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Testing a back-arc 'aulacogen' model for the Central Metasedimentary Belt of the Grenville Province

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Abstract – Nearly 70 new Nd isotope analyses are presented for plutonic orthogneisses from the Grenvillian Central Metasedimentary Belt (CMB) in order to test a back-arc aulacogen model for its origin. Nd isotope signatures of metaplutonic rocks are used as probes of the formation age of the crust at depth, revealing sharp boundaries between old crustal blocks and juvenile (1.2–1.35 Ga) Elzevirian-age crust. Firstly, a hidden block of old crustal basement is revealed between areas of juvenile crust south of Douglas, Ontario. Secondly, T_{DM} ages refine the boundary between juvenile crust and old basement (1.35–1.55 Ga) within the Weslemkoon batholith, showing this pluton to be a polygenetic stitching pluton that straddles a hidden crustal boundary. Finally, the CMB boundary zone is shown to form a sharp age boundary between juvenile and old crustal domains, and is interpreted as a reactivated rift-bounding normal fault. When the distribution of rift-related alkaline rocks is compared with these crustal boundaries, the Bancroft nepheline syenite suite is centrally located in a juvenile ensimatic zone between blocks of old basement. Such a location, near the axis of a juvenile crustal segment, implies emplacement late in the rifting process. Similarly, the Blue Mountain nepheline syenite appears to post-date an earlier rifting event to the southeast. Hence, a multi-stage model is proposed for the evolution of a back-arc aulacogen, which is consistent with the distribution of marble and volcanic/plutonic units in the CMB. The model places the Bancroft nepheline syenites in a precise plate tectonic context for the first time.

Keywords: Nd isotope, model age, crustal formation, nepheline syenite, rift zone.

1. Introduction

The Grenvillian Central Metasedimentary Belt (CMB) is the only part of the SW Grenville Province that preserves low-grade rocks and primary structures. In this it contrasts with high-grade gneiss terranes on either side, comprising the Central Gneiss Belt and the Adirondack Highlands – Central Granulite terrane (Fig. 1). However, the preservation of abundant primary geological features in the CMB has not led to a clear understanding of its tectonic setting. For this reason we use the descriptive term 'CMB', rather than other labels with genetic connotations.

Following the application of plate tectonic principles to the Precambrian (Dewey & Burke, 1973), two alternative models were applied to explain the origins of the CMB. The first of these, based on the study of a sequence of volcanic rocks near Kaladar, Ontario, attributed the CMB to an oceanic arc sandwiched between two continental blocks (Brown *et al.* 1975). This model was based on an apparent change in chemistry within a 7 km thick volcanic sequence, from ultramafic rocks and alkali-poor tholeiites at the base, to calc-alkaline lavas at the top (Sethuraman & Moore, 1973). The fact that this sequence was intruded by granitoid plutons strengthened the conviction of these authors that they were seeing the development of an island arc founded on older oceanic crust.

However, the island arc model of Brown *et al.* (1975) did not consider the origins of the mafic crust on which the calc-alkaline arc was extruded, and did not explain how subsequent basin closure could have created the 'cul-de-sac' geometry of the CMB, trending NNE into the interior of Laurentia (Fig. 1). In contrast, this geometry was specifically addressed by an alternative model (Baer, 1976) that interpreted the CMB as an aulacogen, i.e. the failed arm of a rift zone. This model could explain several distinctive geological features of the CMB, such as the coupled distribution of abundant carbonate and volcanic rocks lying between two bounding shear zones, and the extension of a veneer of carbonate rocks outside these boundaries. In addition, Baer attributed the marked thickening of carbonates on the NW side of the aulacogen (near Bancroft, Ontario) to the development of a half-graben type of structure. He also correlated the down-faulted axis of this graben with a linear development of nepheline-bearing igneous rocks characteristic of continental rifts.

Baer's model had many attractive features, and Baer even identified a specific modern analogue, the Danokil depression (Afar triangle) within the southern Red Sea basin. However, the model had a major weakness: the unexplained presence of calc-alkaline plutonic rocks within the CMB, of similar age to the proposed rift-related units (Brown *et al.* 1975). As a result, the

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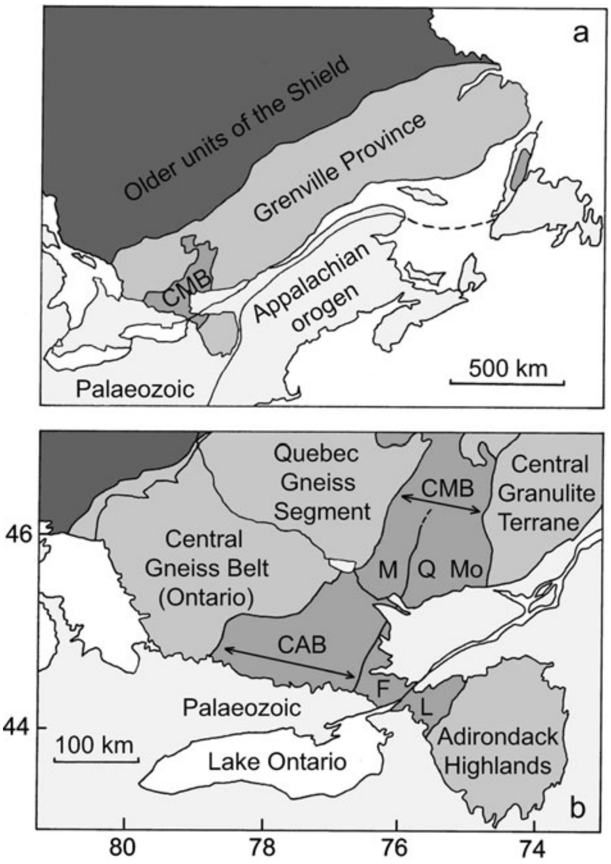

Figure 1. Maps of the Grenville Province to show (a) the location of the CMB within the Grenville Province in eastern North America; (b) location of the CMB between high-grade gneiss belts, and its subdivision into component parts: CAB – Composite Arc Belt; F – Frontenac Terrane, L – Adirondack Lowlands, M – Marble domain; Q – Quartzite domain; Mo – Morin domain.

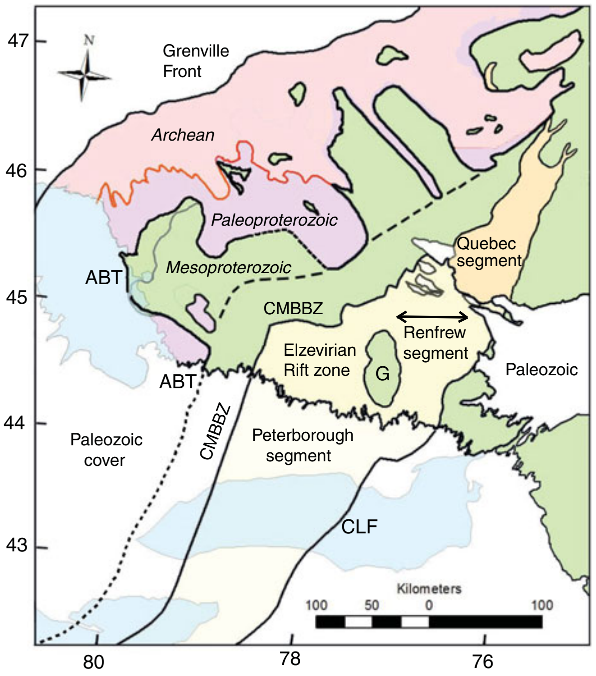

Figure 2. (Colour online) Map of the SW Grenville Province showing major tectonic units and boundaries as modified by Dickin & North (2015). Pink and lilac – Grenvillian parautochthon; pale green – Allochthonous Polycyclic Belt (modified from Rivers *et al.* 1989); yellow and orange – Elzevirian rift zone, divided into ensimatic Peterborough and Renfrew segments and ensialic Quebec segment (marble domain). ABT – Allochthon Boundary Thrust; CMBBZ – Central Metasedimentary Belt boundary zone; CLF – Clarendon–Linden fault; G – Grimsthorpe domain.

aulacogen model was largely ignored, and subsequent research (e.g. Pride & Moore, 1983) emphasized the island arc model, culminating in a review paper by Carr *et al.* (2000). In that paper, the theory that the CMB was composed of a collage of arc fragments was used to coin the term 'Composite Arc Belt'. It should be noted, however, that this term refers only to the westerly marble-dominated part of the CMB, excluding the Frontenac Terrane and the Adirondack Lowlands (Fig. 1b).

More recently, a third model was proposed by interpreting the CMB as a back-arc basin formed behind the (1.2–1.35 Ga) Elzevirian continental margin arc. This model was first proposed to explain the rift-like geochemistry of meta-basic units within the CMB (Holm *et al.* 1985, 1986; Smith & Holm, 1990), and was developed by Hanmer *et al.* (2000) and Rivers & Corrigan (2000). The back-arc basin model resolves the conflicting evidence for rifting and subduction-related signatures in the CMB, but cannot explain its detailed geometry. For example, it does not explain the gradual narrowing of the marble-rich zone going northwards into Quebec, where it eventually dies out in the vicinity of Archaean basement (Fig. 2). Therefore, when Nd isotope mapping by Dickin & McNutt (2007) identified a segmented distribution of juvenile crustal zones and old crustal remnants within the CMB of Ontario and Quebec, they proposed a modified version of the back-arc basin model, arguing that the geometrical pattern of Nd model ages could best be explained by a failed back-arc rift zone.

2. Nd isotope mapping in the Grenville Province

The concept of Nd isotope mapping was developed by Nelson & DePaolo (1985), based on the use of depleted mantle Nd model ages to estimate the crustal formation age of large areas of continental crust, in order to chart the growth history of the North American craton. Depleted mantle model ages (T_{DM}) are based on an empirical model for the composition of the upper mantle believed to give rise to subduction-related magmatism. The model was based on the Nd analysis of modern and Palaeoproterozoic arc rocks (DePaolo, 1981), and has been verified in numerous subsequent studies. This model should not be confused with more depleted (DMM-type) mantle models that represent the source of mid-ocean ridge basalts (Workman & Hart, 2005; Dhuime, Hawkesworth & Cawood, 2010).

Nd isotope mapping was applied to the Grenville Province by Dickin & McNutt (1989), and was used to identify the edge of the Archaean craton within the Central Gneiss Belt of Ontario. Archaean basement within the NW Grenville Province has an average T_{DM} age of 2.73 Ga (Dickin, 1998), in excellent agreement with U–Pb ages of 2.7 to 2.75 Ga for the adjacent western Abitibi belt of the Superior Province (e.g. Jackson & Fyon, 1991).

Immediately north of the CMB, Nd model ages have likewise been verified by U–Pb dating as accurate estimates of the formation age of the crust. For example, Slagstad *et al.* (2009) determined an average T_{DM} age of 1.50 Ga on 16 samples of plutonic orthogneiss from the Muskoka domain of the Central Gneiss Belt, including two samples with U–Pb crystallization ages of 1.44 and 1.47 Ga. Similarly, Dickin *et al.* (2010) determined an average T_{DM} age of 1.52 Ga on a suite of 35 gneisses from a wider E–W suite along the SE edge of the Central Gneiss Belt in Ontario. These ages are in remarkable agreement, bearing in mind that T_{DM} ages are expected to represent the crustal formation age of an arc terrane that was extracted from the mantle over a period of several tens of millions of years, whereas U–Pb dated plutons will normally represent some of the younger intrusive bodies in such a terrane. Comparisons between T_{DM} ages and U–Pb ages in large areas of the CMB have likewise shown excellent agreement. For example, seven plutonic orthogneisses analysed by McNutt & Dickin (2012) gave an average T_{DM} age of 1.24 Ga, while U–Pb ages for the same bodies (quoted with permission from the unpublished data of Heaman) give an average age of 1.236 Ga.

A detailed Nd isotope study of the CMB boundary zone (CMBBZ, Fig. 2) revealed a very sharp age boundary between old (>1.35 Ga) T_{DM} ages in orthogneisses of the Central Gneiss Belt and juvenile (<1.35 Ga) T_{DM} ages in orthogneisses from the CMB (Moretton & Dickin, 2013). This sharp age boundary corresponds within a few hundred metres to the NW limit of marble outcrops, showing that the extent of marble in the NW part of the CMB corresponds very closely to the extent of juvenile (1.2–1.35 Ga) Elzevirian-age crust. Considering the sharpness of this boundary, it was particularly significant that Dickin & McNutt (2007) found Nd evidence for the existence of a block of older crust within a lithotectonic unit of the CMB that Easton (1992) termed the Grimsthorpe domain (G in Fig. 2). This domain is characterized by volcanic and major plutonic lithologies that are largely distinct from the surrounding domains of the CMB, which are dominated by marbles (Easton, 1992). This suggests that the old crustal ages within the Grimsthorpe domain of the CMB are indicative of the existence of a distinct crustal block that was not previously identified.

It was earlier proposed by Hildebrand & Easton (1995) that the large-scale structure of the CMB consists of ‘a regionally extensive thrust fault that places hot, pluton-riddled metamorphic rocks over cool platformal carbonates’. In the light of this model, it was critical to determine whether the old T_{DM} ages of the Grimsthorpe domain could represent an isolated klippe of Hildebrand and Easton’s ‘upper-plate’ (which they correlated with the Frontenac Terrane), emplaced over a ‘lower-plate’ consisting of Laurentian basement overlain by platformal marbles. However, Dickin and McNutt found that juvenile crustal Nd signatures (with T_{DM} ages <1.35 Ga) obtruded into the eastern side of the Grimsthorpe domain. Hence, they proposed that the old crustal Nd signatures represented a buried block of old crust underlying *part* of the Grimsthorpe domain, and that the Grimsthorpe domain could therefore not be an allochthonous displaced terrane (or a tectonic window).

3. The failed back-arc rift model

Geographically, the Elzevir block divides the zone of juvenile Nd model ages in the Ontario part of the CMB into two separate segments. The westerly one continues southwards into the subsurface of southern Ontario and the United States (Peterborough segment in Fig. 2), whereas the easterly (Renfrew) segment continues northwards into the Marble domain of Quebec (Quebec segment in Fig. 2). Hence, the overall shape of this structure was argued to be a series of relatively narrow en échelon rift segments, whose overall shapes have been preserved through subsequent compressional events.

Dickin & McNutt (2007) showed that T_{DM} model ages in the Marble domain of Quebec are significantly older (average = 1.42 Ga) than the Ontario rift segments (average = 1.25 Ga), suggesting that unlike the two ensimatic (juvenile) rift zone segments in Ontario, the Quebec segment was ensialic. This suggests that as the rift zone propagated northwards, it died out when it encountered cold (Archaean) basement (Fig. 2). Hence, the crustal geometry of the rift zone resembles the northwards transition from the ensimatic Red Sea to the ensialic Gulf of Aden.

A surprising aspect of the aulacogen model is that failed rift zones, because they become filled with voluminous mafic rock and sediment, can leave a larger trace in the geological record than continental margins that are involved in a complete Wilson cycle. An example of the latter, the Trans-Adirondack Basin in the Adirondack Lowlands (Fig. 1) has been proposed as a conventional back-arc basin (Chiarenzelli *et al.* 2012) with a full Wilson cycle (in miniature) involving rifting, passive margin sedimentation, basin fill during convergence and tectonic compression. However, plutonic orthogneisses straddling the boundary yield an average T_{DM} age of 1.50 Ga (Chiarenzelli *et al.* 2010), with only one T_{DM} age (1.29 Ga) that shows any indication of juvenile material from the period of basin development. In contrast, the proposed back-arc rift zone of Ontario contains two juvenile crustal zones, each around 100 km in width, with an average T_{DM} age of 1.25 Ga (Dickin & McNutt, 2007 and new data reported here).

Although the back-arc rift zone in Ontario was inverted, in the sense that it was involved in the Grenville orogeny, the geometry of the rift zone appears to have been largely preserved through subsequent compressional events. For example, it formed an 'Ottawan orogenic lid' during the Grenville collisional orogeny, and hence remained at a higher crustal level than the remainder of the Grenville Province (Rivers, 2012). Therefore, although seismic profiles show that the CMB underwent shear, the shallow crustal conditions of the orogenic lid allowed the preservation of large areas of the CMB with relatively little change in surface outcrop pattern. For example, there are many plutons in the CMB that preserve sub-spherical outlines characteristic of diapiric magma emplacement. Hence, it appears that outside of the strongly imbricated Mazinaw domain (to be discussed in more detail in Section 6 below), rocks of the CMB display relatively limited degrees of Ottawan ductile deformation (Schwerdtner, Serafini & Yakovenko, 2005).

A notable feature of the rift zone geometry proposed by Dickin & McNutt (2007) was the sharp 90-degree turn of the CMBBZ at the NW corner of the Peterborough segment (Fig. 2). This feature is attributed to reactivation by 1.19 Ga (Shawinigan-age) deformation (Hanmer & McEachern, 1992) of earlier listric normal faults that defined the northern termination of a rift segment. Geophysical evidence (Boyce & Morris, 2002) suggests that the N–S limb of the CMBBZ continues southwards with almost exactly the same trajectory in the subsurface of southern Ontario (Fig. 2). Similarly, the east side of the juvenile crustal zone adjacent to the Frontenac Terrane can be correlated with the Clarendon–Linden fault (Forsyth *et al.* 1994). This implies that the Peterborough segment of the rift zone is almost parallel sided (Fig. 2). In contrast, the Renfrew segment of the rift zone appears to widen northwards, which is contrary to its overall pattern of narrowing as it propagated into colder Laurentian crust. Therefore, it was conjectured that this local widening (arrowed in Fig. 2) reflects the presence of a hidden old crustal block in this rift segment.

The search for such a block was one of the principal objectives of this study. However, it was also realized that higher resolution Nd isotope mapping was required in other areas. This includes a refinement of the northern extent of the Elzevir block, which was defined by only two samples in the original study of Dickin & McNutt (2007). In addition, more detailed sampling was made of other parts of the juvenile zone to test for the presence of any additional hidden blocks of old crust. Finally, more detailed sampling of the northeastern segment of the CMBBZ was undertaken to more precisely define the geometry of the rift zone in relation to nepheline syenite bodies, which may indicate the locus of rifting events in the CMB (Burke, Khan & Mart, 2008).

4. Sampling and analytical methods

Since the objective of this study was to characterize the protolith age of the crust as an estimate of its regional crustal formation age, sampling was limited to granitoid orthogneisses that are believed to form by anatexis of more mafic juvenile crust. Previous studies have shown that granitoids of this type have Nd isotope signatures that are consistent and predictable, allowing reliable estimates to be determined of the formation age of the crust using the depleted mantle model of DePaolo (1981).

Tonalitic–trondhjemite–granodiorite (TTG-type) gneisses were sampled where possible, since these are believed to be the best examples of the rock types that form the earliest 'primitive' type of continental crust. More granitic samples were used as a second choice, since these may have a more complex geological evolution, but usually still preserve the original formation age of juvenile continental crust (McNutt & Dickin, 2012). In contrast, sampling of mafic gneisses was avoided because of the increased likelihood of a younger mantle-derived component in these rock types. Metasedimentary gneisses were also excluded because of their uncertain sedimentary provenance.

On average, 1 kg of rock was crushed, after the removal of any weathered, veined or migmatized material, and careful attention was given to obtain a fine powder that was representative of the whole rock. Major element analyses were performed by Activation Laboratories, Ancaster, Ontario, using Li-borate fusion inductively coupled plasma (ICP) analysis. The accuracy of Actlabs data is ensured by the inclusion of many international reference standards as part of the analytical protocol.

Sm–Nd analysis followed our established procedures. After a four-day dissolution at 125 °C using HF and HNO_3, samples were converted to the chloride form before splitting and spiking. Standard cation and reverse phase column separation methods were used. Nd isotope analyses were performed on a VG isomass 354 mass spectrometer at McMaster University using double filaments and a four-collector peak switching algorithm, and were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Average within-run precision on the samples was ± 0.000013 (2 sigma), and an average value of 0.51185 ± 2 (2 sigma population) was determined for the La Jolla Nd standard during this work. The reproducibility of $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ is estimated at 0.1 % and 0.002 % (1 sigma), respectively, leading to an analytical uncertainty on each model age of *c.* 20 Ma (2 sigma), based on empirical experience over several years of analysing duplicate dissolutions.

5. Results

Nearly 70 new Nd isotope analyses are presented in Table 1, where they are used to calculate T_{DM} ages using the model of DePaolo (1981). Four samples with T_{DM} ages of 1.35 Ga or greater define the extent of an additional hidden block of old crust south of Douglas (red star in Fig. 3), hence referred to below as the Douglas block (DB in Fig. 3). Samples attributed to one of the juvenile rift zone segments are grouped (Table 1) according to the Grenvillian CMB domains

Table 1. Nd isotope data for CMB orthogneisses

Map#	Field#	Y	X	Nd ppm	Sm ppm	147/144	143/144	TDM	Q	P	Rock*
Douglas block											
1	DA3	5037860	342890	34.3	7.13	0.1258	0.512098	1.63	162	– 83	MG
2	MW25	5033701	340000	14.7	3.24	0.1334	0.512242	1.52	24	– 265	DI
3	MW26	5028827	341895	25.7	5.57	0.1311	0.512312	1.35	62	– 163	QMD
4	MW27	5022197	341193	29.7	7.02	0.1428	0.512395	1.39	110	– 137	GD
							average	1.47			
Elzevir block											
5	WK39	5000731	309900	22.3	4.15	0.1124	0.512062	1.47	129	– 174	TN
6	WK13	4999242	309115	9.3	1.80	0.1170	0.512171	1.37	154	– 168	TN
7	WK18	4992265	303934	8.8	1.38	0.0950	0.511973	1.38	150	– 190	TN
8	WK0	4995785	302540	15.3	2.76	0.1095	0.512033	1.47	183	– 80	GD
9	WK16	4994725	305763	8.9	1.82	0.1235	0.512170	1.47	152	– 169	TN
10	WK17	4993917	308106	10.2	2.13	0.1266	0.512242	1.40	129	– 189	TN
11	WK41	4996482	309860	6.3	1.27	0.1218	0.512192	1.41	156	– 189	TN
12	WK28	4992914	312365	5.1	1.02	0.1227	0.512197	1.42	169	– 123	GD
13	WK10	4993201	313698	6.2	1.27	0.1239	0.512227	1.38	160	– 123	GD
14	WK22A	4985458	301928	14.8	2.21	0.0903	0.511888	1.42	175	– 152	GD
15	WK22B	4985458	301928	15.6	2.87	0.1108	0.512080	1.42	138	– 150	GD
16	WK21	4986948	303529	9.7	1.74	0.1085	0.512053	1.43	170	– 142	GD
17	WK20	4988261	304371	11.8	2.37	0.1216	0.512193	1.41	122	– 201	TN
18	WK33	4987411	306680	9.3	1.84	0.1244	0.512225	1.39	164	– 159	TN
19	WK31	4987857	310377	12.3	2.21	0.1083	0.512083	1.39	149	– 178	TN
20	WK32	4986325	311091	9.7	1.80	0.1119	0.512143	1.35	149	– 199	TN
21	WK54	4979670	310700	21.7	3.90	0.1085	0.512072	1.41	168	– 163	TN
22	WK56	4979570	314970	10.9	2.11	0.1175	0.512159	1.40	178	– 159	TN
							average	1.41			
CMBBZE											
23	MW7	5026367	277894	37.2	9.11	0.1482	0.512401	1.49			QD
24	MW11	5025302	286610	49.5	8.81	0.1076	0.512061	1.41			GD
25	MW23	5059084	330439	45.3	10.17	0.1357	0.512310	1.43			GD
26	MW22	5062108	329022	77.8	17.68	0.1373	0.512351	1.38			MG
27	MW20	5066598	329480	29.5	6.62	0.1358	0.512287	1.48			MG
							average	1.44			
Bancroft Juvenile											
28	MW8	5024453	278499	37.4	8.05	0.1300	0.512308	1.34			GR
29	MW12	5026613	292941	31.3	6.29	0.1217	0.512232	1.34			GD
30	MW24	5058522	325764	64.3	13.28	0.1248	0.512276	1.31			DI
31	MW17	5030814	332729	66.8	12.39	0.1120	0.512256	1.18			DI
32	DA1	5036992	335456	66.2	11.66	0.1065	0.512181	1.23			GR
33	MW18	5045984	338222	158.3	26.44	0.1009	0.512076	1.31			MG
34	DG11	5044913	342571	10.4	1.97	0.1148	0.512271	1.19			MZ
35	DG9	5044577	345278	12.7	2.49	0.1189	0.512229	1.31			TN
36	DA11	5053220	349170	9.4	1.78	0.1139	0.512206	1.28			QMD
37	DA12	5052950	350990	37.5	7.62	0.1230	0.512289	1.27			MG
38	DA15	5054610	354610	34.5	5.79	0.1016	0.512110	1.26			MG
							average	1.27			
Blackdonald Juvenile											
39	MW14	5022962	318270	3.0	0.57	0.1160	0.512244	1.25			Foid
40	DA22	4996770	332110	51.4	9.55	0.1123	0.512175	1.30			TN
41	MW33	5004233	335428	45.0	8.68	0.1166	0.512264	1.23			QD
42	MW32	5008952	330165	20.7	3.76	0.1098	0.512185	1.25			TN
43	MW30	5013834	333472	25.5	4.93	0.1168	0.512258	1.23			GD
44	MW29	5017675	338134	25.4	5.53	0.1317	0.512351	1.29			QD
45	DG1	5018770	338520	20.0	3.92	0.1181	0.512242	1.28			QD
46	DG2	5023344	336035	22.3	4.83	0.1307	0.512388	1.20			QD
47	DA4	5026050	345860	31.7	5.71	0.1089	0.512197	1.23			DI
48	DA20	5009720	346230	10.7	2.42	0.1371	0.512399	1.28			GD
49	JS25	5007723	353210	5.3	0.916	0.1044	0.512188	1.19			TN
50	JS26	5013546	351427	49.9	9.25	0.1121	0.512184	1.29			TN
51	DA8	5016260	361310	14.4	2.61	0.1096	0.512199	1.24			MG
52	DA7	5025530	358640	13.1	3.68	0.1700	0.512675	1.28			DI
53	DG5	5036852	345259	15.4	3.17	0.1244	0.512296	1.27			QD
54	DA5	5037010	354510	50.4	10.38	0.1245	0.512359	1.17			SY
55	DA13	5063460	363350	41.1	5.64	0.0829	0.512009	1.21			GR
56	DA18	5035290	369590	13.0	2.58	0.1199	0.512305	1.20			GD
57	JS10	5030372	373694	5.6	1.00	0.1076	0.512229	1.17			GD
							average	1.24			
Harvey & Belmont Juvenile											
58	JS4	4940071	709168	33.2	7.89	0.1435	0.512483	1.21			GD
59	JS7	4959827	709775	16.1	4.09	0.1537	0.512604	1.12			QD
60	JS8	4964612	708002	33.2	7.40	0.1349	0.512435	1.17			MG
61	MW1	4949870	270050	20.9	4.36	0.1260	0.512290	1.11			GD
62	JS2	4930009	295745	83.8	18.82	0.1358	0.512461	1.14			MZ
63	WK35	4985076	289760	11.9	2.50	0.1269	0.512336	1.24			GD
							average	1.17			

Table 1. Continued

Map#	Field#	Y	X	Nd ppm	Sm ppm	147/144	143/144	TDM	Q	P	Rock*
Grimsthorpe Juvenile											
64	WK3	4981498	317377	9.8	2.03	0.1257	0.512309	1.27	178	− 175	TN
65	WK5	4983466	318277	13.5	2.12	0.0949	0.512049	1.27	152	− 186	TN
66	WK6	4985280	317077	7.2	1.41	0.1180	0.512200	1.34	156	− 195	TN
67	WK8	4993204	318093	10.5	1.75	0.1010	0.512096	1.29	168	− 142	GD
							average	1.29			

* Orthogneisses classified according to rock types in Figure 5, based on Q–P index or hand specimen mineralogy.

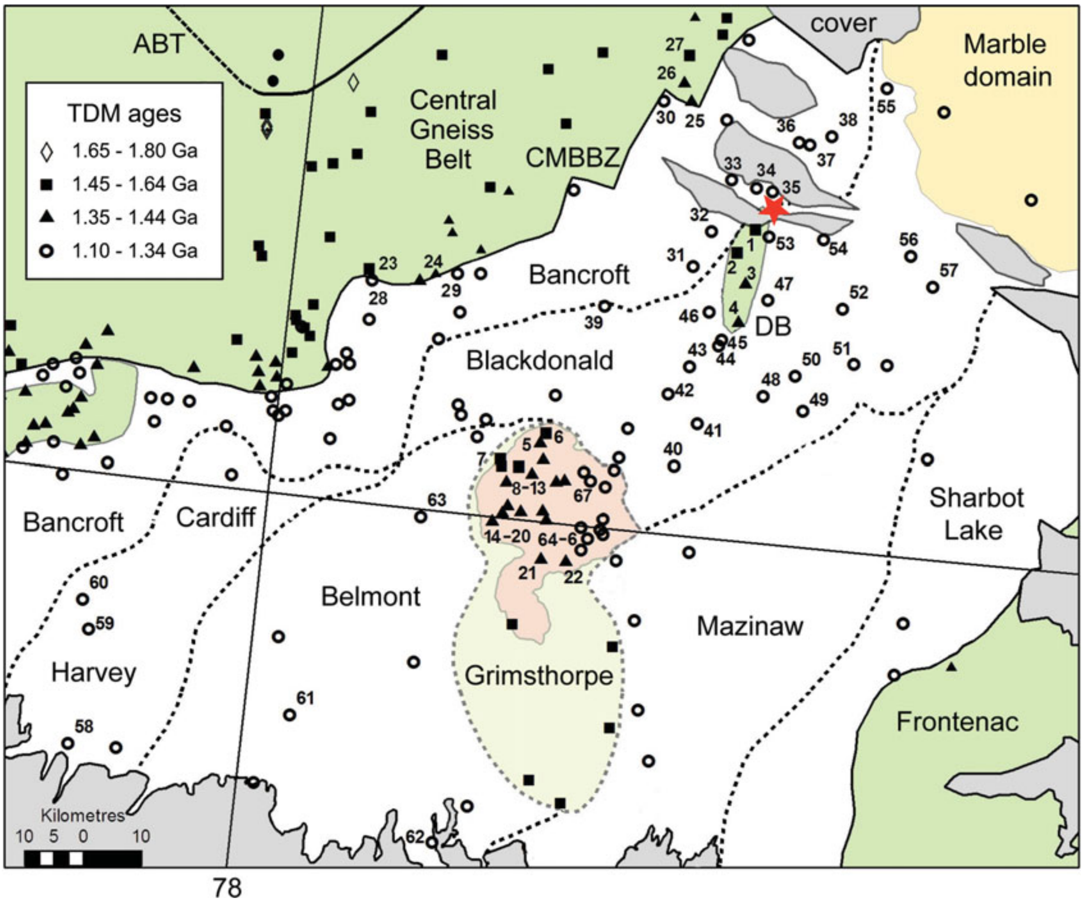

Figure 3. (Colour online) Map of the eastern part of the Ontario CMB showing new and published Nd data relative to CMB domains recognized by Easton and co-workers (see text). Red star indicates the town of Douglas. Pink shading represents mapped extent of the Weslemkoon batholith. DB – Douglas block; ABT – Allochthon Boundary Thrust. Open symbols indicate TDM model ages <1.35 Ga; solid symbols TDM >1.35 Ga.

defined by Easton (1992), as revised by Easton (2004) and Easton (2006). New samples are indicated by a map number that corresponds to their order in Table 1. In addition, published data are shown in Figure 3 as unnumbered points. These include a few samples from each CMB domain (Dickin & McNutt, 2007; McNutt & Dickin, 2012), a suite from both sides of the CMBBZ (Dickin *et al.* 2010) and a more detailed collection from the western part of the Bancroft domain (Moretton & Dickin, 2013). However, the present dataset fills a major sampling gap in the northeastern part of the Ontario CMB (Fig. 3).

Results in Table 1 are compared with data in the above-cited publications on a Sm–Nd isochron diagram (Fig. 4). New samples attributed to juvenile rift zone crust (red circles) are colinear with the published juvenile Nd suite (yellow circles), and fit a 1.27 Ga reference line. Elzevirian plutons studied by McNutt & Dickin (2012) with identical U–Pb and T_{DM} ages of 1.24 Ga (black circles) also lie close to this reference line. The good agreement of U–Pb ages, T_{DM} ages and the Sm–Nd isochron slope verifies the Nd model ages as accurate estimates of the crustal formation age of the juvenile rift zone and shows that the Nd data have not been significantly perturbed by crust–mantle mixing processes.

Samples with older crustal Nd signatures from the newly defined Douglas block (large pale blue squares) and from the Elzevir and Weslemkoon plutons (black and blue squares) show somewhat more scatter than the

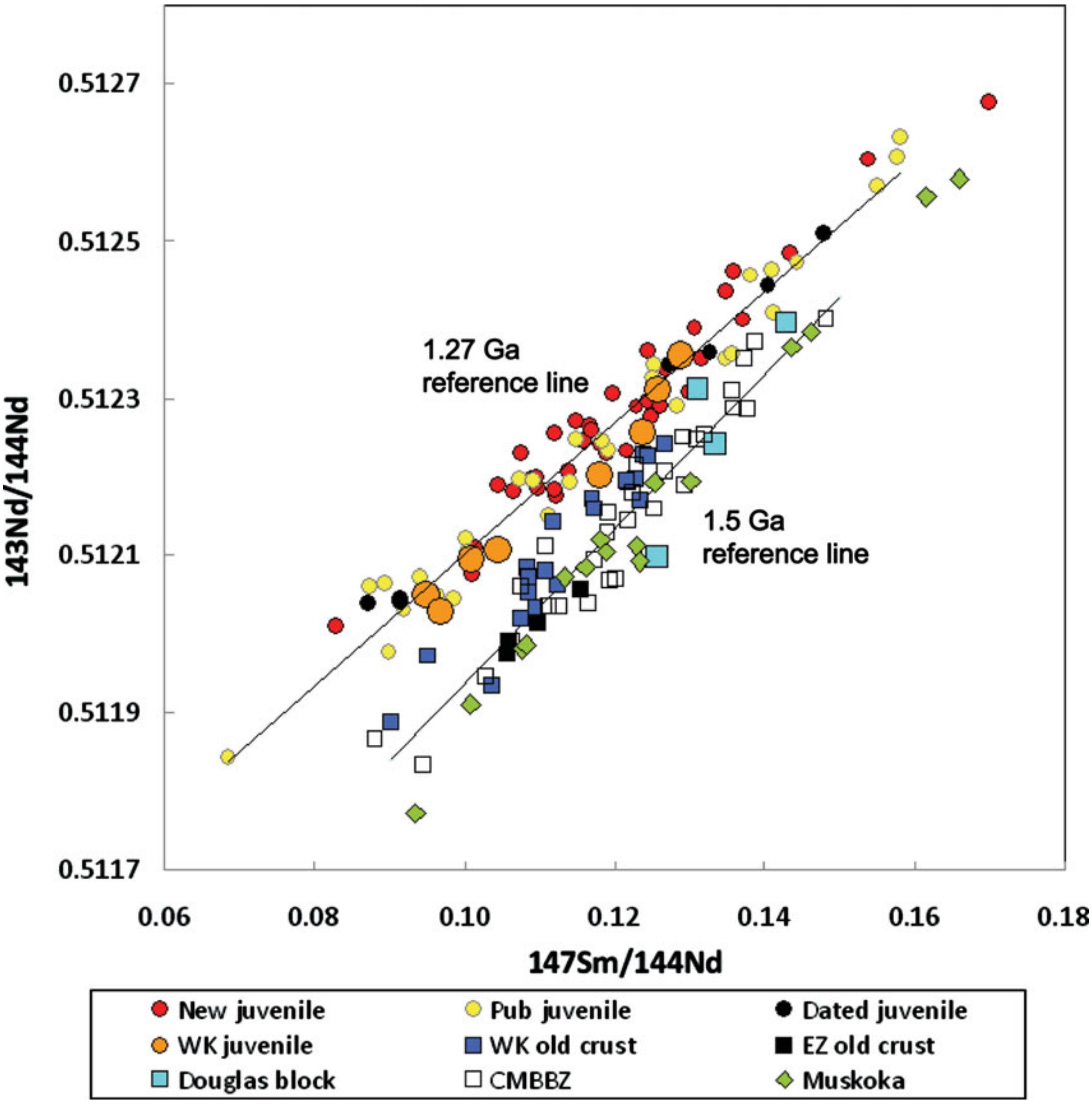

Figure 4. (Colour online) Sm–Nd isochron diagram showing distinct arrays defined by juvenile CMB crust and older crustal blocks. Regression lines are drawn through the published juvenile suite and the CMBBZ for reference.

juvenile suite, but they are colinear with new and published data from the CMBBZ (open squares), which fit a 1.5 Ga reference line. These compositions are also consistent with the suite of Muskoka gneisses analysed by Slagstad *et al.* (2009), including samples with U–Pb ages of 1.45 to 1.47 Ga. Hence, the agreement between U–Pb ages, T_{DM} ages and the Sm–Nd isochron slope again verifies the Nd model ages as indicative of the formation age of the crust, and suggests that the Elzevir–Weslemkoon and Douglas blocks represent fragments of old basement rifted away from the walls of the rift zone.

In addition to revealing the existence a small hidden block of older crust south of Douglas, the new Nd data also clarify the extent of old crust in the northern part of the Grimsthorpe domain. Here, the Weslemkoon pluton (pink shading in Fig. 3) extends across almost the whole width of the domain. However, the reconnaissance work by Dickin & McNutt (2007) revealed old (1.47–1.54 Ga) T_{DM} ages in the western part of the Weslemkoon pluton, but juvenile (1.24–1.33 Ga) T_{DM} ages in its eastern part. This may seem surprising, since there is no visible petrological break between the two areas. Therefore, the pluton was subjected to more detailed sampling to test the previous results and to localize any boundary between the two age domains. The new data fully support the earlier model (Fig. 3), but have not yet delineated a petrological boundary in the field.

Major element data were also obtained on samples from both the ‘old’ and ‘juvenile’ Weslemkoon Nd suites in order to see if there is any systematic difference between their petrology/geochemistry. The data are first presented on the Q–P diagram of Debon & LeFort (1983), which reproduces the Streckeisen (1973) classification for granitoids using major-element chemistry (Fig. 5).

This plot reveals a restricted range of petrology in the Weslemkoon pluton, spanning across the tonalite and granodiorite fields, in contrast to the more variable petrology of samples from the juvenile rift zone, the CMBBZ and the Douglas block (Fig. 5). WK samples

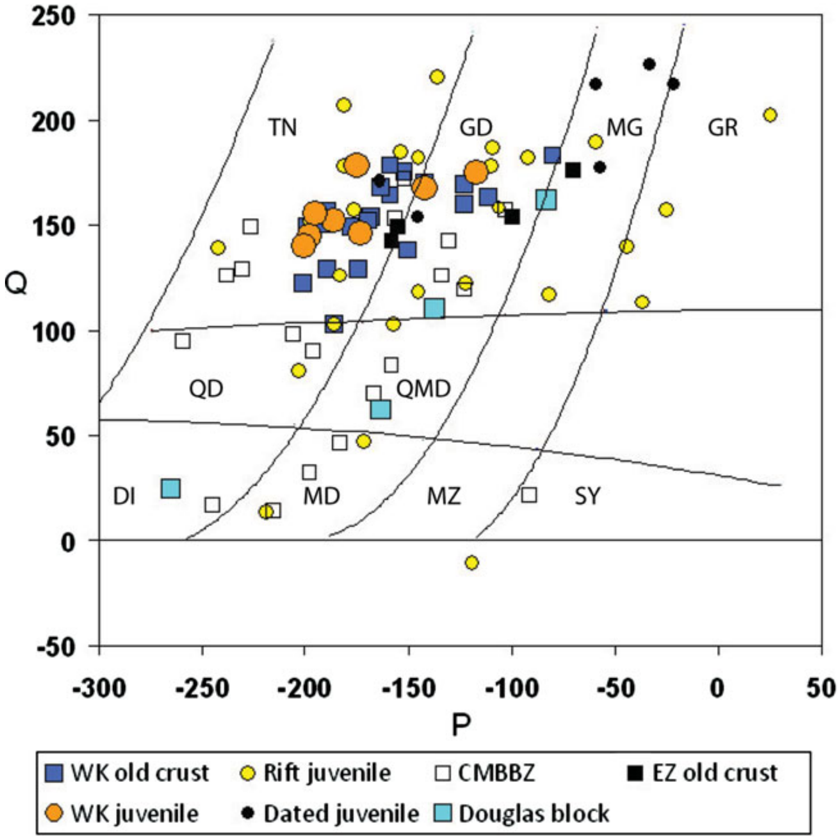

Figure 5. (Colour online) Q–P diagram of Debon & LeFort (1983) which generates an empirical Streckeisen classification. TN – tonalite; GD – granodiorite; MG – monzogranite; GR – granite; QD – quartz diorite; QMD – quartz monzodiorite; DI – diorite; MD – monzodiorite; MZ – monzonite; SY – syenite.

showing juvenile Nd signatures (orange circles) are colinear with the suite of dark blue squares, representing old crustal signatures. This similarity between the two sample suites was unexpected, but samples from the Elzevir pluton and from dated Elzevirian-age plutons elsewhere in the CMB also follow the same trend. This suggests that the geochemical trend is the result of phase control of melt compositions formed at similar depths in the crust, rather than a cogenetic origin.

This explanation is supported by a comparison of the chemistry of the Weslemkoon body with the Coast Mountains batholith, British Columbia (Fig. 6). This batholith straddles a terrane boundary between two accreted arcs with distinct crustal formation ages, the inboard Stikinia terrane and the outboard Wrangellia terrane (Girardi *et al.* 2012). Samples of the batholith from the inboard and outboard segments, spanning an across-strike distance of more than 100 km, have largely distinct Nd isotope signatures (Fig. 6c), but appear to form a single differentiation series on variation diagrams against silica, two of which are shown in Figure 6a, b (Girardi *et al.* 2012). Suites from the Weslemkoon body corresponding to old crustal and juvenile segments show almost identical behaviour, suggesting that the Weslemkoon and West Coast magma suites resulted from similar petrogenetic processes.

Further evidence that a single batholith can sample both sides of a terrane boundary comes from comparison with the Wooley Creek batholith in the Klamath Mountains of northern California (Coint *et al.* 2013). This is a much smaller batholith, little more than 10 km wide, but its structural style more closely resembles Weslemkoon, as shown by the mapping work of Lumbers & Vertolli (2001). Like the Weslemkoon body, the Wooley Creek batholith has a strong concentric foliation pattern of the type often associated with diapiric emplacement. However, the batholith is tilted along its length, so its lower dioritic–gabbroic parts can be sampled at its northern end, for comparison with the tonalitic–granodioritic petrology of the upper part at its southern end. This tilted attitude shows that even though the southern end of the batholith appears to be a single intrusive body, it was actually amalgamated from a series of separate plutons that can be distinguished in the lower parts of the magmatic system (Coint *et al.* 2013).

Taken together, these modern analogues show that what superficially appears to be a single, concentrically foliated pluton can in fact be amalgamated from a series of separate magma bodies at depth, which can therefore sample distinct crustal sources on either side of a terrane boundary. Therefore, the isotopically distinct segments of the Weslemkoon body suggest that it is actually a small batholith with multiple magma pulses from different crustal sources. This is consistent with the label 'Weslemkoon batholith' that was

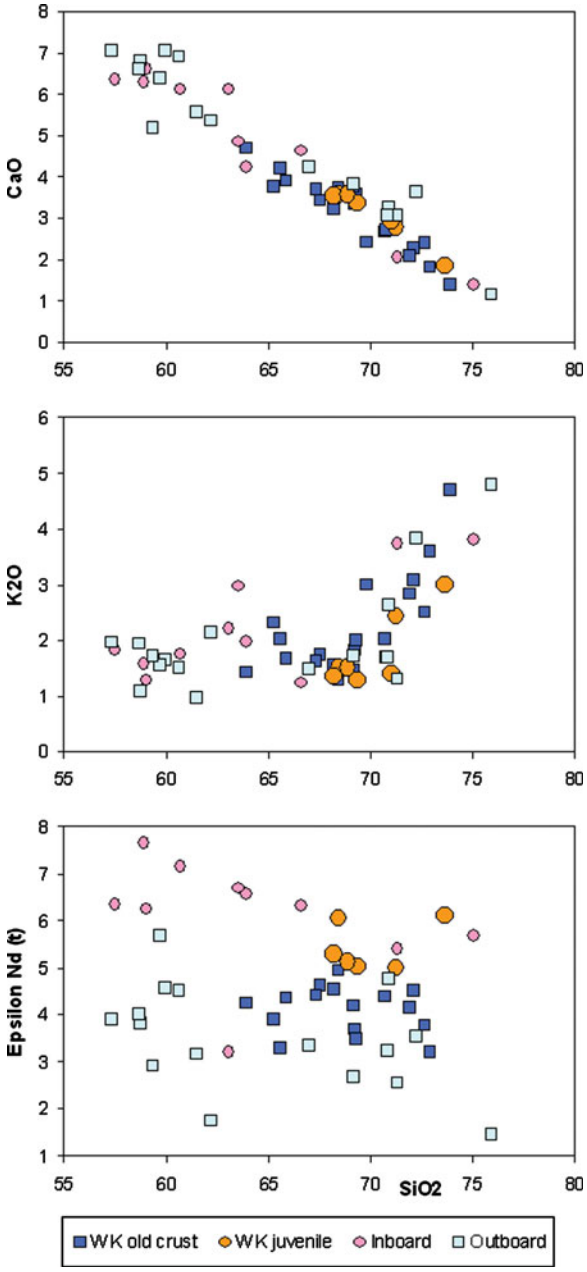

Figure 6. (Colour online) Variation diagrams of CaO, K_2O and epsilon Nd against silica to compare the chemistry of the Weslemkoon body with inboard and outboard segments of the Coast Mountains batholith of British Columbia.

applied by the original field mappers (Lumbers & Vertolli, 2001).

McNutt & Dickin (2012) cited an unpublished U–Pb age of 1276 Ma for the Weslemkoon batholith (Heaman, pers. comm.). Since the batholith represents a ‘stitching’ pluton relative to the terrane boundary between the old crustal block and juvenile Elzevirian-age crust, this implies that these blocks were contiguous prior to 1276 Ma, much earlier than the previously proposed minimum age for the ‘assembly’ of the Composite Arc Belt at 1245 Ma (Easton & Kamo, 2011). This provides a very short time window to create an arc terrane in the form of the Mazinaw volcanics (Sethuraman & Moore, 1973), before its assembly with other CMB terranes took place. These difficulties vanish with the back-arc rift zone model.

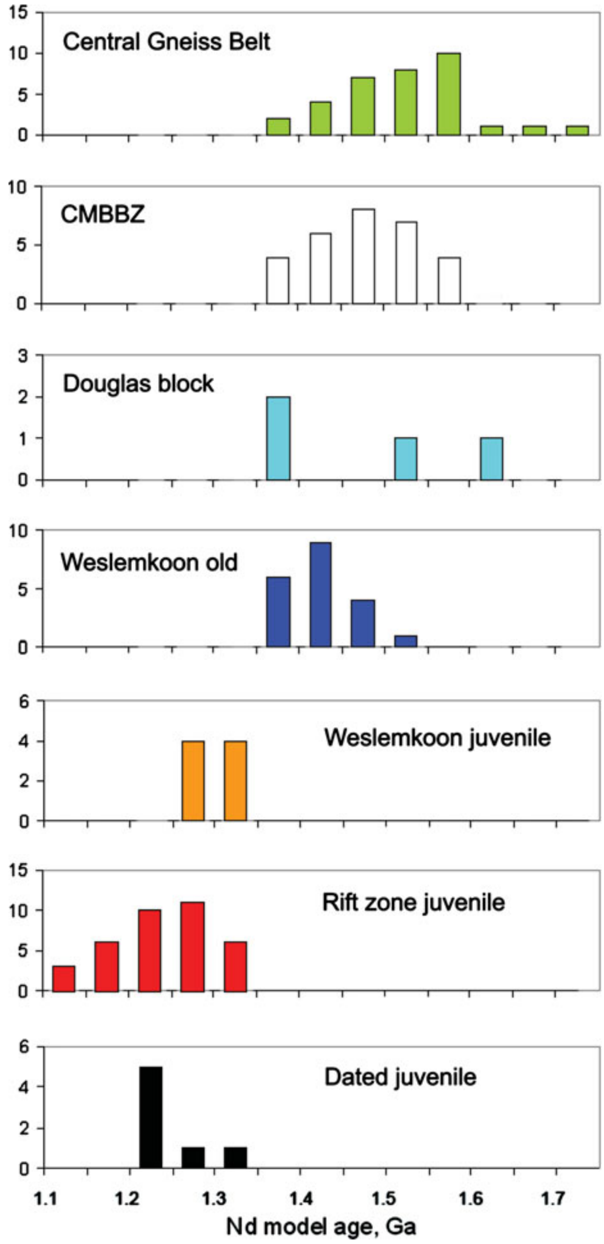

Figure 7. (Colour online) Histograms of T_{DM} age for samples suites analysed in this study, along with reference suites from the Central Gneiss Belt (Dickin *et al.* 2010) and dated Elzevirian-age plutons (McNutt & Dickin, 2012).

6. Discussion

To summarize the new Nd data and compare them with published data, they are plotted as histograms in Figure 7, using the same colour scheme as Figures 4 and 5. This shows that the old crustal blocks (Weslemkoon and Douglas) have the same range of T_{DM} ages (>1.35 Ga) as the CMBBZ and the SE edge of the Central Gneiss Belt (Muskoka and southern Algonquin domains), except that the latter contains a few slightly older ages, consistent with its formation as an ensialic arc on the edge of an older Laurentian continent (Dickin & McNutt, 1990). On the other hand, crust from the juvenile ensimatic rift zone has T_{DM} ages less than 1.35 Ga, overlapping with the range of T_{DM} ages in dated Elzevirian plutons, but displaying somewhat more scatter. Hence, the data define a bimodal distribution, consistent with petrogenesis of the analysed metaplutonic rocks by partial melting either of old (>1.35 Ga) ensialic crust or juvenile (1.2–1.35 Ga) ensimatic crust. There is very little evidence for mixing between these sources, so the analysed rocks can be used to map out the extent of old and young crustal domains.

Our refined Nd isotope mapping of the CMBBZ and the Elzevir and Douglas blocks yields more precise geometrical information about the shape of the proposed Elzevirian back-arc rift zone. When the areas with old crustal signatures are compared with the mapped extent of nepheline syenite bodies in the Bancroft area (red colour in Fig. 8), it can be seen that the nepheline syenites approximately bisect the juvenile crustal zone between the CMBBZ and the two old crustal blocks. We therefore infer that the nepheline syenites were emplaced as a late magmatic suite down the axis of a failed spreading zone between the CMBBZ and the old crustal blocks. On the other hand, if the nepheline syenites had been emplaced as early magmatic products associated with the beginning of rifting, their distribution should have been along the margins of the juvenile crustal zone.

The Blue Mountain nepheline syenite (blue colour Fig. 8) does not fit this model, since it is not colinear with the Bancroft nepheline syenite suite. However, we suggest that it is part of an older age suite. It is well known that there were several episodes of nepheline syenite magmatism in the CMB, spanning nearly 200 Ma and including Elzevirian and Ottawan-age suites (Lumbers *et al.* 1990). It has generally been assumed that the Elzevirian-age representatives were of uniform age, but the evidence suggests otherwise.

A rubidium–strontium isochron for the Blue Mountain nepheline syenite (Krogh & Hurley, 1968) gives an age of 1274 ± 40 Ma using the new decay constant (Dickin, 2005). The isochron was of high quality, but the known mobility of Rb during metamorphism suggests that it should be regarded as a minimum age for intrusion, since Rb–Sr ages for CMB plutons generally underestimate their true ages (Heaman, McNutt & Krogh, 1986). The low zircon content of this body has so far prevented U–Pb dating, but several authors have cited a significantly younger U–Pb age of 1219 Ma on a nepheline gabbro from the Bancroft suite (R. R. Miller, unpub. Ph.D. thesis, Univ. Toronto, 1985). Lumbers *et al.* (1990) argued that this result underestimated the true age, because most zircon in the sample was from an Ottawan-age metasomatic event. Instead, they estimated a minimum age of 1250 Ma for the Bancroft nepheline syenite suite, on the basis that these rocks are cross-cut by the *c.* 1250 Ma age alaskite granite suite. However, more recent work by Easton & Kamo (2011) showed that the alaskite suite of Lumbers *et al.* (1990), termed the Methuen suite by Easton (1992), is diachronous. The estimated age range in the Belmont domain (Fig. 3), including the Methuen pluton itself, was from 1240 to 1250 Ma, whereas the age range in the Harvey–Cardiff domain was from *c.* 1210 to 1230 Ma. Furthermore, McNutt & Dickin (2012) cited an even younger unpublished U–Pb age of 1200 Ma for the Faraday alaskite of the Bancroft terrane (Heaman, pers. comm.).

These new age data remove the basis for a minimum age of 1250 Ma proposed for the Bancroft nepheline syenite suite by Lumbers *et al.* (1990). However, Easton & Kamo (2011) proposed an age only slightly younger (1245 Ma) based on chemical similarities with the 1246 Ma Glamorgan (Trooper Lake) alkali gabbro pluton, dated by Pehrsson, Hanmer & van Breemen (1996). Therefore, although the age of the Bancroft nepheline syenite suite remains uncertain, the available evidence suggests that it is several tens of millions of years younger than the Blue Mountain nepheline syenite. This suggests that the Bancroft nepheline syenites might mark a later stage of magmatic activity towards the end of the CMB rifting process.

The oldest unit of the CMB dated by U–Pb is the Dysart gneiss complex, with a crystallization age of 1337 Ma (Heaman, unpub. data cited by McNutt & Dickin, 2012). However, Nd data from this body shows it to be derived from crust that pre-dates formation of the rift zone (Moretton & Dickin, 2013). The second oldest units, which come from areas of juvenile crust in the Harvey–Cardiff and Belmont domains, are the Anstruther gneiss complex, with a U–Pb crystallization age of 1290 Ma (Burr & Carr, 1994), and the Cordova Lake dacite, with a crystallization age of 1287 +11/−3 Ma (Davis & Bartlett, 1988). Both of these units are calc-alkaline felsic rocks from areas of juvenile crust. Hence, the formation of mafic juvenile crust in these areas probably pre-dated the felsic units by several millions of years. In comparison, the oldest reported U–Pb age for the Mazinaw terrane is slightly younger, at 1276 ± 2 Ma (Corfu & Easton, 1995). However, comparison with the data of Davis & Bartlett (1988) suggests that the upper age uncertainty quoted by Corfu and Easton could have been underestimated, and therefore that the interval between volcanism in the two areas could be less than 10 Ma.

It is well established, as described in the introduction, that volcanism in the CMB began with tholeiitic compositions and transitioned to calc-alkaline. Therefore, it can be anticipated that rifting to generate juvenile mafic crust probably occurred at least 10 Ma before the oldest dated calc-alkaline units. Therefore, rifting in the Harvey–Belmont area probably occurred before 1300 Ma, followed shortly afterwards in the Mazinaw area. In contrast, the oldest ages determined for the Bancroft terrane are significantly younger, with a maximum age of calc-alkaline plutonism represented by the 1250 Ma McArthur Mills tonalite (Heaman, unpub. data cited by McNutt & Dickin, 2012). This suggests that the Bancroft terrane may

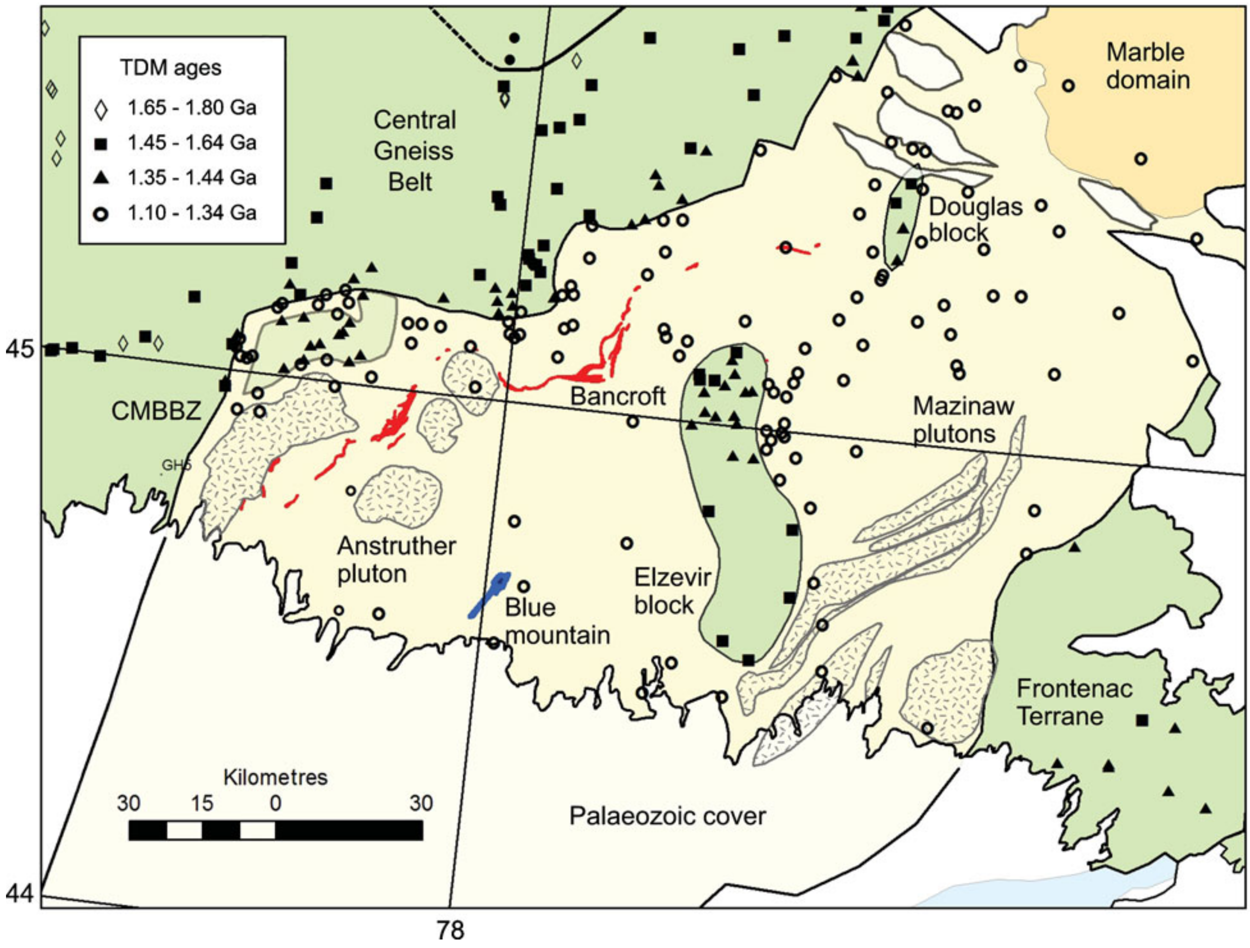

Figure 8. (Colour online) Back-arc 'aulacogen' model for the CMB showing proposed extent of the Elzevir block and the Douglas block. The extent of the Bancroft nepheline syenite suite is shown in red, in contrast to the earlier Blue Mountain body (blue colour). Open symbols indicate T_{DM} model ages < 1.35 Ga; solid symbols TDM >1.35 Ga. Selected plutonic bodies are shown (see text).

represent a younger crustal segment of the CMB than the Harvey–Cardiff–Belmont–Mazinaw domains (Fig. 3). However, younger bimodal tholeiitic volcanic rocks were also found in the Mazinaw domain, dating to 1246 Ma (Corfu & Easton, 1995). Easton (2006) recognized this as a later 'rifted arc' succession, and this suggests (relative to the early tholeiitic series in this area) that the locus of rifting was shifting back and forth as the back-arc rift zone was developing.

This type of behaviour is also seen in the modern Ethiopian rift system, where recent rhyolite volcanism is located in a narrow belt of axial grabens within the earlier rift valley (Beutel *et al.* 2010). However, it is also notable that Quaternary peralkaline activity is located within the older Ethiopian flood basalt province (Natali *et al.* 2013). This suggests that when bimodal rift-related magmatism shifts to a new locus in the rift, older magmatic centres may transition to more alkaline magmatism as the heat source dissipates, producing small-degree alkalic mantle melts. This can explain the locus of nepheline-bearing magmatism in the CMB as an expression of the waning of magmatic activity in one area, as the locus of rifting shifted to a new back-arc spreading centre.

An attempt to explore the geometrical ramifications of such a model is presented in Figure 9 in the form of a schematic geological history of the CMB. This history begins around 1300 Ma with the development of the Peterborough and Renfrew rift segments (Fig. 9a). Creation of new ensimatic crust followed over the next 10 Ma (Fig. 9b), but as the heat supply that had driven this rifting event came to an end around 1275 Ma, the Blue Mountain nepheline syenite was emplaced (Fig. 9c). At the same time, the locus of rifting jumped to the northwest, forming a narrow ensimatic spreading centre (pink shading in Fig. 9c) on the west side of the earlier juvenile crustal segments. This new rift segment, largely corresponding to the Bancroft terrane, is not characterized by large amounts of volcanic rock at the present erosion level, but has the greatest thickness of marbles. When coupled with the juvenile Nd isotope signature of the Bancroft terrane, this implies that mafic volcanic rocks underlie the marbles.

When the heat from this event had almost dissipated, nepheline syenites were emplaced near the axis of the spreading centre (Fig. 9d), at the same time as bimodal rift-related volcanism switched back to the Mazinaw domain (Fig. 9e). The emplacement of the nepheline gabbros and syenites during the waning

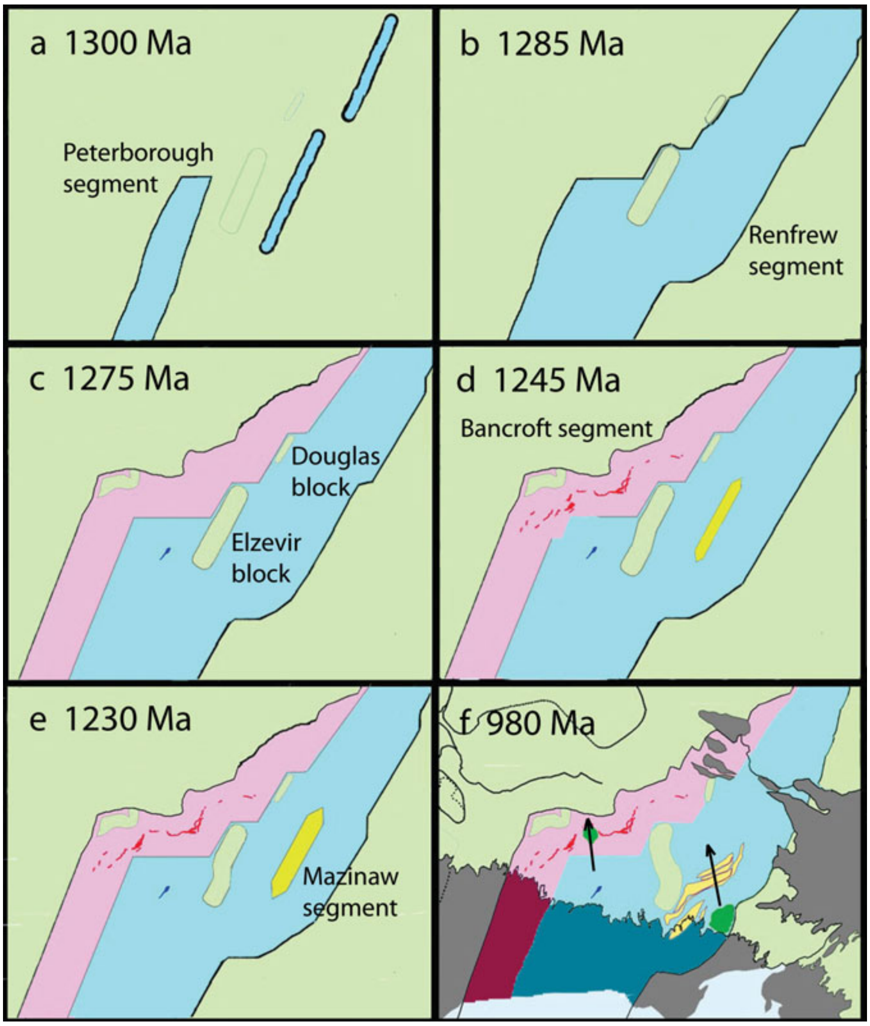

Figure 9. (Colour online) Model showing multi-stage development of the Ontario segment of the Elzevirian back-arc rift zone. Pale green – pre-rift crust; pale blue – early Peterborough and Renfrew rift segments; dark blue – Blue Mountain nepheline syenite; pale pink – late Bancroft rift segment; red – Bancroft nepheline syenite suite; yellow – late Mazinaw rift; yellow-brown – imbricated Mazinaw domain plutons; mid green – Cardiff and Hinchinbrook plutons (see text); dark shading – Palaeozoic cover.

stages of spreading gave rise to similar late alkaline magmatism in the Rio Grande Rift, possibly reflecting small-degree melting of lithospheric mantle sources (Leat *et al.* 1989; Thompson *et al.* 2005).

7. Conclusions

The proposed multi-stage rifting model places the exotic alkaline rock types of the Bancroft area within a viable plate tectonic framework for the first time. It explains why this magma suite, elsewhere specifically associated with rifting events, is here emplaced into juvenile crust approximately intermediate between older crustal blocks. The rifting model also explains how a juvenile crustal zone could cut obliquely into the interior of the Laurentian continent (Fig. 2) dying out where it encountered cold Archaean basement and forming an aulacogen.

It may seem surprising that the proposed geometry of the rift zone could have been preserved through the successive phases of the Grenville orogenic cycle. However, we suggest that the key feature that preserved its geometry was its infilling with mafic igneous rock, which made it act as a relatively rigid block during subsequent tectonic inversion. The presence of large volumes of mafic rock in the CMB is attested to by a regional gravity high, which was modelled by Roy & Mereu (2000) as a dense layer at the bottom of the CMB allochthon, thrust over less dense rock of the Central Gneiss Belt. Probably the CMB became detached from an ultramafic under-plate during the Shawinigan event (*c.* 1180 Ma), and was thrust as a unit over the gneiss belt by reactivation of listric normal faults that defined the original NW margin of the rift zone, thus forming the CMBBZ. The Bancroft shear zone was also developed during the Shawinigan event (Hanmer & McEachern, 1992), possibly following other listric normal faults originally associated with one of the phases of rifting.

The much larger Ottawan collision began to the SE of the exposed Grenville Province, with a suture zone now buried under the Appalachians (Bartholomew & Hatcher, 2010). Relative to this collisional event, the CMB was uplifted as a single unit, acting as a rigid orogenic lid (Rivers, 2012). However, because of the larger size of the orogen, gravitational collapse began much lower in the crustal section, along a new thrust zone to the NW, forming the Allochthon Boundary Thrust (ABT, Rivers *et al.* 1989). Meta-eclogites near the ABT attest to its character as a crustal-scale ramp (Martignole, 1992), but the allochthon to the NW forms a large sub-horizontal thrust sheet (Dickin and North, 2015).

The recognition of widespread ramp-flat thrusting in the SW Grenville Province (Dickin *et al.* 2014) brings its structure into line with the eastern Grenville Province, where such structures were modelled kinematically by assuming a block of higher rigidity in the centre of the orogen (Jamieson *et al.* 2010). In comparison, we argue that the location of the main ramp of the ABT was itself controlled by the existence of the CMB as a rigid block (Dickin & North, 2015). In contrast to the ABT, motion on the CMBBZ was largely extensional during the Ottawan orogeny (van de Pluijm & Carlson, 1989), so that the underlying Muskoka domain of the CMB acted as an extrusion zone similar to the Manicouagan Imbricate Zone (Jamieson *et al.* 2010).

Within the CMB, the only major Ottawan-age tectonism occurred in the Mazinaw domain, which was pervasively imbricated (Corfu & Easton, 1995; Schwerdtner, Downey & Alexander, 2004). The Hinchinbrook pluton (green body in Fig. 9f) may have acted as a relatively rigid block that transmitted stress into the Mazinaw domain as an indentor (large arrow in Fig. 9d). Similar effects are seen at the northern end of the Harvey–Cardiff domain. The series of gneiss domes forming this domain (Fig. 7) probably acted as another rigid block, exerting northward pressure on the Bancroft terrane that caused deformation of the nepheline syenites north of the Cardiff gneiss dome (shorter arrow in Fig. 9f).

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