churchill Province, after Berman et al. (2007). Domains: SH=Southern Hearne; NH=Northern Hearne; SR=Southern Rae; NR=Northern Rae; QM=Queen Maud Block. Additional symbols: AB=Athabasca Basin; TB=Thelon Basin; STZ=Snowbird Tectonic Zone; BL=Baker Lake; CB=Cumberland Batholith; PG=Penrhyn Group.*

them, and their Sm-Nd isotope composition will therefore reflect that of the local lithosphere, or of underlying asthenosphere at that point in time and space. Sedimentary rocks and paragneisses may have sources many hundreds of kilometers away, and although Sm-Nd data can be useful in determining their provenance, their relation to underlying crust is typically much more problematical and subject to greater interpretation. They were therefore not included in this compilation. This compilation complements a previous compilation of 85 Sm_Nd analyses in northern WCP by Skulski and Villeneuve (1999).

Data Organization and Selection

The most meaningful interpretation of Sm-Nd isotopic data requires knowledge of the age of the geological unit the sample was obtained from. Additionally, although the source region can be interpreted from the data, any prior constraints on the source will improve the quality of interpretation. Finally, as some granitic suites can reflect episodic remelting of crustal rocks, it is vital to identify suites of regional distribution that are generated by a common process. For these reasons, the data have been organized by age; into mafic and felsic compositions; and into distinctive suites (e.g., the Proterozoic Hudson granitoid suite, van Breemen et al., 2005).

Analyses of the Mackenzie diabase dyke swarm have been omitted, as it has been reasonably demonstrated that the chilled magma within them has been laterally transported from the Slave Province for many hundreds of km and cannot reflect the composition of local lithosphere. New data is being generated at an accelerating rate for the Western Churchill Province and some details of the picture that emerges from these data will undoubtedly change in the near future. For example, as-yet unpublished data for Southampton Island and the upper Dubawnt Supergroup will probably change current interpretations of the distribution of pre-2.8 Ga lithosphere and the evolution of the lithospheric upper mantle for this region.

The data table includes numerous unpublished analyses that were generously provided by numerous authors. Such data may be unpublished because: it was voluminous, and only representative data could be accommodated in publications; the study was small-scale and did not warrant publication; or it was part of an on-going legacy project which failed to find a publication niche. The sources of published and unpublished data are noted in the table.

The original compilation of this data included numerous analyses which could not be included in the final table because insufficient metadata was available. This usually means the absence of an accurate location, or an uncertain attribution to a map unit or igneous suite. Where it exists, a crystallization U-Pb age for a sample is noted, but in most cases an age is assumed from mapping correlations and an assumed igneous emplacement age is included for all tabulated analyses. Metamorphic U-Pb ages, even when available, have not been included. A strong effort has been made to include Sm and Nd elemental concentrations and isotopic analysis errors, but these were in some cases not published or were unavailable from legacy data. The end user of this data will need to exercise judgement in such cases.

The following fields are present in the data table. Locations use NAD87.

Sample: The recorded sample number.

Domain: The large-scale tectonic domain the sample is located in (see Fig. 2).

Locale: The nearest geographic entity, e.g., a lake, or the crustal domain or supracrustal belt the sample was obtained from.

Suite or group/formation: Where available, the map unit or similar identifier.

Rocktype: A rock description.

Easting: UTM easting coordinate.

Northing: UTM northing coordinate.

Zone: UTM zone.

Long: Longitude.

Lat: Latitude.

U-Pb age: Where available, the published U-Pb (zircon) age for the sample (in myrs).

Age, yrs: The assumed crystallization age of the sample (years). This is generally the known age of the map unit. This is not known for most of the older gneiss samples, for which only a metamorphic age can often be determined. The quoted age is an estimate by the collector, from geological context or from relic zircon ages; if such an age is unavailable an age of 3 Ga is assumed as this is an approximate average age for the older gneisses of the region.

Sm: The Sm concentration in the sample, in ppm.

Nd: The Nd concentration in the sample, in ppm.

147Sm/144Nd: The measured isotopic ratio in the sample.

2sigma: The error in 147Sm/144Nd, 2 X one standard deviation.

143Nd/144Nd: The measured isotopic ratio in the sample.

2sigma: The error in 143Nd/144Nd, 2 X one standard deviation.

Nd(T): The value of 143Nd/144Nd, calculated from the quoted crystallization age and measured isotopic ratios.

TDM Goldstein: The depleted mantle model age, calculated using the method of Goldstein et al. (1984).

TDM DePaolo: The depleted mantle model age, calculated using the method of DePaolo (1981).

TDM N & K: The depleted mantle model age, calculated using the method of Nagler and Kramers (1998).

ENd: Epsilon(Nd), calculated using the quoted crystallization age, relative to CHUR with present-day isotopic ratios of 147Sm/144Nd =0.1967 and 143Nd/144Nd =0.512638.

Reference: The literature source of the data, or the researcher managing unpublished data.

A Comment on Depleted Mantle Model Ages

Depleted mantle model ages are simple in concept but often difficult to interpret. The present-day isotopic composition of a rock is extrapolated backward in time until the calculated $^{143}Nd/^{144}Nd$ ratio matches that of a model depleted mantle. At that time, the magma which cooled to produce the sample in hand, could have been extracted from a depleted upper mantle source.

It is occasionally overlooked that the concept of a depleted mantle model age (T_{DM}) must include a date for the formation of depleted upper mantle, which is considered to be the principal source of basaltic suites from that time to the present day. The reader is referred to the clear description by Nagler and Kramers (1998). There is a broad consensus amongst isotope geochemists that a depleted upper mantle source has existed from approximately 3.5 Ga onwards. Therefore, *any calculated age older than 3.5 Ga falls outside the model and requires a more complex interpretation*.

Granitic magmas rarely if ever develop directly from depleted upper mantle, but they can be considered as such if they formed by re-melting of juvenile basaltic rocks, e.g. from subducted oceanic crust. However, in many cases granitoid rocks are the end result of more than one episode of crustal remelting, and may also be generated in domains which experienced some form of metasomatism (e.g., from high-grade metamorphism). The user of Sm-Nd isotopic data will need to consider if, and to what degree, the Sm/Nd isotopic ratio of the source rock has been affected. Repeated melting episodes will in most cases produce discontinuous increases in LREE/HREE ratios that complicate the interpretation of model ages. While such changes might be modeled for spatially limited and well-studied intrusive complexes, they cannot be confidently calculated for regionally distributed suites.

As the calculation of a model age requires locating the intersection of two time-dependant evolution curves, a model age cannot be confidently calculated if the rock being modeled has an evolution curve which is nearly parallel to that of the assumed source. The limit in present-day $^{147}Sm/^{144}Nd$ for a 'useful' T_{DM} is typically taken as 0.14; we have been somewhat more generous and have included rocks in our model age histograms (see below) for present-day ratios up to 0.17. Very few granitic rocks in our table exceed the 0.14 ratio. However, of samples with $^{147}Sm/^{144}Nd$ <0.17, approximately 38% of the Archean mafic rocks, and 43% of Proterozoic mafic rocks have this ratio above 0.14. We have elected to allow the higher ratio to make our plots of the T_{DM} of mafic rocks regionally significant, but the user must be aware that the model age histograms for mafic rocks must be interpreted cautiously. The issue for Archean mafic rocks is moot, as these overwhelmingly have emplacement ages of 2.7-2.8 Ga and were mostly directly derived from depleted convecting upper mantle (i.e., the model source), but some Proterozoic suites could be products of lithospheric upper mantle or of deep-mantle plumes.

Interpretation of the voluminous data for the Proterozoic Christopher Island Formation and its intrusive equivalents, the ultrapotassic Martell Syenite and the Dubawnt minette dyke swarm, is especially difficult. It has been reasonably demonstrated that the magmas for these suites were generated from lithospheric mantle metasomatized by crustally-derived material, and so tracing the Sm-Nd evolution of the analyzed specimens back to a depleted mantle source is next to impossible. The opinion of the authors is that the Nd isotopic composition of these rocks reflects that of the subducted sediment which yielded the REE, LILE, etc., which were metasomatically emplaced in lithospheric mantle during Proterozoic assembly, at about 1.9 Ga, of the Rae and Hearne domains. In this model, the sediment was derived by erosion of the Rae hinterland and therefore yields an average T_{DM} that is the same as the Rae domain. However, it is possible to interpret the model ages as reflecting Archean subduction of sediment traceable to juvenile igneous rocks (Cousens et al., 2001). We prefer the Proterozoic model because it accords better with current tectonic models for the region, but the issue points out the difficulty of interpreting a T_{DM} in isolation from other data.

Samples which have present-day $^{147}Sm/^{144}Nd$ >0.17, or which yield a T_{DM} greater than 3.6 Ga, have been separated and placed at the end of each data group in the table, and highlighted with bold text.

Interpretations of the Petrogenetic Data Groups

In this section, we point out the principal features of the data for each of the groups, relying primarily on histograms of model ages. This includes the first-order identification of particular crustal blocks or other regional features in the data; these are usually supported by other data, such as U-Pb ages and geochemical anomalies. We employ the model age calculation of DePaolo (1981), as it is most widely used in the literature, but we note that the ages calculated using the more recent model of Nagler and Kramers (1998) gives ages that are nearly 100 myrs younger and are in better accord with the crystallization age of, e.g., near-juvenile granitoid rocks from greenstone belts. The Nagler and Kramers model incorporates a more realistic time-dependent composition of depleted mantle, whereas the DePaolo calculation assumes a constant composition. However, the Nagler-Kramers calculation requires iterative solution of a third order polynomial and is therefore more difficult to apply.

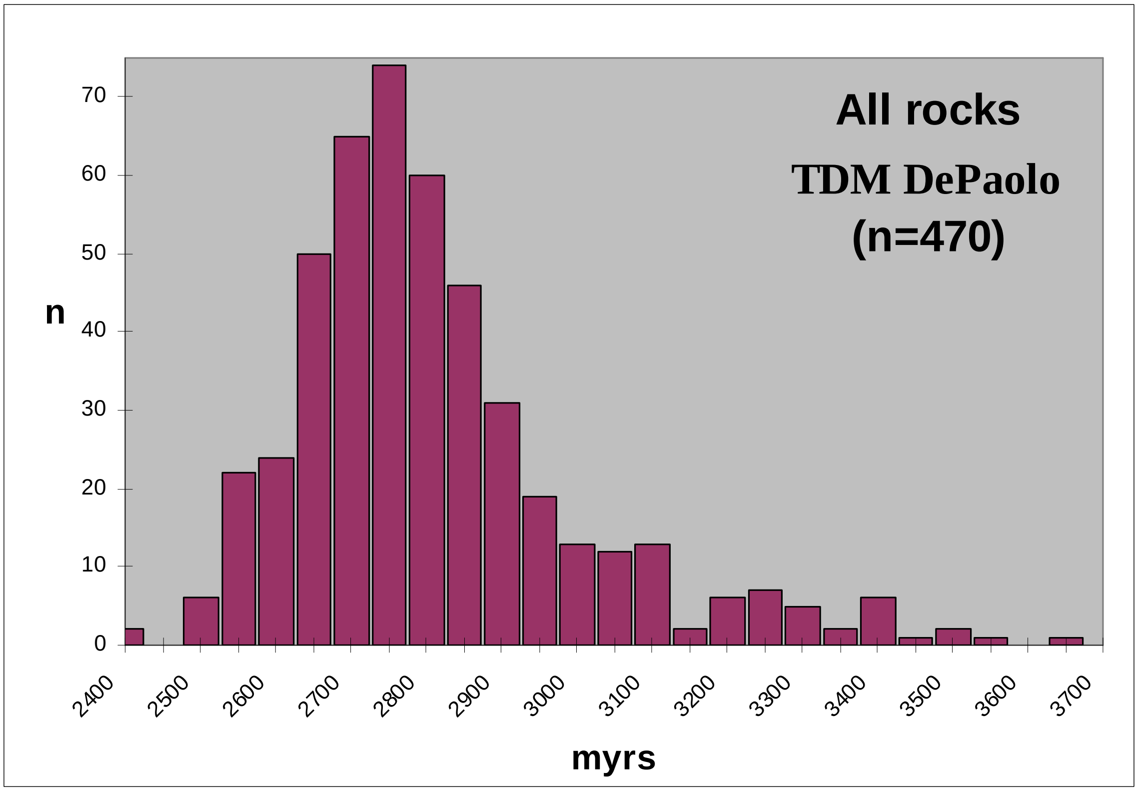


Figure 3. *Histogram of model ages for all samples with $^{147}Sm/^{144}Nd$ <0.17.*

The entire data set can be viewed to reveal the gross features in T_{DM} of the region. Of the 470 samples with $^{147}Sm/^{144}Nd$ <0.17, there is a strong peak at ca. 2.75 Ga, which coincides closely with the age range (ca. 2.7-2.8 Ga) of greenstone belts in the region. To first order then, we suggest that most of the *sampled* crust of the Western Churchill Province was extracted during the formation of the greenstone belts, and to a large extent has simply been recycled by within-plate remelting events since that time. However, there are significant data extending to 3.65 Ga, with notable peaks at ca. 3.1 Ga, 3.25 Ga, and 3.4 Ga (and in specific suites, at 2.9 Ga). These mainly coincide with local crustal blocks that are known to contain older gneisses, and/or contain younger granitoid rocks which are known to have old inherited zircons, implying the presence of older underlying crust. It is noteworthy that these older peaks are discernible in the data of all petrogenetic groups, indicating that island domains, or perhaps lower crustal horizons, composed of these older rocks are widespread throughout the region.

Proterozoic Mafic Rocks

This data set is dominated by samples collected within or near the Kaminak greenstone belt, including the Kaminak dykes (2.45 Ga) and correlative Spi Lake basalts, and gabbros of the Happotyik member of the Ameto Formation (2.1 Ga). All of these rocks yield T_{DM} significantly older than their igneous

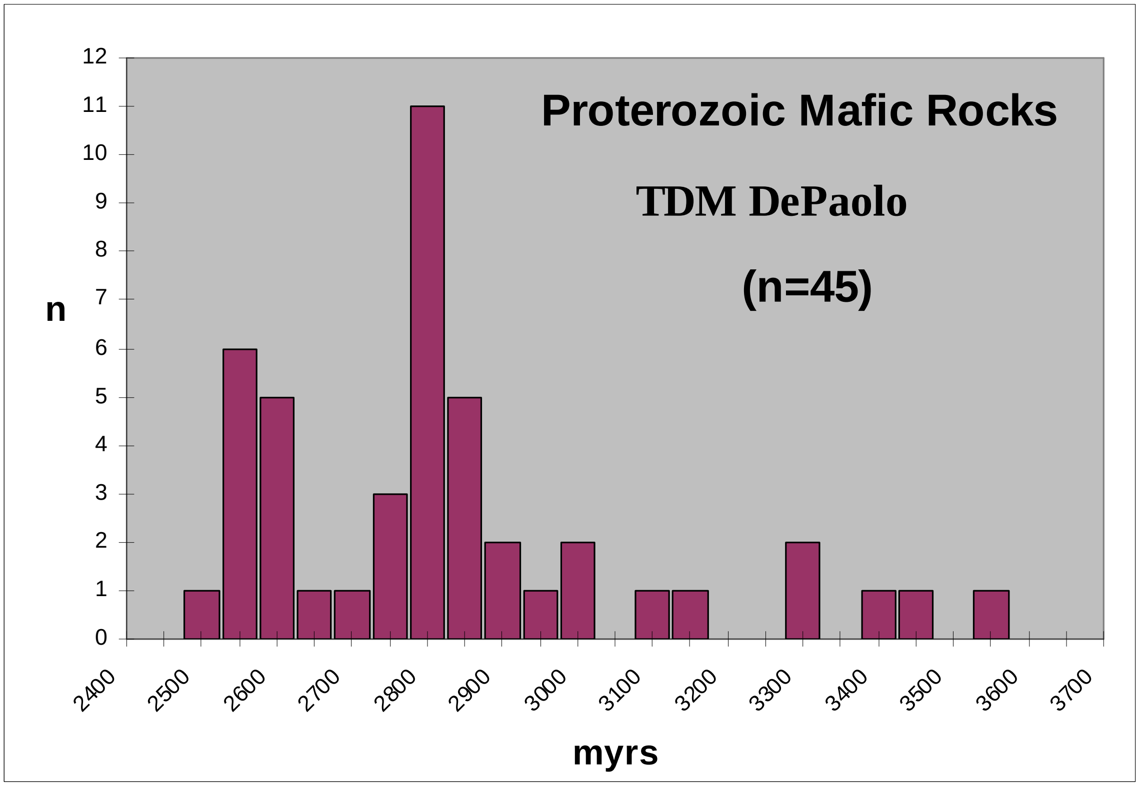


Figure 4. *Histogram of model ages for all Proterozoic mafic rocks with $^{147}Sm/^{144}Nd < 0.17$.*

ages, indicating major contributions from older continental lithosphere (e.g., the Ameto gabbros all are within the 2.5-2.6 Ga peak). There are also several analyses from the MacQuoid Belt and nearby Cross Bay Complex, including the ca. 2.2 Ga MacQuoid Dykes. These yield highly anomalous ages, most in excess of 3 Ga, clearly indicating the presence of old crust in the area (Sandeman et al., 2006).

Proterozoic Granitoid Rocks

This data set consists entirely of samples from the Hudson suite granitoids (ca. 1.83 Ga) and the Nueltin Suite granites plus correlative Pitz Formation rhyolites (1.75 Ga). Both suites are considered to be crustal melts, with possible minor but unknown contributions from juvenile mafic melts (Peterson et al., 2002). As such, they are considered representative of local crust and model ages should give valid indications of its mean mantle extraction age. Strong peaks at ca. 2.65 Ga and 2.55 Ga are consistent with contributions from Archean greenstone belts. A strong peak at ca. 2.9 Ga, with ages extending to 3.25 Ga, primarily represents rocks of the southern Hearne domain, immediately south of the Kaminak supracrustal belt, where Hudson granitoids can contain relic zircons of similar vintage (van Breemen et al., 2005). Old ages in Hudson granitoid rocks are also recorded from west-central Baffin Island, and at Mosquito Lake, west of Dubawnt Lake, near a N-S band of ancient crust uplifted east of the Thelon Tectonic Zone (Thériault et al., 1994).

Relatively young (ca. 2.4-2.5 Ga) ages are recorded in Hudson granitoids in the region of Chesterfield Inlet, where unusually high levels of K and other LILE are also noted. The younger ages indicate possible mixing with juvenile mafic melts. This is also an area where substantial mixing between Hudson granitoids and minette magma related to the Dubawnt minettes (below) is observed (Peterson and Scott, in prep.). Such mixing is consistent with models invoking extreme crustal thinning at or shortly before 1.85 Ga, to bring the mantle source of the minette magma in proximity to the lower

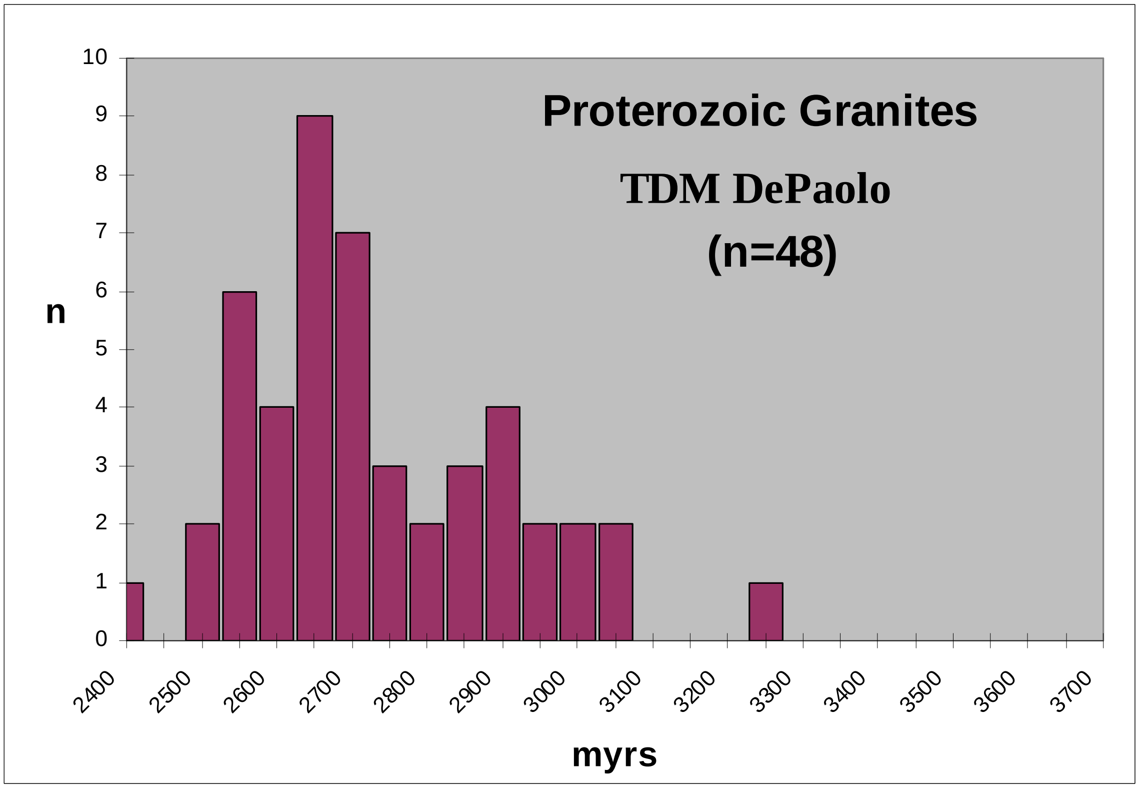
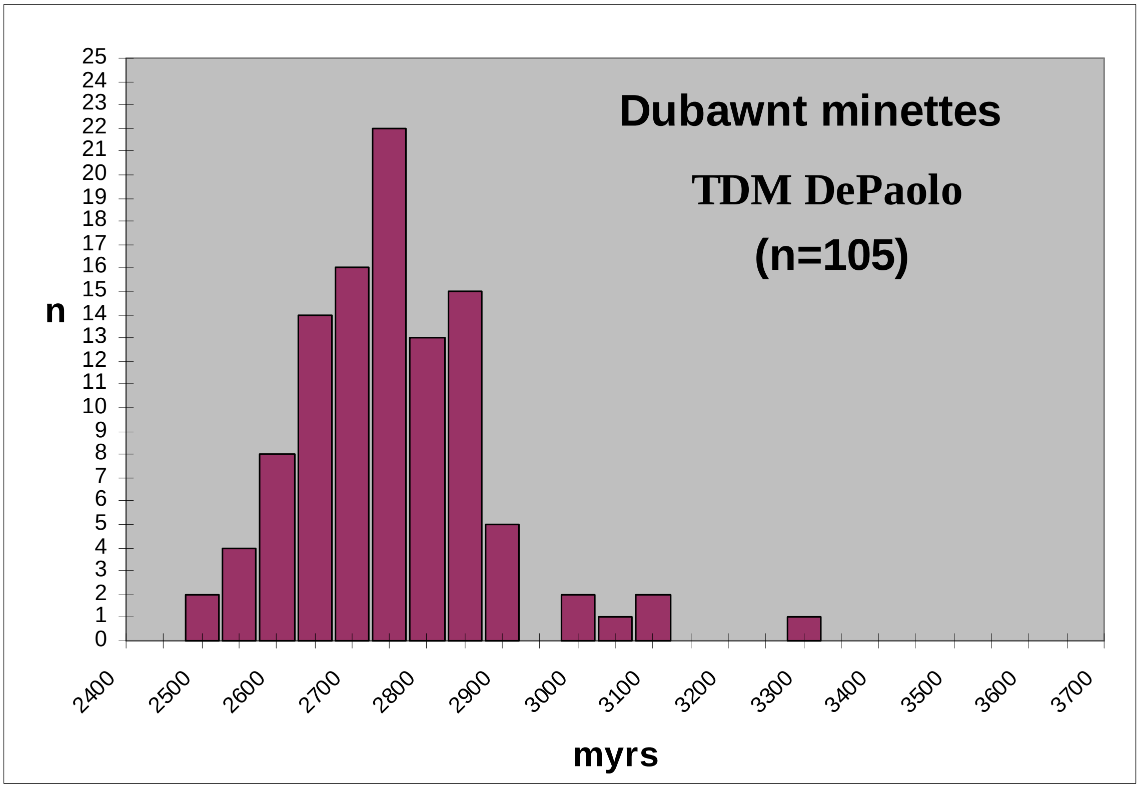


Figure 5. *Histogram of model ages for all Proterozoic granitoid samples.*

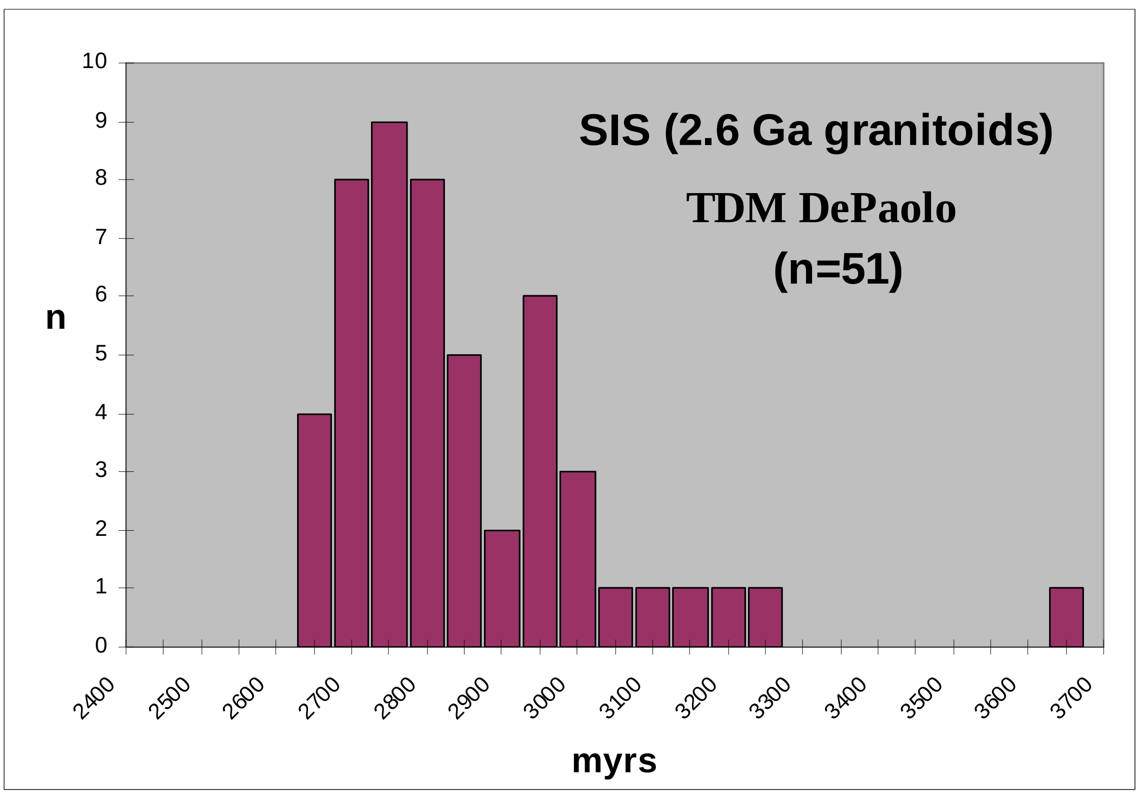
crustal source of the Hudson granitoids. Crustal thinning at that time may also have promoted emplacement of juvenile mafic magmas from asthenosphere, which could be the source of the younger T_{DM} observed in the granites. Dramatic, rapid crustal thinning in the area has been invoked to account for uplift of the granulite massif of the Kramanituar Complex, at ca. 1.9 Ga (Sanborn-Barrie et al., 2001).

Proterozoic Minettes

A disproportionately large amount of Sm-Nd data has been collected for the ultrapotassic minette lavas of the Christopher Island Formation, and for its feeder dykes. It is remarkable that this data set strongly resembles the region as a whole, as these magmas must originate in high-Mg lithospheric mantle rocks overprinted by an episode of metasomatism. As the LREE contents of the minette magmas are too high to be appreciably affected by crustal contamination, the similarity poses a significant problem. It is our opinion that the observed pattern is produced by a combination of the pre-metasomatic mantle protoliths (which includes some ancient domains) and sediment eroded from the Rae domain, subducted during amalgamation of the Rae and northern Hearne domains (model of Berman et al., 2007).



<u>Figure 6.</u> *Histogram of model ages for all samples of Dubawnt minette, Martell Syenite, and the Christopher Island Formation.*



<u>Figure 7.</u> *Histogram of model ages for all samples of Rae domain ca. 2.6 Ga granitoids.*

2.6 Ga Granitoids of the Rae Domain (Snow Island Suite)

The Snow Island Suite is an extensive set of plutons, and very rare extrusive silicic rocks, widespread throughout the Rae domain but entirely absent from the north and south Hearne domains. The suite is dominated by granodiorite, megacrystic monzonite, and leucogranite, but includes minor diorites. A generally accepted genetic model for these rocks does not exist, and their tectonic context is unknown. As the T_{DM} histogram is not distinctly different from that of the Proterozoic granitoids, we see no compelling reason not to assume that they originate as melts of lower crustal rocks. The absence of any model ages near 2.6 Ga strongly indicates that juvenile basaltic magmas had no part in their generation.

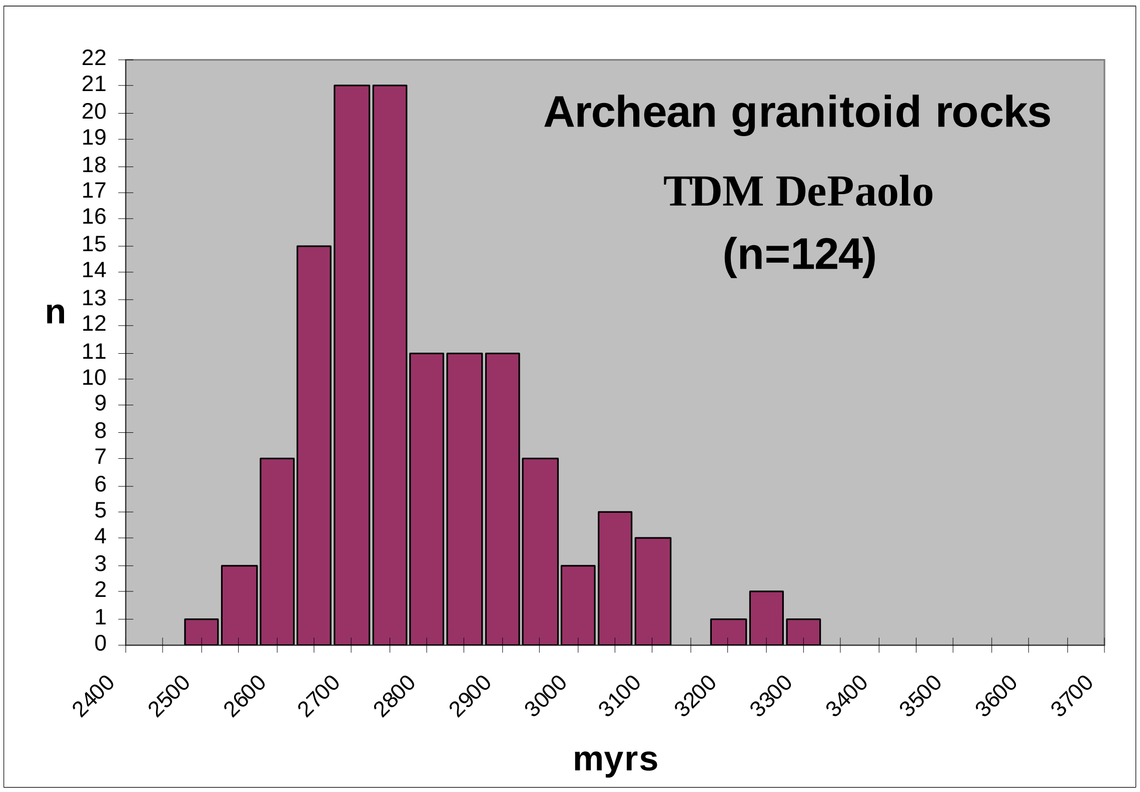


Figure 8. *Histogram of model ages for all Archean silicic rocks.*

Archean Granitoid Rocks

This data set is dominantly from syn- to post-tectonic granitoids of greenstone belts. The T_{DM} range is similar to the igneous ages of juvenile mafic to intermediate volcanic protoliths, with significant contributions from older crust over which the belts were emplaced.

Archean Mafic Rocks

The dominant peak in this data, at 2.75-2.8 Ga, corresponds to a mantle extraction event for the parental magmas. Some minor scattering at younger and older (>3.1 Ga) ages can be partly attributed to the inherent error of calculating T_{DM} for basaltic rocks. However, the strong peak at ca. 2.95 Ga appears to be real. This peak is primarily from data collected in the Angikuni Lake area, with some older analyses also from the MacQuoid/Cross Bay area, as for Proterozoic mafic rocks.

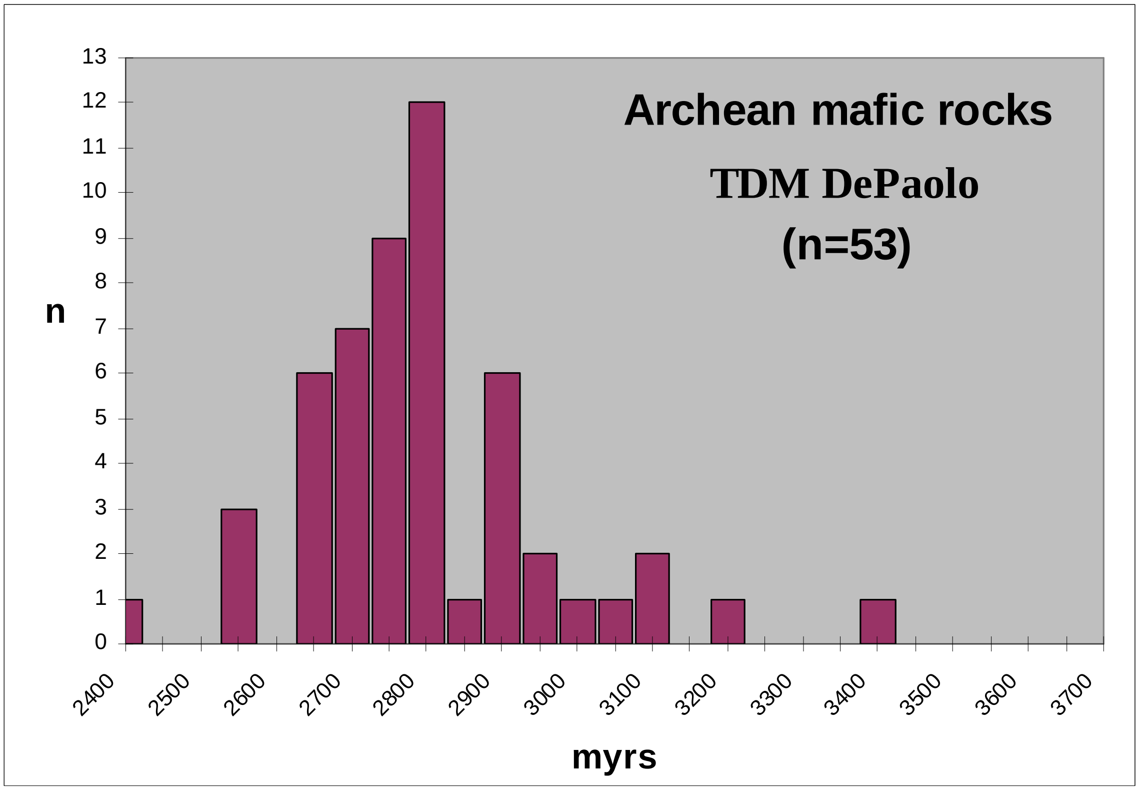


Figure 9. *Histogram of model ages for all samples of Archean mafic rocks with* $^{147}Sm/^{144}Nd < 0.17$.

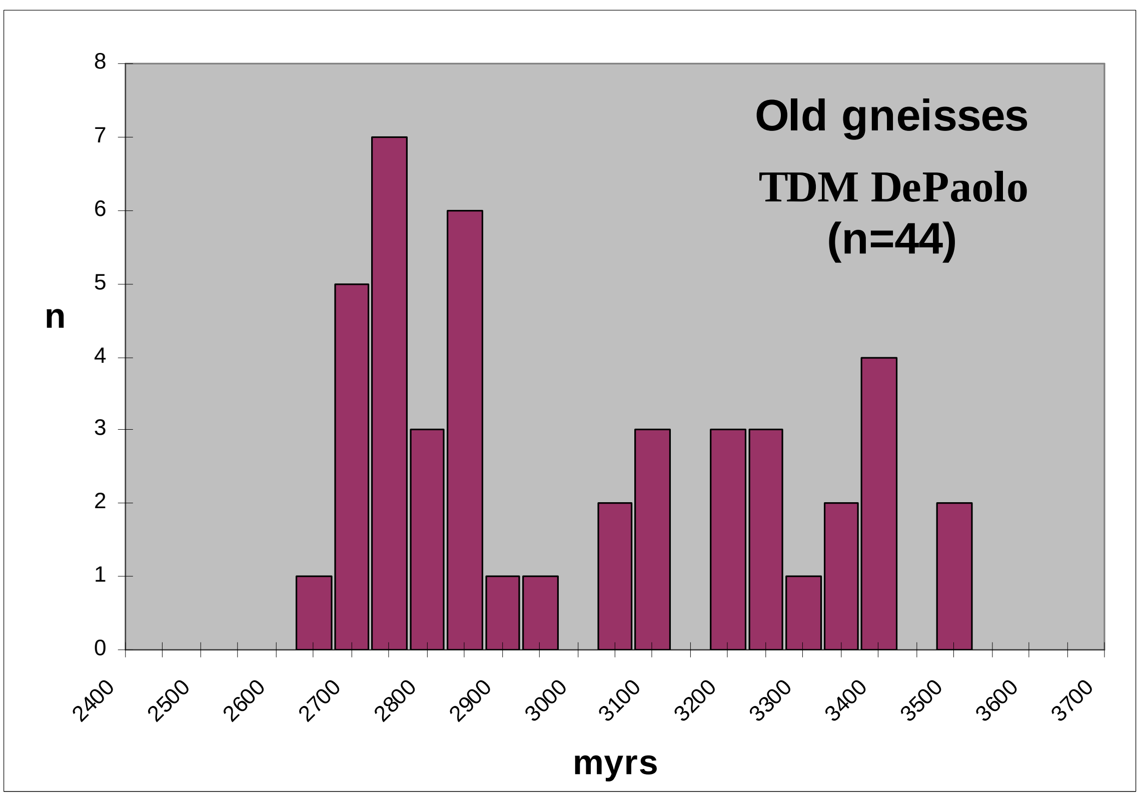


Figure 10. *Histogram of model ages for all gneisses presumed older than 2.8 Ga with* $^{147}Sm/^{144}Nd < 0.17$.

Older Gneisses

For this study, 'older gneisses' refers to presumed orthogneisses that are interpreted, from mapping correlations or scant U-Pb data, to pre-date 2.7-2.8 Ga supracrustal rocks. Most of the data is from the western edge of the Northern Rae domain, where older crust was identified by Thériault et al. (1994) (and since supplemented by additional data from archival samples) and from gneisses north of Chesterfield Inlet, within the Southern Rae domain (van Breemen et al., 2007). With only 30 analyses, statistically significant patterns cannot be discerned, but it is noteworthy that Archean and Proterozoic granitoid samples yield peaks near 2.85 Ga and 3.25 Ga, which are also apparent in this data.

Interpretations of the Domain Data Groups

Current tectonic models for the Western Churchill Province (Berman et al., 2007) recognize 5 distinct crustal domains, identified on the basis of unique supracrustal sequences, metamorphic history, and bounding shear zones. From southeast to northwest, these are the Southern Hearne, Northern Hearne, Southern Rae, Northern Rae, and the Queen Maud block (Fig. 1). The Southern Hearne domain contains both ca. 2.7 Ga greenstone belts along its northern edge, and a southern portion which demonstrably contains older crust with an uncertain relationship to the greenstone belts (the intervening area being very poorly exposed and not well-studied). These two subdomains were probably accreted as a single unit. As each of the tectonic domains contains a variety of igneous rock types, the model age data can only be interpreted in a very general sense. Nevertheless, some patterns in model ages, which can be attributed to differences in tectonic history and to the current level of crustal exposure, can be discerned.

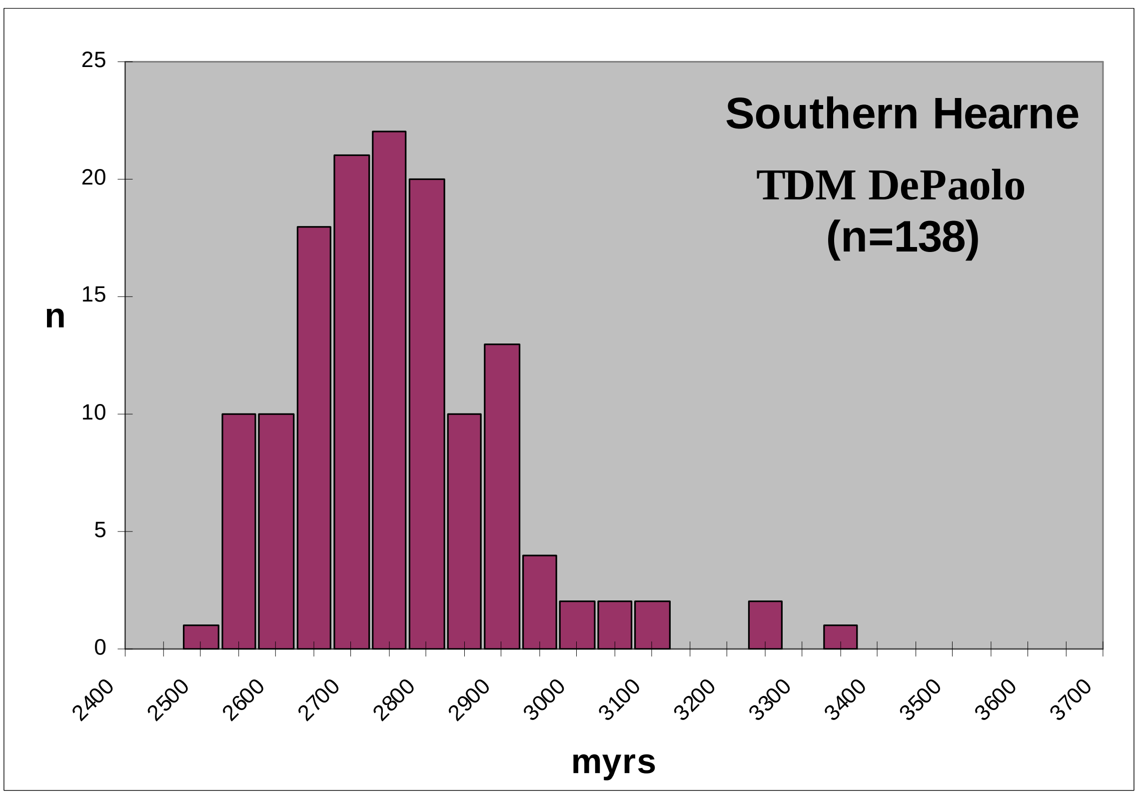


Figure 11. *Histogram of model ages for all samples from the Southern Hearne domain with* $^{147}Sm/^{144}Nd$ *<0.17.*

Southern Hearne Domain

The histogram is highly skewed by the voluminous data for the Kaminak greenstone belt; older ages are derived from samples from Hudson suite plutons which contain relic zircons up to 3.3 Ga in age (van Breemen et al., 2005).

Northern Hearne Domain

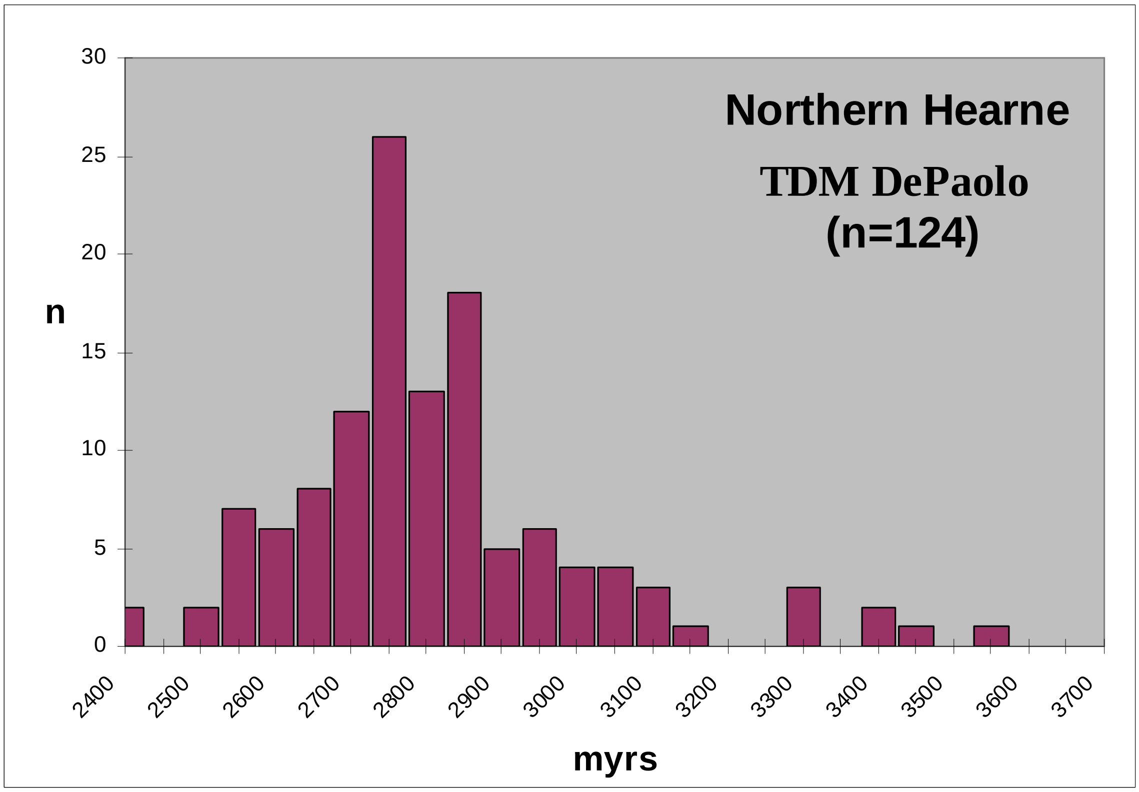


Figure 12. *Histogram of model ages for all samples from the Northern Hearne domain with* $^{147}Sm/^{144}Nd < 0.17$.

The Northern Hearne domain is a relatively small block with an unusually large number of ages greater than 2.8 Ga. These are mostly from Proterozoic basaltic dykes and supracrustal rocks from the MacQuoid Lake area (Sandeman, unpublished data).

Southern and Northern Rae Domains

The Rae domain is divided into two portions primarily on evidence of a NE-trending, SE-dipping shear zone with uplifted high-grade gneisses in its hanging wall south of Wager Bay (van Breemen et al, 2007) and an interpreted continuation to the SW, towards Dubawnt Lake. There are no statistically significant differences in their model age distribution, except perhaps within pre-3 Ga ages which are located in specific locations. These are: (1) a high-grade gneiss domain between Chesterfield Inlet and Wager Bay, and (2) along a ribbon of older crust along the western edge of the Northern Rae, adjacent to the Thelon Tectonic Zone, which was probably uplifted in a time and manner similar to that of the Queen Maud Block (below). Peaks at ca. 2.7 Ga and 2.8 Ga correspond to supracrustal belts.

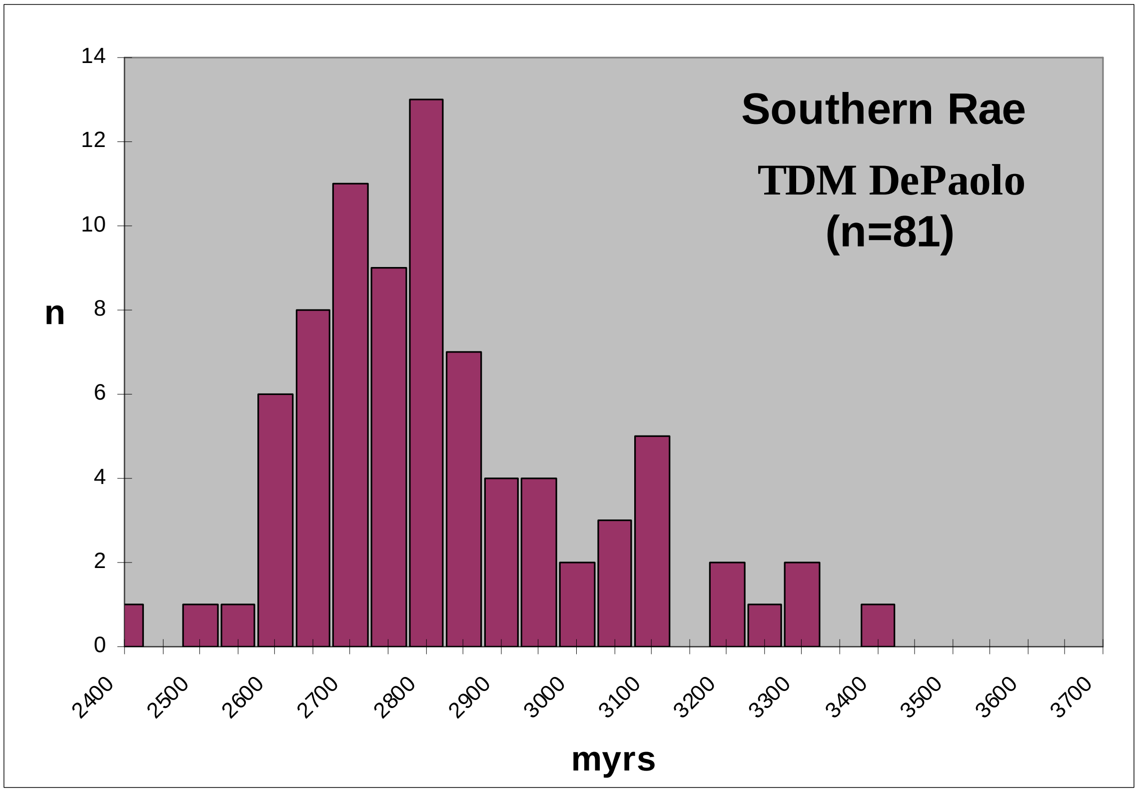


Figure 13. *Histogram of model ages for all samples from the Southern Rae domain with* $^{147}Sm/^{144}Nd$ *<0.17.*

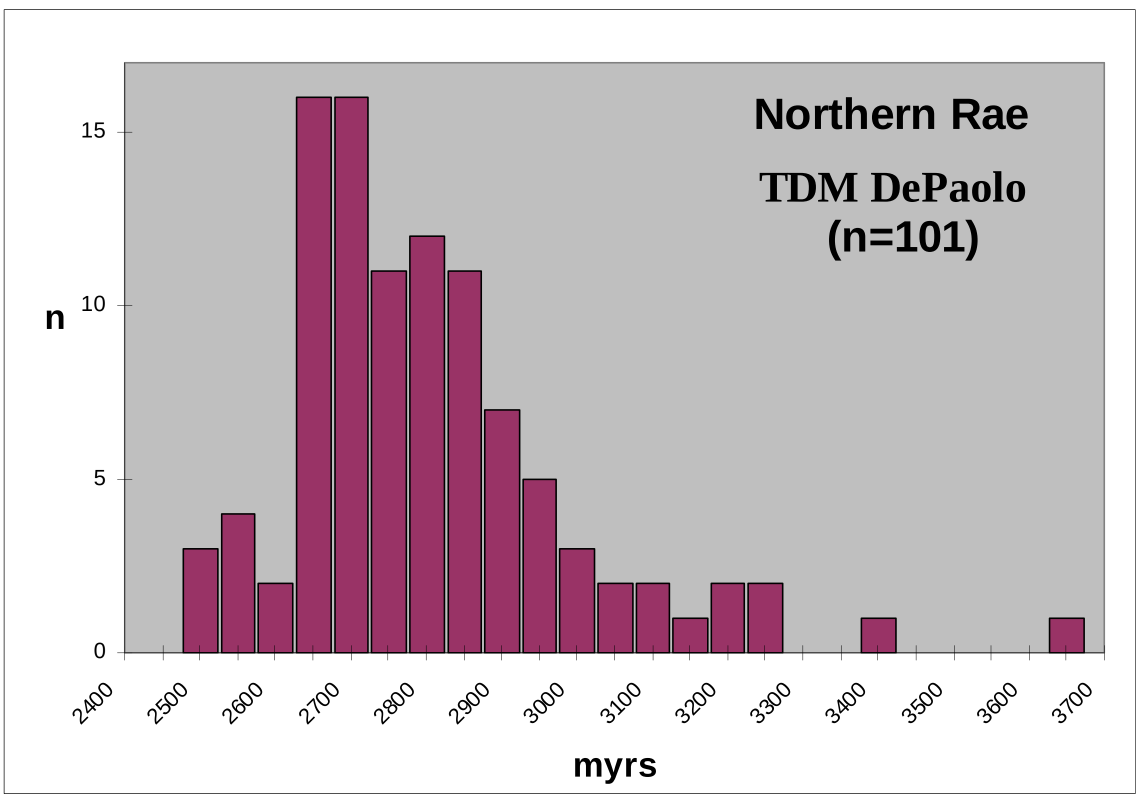


Figure 14. *Histogram of model ages for all samples from the Northern Rae domain with* $^{147}Sm/^{144}Nd$ *<0.17.*

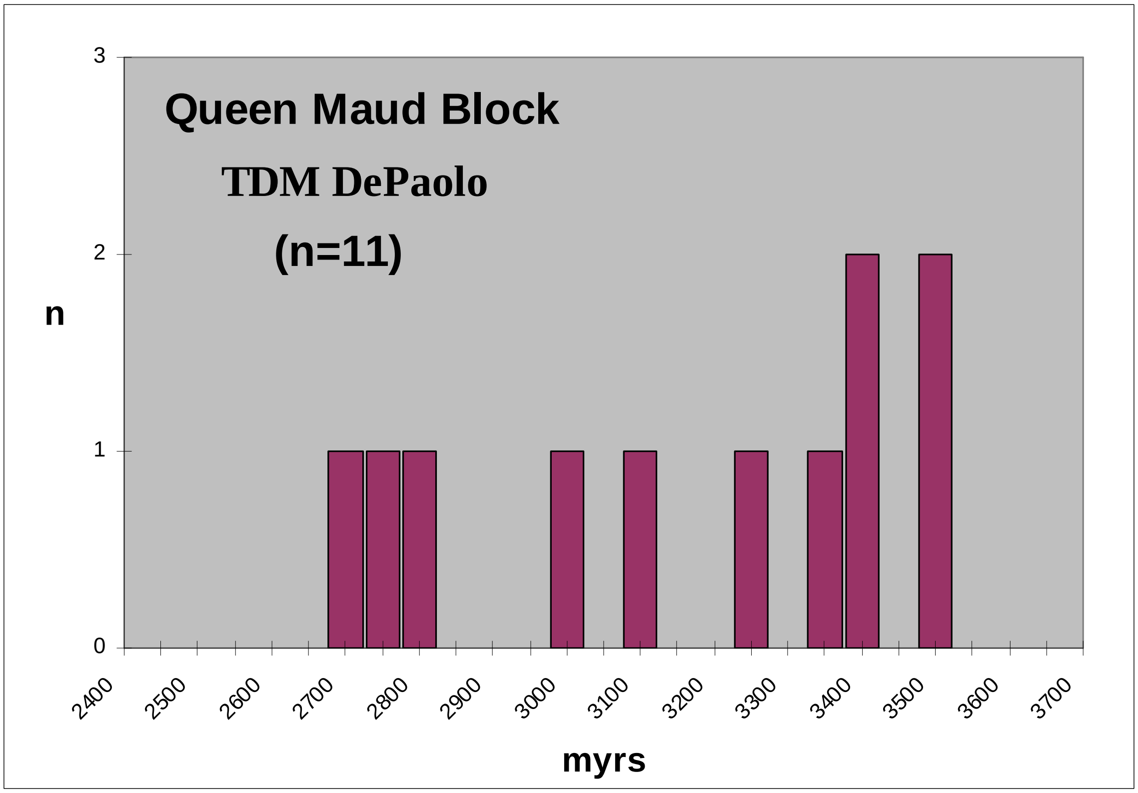


Figure 15. *Histogram of model ages for all samples from the Queen Maud block with $^{147}Sm/^{144}Nd$ <0.17.*

Queen Maud Block

The Queen Maud block is a little-studied granulite facies domain which was uplifted during Proterozoic assembly of Laurentia, from ca. 2.0-1.8 Ga. The dominance of old ages probably reflects relatively deep exposure levels, below the level of Neoarchean supracrustal belts.

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