CHAPTER 23

TECTONIC HISTORY

23.1 PRE-MAKKOVIKIAN AND MAKKOVIKIAN

Pre-Makkovikian and Makkovikian tectonic history is best preserved in the Makkovik Province and can be readily subdivided into an early extensional phase, and later accretionary phases, thus representing a complete Wilson cycle. The extensional phase (2250 – *ca.* 1950 Ma) falls outside the time period adopted for this report (commencing at 1900 Ma) but, nevertheless, it needs to be briefly addressed in order to provide context to the events that followed. Tectonic evolution models according to Kerr (1989a), Ketchum *et al.* (2002) and Culshaw *et al.* (2000) are compared in Figure 23.1. Ketchum and Culshaw are mutual co-authors (with others), so their models are complementary rather than competing. Also to be noted is that Kerr lacked much of the data (especially U–Pb geochronological) available to Ketchum and Culshaw, so his 1989 model should be considered a snapshot of his thinking at that time. It is included here because the author feels that it is foundational in many ways. Kerr's later publications (*e.g.*, Kerr *et al.*, 1996, 1997) add superstructure.

23.1.1 RIFTING STAGE (2250–2100 Ma)

The earliest recognized event related to rifting was the emplacement of the northeast-trending Kikkertavak diabase dykes at 2235 ± 2 Ma into Archean quartzofeldspathic crust (Cadman *et al.*, 1993).

Diabase dyke injection was followed by deposition of supracrustal rocks, of which the Moran Lake and Post Hill groups are preserved remnants. The Moran Lake Group is situated at the western margin of the Kaipokok domain and rests unconformably on Archean basement and its included Kikkertavak dykes (Ryan, 1984). The Warren Creek Formation is the basal unit, comprising quartzite and sandstone, overlain by shale, silicate-facies oxide iron formation, siltstone and greywacke. Stratigraphically overlying the sedimentary rocks is the Joe Pond Formation, a 1-km-thick sequence of pillowed and non-pillowed mafic volcanic rocks, with which minor chert–carbonate rocks are interbedded (Ryan, 1984). Trace-element discrimination diagrams indicate that the mafic volcanic rocks show stratigraphic evolution from oceanic island-type basalts to mid-ocean ridge basalts (Ryan, 1984; Kerr *et al.*, 1996). The Joe Pond Formation is the uppermost stratigraphic unit preserved in the Moran Lake Group.

The Post Hill Group (formerly Lower Aillik Group, but now following the revised stratigraphic terminology of Ketchum *et al.*, 2002), is situated mostly at the western margin of the Aillik domain and is interpreted to be correlative with the Moran Lake Group (Wardle and Bailey, 1981). The structurally lowermost rocks are quartzite-dominated, shallow-water sediments of the Drunken Harbour supracrustal belt, which contain detrital zircon only of Archean age . The rocks are situated above a mylonitic base forming the contact with reworked Archean gneiss. Structurally above the quartzite is the Post Hill amphibolite, dated to be 2178 ± 4 Ma (Ketchum *et al.*, 2001b). The contact between the Post Hill amphibolite and underlying quartzite has been interpreted as structural (Culshaw *et al.*, 2000) or stratigraphic (Ketchum *et al.*, 2001b). Based on petrochemical evidence, the Post Hill amphibolite is considered to have formed in a rifted continental margin (Ketchum *et al.*, 2001b).

Collectively, the Moran Lake and lower part of the Post Hill groups have been fairly consistently interpreted as representing a Paleoproterozoic passive margin succession that developed on, or adjacent to the Archean North Atlantic craton (Kerr, 1989a; Kerr *et al.*, 1996; Culshaw *et al.*, 2000; Ketchum *et al.*, 2001b, 2002).

Two higher level formations are present in the Post Hill Group, termed the Metasedimentary Formation and the Kitts Formation (Marten, 1977) (*see* next section).

23.1.2 ACCRETIONARY PHASE (2100–1800 Ma)

As a generalized statement of published models, accretionary phases of the tectonic history of the Makkovik Province can be considered to be as follows: i) approach and accretion of an outboard arc, ii) development of a continental-margin arc, followed closely by back-arc rifting, iii) formation/accretion of a second (outboard?) arc, and iv) post-collisional events.

23.1.2.1 Approach and Accretion of an Outboard Arc (2100–1900 Ma)

Following the rifting stage at *ca.* 2200 Ma, there is a hiatus in the U–Pb geochronological record of at least 165

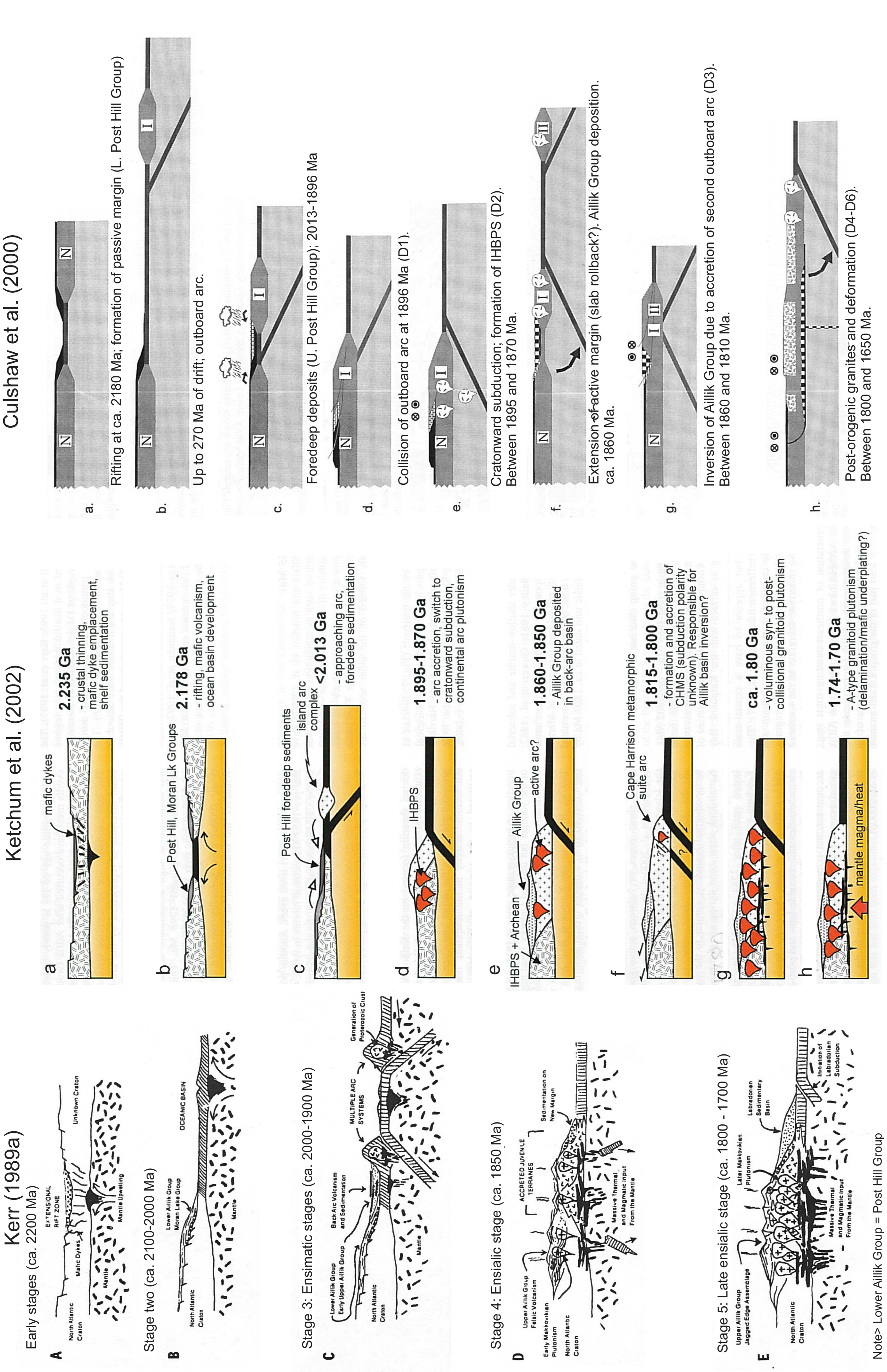

Figure 23.1. *Comparison of models for the tectonic evolution of the Makkovik Province.*

million years, until sometime after 2013 Ma. This age is derived from a range of detrital zircons (2.15–2.0 Ga) from a psammite of the Metasedimentary Formation from the upper part of the Post Hill Group, and thus defines its maximum age of deposition (Ketchum *et al.*, 2001b). The Metasedimentary Formation comprises micaceous psammite with minor pelitic and graphic paragneiss. It is succeeded by the Kitts Formation, which comprises pillowed metabasalt, pelite, semipelite, metachert, and magnetite iron formation. Because the detrital zircon age-range is not characteristic of the pre-Makkovikian Laurentian hinterland, it is reasoned that the detritus came from erosion of an outboard juvenile arc, the products of which were deposited in an evolving foredeep linked to the about-to-collide arc. Kerr (1989a), Ketchum *et al.* (2002) and Culshaw *et al.* (2000) all envisage such an outboard arc, although Kerr (1989a) depicts it as having accreted after the formation of a continental-margin arc.

23.1.2.2 Development of a Continental-margin Arc, Closely Followed by Back-arc Rifting (1900–1850 Ma)

The emplacement of the 1895–1870 Ma calc-alkaline Island Harbour Bay plutonic suite (IHBPS) into Archean crust of the Kaipokok domain is compelling evidence for the existence of a continental-margin arc at this time. Metamorphism at 1896 ± 6 Ma (Ketchum *et al.*, 2001a) and truncation of fabrics by the IHBPS, provide evidence of a deformational event preceding the IHBPS, which is taken as support for accretion of the outboard arc before the continental-margin arc formed. Evidence of cratonward subduction under pre-Makkovikian Laurentia is also provided by a zone of northwestward-dipping seismic reflectors in the upper mantle (Kerr *et al.*, 1997). The cessation of oceanward subduction and initiation of cratonward subduction is a consistent tenet of the Kerr, Ketchum and Culshaw models.

The deposition of the 1885–1850 Ma Aillik Group partly overlapped, but mostly postdated, emplacement of the IHBPS (*cf.* Figure 22.1). Deposition took place under shallow-marine and subaerial conditions and the consensus is that a back-arc tectonic setting is most likely. Culshaw *et al.* (2000) suggest that the back arc formed as a result of slab rollback.

23.1.2.3 Formation/Accretion of a Second (Outboard?) Arc (1850–1800 Ma)

After 1850 Ma, the history becomes murkier. Severe deformation of the Aillik Group is bracketed between its time of deposition and 1802 Ma (time of emplacement of the Long Island pluton, which did not experience the deformation). During this time, parts of the Aillik Group were structurally inverted, and interthrust with slices of Archean basement and earlier Proterozoic crust. Although the nature of the deformation is established, its cause is less well understood. Ketchum *et al.* (2002) focus on the calc-alkaline Cape Harrison Metamorphic Suite as culpable. The Cape Harrison Metamorphic Suite was deformed at high temperatures at 1815 Ma, with deformation lasting until 1798 Ma. The prevailing thought (Culshaw *et al.*, 2000; Ketchum *et al.*, 2002) is that these rocks might be representatives of a second outboard arc that was accreted to late-Makkovikian Laurentia (or formed adjacent to it) during a short-lived event mostly prior to 1800 Ma. Consensus is lacking whether the arc formed above an oceanward- or cratonward-subduction zone. Note that Kerr's model envisioning the 'first' outboard arc colliding after the continental-margin arc was established, obviates the need for any 'second' arc, but creates difficulties in regard to the source of the 2.15–2.0 Ga zircons in the Metasedimentary Formation, as well as the role of the Cape Harrison Metamorphic Suite.

23.1.2.4 Post-collisional Events (1800–1700 Ma)

Activity around 1800 Ma is exemplified by the short-lived Numok Intrusive Suite. These rocks have A- and I-type geochemical characteristics typical of late- and post-orogenic suites (Kerr *et al.*, 1996; Barr *et al.*, 2001). As Ketchum *et al.* (2002) have pointed out, the widespread nature of the granitoid magmatism makes it difficult to interpret, but appeal is made to a broad back-arc setting over a new cratonward subduction zone.

Excluding Labradorian and younger events (later sections), the final significant event in the Makkovik Province was the widespread emplacement of the A-type Cape Strawberry and related granitoid rocks at *ca.* 1720 Ma. Mafic underplating is offered as an explanation by Kerr and Fryer (1994), but that alone does not define the tectonic setting. It could be related to subduction, but investigators have mixed views on whether or not it was still active.

23.1.3 GRENVILLE PROVINCE CHRONOLOGICAL CORRELATIVES

Over the past two decades, evidence has gradually accumulated for events in the Grenville Province in eastern Labrador that are chronologically correlative with late Makkovikian events in the Makkovik Province. The oldest reliably dated rocks have ages between 1805 and 1775 Ma, hence were formed at the same time as, or slightly later than, the Numok Intrusive Suite. These rocks include the White Bear Islands granulite complex in the Smokey area, the Eagle River complex in the Mealy Mountains terrane, and an enclave of granitoid gneiss in a younger granitoid intrusion in the Pinware terrane (Figure 22.1). Unlike the A-type characteristics of the Numok Intrusive Suite and its undeformed state, the near-coeval granitoid rocks in the Grenville Province are calc-alkaline and were accompanied by high-grade metamorphism and deformation (Krogh *et al.*, 2002; Gower *et al.*, 2008b). Krogh *et al.* (2002) suggested that they provide evidence for subduction at this time that seems to be lacking in the Makkovik Province, being the continental-margin complement to inboard granitoid magmatism represented by the Numok Intrusive Suite.

Some evidence also exists in the Grenville Province in eastern Labrador for geological activity correlative with the *ca.* 1720 Ma Strawberry intrusive event in the Makkovik Province. The most conclusive information is from the Makkovik Province–Groswater Bay terrane boundary in the Smokey area where Krogh *et al.* (2002) identified metamorphism, deformation (including thrusting) and pegmatite emplacement between 1730 and 1700 Ma. They addressed potential correlations with coeval events in the Makkovik Province, as well as the 1709 Ma Cuff Island nebulitic granodiorite farther south in the Groswater Bay terrane. Also noted was that links between the Makkovik Province and Groswater Bay terrane weaken models that envision an intervening pre-Labradorian basin (*see* next section).

23.2 PRE-LABRADORIAN AND LABRADORIAN (1800–1600 Ma)

23.2.1 APPROACH OF OUTBOARD ARC, OR CONTINENTAL-MARGIN ARC (1800–1680 Ma)

In eastern Labrador after 1700 Ma, tectonic activity had clearly shifted from the Makkovik Province to the Grenville Province, but the period between 1800 and 1700 Ma remains enigmatic. In addition to the igneous, metamorphic and deformational events between 1800 and 1700 Ma mentioned in the last part of the previous section (in both the Makkovik and Grenville provinces), vast volumes of metasedimentary rocks were deposited in the eastern Grenville Province. The rocks are overwhelmingly pelitic, but include psammitic rocks, quartzite/metachert, and basaltic lavas, some of which are pillowform. Gower *et al.* (2008b) argued that these sediments were most likely deposited between 1810 and 1770 Ma, which means that they were coeval with the emplacement of the Numok Intrusive Suite in the Makkovik Province, and the White Bear Islands and Eagle River complexes in the Grenville Province. The following points relevant to their tectonic setting are: i) Archean and Paleoproterozoic inherited grains (2700 to 1900 Ma) in the metasedimentary rocks are consistent with derivation from pre-Labradorian Laurentia (*e.g.*, the Nain craton and its flanking Paleoproterozoic orogens), ii) an attractive correlation is with gneisses of metasedimentary origin in the southern part of the Ketilidian Mobile Belt in southern Greenland (psammitic and pelitic zones), which have been interpreted as erosion products from the emerging Julianehåb batholith (Chadwick and Garde, 1996; Garde *et al.*, 2002), and iii) dominance of pelitic rocks suggests derivation from a low-energy erosion environment.

For the period leading up to 1680 Ma, Gower and Krogh (2002) envisaged an outboard pre-Labradorian arc above an oceanward subduction zone (Figure 23.2A). The arc, converging on pre-Labradorian Laurentia, eventually collided, resulting in Labradorian orogenesis. Gower and Krogh's oceanward-subduction model relies heavily on the apparent lack of evidence of early Labradorian magmatism and metamorphism within pre-Labradorian Laurentia, arguing that, had the rocks formed in a continental margin setting, such products would be expected to be commonplace. It also derives support from seismic reflection data, interpreted to mean Labradorian southward-directed (*i.e.*, away from the pre-Labradorian craton) underthrusting of the mantle and lowermost crust (Gower *et al.*, 1997a). On the other hand, Krogh *et al.'s* observation (Section 23.1.3) that there are 1800–1700 Ma links between the Makkovik Province and Groswater Bay terrane weakens models arguing in favour of a major intervening pre-Labradorian basin. Note that Gower and Krogh's model is also at variance with those proposed by Kerr (1989a) and Culshaw *et al.* (2000), who both adopted models that involved cratonward subduction.

23.2.2 LABRADORIAN ARC MAGMATISM AND COLLISION(?) OF OUTBOARD ARC (1680–1645 Ma)

Labradorian calc-alkaline magmatism occurred between 1680 and 1655 Ma (Figure 23.2B) and was divided into three tentative age events at 1677, 1671 and 1658–1649 Ma that correlate spatially with the Lake Melville, Hawke River and Groswater Bay terranes, respectively, suggesting northward decrease in age of plutonism (Gower *et al.*, 1992). Rocks involved are dominated by biotite- and hornblende-bearing quartz diorite to biotite granodiorite, but also include some tonalite, large quantities of K-feldspar megacrystic hornblende–biotite granodiorite to quartz monzonite, and lesser granite.

Deformation and migmatization were concentrated between 1665 and 1655 Ma (*cf.* Table 10.1). Very high-grade rocks now exposed in the Groswater Bay and Hawke River terranes must be the product of this activity as geochronological evidence conclusively demonstrates that subsequent orogenies only superimposed modest effects. The activity is interpreted by Gower and Krogh (2002, 2003) to be due to collisional tectonism.

After 1655 Ma, tectonic conditions changed, heralding the start of post-collisional events. A major geological ele-

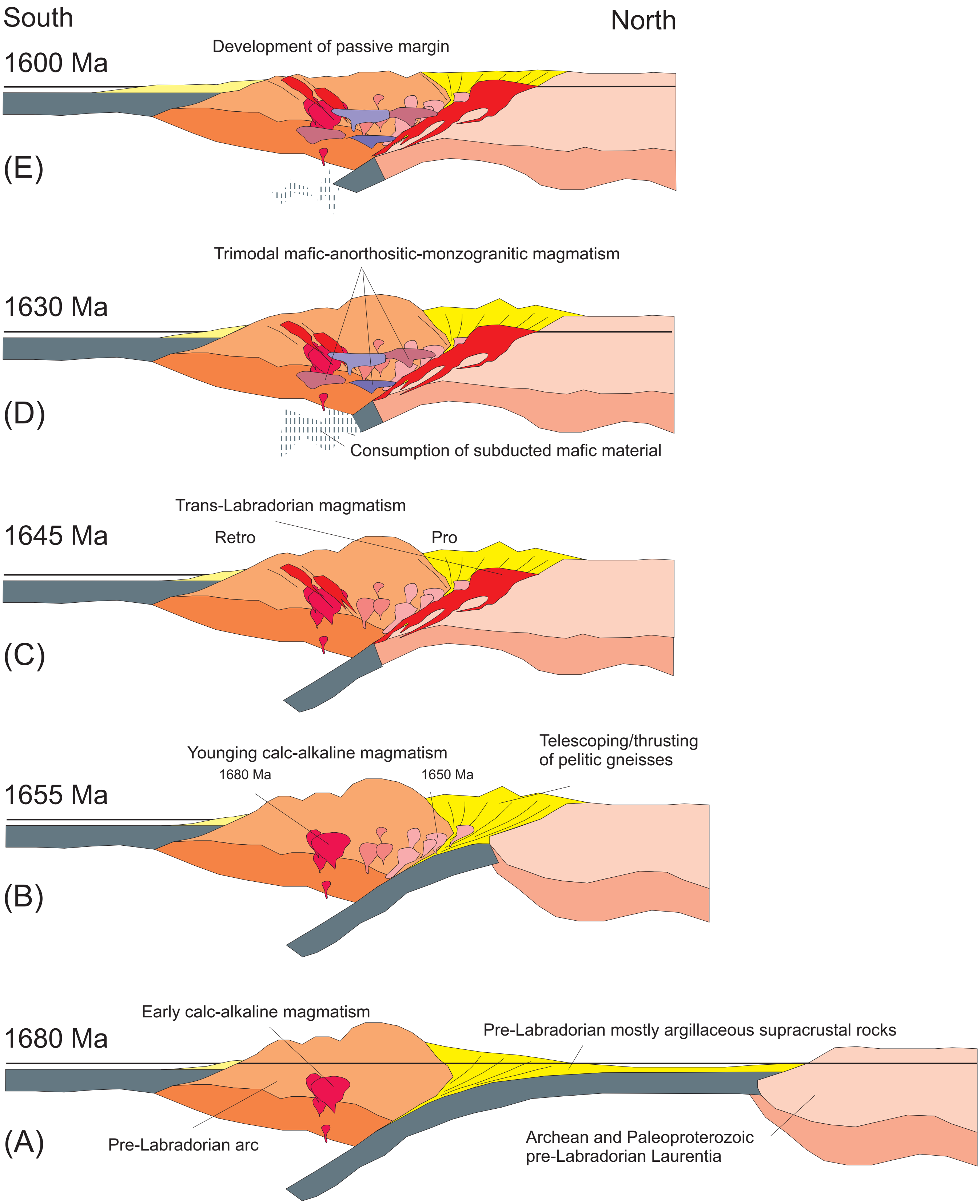

Figure 23.2. *Model for tectonic evolution in the Grenville Province in eastern Labrador during Labradorian orogenesis.*

ment was the generation of granitoid magmas triggered by melting due to crustal thickening (Gower and Krogh, 2002, 2003). The 1655–1645 Ma calc-alkaline to alkali-calcic Trans-Labrador batholith and its coeval supracrustal carapace are thought by Gower and Krogh to have been emplaced along the collisional interface between the accreting arc and pre-arc Laurentia (‘pro’ side of the orogeny – Gower *et al.*, 1997a). As the Trans-Labrador batholith also intruded pre-Labradorian Laurentia (including the Makkovik Province), this means that the Labradorian calc-alkaline arc also flanked pre-Labradorian Laurentia at this time, regardless of how it got there. Granitoid and felsic volcanic/volcanoclastic rocks in the Pinware terrane that are coeval with the Trans-Labrador batholith (or slightly younger than it) are interpreted to have been emplaced in the ‘retro’ side of the orogeny (Figure 23.2C). After 1645 Ma, subduction in the region ceased.

One drawback to the accretionary model is that, in the eastern Groswater Bay terrane, the Trans-Labrador batholith does not seem to be a continuous entity separating the Makkovik Province from granitoid gneisses farther south. A variant of the ‘standard’ arc-accretionary model is a more limited back-arc basin, as formerly envisaged by Gower (1996).

23.2.3 POST-COLLISIONAL LABRADORIAN EVENTS (1645–1600 Ma)

The histories of the Trans-Labrador batholith and the overlapping and subsequent 1650–1620 Ma) trimodal mafic–anorthositic–monzogranitic magmatism (or AMCG suites – anorthosite–monzonite–charnockite–granite) are inextricably linked, as are their time ranges and compositions. For example, Kerr (1989b) pointed out that some aspects of the Trans-Labradorian geochemical character (high F and high FeOt/FeOt+MgO) are comparable with AMCG suites. In addition, it should be stressed that these rocks are very different from the 1680–1655 Ma pre-collisional calc-alkaline products. Gower and Krogh (2002) suggested that the trimodal magmatism was the later product of the same crustal thickening that initially generated the Trans-Labrador batholith. Mafic magmas required as source material for the trimodal magmatism came from the last of the oceanic crust to go down the subduction zone.

Post-Trans-Labradorian deformation and metamorphism (between 1645 and 1625 Ma) is distinguished from pre-Trans-Labradorian deformation in that it extended over a longer period, was more sporadic, and was less intense (Figure 23.2D) . Late Labradorian events, between 1625 and 1600 Ma, involved the emplacement of minor granitic intrusions and sporadic, diverse, and mostly minor, metamorphism/deformational activity. All available evidence indicates that orogenic activity gradually waned and finally ceased, allowing for the development of a passive continental margin (Figure 23.2E).

The striking feature of Labradorian orogenesis is that it did not involve a long-lived steady-state setting (as is more characteristic of a continental-margin arc environment). Instead, it evolved from early calc-alkaline, through a severe metamorphic and deformational phase into an AMCG setting and, finally, to the serenity of post-orogenic passivity. It is for this reason (coupled with the lack of early Labradorian rocks in pre-Labradorian Laurentia) that the author still favours the uni-directional tectonic evolution that the accretion of an outboard arc model allows.

23.3 PRE-PINWARIAN AND PINWARIAN (1600–1460 Ma)

23.3.1 POST-LABRADORIAN–PRE-PINWARIAN EVENTS (1600–1520 Ma)

As noted by Gower *et al.* (1990b) and iterated by Gower (1996), and Gower and Krogh (2002), the 1600–1520 Ma period across Laurentia is a period characterized by scarcity of geological activity, and has been interpreted as reflecting a passive continental margin setting. No information relevant to this evolutionary stage is available from eastern Labrador. In a wider context, Gower and Krogh (2002) reviewed evidence available to them for the eastern Grenville Province. Reference to subsequent information is provided by Augland *et al.* (2015), who mention metasedimentary rocks of the Plus Value complex in the central Grenville Province that were deposited between 1600 and 1497 Ma.

23.3.2 PINWARIAN OROGENESIS (1520–1460 Ma)

The term Pinwarian orogeny was introduced by Tucker and Gower (1994) for rocks having ages between 1500 and 1470 Ma, but subsequent dating has modified these limits to between *ca.* 1520 and 1460 Ma (Gower and Krogh, 2002). Its effects were felt in all terranes in the Grenville Province in eastern Labrador, although large magmatic bodies are confined to the southern part. Activity involved magmatism (dominantly granitic but included AMCG-type rocks in the Upper Paradise River intrusion), metamorphism and deformation, all seemingly operating throughout the period. The Pinwarian event was interpreted (Gower, 1996) as reflecting a continental margin arc over a north-dipping subduction zone (Figure 23.3A). The K-rich nature of the granitoid rocks and related AMCG-type rock types were taken to mean that they were generated inboard of the main arc.

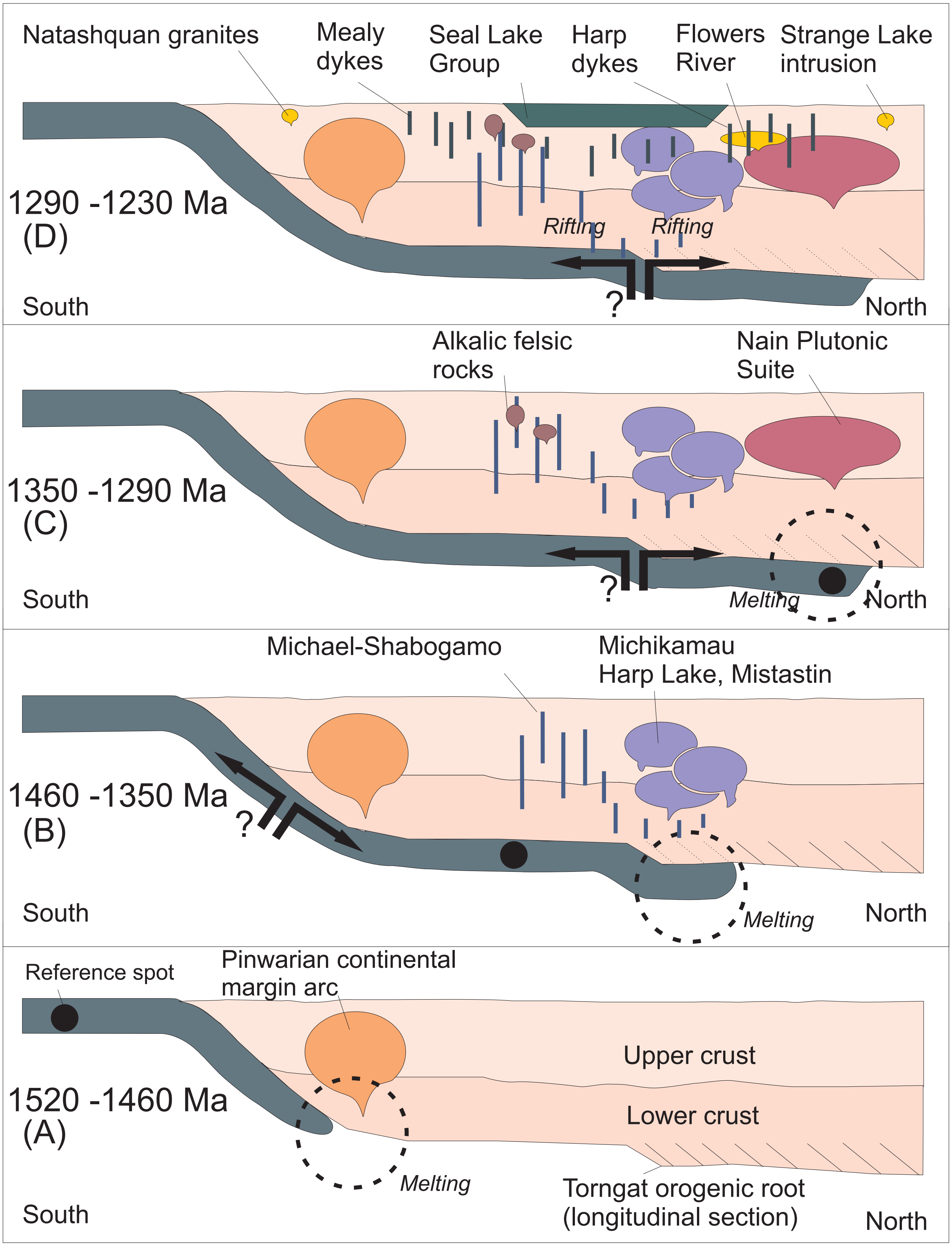

Figure 23.3. *Model for tectonic evolution in eastern Laurentia during the Pinwarian orogeny and post-Pinwarian to pre-Grenvillian period.*

23.4 POST-PINWARIAN–PRE-GRENVILLIAN (1460–1090 Ma)

23.4.1 EARLY AND MIDDLE ELSONIAN (1460–1290 Ma)

Gower and Krogh (2002) reactivated the term 'Elsonian' to refer to the time period between 1460 and 1230 Ma. The term Elsonian orogeny was originally introduced by Stockwell (1964) to describe an event characterized by AMCG magmatism and reworking of older gneisses. As pointed out by Emslie (1978b), the Elsonian never attained status as an orogenic event and was better regarded in a magmatic context – as has been subsequent usage. Gower and Krogh (2002) subdivided the Elsonian in three parts: Early (1460–1350 Ma), Middle (1350–1290 Ma), and Late (1290–1230 Ma).

To address properly possible tectonic models for this period it is necessary to go outside eastern Labrador, to consider the rest of the eastern Grenville Province and the region to the north. As discussed by Gower and Krogh (2002), there is a pattern of decreasing age of emplacement of mafic rocks (*e.g.*, Michael gabbro) and AMCG suites progressing from south to north during Early and Middle Elsonian times (Figure 23.3B, C). Their model envisaged a spreading ridge being overridden and flat subduction ensuing. Such a model provided conditions needed to deliver mantle-derived melts and foster basal crustal melting, which are features consistently demanded in models explaining AMCG suites. A further suggestion by Gower and Krogh (but not essential to the model), based on a change from oblate to prolate surface shape of intrusive bodies from south to north, was that a funnelling effect occurred caused by constriction between the Superior and North Atlantic cratons.

23.4.2 LATE ELSONIAN (1290–1230 Ma)

During the Late Elsonian, the geographic pattern differs. Instead of the south-to-north younging, Gower and Krogh (2002) observed that felsic magmatism was concentrated north and south of a central region of mafic magmatism, all products having formed more-or-less concurrently (Figure 23.3D). In eastern Labrador, the 'felsic magmatism to the south' is represented by the Upper North River pluton and Fox Harbour felsic volcanic rocks, and the 'central region of mafic magmatism' by the Mealy dykes. Gower and Krogh (2002) suggested that northward migration of the spreading centre ceased and that final delivery of heat and magma from the mantle was static, under the present site of the Seal Lake Group.

A key element of the model is that, although the spreading centre was migrating under pre-Elsonian Laurentia, no subduction at the craton margin was involved. This is simply illustrated by imagining a zipper being anchored at one end (the southern edge of the craton), but being pulled manually at the other end (Figure 23.4). The zipper would continue to open and, at the same time, the point of separation of the two parts of the zipper would gradually migrate north (to the right in the figure). In a geological context, the opening of the zipper would be driven by magma up-welling from the mantle, rather than being pulled from the north. If the spreading ridge was being overridden obliquely, then normal subduction would continue on the acute-angle side of the overriding ridge, but cease on the obtuse-angle side. Such a scenario could explain continued subduction in the central Grenville Province after it had ceased in the east.

23.4.3 POST-ELSONIAN–PRE-GRENVILLIAN (1230–1090 Ma)

Evidence for geological activity in eastern Laurentia between the end of the Elsonian event at 1230 Ma and the start of Grenvillian orogenesis at 1090 Ma is very meagre, and suggestive of cratonic stability. The only events known in eastern Labrador are the deposition of the Battle Island supracrustal rocks and the emplacement of the Gilbert Bay granite. The 'platformal' character of the Battle Island supracrustal rocks is in keeping with crustal stability. The emplacement of the Gilbert Bay granitoid pluton would seem at variance with such a setting, but it is associated with

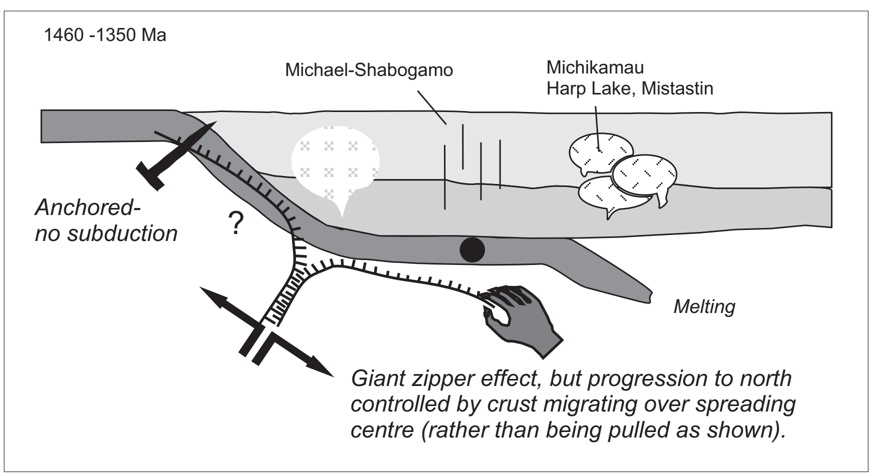

Figure 23.4. *Zipper model illustrating migration of a spreading centre under a cratonic block without concomitant subduction.*

a long-lived zone of weakness (Gilbert River fault), hence may be a local anomaly to overall stability.

23.5 GRENVILLIAN (1090–985 Ma)

Grenvillian orogenesis in the eastern Grenville Province extended from 1090 Ma to 985 Ma followed by late- to postorogenic activity until 950 Ma (Gower, 1996; Gower and Krogh, 2002; Gower *et al.*, 2008b). In a major departure from previously proposed tectonic concepts for the Grenville Province in eastern Labrador, Gower *et al.* (2008a) suggested a model that they termed 'indentor tectonism', although some elements of the model are evident in earlier publications (*e.g.*, Gower *et al.*, 1997a). According to this model, whereas frontal-thrust ramp tectonics prevailed throughout most of the Grenville Province, eastern Labrador mostly involved dextral-strike-slip, lateral-ramp tectonics. The point where frontal-thrust ramp tectonics gives way to a lateral-ramp regime is interpreted as an indentor corner. Such an indentor corner is analogous to those in the Himalayas (Nanga Parbat and Namche Barwa), except the indenting crust in the Grenville Province is envisaged as overriding pre-Grenvillian Laurentia, whereas, in the Himalayas, the indenting crust (India) is being carried under Asia.

23.5.1 EVIDENCE FOR INDENTOR CONFIGURATION

When extrapolated into the Atlantic Ocean, the Grenville front is generally shown as continuing the northeast trend that is has along its full length. The coastal position of the front was taken to be near Smokey. Gower *et al.* (2008a) acknowledged that the coastal position was structurally active during Grenvillian orogenesis but cited Krogh *et al.'s* (2002) conclusion that the area did not have tectonic significance during Grenvillian orogenesis. Whatever major structural control it once exerted had ceased after 1800 Ma. Gower *et al.* (2008a) address three lines of evidence demonstrating that, instead of continuing northeast to the coast and then offshore, the Grenville Province makes a right-angle turn at Rigolet and then trends southeast, at the same time changing its character. The core of the information in this section was given by Gower (2012).

23.5.1.1 Geochronological Data

U–Pb geochronological data compiled by Gower and Krogh (2002), together with Ar–Ar and K–Ar data reviewed by Gower (2003) and additional data/interpretation by Gower *et al.* (2008a) show that the boundary between Grenvillian and pre-Grenvillian ages (*i.e.*, 1085 Ma) is very nearly coincident regardless of whether U–Pb, Ar–Ar or K–Ar data are used. The 1000 Ma thermochron was termed by Gower (2003) as the 'Grenvillian thermal threshold' (Figures 22.12 and 23.5). The U–Pb data rely on Grenvillian ages for zircon and monazite south of the line and pre-Grenvillian ages for titanite north of it. The Ar–Ar and K–Ar 1000 Ma thermochron occupies a position very close to the 1085 Ma boundary where both trend northeast, but the two lines diverge in the easternmost Grenville Province. The 1085 Ma line conforms to the northeast side of the Lake Melville terrane, whereas the 1000 Ma thermochron is coincident with the terrane's southwest boundary. This means the Lake Melville terrane was tectonically active from 1085 Ma (Section 22.1.4), but had cooled below biotite and hornblende closure temperatures before 1000 Ma, whereas more interior terranes had not.

U–Pb geochronological data, apart from confirming the dog-legged shaped boundary between pre-Grenvillian and Grenvillian ages, can also be used to show the same dog-leg shape in other ways. One such way is a boundary marking the northern limit of widespread U–Pb zircon and monazite 1045–1020 Ma ages (Figure 23.6). Data are only adequate to position this boundary in easternmost Labrador. Hints exist, even farther south, that the dog-legged pattern is likely to be mimicked by: i) the northern limit of 1043–1039 Ma K-feldspar megacrystic granitoid plutons, and ii) the northern limit of the late- to post-Grenvillian plutons (975–950 Ma). In the same area, the sharp change in trend from northeast to southeast is shown by the inferred surface boundary between Labradorian (1710–1600 Ma) and Pinwarian (1520–1460 Ma) crust as determined from U–Pb dating. Detailed information constraining these boundaries is given by Gower *et al.* (2008a).

23.5.1.2 Structural Criteria

In contrast to the system of northwest-vergent, lobate frontal thrusts that characterize much of the northern Eastern Grenville Province, the key geological feature of eastern Labrador is a major northwest-trending zone of thrusts and strike-slip faults (Figure 5.7). This zone intersects the southeast coast of Labrador in the vicinity of St. Lewis and follows a sinuous trend northwest to the Rigolet area. The dog-leg change in trend from east-northeast in the west to south-southeast in the east is shown by both geological mapping and magnetic data. The zone coincides with the Lake Melville terrane, the southern part of which has also been termed the Gilbert River belt.

The southern half of the shear belt, between Paradise River and St. Lewis, is interpreted as a composite Labradorian/Grenvillian feature involving southwest-directed Labradorian thrusting onto which dextral Grenvillian strike-slip movement has been imposed (Gower *et al.*, 1997a; Gower, 2005). Farther north, between Paradise River and Rigolet, it seems more likely that the northeast- and

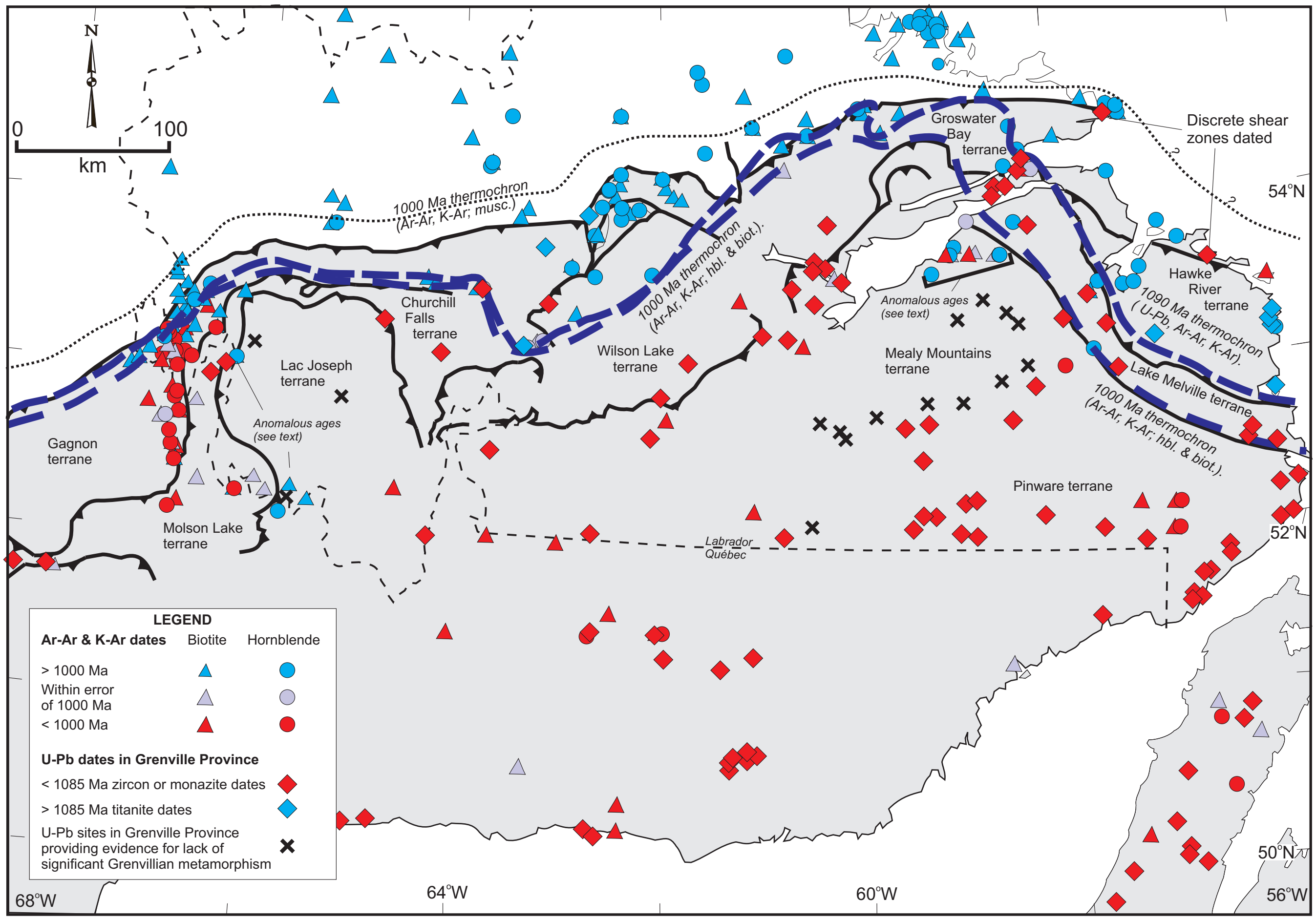

Figure 23.5. *Refined depiction of thermochrons in the eastern Grenville Province, including U–Pb data in addition to Ar–Ar and K–Ar data. A composite 1090 Ma thermochron (the time of the start of Grenvillian orogenesis) is included as the defining line between Grenvillian and pre-Grenvillian dates, but it can only be separated from the 1000 Ma thermochron in eastern Labrador.*

north-directed thrusting is Grenvillian, but that it reactivated early Labradorian thrusting with the opposite sense of vergence (but kinematic data and age controls are scarce). West of Rigolet, the northwest-verging thrusts are Grenvillian.

From a Grenvillian perspective, the overall structural interpretation (Gower *et al.*, 1997a; Gower, 2005) is that the northwest-trending part from St. Lewis to Rigolet is a lateral ramp, whereas, west of Rigolet, the system is frontal. The existence of much of the frontal ramp in eastern Labrador is obscured by the Lake Melville rift system (Figure 18.1).

23.5.1.3 Geophysical Criteria

In addition to magnetic data alluded to in the previous section, evidence that the Grenville Province terminates in easternmost Labrador is provided by gravity and seismic information. Gravity data are particularly telling (Figure 23.7). Whereas the well-known Grenville front 'gravity low' is clear in the western and central parts of the eastern Grenville Province, it is extremely attenuated in the easternmost Grenville Province. There is no indication that it continues offshore. Gower (2003) suggested that the anomaly is lacking in the east because the crustal thickening that accompanied the northwest-directed frontal thrusting farther west (and to which the negative anomaly is related) was lacking in the east because of the indentor corner.

Seismic reflection data acquired during the Lithoprobe ECSOOT project also deny extension of the Grenville Province offshore. There is no sign of the whole-crustal south-dipping shear zone reflectivity associated with the Grenville front to the west (Hall *et al.*, 2002).

23.5.1.4 Indentor Model

The indentor model for the Grenville Province in eastern Labrador envisages the corner of a colliding continent

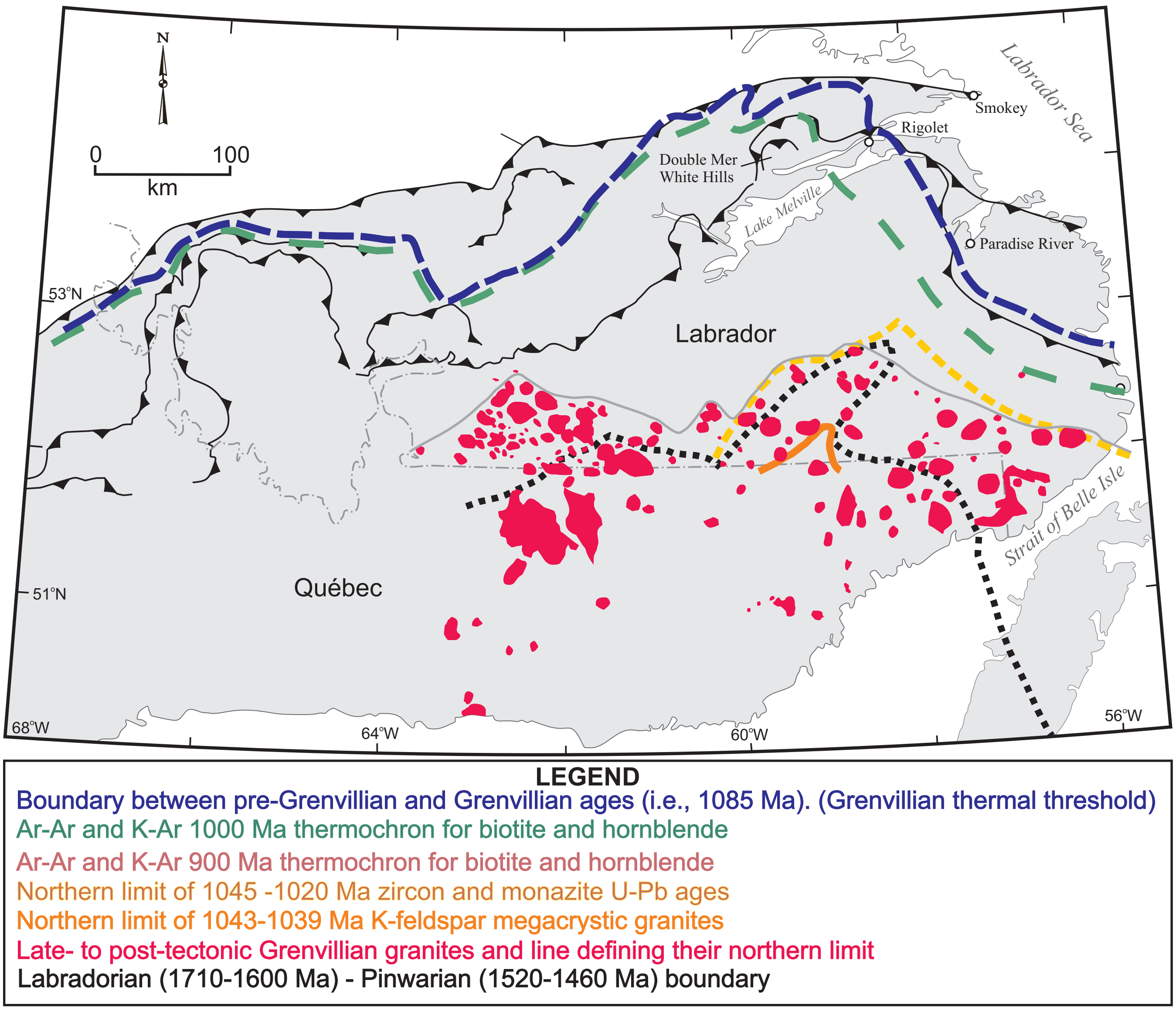

Figure 23.6. *Thermochrons and Grenvillian features farther south in eastern Labrador showing complementary pattern.*

(Amazonia being the preferred candidate) impinging on pre-Grenvillian Laurentia and attempting to override and indent into it. Such a situation is analogous to India colliding with Asia, except that the Indian subcontinent is attempting to subduct under Asia, rather than override it. In the Indian situation, the subduction zone was to the north, in contrast to eastern Laurentia where the subduction zone was to the south (Figure 23.8).

In eastern Labrador, the indenting corner is at Rigolet. West of Rigolet, frontal ramp tectonism applies (northwest-verging thrusts), whereas southeast of Rigolet the tectonic regime involved a lateral ramp and dextral, strike-slip faults. At the indenting corner, very different tectonic conditions apply in an under-riding indenting continent configuration *vs.* conditions in an overriding tectonic configuration. In the Himalayan under-riding situation, the interior right angle is a region of constriction, resulting in tight, lithospheric-scale, syntaxial, antiformal folds and vertical escape, and therefore extremely high erosion rates. In eastern Labrador, over-thrusting of the indenting continent would not be so constraining in a horizontal sense, thus allowing 'tectonic spillover' at the syntaxial corner.

The indentor tectonic model for the Grenville Province in eastern Labrador has major implications on a broader scale. In contrast to previous models, the Grenville Province does not continue as a major belt offshore and does not directly correlate with similar-aged rocks of the Sveconorwegian orogen in southern Baltica.

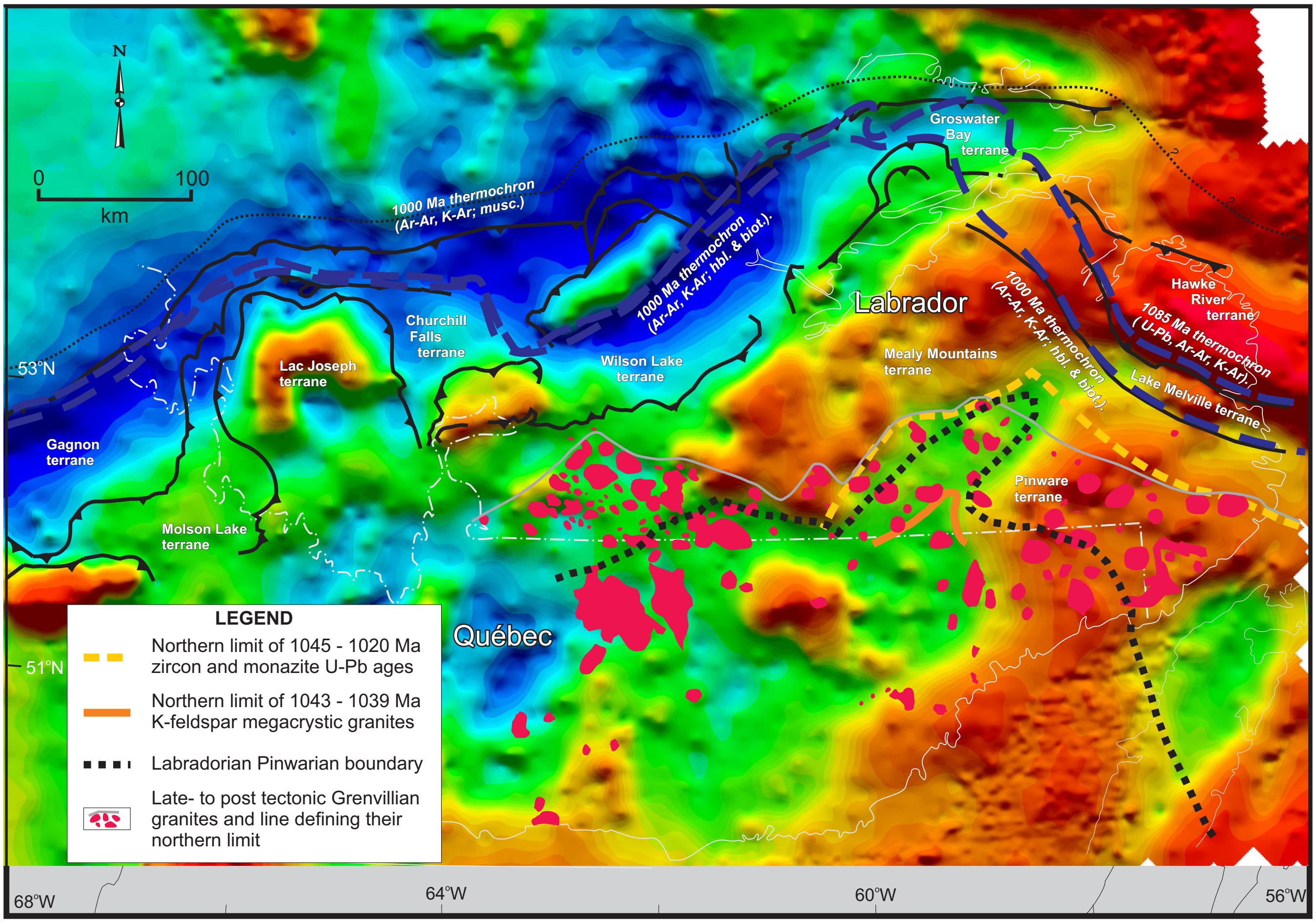

Figure 23.7. *Regional Bouguer anomaly map for the eastern Grenvillian Province, also including some geochronological boundaries transferred from previous figure. High Bouguer anomalies – red; low Bouguer anomalies – blue.*

23.5.2 ROLE OF INDIVIDUAL TERRANES IN GRENVILLIAN INDENTOR MODEL

23.5.2.1 Groswater Bay and Hawke River Terranes

Grenvillian metamorphism was comparatively mild in the Groswater Bay terrane, as has been demonstrated in the previous section by scarcity of Grenvillian U–Pb zircon or monazite, Ar–Ar, or K–Ar dates. With two exceptions, all Grenvillian ages are based on titanite, although zircon is included on the regression line in two cases. The ages range from 995 to 970 Ma (Schärer *et al.*, 1986; Philippe *et al.*, 1993; Kamo *et al.*, 1996). Of the two exceptions, one is an imprecise date of 941 Ma from the Double Mer granite based on a long extrapolation from upper intercept analyses (Schärer *et al.*, 1986). The other is rutile from a gabbro at Cuff Island, having ages of 931 Ma and 923 Ma, which, effectively, establishes the end of Grenvillian effects in the Groswater Bay terrane. The reader is reminded that the high-grade assemblages in the Michael gabbro are attributed to subsolidus (isobaric?) cooling after intrusion, rather than being the product of high-grade Grenvillian metamorphism (Section 21.3.2).

In the Hawke River terrane, an emplacement age of 1029 Ma for the Beaver Brook microgranite dyke (Schärer *et al.*, 1986) and a metamorphic age of 1020 Ma from the 1645 Ma Cartwright alkali-feldspar granite (Kamo *et al.*, 1996) provide the only indications of Grenvillian activity in the Hawke River terrane. Both of the dating sites mentioned here are near the margins of the Hawke River terrane, which probably experienced some Grenvillian adjustments.

The lack of more than modest Grenvillian metamorphism in the eastern Groswater Bay and Hawke River terranes is in keeping with the indentor tectonic model as it obviates deep burial of crust during Grenvillian orogenesis in this region. More severe Grenvillian metamorphism might be expected in the western Groswater Bay terrane, which would have been overthrust from the southeast (but data are rather scarce for that region).

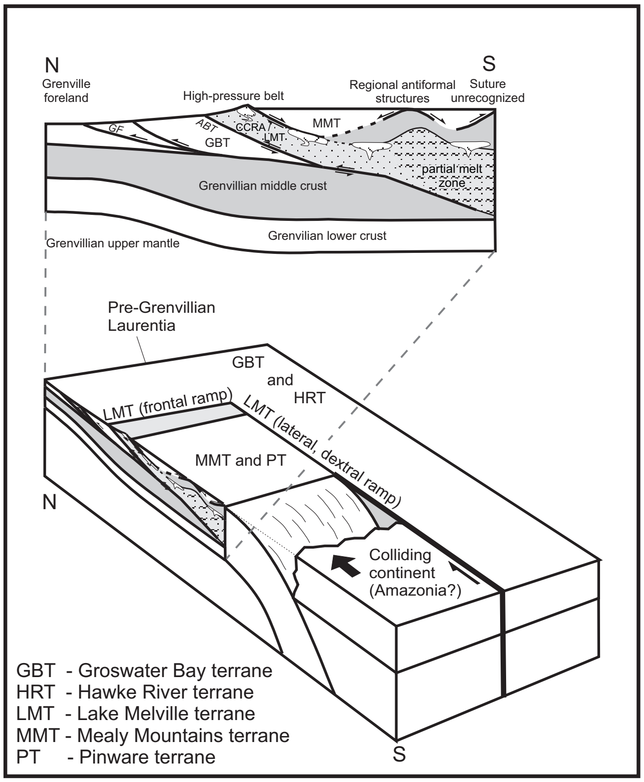

Figure 23.8. *Essence of Grenvillian indentor model configuration (from Gower* et al.*, 2008a). The upper cross-section, based on the models of Beaumont* et al. *(2001, 2004), is incorporated into the lower block diagram depicting the Grenville Province in eastern Labrador to be the result of a colliding, overriding, indenting continent.*

23.5.2.2 Lake Melville Terrane

A date of 1088 Ma from metapelite on Henrietta Island (Corrigan *et al.*, 2000) is the oldest age that can be considered Grenvillian in eastern Labrador. Grenvillian activity in the Lake Melville terrane was well underway by 1080 Ma, as indicated by several zircon and monazite ages of 1080–1075 Ma (Schärer and Gower, 1988; Scott *et al.*, 1993; Corrigan *et al.*, 2000). Ongoing Grenvillian activity in the Lake Melville terrane is recorded by several 1060–1040 Ma zircon and monazite ages (Scott *et al.*, 1993; Wasteneys *et al.*, 1997; Corrigan *et al.*, 2000). The end/aftermath of the event is inferred from titanite dates between 1040 and 1025 Ma (Schärer *et al.*, 1986). Geochronological data demonstrate two important points:

i) There was no voluminous magmatism in the Lake Melville terrane during early Grenvillian orogenesis; the results date either minor granitoid intrusions, metamorphic events, or are linked to deformation. The sporadic magmatism that occurred throughout the period was localized and linked to the prevailing metamorphic conditions. Most zircon and monazite dates are pre-1040 Ma and both span the entire 1090–1040 Ma time period, suggesting that high-grade conditions in the northern Lake Melville terrane were maintained throughout the period, rather than indicating any progressive decline in temperature. Dating also suggests most deformation was over by 1045 Ma.

ii) All titanite ages postdate 1040 Ma. That the titanite results fall within a specific period was first recognized by Schärer *et al.* (1986), who provided the first quantitative data substantiating distinction between the Lake Melville and Groswater Bay terranes. Schärer *et al.* (1986) regarded the period between 1040 and 1030 Ma as being a short-lived metamorphic–anatectic event, but it is now clear that it reflects cooling and closure after a 40-million-year period of tectonism.

In the context of the indentor model, the Lake Melville terrane is its most critical element, encompassing the frontal ramp west of Rigolet and the lateral ramp from Rigolet southeast to the southern Labrador coast. The most active part of its tectonic history was during the earlier part of Grenvillian orogenesis.

23.5.2.3 Mealy Mountains and Pinware Terranes

On the northeast flank of the Mealy Mountains terrane, long interpreted to be a strike-slip fault, 1015–1005 Ma dates (Corrigan *et al.*, 2000) provide strong evidence for displacement coeval with that determined for the Cape Caribou River allochthon. The dating was done in areas previously assigned to the Lake Melville terrane, but, given the Lake Melville terrane's older Grenvillian metamorphic history and the close proximity of these dating sites to the Mealy Mountains terrane boundary, it is appropriate to include them here. Thrusting was therefore around 1010 Ma, which also initiated cooling, for which, 1003-Ma titanite in the Second Choice Lake pegmatite and 990-Ma titanite from Lower Brook domain leucosome in the Goose Bay area provide evidence (Gower *et al.*, 1991; Philippe *et al.*, 1993).

In the Pinware terrane, geochronological data indicate that the onset of Grenvillian metamorphism was about 1030 Ma (Tucker and Gower, 1994; Wasteneys *et al.*, 1997).

High-grade metamorphism and pluton emplacement continued until 985 Ma. The last major deformation is bracketed between very strongly deformed 991 Ma aegerine syenite and weakly deformed 985 Ma L'Anse-au-Loup alkalic mafic dyke. After the last major deformation, metamorphism declined but was slow, due to emplacement of late- to post-Grenvillian granitoid plutons that resulted in higher temperatures being sustained over a longer period. The Mealy Mountains and Pinware terranes represent the orogenic lid to the Grenvillian orogeny.

23.5.3 LATE GRENVILLIAN MAGMATIC EVENTS

Late Grenvillian events are divided here into two groups. The older event (985 to 975 Ma) was characterized by alkalic mafic dyking and anorthositic/alkalic magmatism, whereas the younger event (975 to 955 Ma) was one of monzonitic, syenitic and granitic magmatism. The first clearly developed into the second without any hiatus, but there are sufficient time-compositional contrasts to merit reviewing them separately.

23.5.3.1 Early Posttectonic Magmatism (985–975 Ma)

Alkalic mafic dykes have been recognized in the Lake Melville terrane (Gilbert Bay dykes), where they are spatially associated with the Gilbert River fault, and they are also widespread in the Pinware terrane (L'Anse-au-Diable and York Point dykes).

The dykes discordantly intrude their host rocks; are overall east-southeast-trending (although commonly irregular and branching); in some cases are extremely xenolithic; and may show magma-mingling characteristics (Gower *et al.*, 1994). The L'Anse-au-Diable dykes show the most mineralogical modification and were emplaced at deeper levels than the near-surface pristine Gilbert Bay dykes. Emplacement ages of 985 Ma from a L'Anse-au-Diable dyke and 974 Ma from a Gilbert Bay dyke have been obtained (Wasteneys *et al.*, 1997). The nominally older age obtained from the L'Anse-au-Diable dyke is consistent with its mildly metamorphosed state, having been injected during waning Grenvillian metamorphism in the area. Major intrusive bodies emplaced at the same time include the 980-Ma Red Bay gabbro (Gower *et al.*, 1994; Greenough and Owen, 1995), the 975-Ma Vieux-Fort granophyric leuconorite, and the 973-Ma fayalite-bearing Lower Pinware River alkali-feldspar syenite (Heaman *et al.*, 2004).

23.5.3.2 Late Posttectonic Magmatism (975–955 Ma)

Late posttectonic magmatism includes minor granitic intrusions, up to a few metres across and plutons several kilometres in diameter. The granitoid plutons are discrete, circular to elliptical (in plan) bodies and are commonly associated with distinct positive aeromagnetic anomalies, which were used by Gower *et al.* (1991) to predict (prior to mapping) that such plutons would be found to be extensive and concentrated in the southern half of the Eastern Grenville Province. The names 'Exterior Thrust Belt' and 'Interior Magmatic Belt' were proposed to distinguish the northern area lacking plutons from the southern region, where they are abundant. Ages determined range from 966 to 956 Ma (Gower and Loveridge, 1987; Gower *et al.*, 1991; Tucker and Gower, 1994; James *et al.*, 2001; Gower *et al.*, 2008b).

23.5.3.3 Post-Grenvillian Waning (955–920 Ma)

On the basis of results from rutile from various parts of the eastern Grenville Province, tectonothermal activity waned between 955 and 920 Ma. After this, the region subsided into repose after 900 million years of mountain building, moving and destroying.

23.6 POST-GRENVILLIAN

For 300 million years following the end of the Grenvillian orogeny, there is no record of geological activity in the region. The next events are related to the rifting and drifting phases of the opening of Iapetus Ocean during the late Neoproterozoic. Rifting was marked in the region by the emplacement of the 615 Ma Long Range dykes, huge quartz veins, deposition of the Double Mer Formation in the Lake Melville rift system and Sandwich Bay graben, deposition of the Bateau Formation and extrusion of the Lighthouse Cove mafic volcanic rocks. The start of the drifting phase in the early Phanerozoic is marked by flooding of the ancient Laurentian margin, as indicated by the deposition of ferruginous clastic and mixed clastic–carbonate sediments of the Bradore and Forteau formations. Excluding glaciation, evidence of later Phanerozoic activity is confined to the emplacement of a few mafic dykes (*e.g.*, Sandwich Bay, Battle Harbour, Charlottetown Road), the exact age(s) of which remain unknown.