CHAPTER 22

ISOTOPIC DATA SYNTHESIS

Geochronological information for eastern Labrador draws on U–Pb, Sm–Nd, Rb–Sr, Ar–Ar and K–Ar isotopic sources. These are addressed in the following sections.

22.1 U–Pb

The U–Pb geochronological review presented here provides one approach to synthesis of the geological history developed throughout this report. It does so in a largely pictorial manner in four time segments, namely: i) 1900–1700 Ma, ii) 1700–1500 Ma, iii) 1500–1100 Ma, and iv) 1100–900 Ma. In the figures, error bars have been given for magmatic and metamorphic events, but excluded for inherited ages (to avoid clutter). Error bars are indicated up to ± 30 million years, beyond which '*ca.*' is indicated beside the nominal point. The size of the data symbols corresponds to an error of about ± 1 Ma. Where ages depend on a combined regression of two minerals, these are noted.

Data points are arranged in order of decreasing age within a particular structural domain/terrane, utilizing magmatic age, or, where such is not known, earliest metamorphism within the time period represented by the figure. The data points typically form chains from top left to lower right. Horizontal discontinuities indicate breaks in geological activity. Vertical chain segments tend to imply regionally extensive events, but may also be an artifact of more data being available for that time period. Data points in areas to the left and below the data-point chains represent inherited and detrital ages, whereas those to the right and above the data-point chains represent later metamorphic and cooling events. If inherited points plot in the latter area, it is because the sample has a younger magmatic/metamorphic age, outside the frame of the diagram.

22.1.1 1900–1700 Ma

U–Pb geochronological data for all of the Makkovik Province, and for the part of the Grenville Province in eastern Labrador for the 1900 to 1700 Ma period are summarized in Figure 22.1. Inherited age data in Makkovik Province samples have been omitted because of lack of space and low relevance to this synthesis, but such ages have been included for samples from the Grenville Province. For the Makkovik Province, the data are assigned according to the three principal domains outlined earlier (Kaipokok, Aillik and Cape Harrison), but also separately distinguishing a transition zone between the Kaipokok and Aillik domains.

Perhaps the most compelling feature of the diagram is the clear demonstration of the (already well-recognized) magmatic episodes. These are the Island Harbour Bay intrusive event, the Numok intrusive event and, to a lesser extent, the Strawberry intrusive event. Note that the Island Harbour Bay intrusive event is apparently absent from the Cape Harrison domain (hence the vertically gradational grey- to white-background), but as Aillik Group felsic volcanism is clearly temporally associated with (and following) the Island Harbour Bay intrusive event and is also found in the Cape Harrison domain, it seem likely that the event was manifest in the Cape Harrison domain in some form. For the Numok intrusive event in the Cape Harrison domain, the data suggest two magmatic events, at *ca.* 1815 and 1800 Ma. The 1815 Ma event applies to the Cape Harrison Metamorphic Suite, which is more migmatized than the 1800 Ma granitoid rocks, so it seems probable that two separate pulses of magmatism occurred. The *ca.* 1840 Ma Deus Cape monzogranite is an anomaly in the Cape Harrison domain, but note that Ketchum *et al.* (1997) tentatively dated dextral transposition in the Drunken Harbour shear zone (Kaipokok domain) to be 1841 ± 2 Ma (sample 94MKJ-16b). Further geochronological study is required to establish whether a genuinely distinct event occurred at this time.

The figure also suggests that tectonic activity was almost continuous in the Kaipokok Bay–Aillik domain transition zone, in contrast to it being apparently minor or absent elsewhere in the Makkovik Province between intrusive events. Given that this is a major zone of structural weakness, perhaps such is to be expected. On the other hand, it is also an area that has been the target of more detailed geochronological study, so indication of greater geological activity may simply be due to more data being available. Several titanite dates serve to indicate that high-grade conditions were not sustained between the Island Harbour Bay and Numok intrusive events – at least, not at the crustal level now exposed.

The key feature of 1900–1700 Ma data in the Grenville Province is demonstration of an 1805–1775 Ma event, to which the name Eagle River orogeny is applied. This is

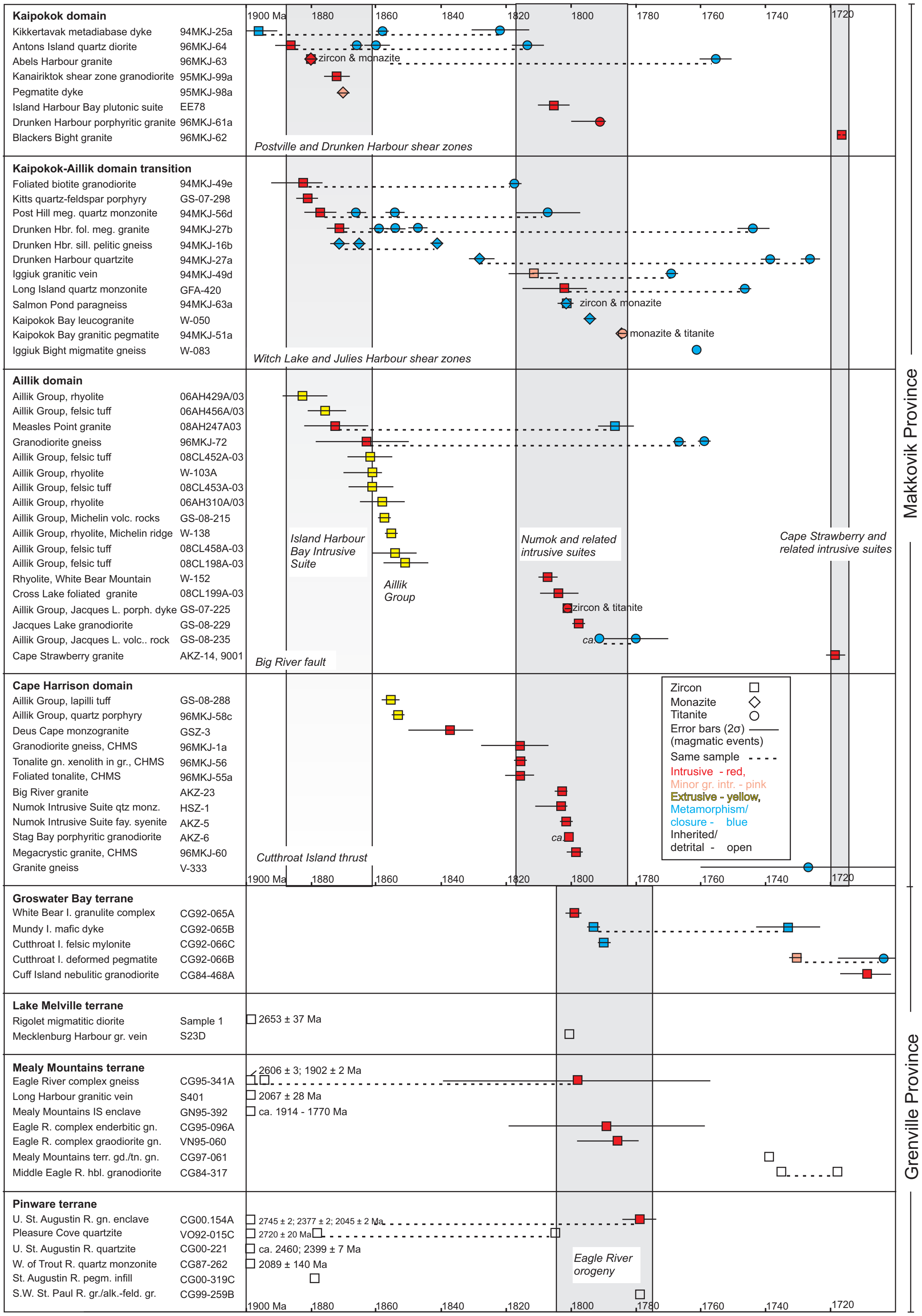

Figure 22.1. *U–Pb geochronological data between 1900 and 1700 Ma for the Makkovik and Grenville provinces in eastern Labrador.*

coeval or slightly younger than the Numok intrusive event in the Makkovik Province, with which it must be tectonically linked – that is, at least to the second Numok intrusive event suggested earlier in this section. Also, there is some hint that an event broadly coeval with the Strawberry intrusive event occurred in the Groswater Bay terrane, but the data are imprecise. The three 'inherited' points in the Mealy Mountains terrane were argued earlier in the text as more likely linked to the Eagle River orogenic event (Gower *et al.*, 2008b).

22.1.2 1700–1500 Ma

Figure 22.2 summarizes U–Pb geochronological data for the 1700–1500 Ma time period. It clearly shows that Labradorian activity occurred in both the Makkovik Province and all terranes in the Grenville Province in eastern Labrador, and that it occurred mostly between 1680 and 1620 Ma.

The lack of pre-1680 Ma data points, except those that can be interpreted as inherited (because younger magmatic ages were obtained from the same samples), challenges extending Labradorian orogenesis back to 1710 Ma, which is the date that has been traditionally adopted. There is certainly merit in considering dates around 1710 Ma as being linked to the Strawberry intrusive event, as noted in the previous section.

One technical feature, particularly applicable to this figure but also apparent in the others, is that the oldest and youngest points of a data chain are those tending to have the largest precision errors. High errors, of course, imply lower confidence in the nominal age. If these low-precision data points are conceptually discarded, then it is evident that most Labradorian activity could have been restricted to an even shorter period, say 1670 to 1630 Ma.

Labradorian orogenesis has been subdivided into a series of discrete magmatic events, separated in part by mafic dyking and metamorphic/deformational events (Gower *et al.*, 1992; Kamo *et al.*, 1996). These were termed Neveisik Island magmatic event in the Lake Melville terrane (*ca.* 1677 Ma), Red Island magmatic event in the Hawke River terrane (*ca.* 1671 Ma) and Double Island magmatic event in the Groswater Bay terrane (*ca.* 1658–1649 Ma). These events imply a northerly decrease in age with time, and overlap at the younger end of the age range with the 1654–1646 Ma emplacement for the Trans-Labrador batholith. Additional U–Pb geochronological studies have introduced some complications to the event–terrane concept, but not destroyed its broad viability. The most significant modification introduced is evidence for the Red Island and Double Island magmatic events in the Mealy Mountains terrane.

Two other points pertinent to Labradorian age data are noteworthy. The first is the common presence of Labradorian titanite ages in the Hawke River terrane. The preservation of these denies severe subsequent metamorphism (particularly, Grenvillian) having ever taken place in this region. Thus the structural histories, which can be extracted by combining field evidence and geochronological data at various localities in the terrane, document Labradorian events. The second refers to the relative dearth of Labradorian data for the Lake Melville terrane, and the low precision of that available. Conversely to what happened in the Hawke River terrane, this is a consequence of the Lake Melville terrane having been severely re-tectonized during Grenvillian orogenesis, making it more difficult to access earlier events geochronologically (*i.e.*, to 'see through' the Grenvillian overprinting).

The close of the 1700–1500 Ma period marks the start of the Pinwarian orogeny, which is addressed in the next section.

22.1.3 1500–1100 Ma

The time period adopted for the Pinwarian orogeny is 1520 to 1460 Ma. As for Labradorian age data, some lower precision results tend to plot at the time extremities of the event, but overall the data are high-precision and do not permit much latitude in re-defining the event's duration (Figures 22.2 and 22.3). The 1520 to 1500 Ma part of the event appears to be confined to the Pinware terrane, as indicated in Figure 22.2, but the author does not attach much significance to this, as reliable dates only slightly younger than 1500 Ma are known from the Groswater Bay terrane. U–Pb geochronological evidence for the event is found in all terranes, but note that titanite Pinwarian dates are known from the Hawke River terrane, providing further testimony for lack of severe Grenvillian metamorphism in this region.

One further point is a reminder regarding the Rigolet magmatic diorite. The author has challenged the reported interpreted emplacement date (*cf.* Section 14.3.3) as not reflecting the time of intrusion (the unit being Labradorian). The data may provide evidence for Pinwarian metamorphism, however.

The Elsonian refers to the 1460 to 1230 Ma period. In eastern Labrador, U–Pb data provide evidence for three main events during this time. These are the 1450–1425 Ma Michael gabbro (with which the 1417 Ma Mokami Hill quartz monzonite is conceptually linked), 1300 Ma activity represented by the Upper North River syenite and the Fox Harbour alkali volcanic belt, and the 1250 Ma Mealy dykes. There is no evidence of concomitant metamorphism,

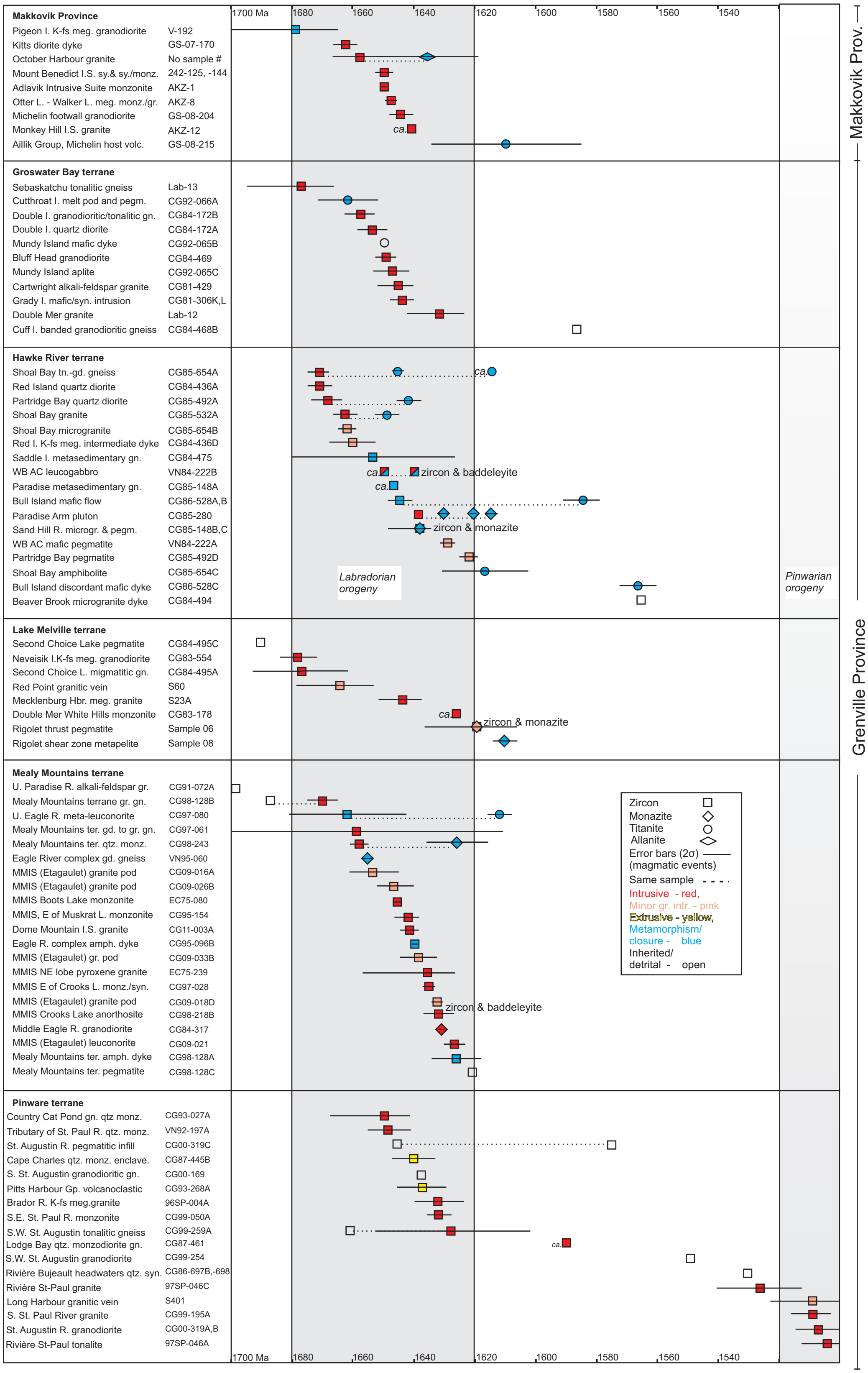

Figure 22.2. *U–Pb geochronological data between 1700 and 1500 Ma for the Makkovik and Grenville provinces in eastern Labrador.*

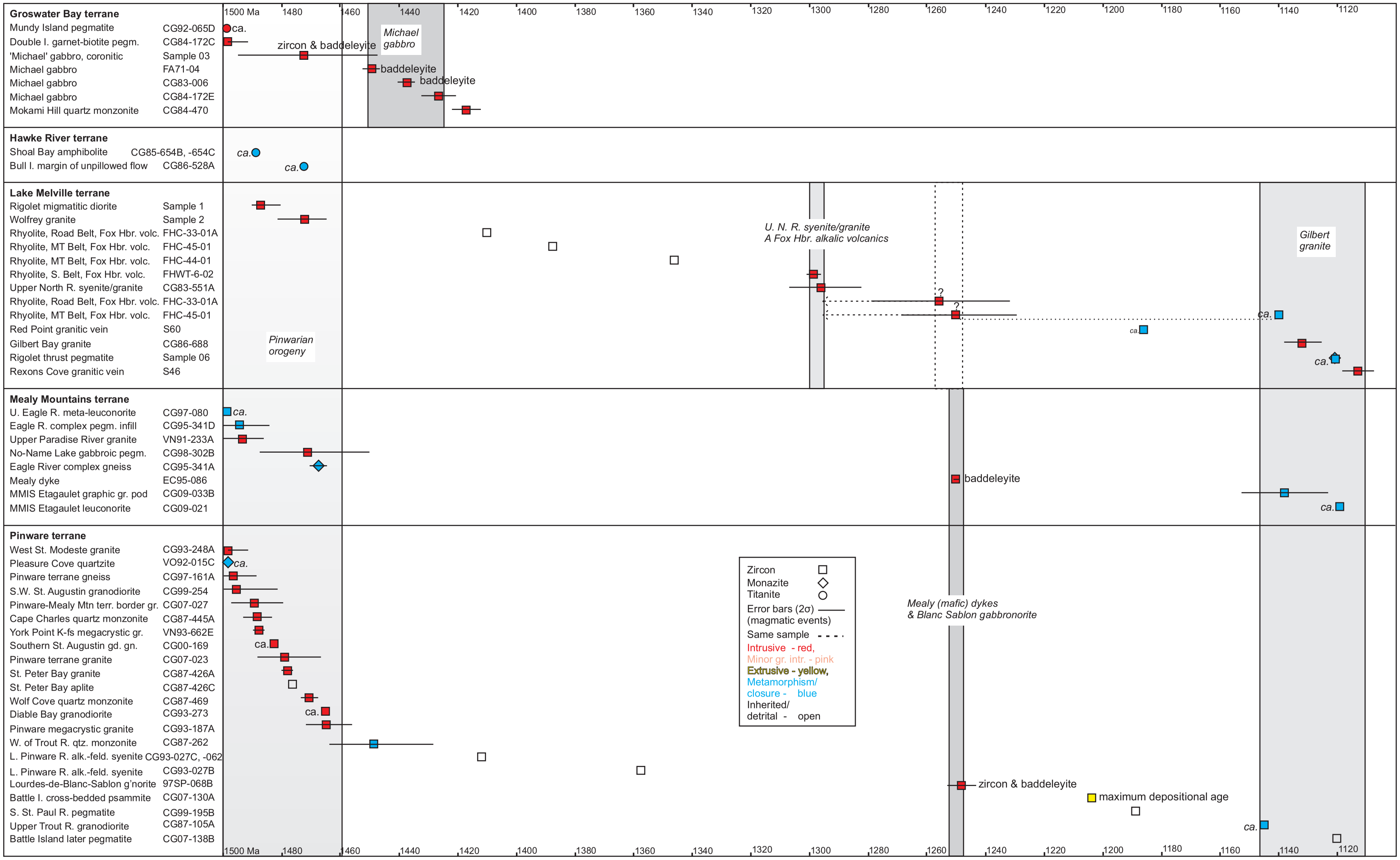

Figure 22.3. *U–Pb geochronological data between 1500 and 1100 Ma for the Grenville Province in eastern Labrador.*

and all can be considered anorogenic events, possibly linked to widespread rifting during this period (Gower and Tucker, 1994).

The only post-Elsonian–pre-Grenvillian (1230–1090 Ma) magmatic event is eastern Labrador recognized so far is the emplacement of the Gilbert granite in the Lake Melville terrane, although there are hints from other (imprecise) data that minor activity occurred elsewhere in eastern Labrador during this period. The Battle Island supracrustal rocks were deposited toward the end of this period.

22.1.4 1100–900 Ma

The 1100 to 900 Ma time period includes the 1090–985 Ma Grenvillian orogeny and its late- to post-Grenvillian aftermath (985–920 Ma). Figure 22.4 shows that Grenvillian orogenesis varied considerably between terranes. Orogenic

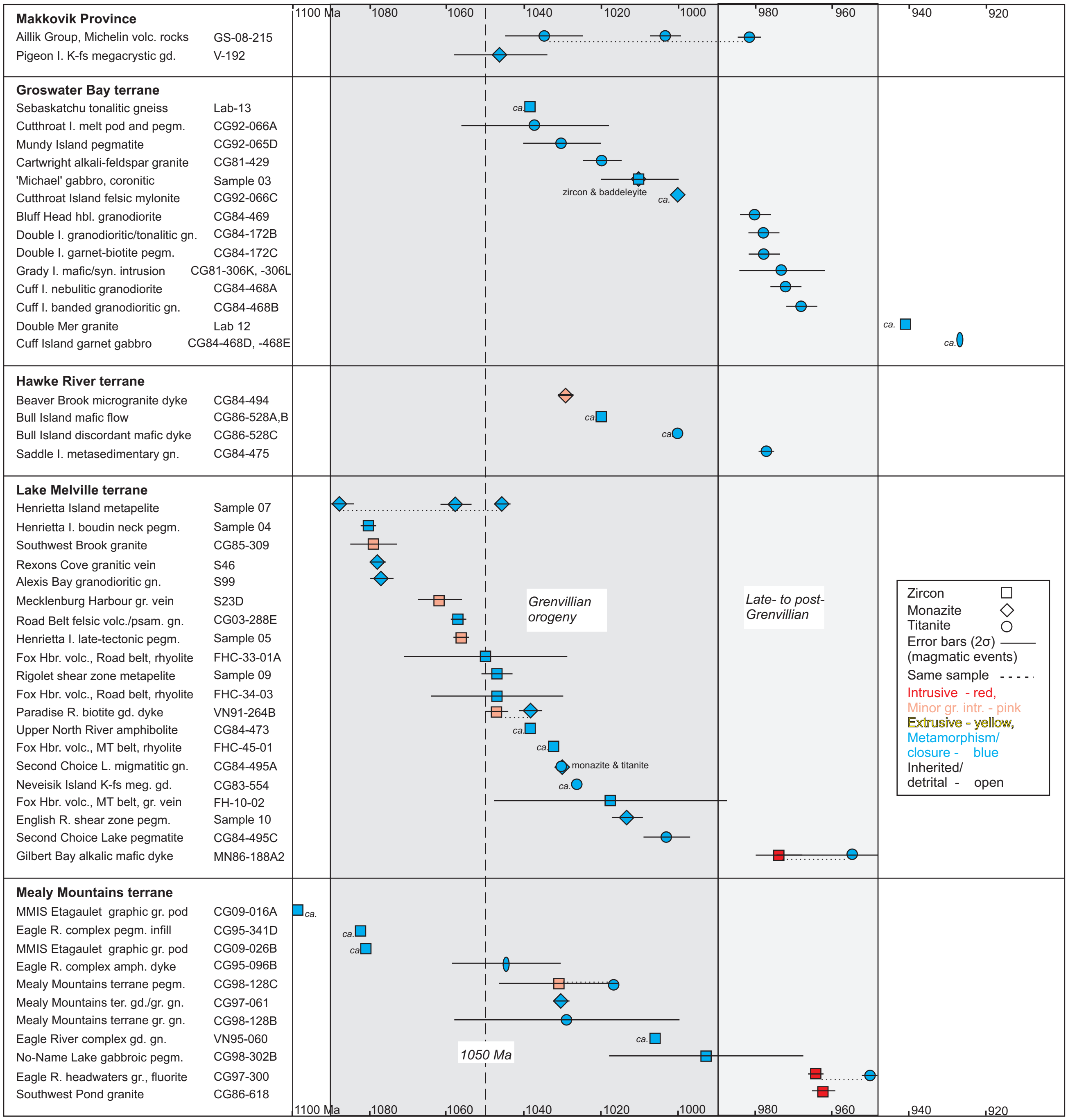

Figure 22.4 *U–Pb geochronological data between 1100 and 900 Ma for the Makkovik and Grenville provinces in eastern Labrador.*

effects were weak in the Groswater Bay and Hawke River terranes, and expressed mostly by titanite results. The few zircon and monazite results are very imprecise, reflecting long extrapolations from pre-Grenvillian upper intercepts and only minor Grenvillian Pb loss. One magmatic event in the Hawke River terrane (emplacement of the Beaver Brook microgranite) could equally well be assigned to the Lake Melville terrane, as the site is very close to the currently chosen terrane boundary.

A key feature of the data is the demonstration that early Grenvillian activity (pre-1050 Ma) was almost entirely confined to the Lake Melville terrane, and that it comprised both metamorphism and emplacement of minor granitoid intrusions. The late- to post-Grenvillian magmatic event depicted in Figure 22.4 in the Lake Melville terrane is the emplacement of the mafic alkalic Gilbert Bay dykes.

Three data points in Figure 22.4 suggest some early Grenvillian activity in the Mealy Mountains terrane. These are extremely imprecise results (minimum error ± 80 million years) from Labradorian granitoid pods and not much credence should be attached to the nominal ages, beyond indicating slight Grenvillian Pb loss. As was the case for the

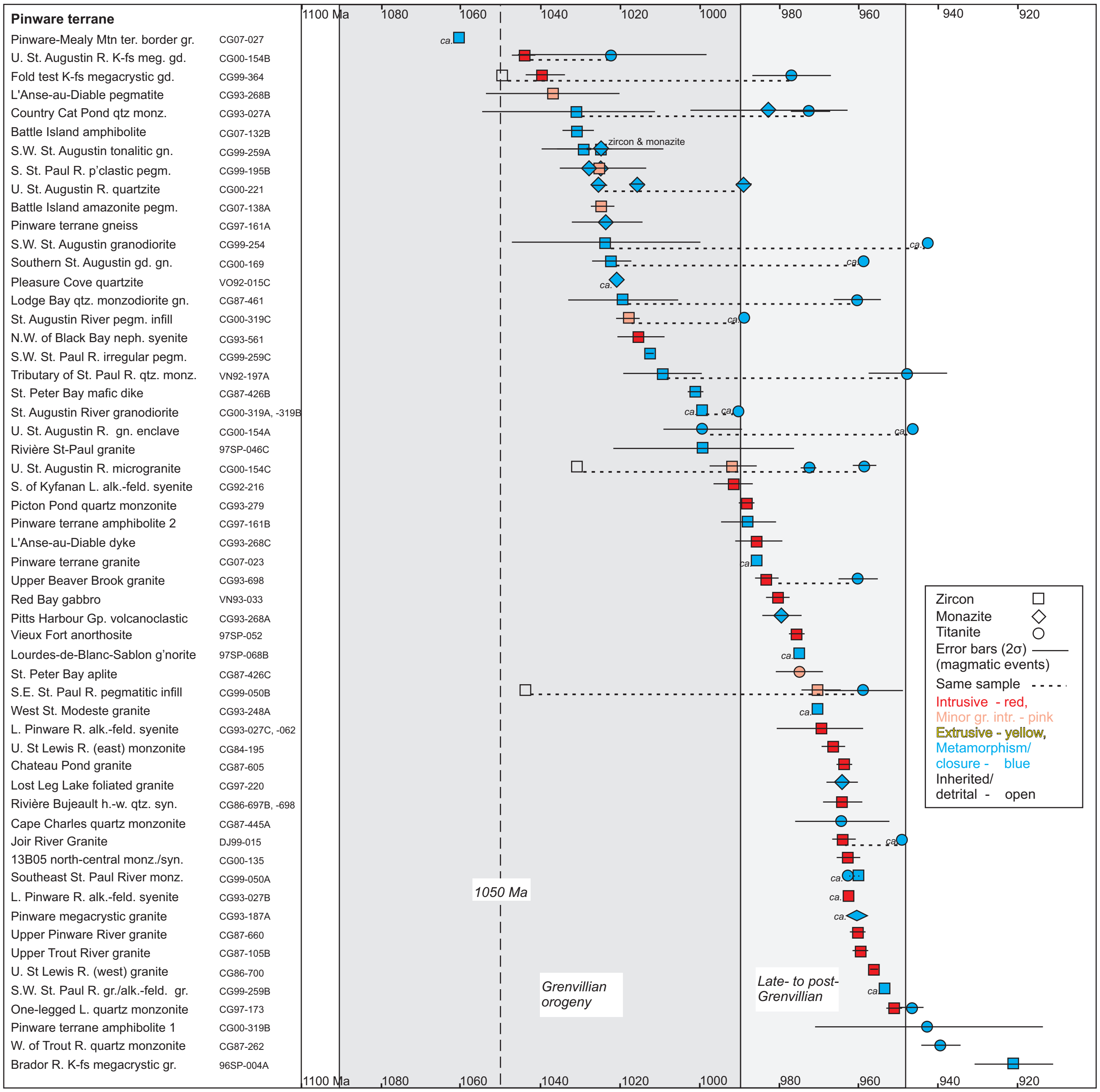

Figure 22.4 *Continued.*

Lake Melville terrane, magmatic activity was confined to minor granitoid intrusions, except during the late- to post-Grenvillian phase when granitoid plutonism was widespread through the southern part of the eastern Grenville Province.

The contrast in Grenvillian activity in the Pinware terrane *vs.* other terranes farther north is striking. As Figure 22.4 shows, activity was continuous from 1040 Ma to 940 Ma. Combined field, compositional and geochronological data indicate that the last major deformation occurred at 990 Ma and that a distinction can be made between early post-Grenvillian magmatism (985–975 Ma) and late post-Grenvillian magmatism (975–950 Ma). Such differences go beyond the utility of Figure 22.4, which merely shows that the early part of Grenvillian orogenesis in the Pinware terrane mostly involved metamorphism, whereas magmatism was voluminous during the later part.

22.2 Rb–Sr

It has been more than 25 years since Rb–Sr isotopic analysis has been carried out in eastern Labrador with the objective of dating geological units, having been superseded by other methods, especially U–Pb geochronological techniques. The changeover from Rb–Sr to U–Pb started in the mid-1980s. Mapping at 1:100 000 scale started in the north and gradually progressed southward, thus the Rb–Sr data that was acquired is based on sample suites from the Makkovik Province, and more northerly terranes in the Grenville Province.

The Rb–Sr whole-rock dating technique requires a suite of cogenetic samples having a sufficient spread in Rb/Sr ratios to facilitate meaningful regression analysis of the results. Two inherent disadvantages in assembling such suites are: i) that the greater their compositional range, then the increased probability of the samples not being co-genetic, and ii) even if they are, that they all remained closed systems (*cf.* discussion by Dickin, 2005). Both issues apply to the eastern Labrador suites investigated, and they are addressed in the following sections. Nevertheless, although replaced as a dating technique, the Rb–Sr technique is still potentially useful as a petrogenetic tool in crustal evolutionary studies.

All data for eastern Labrador are compiled in a database, which contains complete analytical data, regression treatment, and other pertinent information. The results extracted from this database are reviewed in two parts, namely: i) suites to which regression analysis has been applied and, ii) model initial Sr ratios ($I_{Sr(t)}$) for single samples using an inferred age, or a known age from U–Pb methods.

22.2.1 SUITES TO WHICH REGRESSION ANALYSIS HAS BEEN APPLIED

A listing of units for which isochrons or errorchrons (these are distinguished in the database) have been determined is given in Table 22.1, arranged in order of structural region, from north to south, then in order of decreasing regression age within each region. The known or inferred emplacement age (the latter with a question mark if based partly on field relationships and some guesswork) is also given. For the most part, in the original Rb–Sr regressions, the age obtained correlates, within error, with the U–Pb age where known, although large errors associated with some regressions make that 'consistency' readily achievable.

Initial ratios calculated from the regression (I_{Sr}) are given in Table 22.1 and plotted against regression age in Figure 22.5A. The data are divided according to initial ratio precision (I_{Sr} error greater or less than 0.001), but varying precision does not seem to be a major factor. Despite some of the ages being imprecise, there is a reasonable consistency in regard to the initial ratios obtained – with two exceptions. One is the Strawberry Intrusive Suite, which may have experienced loss of radiogenic Sr. In the case of the other exception (Upper North River pluton), the emplacement age is known to be 1296 Ma from U–Pb dating. The regression age is consistent with time of Grenvillian metamorphism, so the high initial ratio is interpretable in terms of isotopic resetting of the Rb–Sr system at that time.

Units listed in Table 22.1 that require individual explanation are as follows:

i) West of Brig Island gabbro. This is a layered mafic unit that is assumed to be temporally correlative with the Adlavik Intrusive Suite, but such has not been demonstrated,

ii) Stag Bay granitoid. Although the Rb–Sr date is almost certainly 'too young', the U–Pb age is only based on one analysis,

iii) The Cuff Island granodiorite regression is based on a geographically spread suite, which may not comprise co-genetic samples, and the 1709 Ma U–Pb age is somewhat anomalous for the region,

iv) Both the Saddle Island metasedimentary gneiss and the Paradise metasedimentary gneiss belt are part of the PMGB, but from separate areas. The emplacement age of 1800 Ma is a guess, as the U–Pb dates that are available (1654 and 1638 Ma) date metamorphism, and

Table 22.1. Units in eastern Labrador for which Rb–Sr isochrons or errorchrons hae been reported

Unit	U–Pb Emplacement Age (Ma)	Rb–Sr Regression Age (Ma)	Initial Sr ratio	Reference
Makkovik Province (Cape Harrison domain)				
Big River granite	1802	1798 ± 28	0.70173 ± 88	Kerr (1989)
Benedict Mountains Intrusive Suite granodiorite (Unit 6A)	1800?	1787 ± 35	0.70233 ± 20	Owen *et al.* (1988)
West of Brig Island gabbro (Unit 6)	1650?	1747 ± 310	0.7025 ± 7	Owen (1985)
Cape Harrison gneissic tonalite	1815?	1740 ± 85	0.7034 ± 6	Brooks (1982a)
Benedict Mountains Intrusive Suite biotite granite (Unit 6E)	1750?	1725 ± 31	0.7032 ± 6	Owen *et al.* (1988)
Holton Harbour syenite	1700?	1725 ± 134	0.7024 ± 41	Brooks (1982a)
Stag Bay granitoid	1800?	1714 ± 44	0.70352 ± 46	Kerr (1989)
Benedict Mountains Intrusive Suite monzodiorite (Unit 6B)	1750?	1697 ± 41	0.7040 ± 5	Owen *et al.* (1988)
Strawberry Intrusive Suite–Bayhead granite	1719	1694 ± 56	0.69790 ± 640	Kerr (1989)
Holton Harbour ferrosyenite–ferrodiorite (Unit 9)	1700?	1676 ± 77	0.7020 ± 13	Owen *et al.* (1988)
Mount Benedict (1649 Ma) syenite–monzonite	1649	1625 ± 50	0.7016 ± 24	Brooks (1982a)
Groswater Bay terrane				
White Bear Islands dioritic gneiss (Unit 2)	1799	1923 ± 148	0.7026 ± 5	Owen *et al.* (1988)
White Bear Islands jotunitic gneiss (Unit 3A)	1799	1899 ± 187	0.7028 ± 15	Owen *et al.* (1988)
Cuff Island (1709 Ma) homogeneous granodiorite (337)	1709?	1629 ± 68	0.70287 ± 62	Brooks (1982b)
Hare Harbour tonalite gneiss	1650?	1610 ± 50	0.70302 ± 40	Brooks (1983a)
Grady Island intrusion	1644	1610 ± 30	0.70264 ± 12	Brooks (1983a)
Michael gabbro	1450–1425	1461 ± 96	0.7033 ± 21	Fahrig & Loveridge (1981)
Michael gabbro	1450–1425	1175 ± 130	0.70428	Emslie *et al.* (1997)
Hawke River terrane				
Paradise Metasedimentary Gneiss Belt (amphibolite facies)	1800?	1663 ± 64	0.7043 ± 10	Prevec *et al.* (1990)
White Bear Arm complex (granitoid rocks)	1640	1621 ± 48	0.7035 ± 8	Prevec *et al.* (1990)
Paradise Arm pluton	1639	1573 ± 40	0.7043 ± 5	Prevec *et al.* (1990)
Eagle River granodiorite	1650?	1555 ± 195	0.7036 ± 30	Brooks (1983a)
Saddle Island (>1654 Ma) metasedimentary gneiss	1800?	1445 ± 220	0.7048 ± 24	Brooks (1983a)
Lake Melville terrane				
East Lake Melville granodioritic gneiss	1650?	1547 ± 60	0.703 ± 3	Brooks (1984)
Upper North River pluton	1296	1085 ± 110	0.717 ± 8	Brooks (1984)
Mealy Mountains terrane				
Mealy Mountains Intrusive Suite monzonite–granite	1655–1625	1678 ± 77	0.7031 ± 10	Emslie *et al.* (1983)
Mealy dyke	1250	1380 ± 54	0.7028 ± 2	Emslie *et al.* (1984)

v) The U–Pb age of 1296 Ma for the Upper North River pluton is precise, so the 1085 Ma regression age is clearly indicating Grenvillian metamorphism, and is the only sample that does. This is in keeping with it being in the Lake Melville terrane, known to have been strongly affected during Grenvillian orogenesis, whereas the terranes farther north were not.

22.2.2 INITIAL Sr RATIOS FOR SINGLE SAMPLES DATED BY U–Pb METHODS

Initial Sr ratios can be determined from the Rb–Sr isotopic systematics of single samples, if the age of the sample is known by other means. The most reliable and precise dating is generally by U–Pb methods, but ages can also be assigned drawing on inferences from field relationships and knowledge of times and characteristics of regional geological events.

Figure 22.5B depicts model initial Sr ratios ($I_{Sr(t)}$) for samples to which a time of emplacement has been assigned by the author using a variety of approaches. It is immediately obvious that many of the initial Sr ratios thus calculated are geologically unreasonable, in that they fall below (or well above) the ^{87}Rb/^{86}Sr mantle evolution line for their inferred age. As is evident from the figure, these samples are characterized by high ^{87}Rb/^{86}Sr ratios. The most egregiously

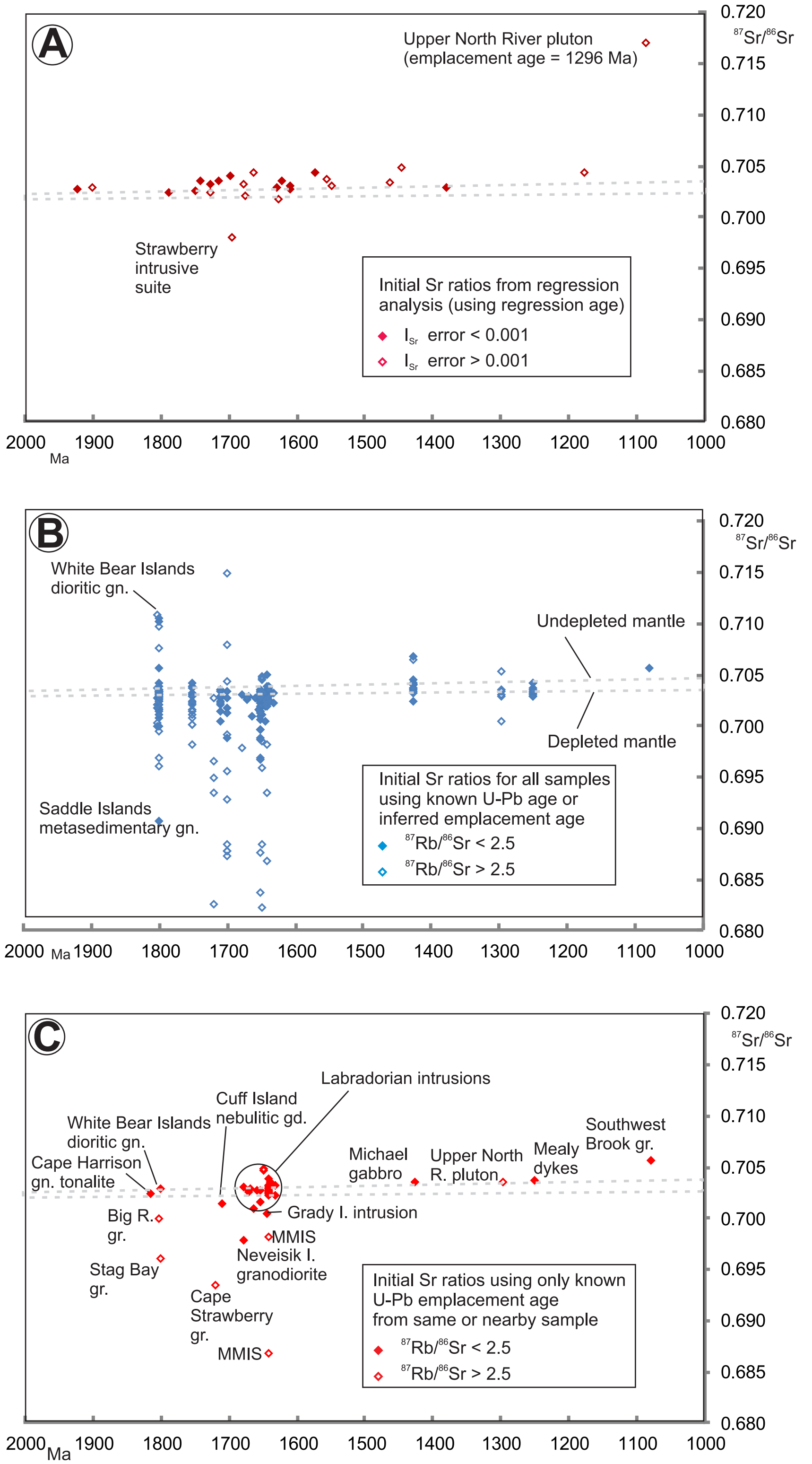

Figure 22.5. *Rb–Sr isotopic data. A. Initial ratios from regression analysis using regression age, B. Initial ratios for all samples using known U–Pb age or inferred emplacement age, C. Initial ratios using only known emplacement ages from same or nearby sample.*

low $I_{Sr(t)}$ values are mainly from Makkovik Province suites, namely from the Stag Bay granitoid, the Cape Strawberry granite, the Holton Harbour ferrosyenite, and the Mount Benedict syenite–monzonite (suites not identified separately on Figure 22.5B). The Sr initial ratios calculated for each of the Stag Bay Rb–Sr samples assumed that the single 1800 Ma U–Pb analysis that was adopted is a more valid age for the body than the 1714 ± 44 Ma Rb–Sr errorchron date (which gives a reasonable I_{Sr} = 0.70352). In the Grenville Province, the East Lake Melville granodiorite gneiss in Lake Melville terrane also includes some very high $^{87}Rb/^{86}Sr$ ratios (34.6 and 17.7 for two samples) thereby allowing the same explanation for anomalously low values of $I_{Sr(t)}$. Other samples from this suite have quite low $^{87}Rb/^{86}Sr$ ratios. The rocks have not been dated and assigning a 1650 Ma age is a guess. If 1500 Ma (Pinwarian) is assumed, then $I_{Sr(t)}$ would be reasonable, although there is no independent reason to believe that this age applies.

If filtered according to their $^{87}Rb/^{86}Sr$ ratio (accepting only those having the ratio below 2.5), most of the deviant points in Figure 22.5B are removed, with the exception of the Saddle Island metasedimentary gneiss (for which its *ca.* 1650 Ma metamorphic age probably is more relevant) and the White Bear Islands dioritic gneiss (which may not have the 1800 Ma age assigned to it). In addition, both of these rocks have $^{87}Rb/^{86}Sr$ ratio only slightly less than 2.5.

Figure 22.5C shows only those samples for which the age of the rock is generally considered to be reliably established by U–Pb methods. In most cases, the same sample was used for both U–Pb and Rb–Sr investigations, but some ages rely on dating of a nearby sample deemed to be from the same unit. Some 'problem' units have already been addressed above, to which can be added the Neveisik Island granodiorite and two samples from the Mealy Mountains intrusive suite. The samples from the

Mealy Mountains intrusive suite were reported by Hegner *et al.* (2010), who attributed them to disturbance related to high $^{87}Rb/^{86}Sr$ ratios. Along with the units in Figure 22.5C eliminated by having $^{87}Rb/^{86}Sr$ ratios >2.5 are the otherwise acceptable Bluff Head granodiorite, a Mealy Mountains intrusive suite granite, and the Upper North River pluton.

It can be concluded that the dual issues of inadequately established emplacement ages and sensitivity to open-system radiogenic Sr behaviour are too severe to allow indiscriminant appeal to $I_{Sr(t)}$ as a petrogenetic tool. If the age is known and samples are filtered to retain only those samples having low $^{87}Rb/^{86}Sr$ ratios, then perhaps meaningful results may be achieved. On this basis, left remaining in Figure 22.5C is a tight cluster of well-dated samples having a Labradorian age that plot realistically close to the Sr evolution line. As has already been argued by Schärer (1991), this suggests minimal involvement of appreciably older crust in the generation of these rocks. For post-Labradorian rocks, dated samples of Michael gabbro, Upper North River pluton and Mealy dykes all fall near the undepleted mantle Sr evolution line, but note that this is not necessarily the case for undated samples of the same suites for which the same age has been assumed. The Southwest Brook granite lies above the mantle Sr evolution line, explicable in terms of crustal anatexis of older crust.

22.3 Sm–Nd

During the last three decades, a substantial body of Sm–Nd isotopic data has accumulated for eastern Labrador, adjacent Québec and western Newfoundland, extending from the Paleoproterozoic Makkovik Province in the north, to the Paleo- and Meso- Proterozoic crust in the Long Range Inlier in the south.

The published studies can be divided into two groups. The first group comprises regional studies addressing crustal formation issues. Included here are the investigations of Kerr and Fryer (1994) in the Makkovik Province, Schärer (1991) in the northern part of the Grenville Province in eastern Labrador, and Dickin (2000, 2004) in southern part of the Grenville Province in eastern Labrador, and adjacent Québec and western Newfoundland. The second group either focuses on small areas and/or petrogenetic topics in specific units, such as the Cape Harrison Metamorphic Suite (Ketchum *et al.*, 2002), the Mealy Mountains intrusive suite (Ashwal *et al.*, 1986; Hegner *et al.*, 2010; Bybee *et al.*, 2014; 2015; Bybee and Ashwal, 2015), the White Bear Arm complex (Prevec *et al.*, 1990), the Michael gabbro (Emslie *et al.*, 1997; Devereaux, 2011), the Mealy dykes (Ashwal *et al.*, 1986), and miscellaneous data obtained by Brooks (1983), Owen *et al.* (1992), Sinclair *et al.* (2002), Kerr and Wardle (1997), and Parsons and James (2003).

In additional, throughout much of eastern Labrador, Sm–Nd isotopic data have also been obtained on some of the author's samples by R. Creaser (University of Alberta, Edmonton) and J. Daly (University College, Dublin), through contracts with the Geological Survey of Newfoundland and Labrador. The depleted mantle model ages (T_{DM}; DePaulo, 1981) and εNd values for these samples have been included on the 1:100 000-scale geological maps of the author and are in the author's database, but are otherwise formally unpublished. With the analysts' agreement, the analytical data were made available to Hewitson (2010) for incorporation into her M.Sc. thesis on Nd isotopic mapping in southern Labrador. Additional data on the author's samples were acquired by Moumblow and incorporated into her region-wide Ph.D. synthesis (Moumblow (formerly Hewitson), 2014).

The rocks investigated are reviewed according to the following groups, namely: i) Paleoproterozoic and early Mesoproterozoic felsic plutonic and volcanic rocks, ii) Paleoproterozoic metasedimentary gneiss and mafic volcanic rocks, iii) late Paleoproterozoic mafic plutonic and anorthositic rocks, iv) Mesoproterozoic mafic intrusions, and v) Mesoproterozoic plutonic and minor felsic intrusions. All are included in an emplacement age *vs.* εNd plot in Figure 22.6A. The felsic plutonic rocks, by far, form the largest group of analyses, being the rock type of choice for crustal formation studies. The felsic volcanic rocks (some may be hypabyssal) are minor and U–Pb ages and geochemical data indicate that they are the high-level intrusive or extrusive equivalents of the felsic plutonic rocks, so their Sm–Nd analytical data can be treated similarly to the plutonic rocks. Both Makkovikian and Labradorian felsic volcanic rocks are present. The metasedimentary gneiss group is also small. The rocks are probably coeval with late Makkovikian plutonic and volcanic rocks and derived from them. A single analysis of mafic volcanic rock from Bull Island in the Hawke River terrane is interpreted as having an 1800 Ma extrusion age, based on its having a (minimum) 1645 Ma U–Pb metamorphic age and its association with pelitic gneiss. Mafic and anorthositic rocks mostly have mid- to late-Labradorian ages, and are co-related. Mesoproterozoic mafic rocks include the Michael gabbro and the Mealy dykes. Mesoproterozoic felsic plutonic and minor intrusions are late Mesoproterozoic, and include those emplaced during various phases of Grenvillian orogenesis.

In the author's database, ages to be used in calculations have been assigned to each sample. This has been done on the basis of four levels of decreasing reliability, namely: i) the same sample was used for Sm–Nd analysis and U–Pb dating, ii) the Sm–Nd and U–Pb analyses were made on different samples from the same locality, iii) the Sm–Nd analysis is inferred to be from the same unit as a sample dated

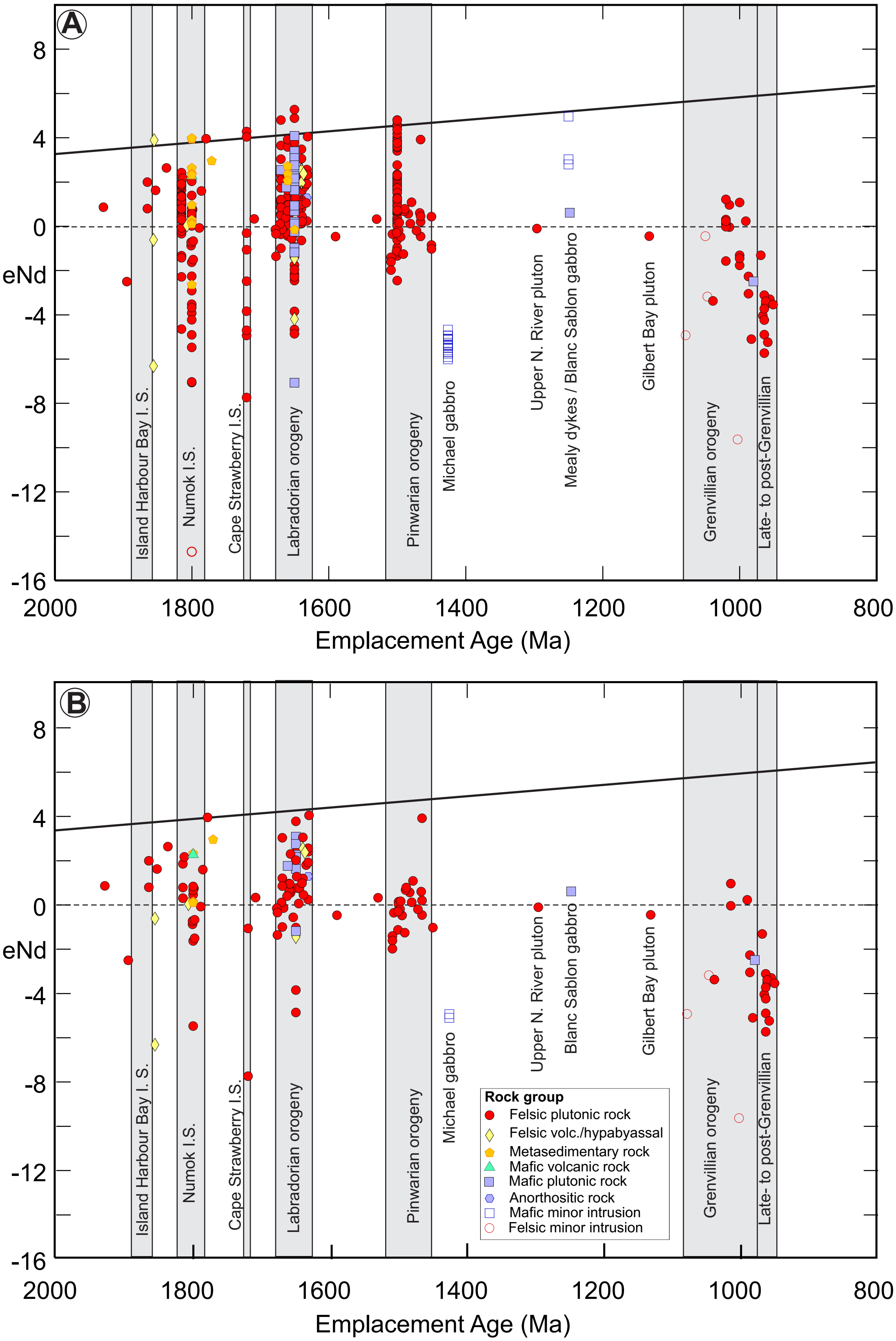

Figure 22.6. *Sm–Nd epsilon* vs. *age plots. A. All samples, assuming emplacement age where not determined, B. Only samples for which emplacement age is known.*

from another locality, and iv) the age of the sample used for Sm–Nd analysis is unknown and inferred on the basis of regional probability. About one quarter of the samples fall into the same-sample category. These have been plotted in Figure 22.6B and show much more restricted εNd values. This does not mean that all Sm–Nd undated samples should be discarded. Those from the same locality are generally almost as reliable, and some units are so well-defined chemically such that, even if sampled from a separate site, there is little doubt regarding the unit's age (*e.g.*, Mealy dykes, for which 3 Sm–Nd analyses are available, but none from the dated locality).

The reader should also be aware that the original Sm–Nd data have been modified by the author for the following reasons: i) to correct errors in original sources (*see* 'comments' column in database), ii) to recalculate εNd values from originally reported values using more reliable age data, iii) to standardize calculation methods, and iv) to provide exact co-ordinates, rather than sketch-map locations given previously in many instances.

22.3.1 PALEOPROTEROZOIC AND EARLY MESOPROTEROZOIC FELSIC PLUTONIC AND VOLCANIC ROCKS

Depleted mantle model ages for pre-Makkovikian, Makkovikian, Labradorian and Pinwarian felsic plutonic and felsic volcanic rocks are shown in Figure 22.7 subdivided here into four T_{DM} age groups. Samples having T_{DM} ages >2.25 Ga occur mostly in Kaipokok and Aillik domains in the Makkovik Province and were interpreted by Kerr and Fryer (1994) and Kerr *et al.* (1996) as having been derived (at least in part) from an Archean source. Kerr and Fryer defined a boundary that more-or-less coincides with the Aillik–Cape Harrison domain boundary. The Sm–Nd isotopic boundary was interpreted as marking the interface between Archean crust (reworked and largely cryptic) in the Aillik domain, and Lower Proterozoic juvenile crust in the Cape Harrison domain. This boundary is about 40 km east of the mapped limit of 'intact' Archean crust in the Nain Province. The extrapolation of this boundary into the offshore region is based on analyses of core samples obtained from offshore drilling (Kerr and Wardle, 1997). Moumblow (2014) and Moumblow *et al.* (2018) added considerably to the data available for the Cape Harrison domain, determining that T_{DM} model ages across the domain are relatively uniform. She noted that this discourages models involving accretion of two separate arcs, as has been previously proposed by Ketchum *et al.* (2002).

A new finding, reported by Moumblow (2014) and Moumblow *et al.* (2018), is the presence of two anomalously old T_{DM} ages from the eastern Makkovik Province, in its border region with the Grenville Province. One is from the East Lake Michael granite and has T_{DM} = 2.64 Ga and εNd (1815 Ma) = –4.65, and the other is from the Alliuk Bight megacrystic granitoid unit and has T_{DM} = 2.25 Ga and εNd (1815 Ma) = –1.3. The two samples are aligned with the regional structural trend and are about 17 km apart. Moumblow (2014) interpreted the results to imply Archean crust, and/or lower Proterozoic crust with an Archean crustal component.

Within the Grenville Province, a north-to-south overall decrease in T_{DM} ages is evident, inasmuch as pre-1.93 Ga model ages are most common in the north, whereas post-1.93 Ga ages dominate farther south. This distinction was first recognized by Dickin (2000), who assigned the names 'Makkovikia' and 'Labradoria' to the northern and southern regions, respectively. Using more data, Moumblow (2014) grouped the older (pre-1.85 Ga) T_{DM} ages in the northern terranes (Groswater Bay, Hawke River, Lake Melville and part of the Mealy Mountains terrane) as a 'Cartwright Suite'. In the south, Moumblow (2014) suggested that an additional boundary exists between the northern Pinware terrane characterized by some 1.85 Ga or older model ages, and the southern Pinware terrane where >1.85 Ga model ages are rare (not evident in Figure 22.7 because of data bins adopted).

In the southern part of the Pinware terrane, one sample is particularly anomalous (CG99-195A, at the Labrador–Québec border). This sample has been analyzed three times, yielding T_{DM} model ages of 2.11 Ga (R. Creaser, personal communication, 1999), 2.13 and 2.18 Ga (both by Moumblow, 2014), and having εNd (1509 Ma) values of –1.41, –1.61 and –1.98, respectively. One might be tempted to interpret the rock as having a metasedimentary origin, but such an explanation is difficult to reconcile with its petrographic appearance as foliated granite and its U–Pb zircon age of 1509 +7/–6 Ma, without indication of older inherited material. Nevertheless, detrital zircon having *ca.* 2.4 Ga ages does occur 30 km to the northwest in a feldspathic quartzite, so such a source may not be far away.

Although outside the scope of this report, Sm–Nd isotopic data for the Long Range Inlier in western Newfoundland have been included for completeness. The results show even younger T_{DM} ages (<1.71 Ga) in the southern part of the inlier. These were recognized as distinct by Dickin (2004) and included as part of his 'Quebecia' crustal block.

22.3.2 PALEOPROTEROZOIC METASEDIMENTARY AND MAFIC VOLCANIC ROCKS

As mentioned earlier, evidence suggests that the metasedimentary gneiss is probably coeval with the Makkovikian felsic plutonic rocks and partly derived from them when

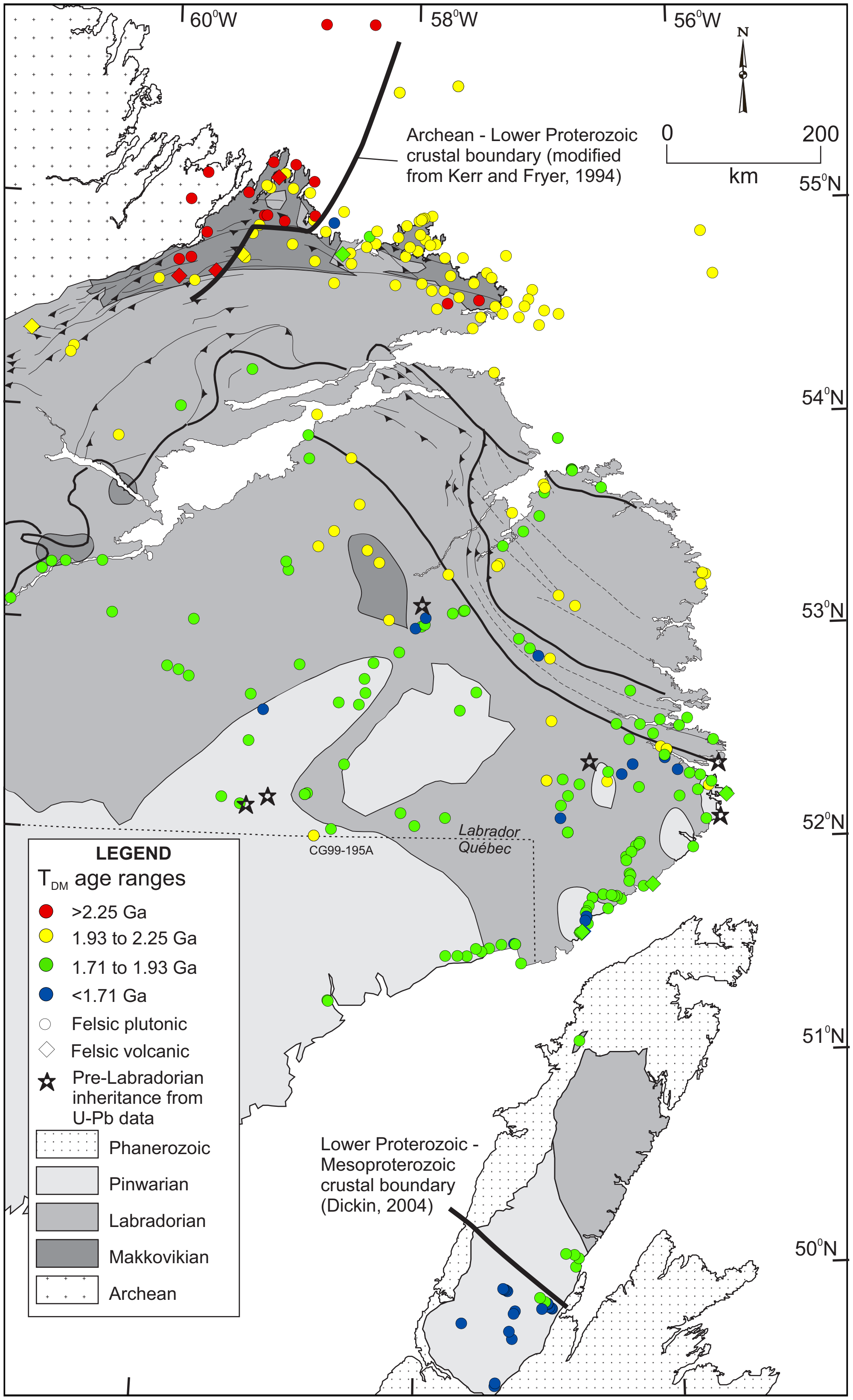

Figure 22.7. *Depleted mantle (T_{DM}) age-group distribution in eastern Labrador for felsic plutonic and volcanic rocks.*

they were uplifted and eroded. The data (Figure 22.8) show T_{DM} ages ranging from 2.29 to 1.78 Ga, compatible with a mixed Archean–Lower Proterozoic (Makkovikian) source. Three additional explanatory comments are warranted.

First, time of deposition is uncertain for most samples and the protolith questionable for some. Three directly U–Pb-dated metasedimentary gneiss samples in the Hawke River terrane yielded ages that were interpreted to date metamorphism. Two other directly dated samples, in the west, are from quartzofeldspathic enclaves, for which a supracrustal protolith is equivocal, although the most likely. Similarly, the three granulite gneiss results from the northwest, which were reported by Hegner *et al.* (2010), are inferred by the author to have a metasedimentary protolith, on the basis of him having seen cordierite-bearing enclaves

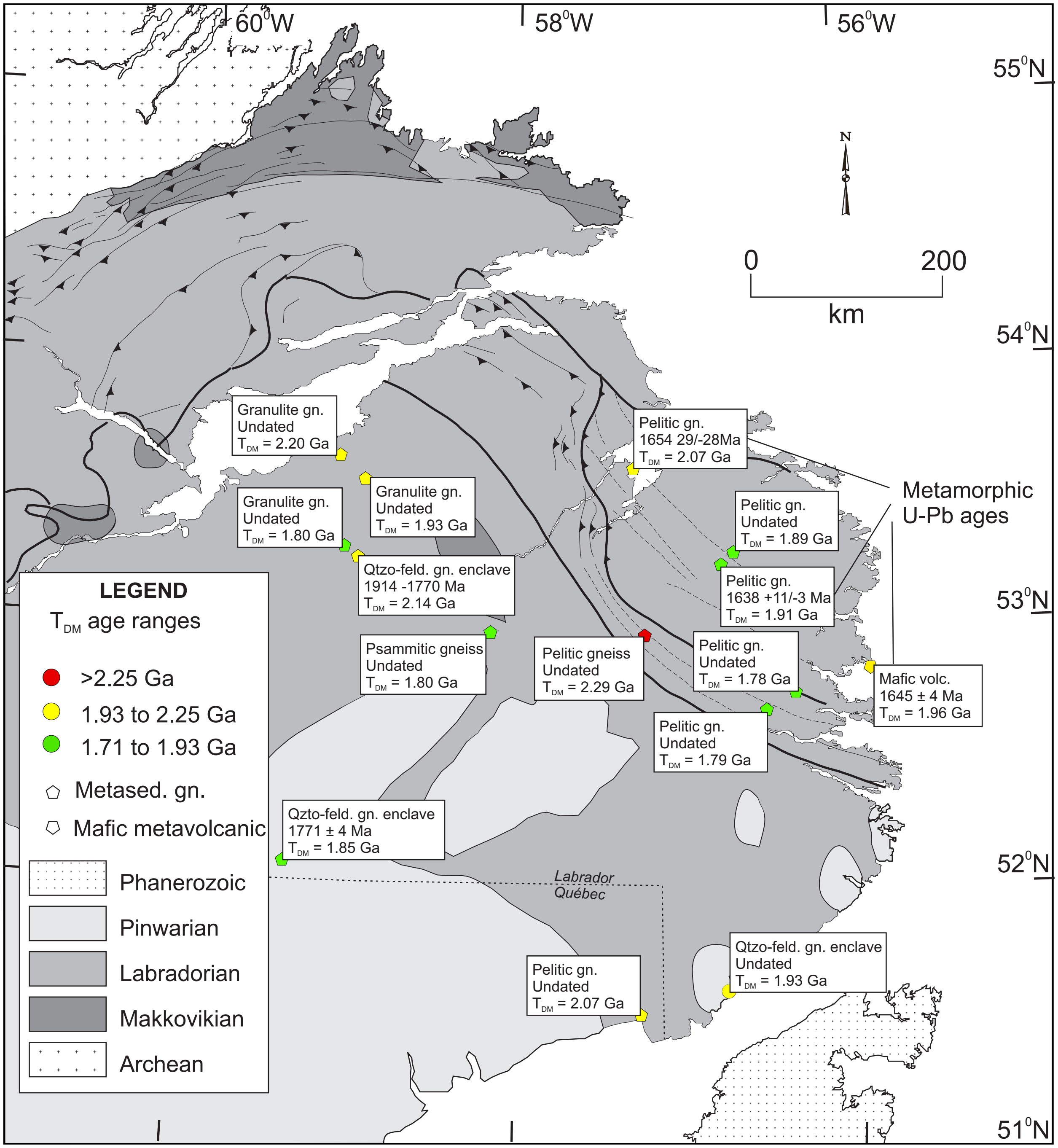

Figure 22.8. *Depleted mantle (T_{DM}) age-group distribution in eastern Labrador for metasedimentary gneiss and mafic volcanic rocks.*

within the Mealy Mountains intrusive suite in the same area, and matching rocks that were termed by Emslie (1976) as ‘granulites of uncertain origin’.

Second, the oldest T_{DM} age is for pelitic gneiss in the Lake Melville terrane at T_{DM} = 2.29 Ga. The gneiss forms rafts within K-feldspar megacrystic granitoid rock, which has a T_{DM} age of 1.91 Ga. The granitoid rock is undated at this locality but is likely Labradorian, on the basis of similarity with K-feldspar megacrystic granitoid rocks elsewhere in the terrane for which ages are known.

Third, the sample of mafic volcanic rock comes from unpillowed mafic flow, within pillowed mafic volcanic rocks. In this case, of course, the rock is not from mixed surface-rock sources, so the T_{DM} age (1.96 Ga) more directly reflects time of separation from the mantle.

22.3.3 LATE PALEOPROTEROZOIC MAFIC PLUTONIC AND ANORTHOSITIC ROCKS

The late Paleoproterozoic mafic plutonic rock samples, for which Sm–Nd data are available, are mostly from the Makkovik Province, Groswater Bay and Hawke River terranes, apart from two from the Mealy Mountains terrane. In contrast, the anorthositic samples are all from the Mealy Mountains intrusive suite, in the Mealy Mountains terrane. Regardless of location or composition, most of the T_{DM} values are between 2.0 and 1.8 Ga, similar to their felsic plutonic counterparts. The values do not show any systematic variation (Figure 22.9).

A few exceptions deserve mention. One is a gabbro/monzodiorite at the western margin of the Aillik domain that has T_{DM} = 2.45 Ga. The rock has not been dated but was interpreted by Kerr and Fryer (1994) to be Labradorian. Its close proximity to intact Archean crust and anomalous T_{DM} value may imply that the rock is older. Another undated mafic plutonic unit is the Pottles Bay mafic intrusion in the eastern part of the Groswater Bay terrane. It has been interpreted (by the author) to be Labradorian, but shows anomalously old T_{DM} ages of 2.19 and 2.30 Ga. Note that these are from the same area (but 10 km farther south) as two felsic plutonic rocks that show anomalously old T_{DM} ages (>2.25 Ga). Curiously, a mafic rock from the same area has an anomalously old K–Ar age of 2179 ± 68 Ma (termed Michael gabbro when reported; Wanless *et al.*, 1973, sample GSC72-140). One gabbro/ultramafic rock, from the Groswater Bay terrane, shows a much younger T_{DM} age of 1.66 Ga.

The anorthositic Sm–Nd isotopic results from the Mealy Mountains intrusive suite were evaluated by Hegner *et al.* (2010), Bybee *et al.* (2014) and Bybee and Ashwal (2015). The data are interpreted in terms of assimilation of crust by a mantle-derived melt at the mantle–lower crust interface.

22.3.4 MESOPROTEROZOIC MAFIC INTRUSIONS

Three units are included in this section, the 1450 Ma Michael gabbro, the 1250 Ma Mealy dykes, and the 1248 Ma Blanc-Sablon gabbro (Figure 22.10).

22.3.4.1 Michael Gabbro

The Michael gabbro has been investigated by Emslie *et al.* (1997) and Deveraux (2011). These studies reported T_{DM} = 2.26 to 2.46 Ga and εNd (1426 Ma) = –6.01 to –4.94. Emslie *et al.* (1997) concluded that the average Sm–Nd isotopic composition of the Labradorian crust into which the Michael gabbro is emplaced was not sufficiently enriched (*i.e.*, εNd not ‘negative’ enough) to be an assimilated source that would account for the Sm–Nd isotopic composition of the Michael gabbro (or the Shabogamo gabbro, its correlative in western Labrador). An alternative source was suggested to be subcontinental lithospheric mantle, which had been enriched during its formation or shortly thereafter. The study of Devereaux (2011) utilized the markedly enriched Sm–Nd character of the Michael gabbro to distinguish between it and Adlavik Intrusive Suite. Both units occur geographically together, have similar petrographic features (especially when strongly metamorphosed), and have overlapping whole-rock chemical compositions, so this work provided a very useful identification tool.

One anomalous sample (CG82-036) requires special mention. It was originally mapped as Michael gabbro by the author but, from duplicate analyses of the same sample, has T_{DM} = 1.47 and 1.32 Ga and εNd = +1.6 and +4.0 (Devereaux, 2011). It clearly is not Michael gabbro, but does not readily match any other unit either. The outcrop needs resampling and further investigation.

22.3.4.2 Mealy Dykes

The Sm–Nd isotopic character of the Mealy dykes is in stark contrast to the Michael gabbro. Three analyses are available, having T_{DM} = 1.27 to 1.51 Ga and εNd (1250 Ma) = +2.79 to +4.95 (Ashwal *et al.*, 1986). The εNd values are comparable to depleted mantle at 1250 Ma, which was deemed by Ashwal *et al.* (1986) to be the probable magmatic source. The present close mutual proximity of the Michael gabbro and Mealy dykes, plus only a 200-million-year time difference but contrasting mantle sources, might be regarded as a problem. As has been pointed out by Emslie *et al.* (1997), however, given the telescoping nature of Grenvillian thrusting, neighbourliness may not have an issue during emplacement.

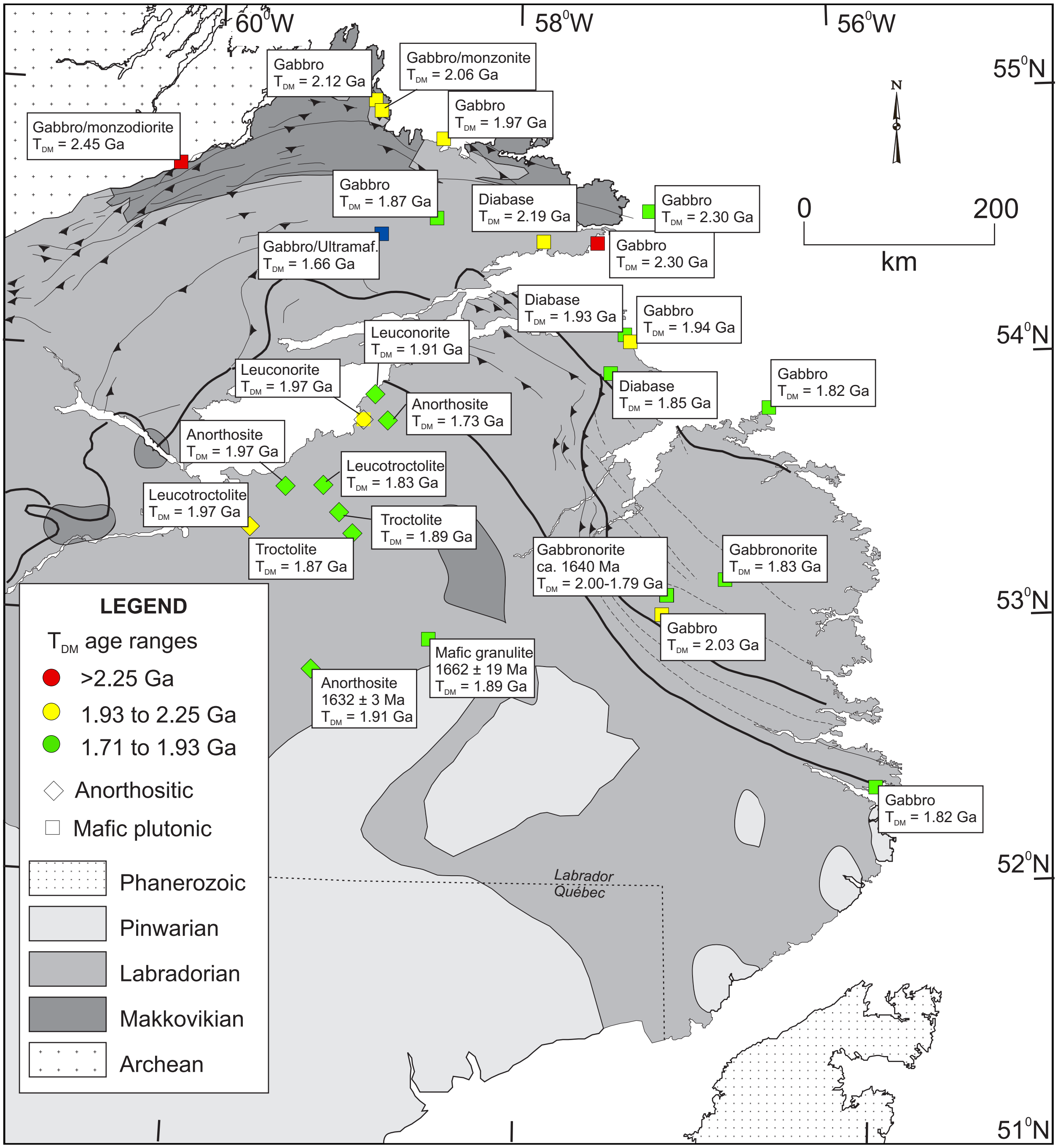

Figure 22.9. *Depleted mantle (T_{DM}) age-group distribution in eastern Labrador for late Paleoproterozoic mafic plutonic and anorthositic rocks.*

22.3.4.3 Blanc-Sablon Gabbro

The 1248 Ma Blanc-Sablon gabbro has very different character to that of the Mealy dykes, having T_{DM} = 1.73 Ga and εNd = +0.61. These values are compatible with a Pinwarian mantle source.

22.3.5 MESOPROTEROZOIC FELSIC PLUTONIC ROCKS AND MINOR INTRUSIONS

Sm–Nd isotopic data for late Mesoproterozoic samples are displayed in Figure 22.11, and have been separated into two groups, namely samples having U–Pb emplacement

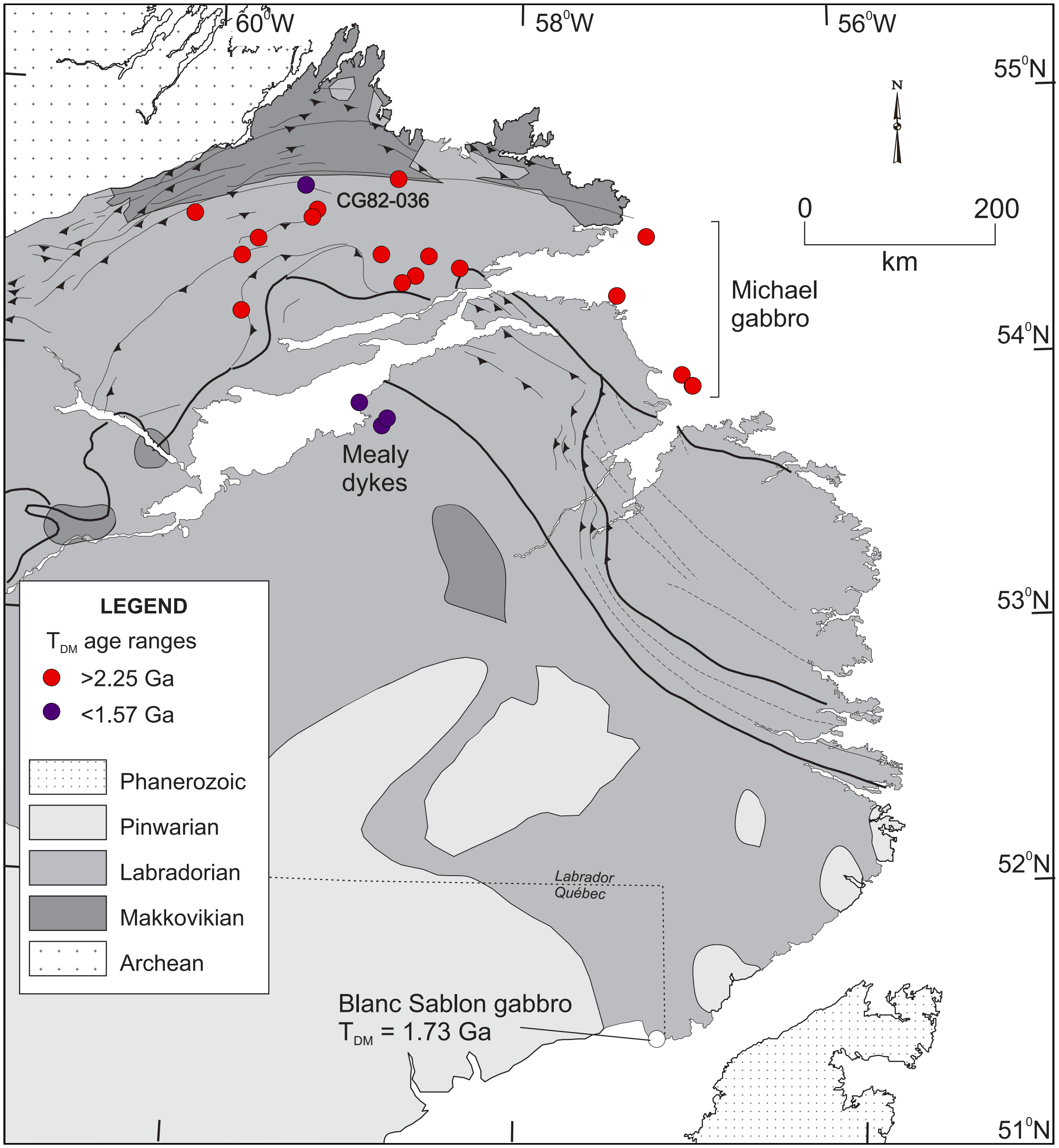

Figure 22.10. *Depleted mantle (T_{DM}) age-group distribution in eastern Labrador for Michael gabbro, Mealy dykes and Blanc-Sablon gabbro.*

ages between 1300 and 990 Ma and those between 990 and 950 Ma. The 990-Ma time boundary was chosen because this marks the end of severe Grenvillian deformation, signalling a change in tectonic regime.

Apart from two exceptions, all results are related to Grenvillian orogenesis. The two exceptions are 1296 Ma Upper North River pluton and the 1132 Ma Gilbert Bay granite, both in the Lake Melville terrane. The Upper North River syenite has all the hallmarks of a crustally derived body and its T_{DM} age of 1.90 Ga is consistent with values determined from the surrounding granitoid gneisses. The Gilbert Bay pluton is isotopically quite different, having a T_{DM} age of 1.47 Ga, thus denying significant contribution from a lower Proterozoic crustal source. Note that, along with the intervening syn-Grenvillian minor granitoid intru-

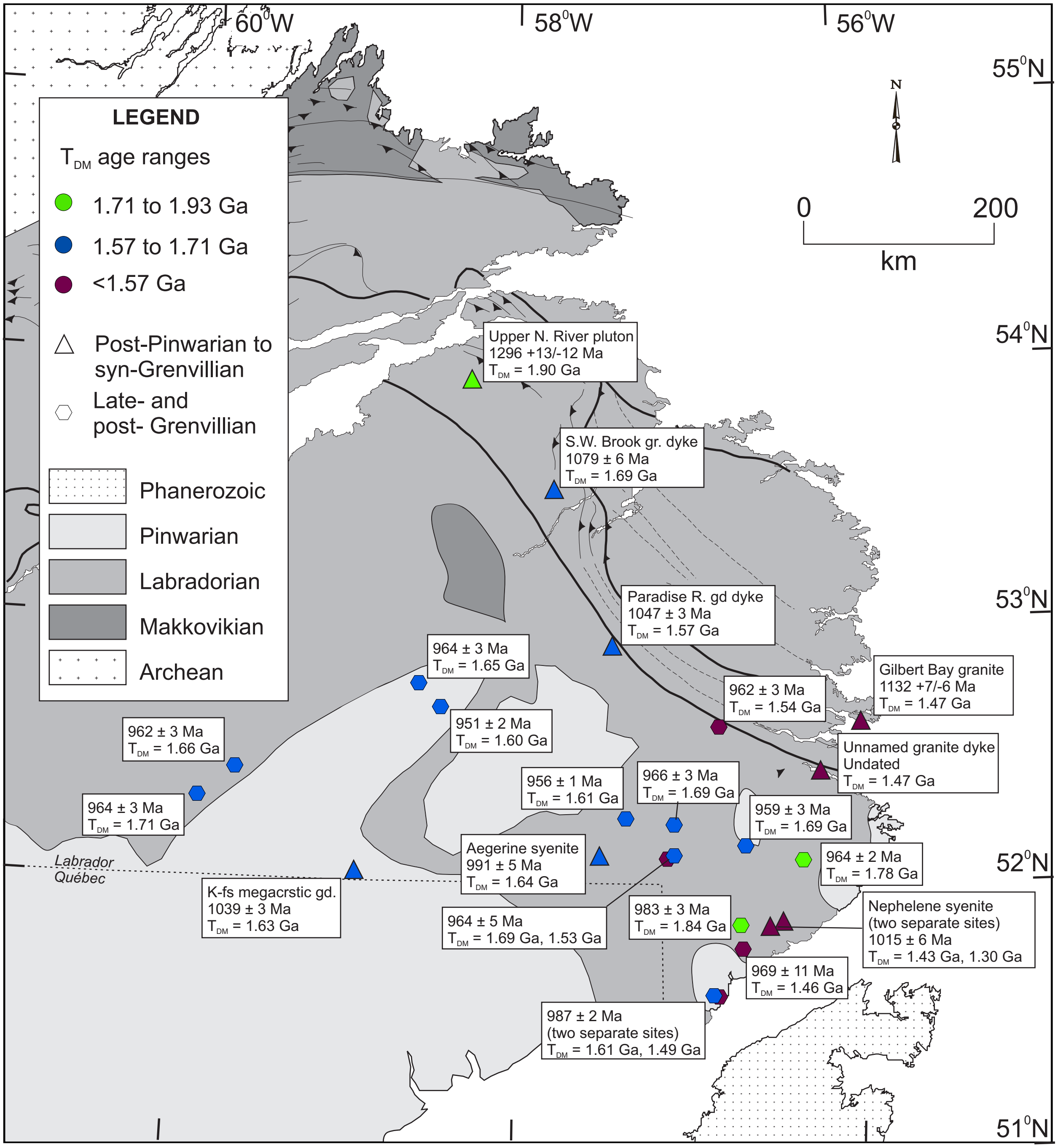

Figure 22.11. *Depleted mantle (T_{DM}) age-group distribution in eastern Labrador for Mesoproterozoic felsic plutonic rocks and minor felsic intrusions.*

sions, the T_{DM} ages for this group of samples steadily decrease from northwest to southeast along the length of the Lake Melville terrane.

In the Pinware terrane, Sm–Nd isotopic data have only been obtained from three syn-Grenvillian felsic plutonic intrusions. The western two (one at 1039 ± 3Ma and the other at 991 ± 5 Ma) have T_{DM} ages of 1.64 and 1.63 Ga, whereas, in the east, two analyses from separate sites on the same intrusion (a nepheline syenite) yielded T_{DM} values of 1.43 and 1.30 Ga.

In regard to late- to post-Grenvillian granitoid plutons, which have emplacement ages between 969 and 951 Ma, the striking feature is the uniformity in T_{DM} ages between 1.71 and 1.61 Ga, with the exception of four of the most easterly bodies, two of which have older T_{DM} ages of 1.84 and 1.78 Ma, and two of which have younger values of 1.49 and 1.43 Ga.

Collectively, the post-Pinwarian data from the Lake Melville and Pinware terranes suggest contribution from a progressively younger mantle source in a southeast direction. The greater diversity of T_{DM} ages in the southeasternmost area may imply less thorough mixing of older crustal and younger mantle material (as the cratonic margin is approached?).

22.4 Ar–Ar AND K–Ar

A thorough review of Ar–Ar and K–Ar geochronological data for the whole of the eastern Grenville Province in Labrador and adjacent Québec was delivered by Gower (2003), and little has changed since then. Gower showed the distribution of Ar–Ar and K–Ar dates according to minerals analyzed, namely hornblende, biotite and muscovite. Whole-rock K–Ar data for mafic dykes, which could reflect emplacement and cooling, were excluded from the review, as was an anomalous 1242 ± 50 Ma date near Goose Bay that Gower (2003) argued was erroneously located in the original publication and, in reality, applied to a Harp dyke in the Hopedale area.

The key utilization made of the data in the eastern Grenville Province was to gain insights into the thermal history of the region by mapping thermochrons (a thermochron is defined as an equal-age contour, considered to be temperature dependent; Harper, 1967). This was the approach adopted by Gower (2003), who updated previous attempts at thermochron mapping carried out by Harper (1967), Baer (1976) and Easton (1986).

One of the findings of Gower (2003) was that the data allowed a single 1000 Ma thermochron to be defined, regardless of whether the ages were Ar–Ar or K–Ar based, plateau or total-gas, and whether the mineral was hornblende or biotite (Figure 22.12). The coincidence of hornblende and biotite thermochrons was a little surprising, as

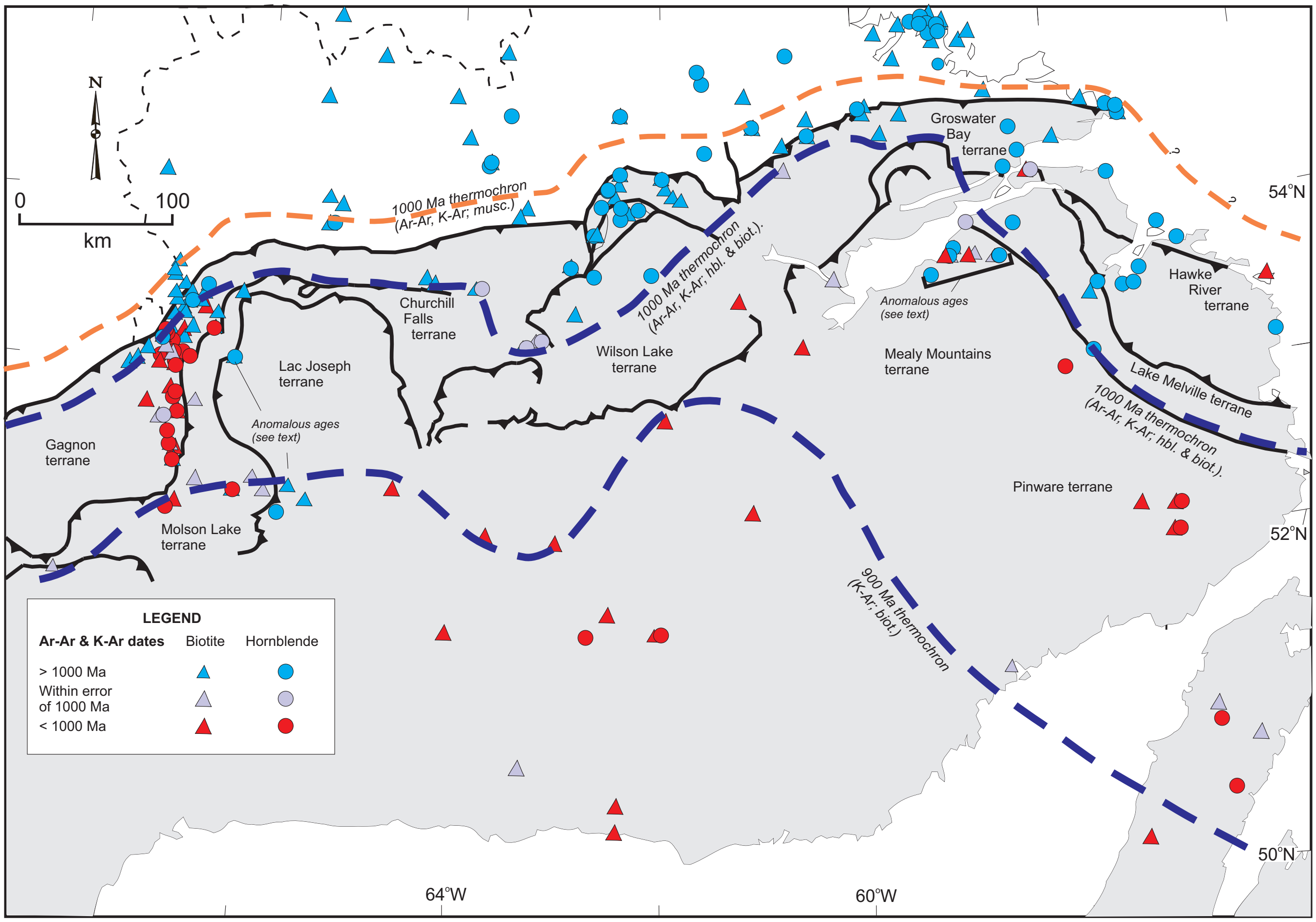

Figure 22.12. *Ar–Ar and K–Ar biotite and hornblende geochronological data for the eastern Grenville Province. Location of 1000 Ma muscovite thermochron based on data shown by Gower (2003).*

the blocking temperature of hornblende is taken to be 500°C and that of biotite to be 300°C (Shirey, 1991). It can be argued that this implies rapid uplift, an interpretation that derives support from Grenvillian U–Pb data (Gower and Krogh, 2002). The 1000 Ma thermochron does not coincide with the Grenville front, but lies some 10–80 km south of where the front is conventionally drawn. The Grenville front, however, is still delineated by a 1000-Ma muscovite thermochron (Gower, 2003), although the relative scarcity of data means the line is not well defined.

Gower (2003) termed the 1000-Ma hornblende–biotite thermochron as the 'Grenvillian thermal threshold', which he defined as the generalized limit of complete mineral resetting to Grenvillian ages in the K–Ar isotopic system. A 900 Ma thermochron, based on K–Ar biotite dates, can also be drawn farther south, having the same general shape as the 1000 Ma thermochron. The two boundaries make dog-leg changes in trend from northeast to southeast in eastern Labrador, to follow the Lake Melville–Mealy Mountains terrane boundary.

As might be expected, the division between dates above and below 1000 Ma is not knife-edge sharp. A few sites geochronologically straddle the dividing line, having ages around 1000 Ma and precision errors (commonly ± 50 Ma) that prevent more definite assignment. Gower (2003) also showed that Ar–Ar and K–Ar ages in both hornblende and biotite north of the threshold decrease southward in a systematic way as the threshold is approached. This feature was attributed to Ar loss and very few instances were recognized where there was a need to appeal to interpretations involving excess Ar.

There are remarkably few aberrant dates on the 'wrong' side of the thermochron line. In the region north of the Grenvillian thermal threshold, there are only two results inconsistent with the prevailing greater-than-1000 Ma ages. Both are K–Ar biotite dates and both are near the southern boundary of the Groswater Bay terrane (Figure 22.12). One is microcline granite dated by Grasty *et al*. (1969) to be 944 ± 12 Ma. The other is a mafic rock dated by Hunt and Roddick (1987) to be 984 ± 14 Ma, – which is spatially and temporally very close to the 1000 Ma thermochron in any case. They can be interpreted as due to localized thrust-related Grenvillian reactivation, for which U–Pb dating provides supporting evidence (*e.g.*, 1020 ± 5 Ma titanite date from sample CG81-429; location of sample shown in Figure 12.5).

In the region south of the Grenvillian thermal threshold, there are seven dates above the prevailing less-than-1000 Ma ages. They are restricted to the Lac Joseph and Mealy Mountains terranes (the 'anomalous ages (*see* text)' groups in Figure 22.12). In the case of the Mealy Mountains terrane, Gower (2003) suggested that the anomalously old ages, which are confined to the Mealy Mountains intrusive suite, might be attributed to anorthosite resistance to strain, hence denying fluid ingress and inhibiting resetting of Ar ages. It was subsequently recognized that the whole of the northern Mealy Mountains terrane was only modestly affected by Grenvillian metamorphism (Gower *et al.*, 2008b), as were parts of the Lac Joseph terrane farther west. From that observation, the concept has developed that both were part of a tectonic 'lid' during Grenvillian orogenesis (*cf.* Gower *et al.*, 2008a).

The thermochron configuration, especially when taken in conjunction with the distribution of Grenvillian U–Pb dates, is fundamental to understanding Grenvillian tectonic evolution in the eastern Grenville Province. The topic is addressed in Section 23.5.1.1.