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RAPID COMMUNICATION

A revised model for the crustal structure of the SW Grenville Province, Ontario, Canada

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Abstract

The Grenville Province forms the exhumed remnants of a 1.1 Ga collisional orogeny that telescoped an older continental margin. Terranes with distinct crustal formation ages can be mapped using Nd isotopes, revealing a ramp–flat thrust structure. The ramp is identified by the presence of retrogressed eclogites, and its trajectory is refined using Nd model ages. The main allochthon is locally overlain by the Parry Sound klippe, but is also underlain by a tectonic duplex. Northwest-directed nappes represent remnants of a corrugated thrust sheet, but a ring-shaped remnant was also preserved where the thrust sheet was down-buckled under the dense rocks of Parry Sound domain.

Keywords: Nd isotope mapping, Nd model ages, crustal formation, ramp-flat thrusting

1. Introduction

The SW Grenville Province represents a deeply exhumed ancient collisional orogen with similarities to the modern Himalayas (Windley, 1986). Like the Himalayas, the Grenville Province underwent crustal shortening and gravitational collapse by thrusting, generating a series of sub-parallel high-strain zones. Modern understanding of the history of the orogen has been based on mapping this series of thrusts (Rivers *et al.* 1989). However, detailed mapping has been hampered by high-grade metamorphism, coupled with late extensional shearing, which has tended to overprint earlier convergent structures (Culshaw *et al.* 1994).

Rivers *et al.* (1989, 2002) recognized the Allochthon Boundary Thrust (ABT) as the principal locus of crustal shortening during the *c.* 1080–1040 Ma Ottawan phase of the Grenville Orogenic Cycle, separating a relatively *in situ* parautochthon to the NW from more far-travelled allochthonous terranes to the SE (Fig. 1). However, it should be noted that in the Grenvillian context, the term 'allochthonous' does not mean that these terranes were exotic to Mesoproterozoic Laurentia.

In Quebec and Labrador, the ABT was localized on the basis of magnetic signatures, which separate the magnetically 'quiet' Archaean parautochthon from the magnetically 'noisy' Proterozoic allochthon, reflecting the more complex geological history of the latter. However, in Ontario the ABT is located further south within Proterozoic rocks. This location was originally based on recognition of the basal Parry Sound Shear Zone (PSSZ) on the west side of the Parry Sound domain as a major thrust zone. The PSSZ is the most prominent high-strain zone on the Georgian Bay shoreline (Davidson, Culshaw & Nadeau, 1982), and was therefore a likely locus of the ABT. Hence, Rivers *et al.* (1989) sketched a possible trajectory for the ABT running round the north side of Parry Sound domain (PS, Fig. 1) and then trending eastwards, sub-parallel to the Monocyclic Belt Boundary (MBB, Fig. 1). However, its connection to the ABT in Quebec remained unclear (question mark in Fig. 1).

In their early mapping of the Georgian Bay shoreline, Davidson, Culshaw & Nadeau (1982) also identified a second, less prominent shear zone *c.* 10–20 km north of the Parry Sound Shear Zone. This more northerly structure was later referred to by Culshaw *et al.* (1997) as the Shawanaga Shear Zone (SSZ, Fig. 2). It was found to contain mafic pods that were tentatively recognized by Davidson, Culshaw & Nadeau (1982) as retrogressed eclogite, an identification supported by detailed textural and chemical analysis (Grant , 1989). Subsequently, retrogressed eclogites were also recognized at other localities in the Parry Sound region (Ketchum & Davidson, 2000), of which the examples shown by red stars in Figure 2 were verified by Davidson, Nadeau & Culshaw (2012).

The Shawanaga Shear Zone was also found to separate two other meta-basic suites with apparently non-overlapping geographical distributions. These are represented by olivine meta-diabase equivalent to 1.24 Ga Sudbury dykes in the northwest, and 1.17 Ga coronitic olivine meta-gabbro in the southeast (Culshaw *et al.* 1994). The juxtaposition of these non-overlapping suites at the Shawanaga Shear Zone implied that this was a locus of significant tectonic convergence. Hence, Ketchum & Davidson (2000) concluded that the Shawanaga Shear Zone rather than the PSSZ was the local expression of the ABT.

Based on stacking relationships, it was evident from the early work of Davidson, Culshaw & Nadeau (1982) that the Parry Sound domain was partially overthrust by other thrust sheets from the SE (the Moon River and Seguin nappes; Fig. 2). However, with the recognition that the ABT is located structurally below the Parry Sound shear zone, it became apparent that the Allochthonous Polycyclic Belt (belt 2 in Fig. 1) has two major structural decks (e.g. Culshaw

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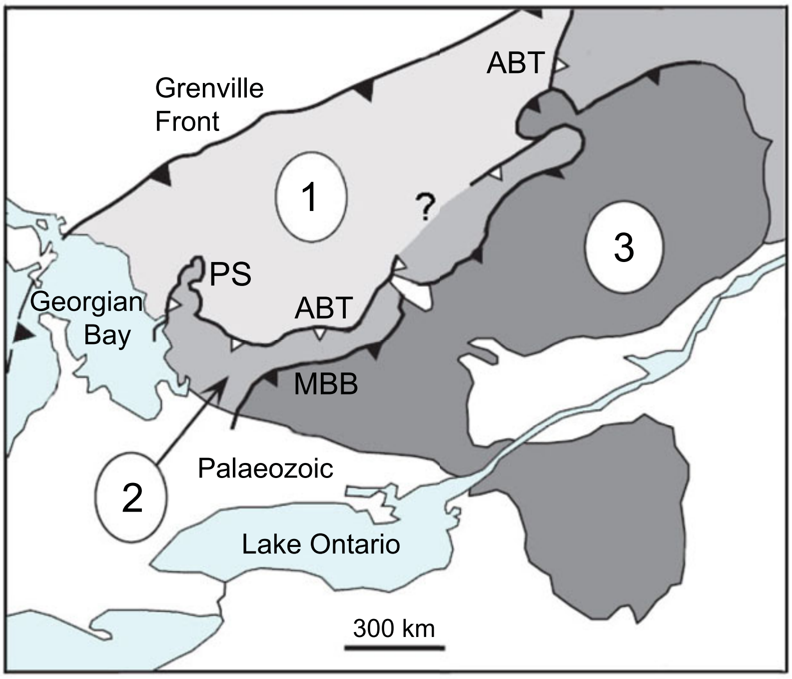

Figure 1. (Colour online) Map of the SW Grenville Province in the Great Lakes region showing structural belts proposed by Rivers *et al.* (1989): 1 = Parautochthon; 2 = Allochthonous Polycyclic Belt; 3 = Allochthonous Monocyclic Belt. ABT = Allochthon Boundary Thrust; MBB = Monocyclic Belt Boundary; PS = Parry Sound domain. Modified after Rivers *et al.* (1989).

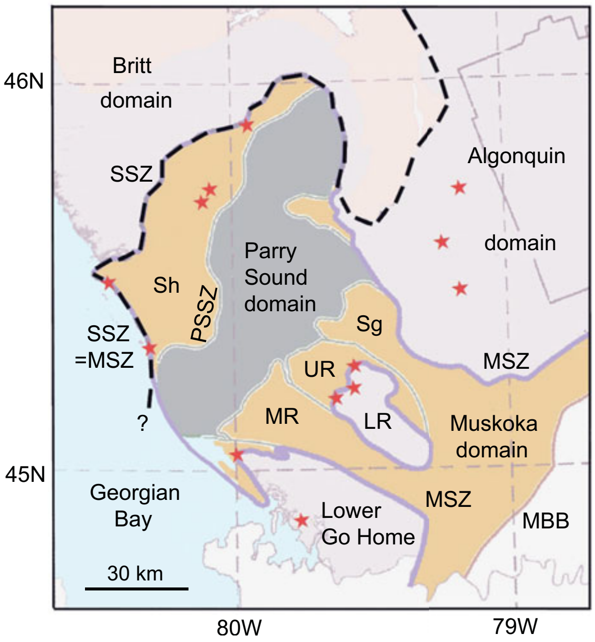

Figure 2. (Colour online) Map of the Parry Sound region showing major shear zones: PSSZ = Parry Sound Shear Zone; SSZ = Shawanaga Shear Zone (bold dashed line); MSZ = Muskoka Shear Zone (solid purple line); MBB = Monocyclic Belt Boundary. Lithotectonic domains: Sh = Shawanaga; UR and LR = Upper and Lower Rosseau. Red stars = retrogressed eclogites. Modified after Culshaw *et al.* (2016).

et al. 1997, 2016). The upper deck (Muskoka domain, including Seguin and Moon River sub-domains), is separated from the lower deck (Algonquin domain) by a major shear zone, which we will refer to here as the Muskoka Shear Zone (MSZ, Fig. 2).

This shear zone, which forms the footwall of the Muskoka domain, was the original locus of the ABT proposed by Rivers *et al.* (1989). However, this model was abandoned by Rivers *et al.* (2002) when they chose the more northerly ABT trajectory of Ketchum & Davidson (2000), shown as a heavy dashed line in Figure 2. On the other hand, it was recently proposed by Culshaw *et al.* (2016) that these two shear zones (SSZ and MSZ in Fig. 2) coincide geographically on the Georgian Bay shoreline and northwards round the Parry Sound domain. Nevertheless, they appear to separate on the east side of the Parry Sound domain, which raises the question of which of these shear zones should be recognized as the principal locus of crustal convergence during Ottawan tectonism.

2. Significance of retrogressed eclogites

The presence of high-pressure rocks such as eclogite in the vicinity of the ABT implies exhumation from the deep crust. This supports the identification of the ABT as a crustal-scale ramp, as first proposed for the eastern Grenville Province (Indares, 1993; Rivers, Van Gool & Connelly, 1993). Retrogressed eclogites are seen prominently in the vicinity of the ABT on Georgian Bay (red stars in Fig. 2). However, elsewhere in the gneiss belt, the eclogites often occur at structural levels that appear to be far above the assumed ABT trajectory (heavy dashed line, Fig. 2). Of particular interest is their location on a shear zone that separates structurally lower and upper parts of the Rosseau domain (LR, UR, Fig. 2), interpreted by Culshaw *et al.* (2016) as equivalent to the Muskoka Shear Zone. Culshaw *et al.* refer to this boundary as the Monocyclic Boundary Thrust (based on recognizing the Muskoka domain as having a monocyclic metamorphic history). However, we prefer not to use this term, because the rocks of the Muskoka terrane were formed more than 350 Ma before the Grenville orogeny (Slagstad

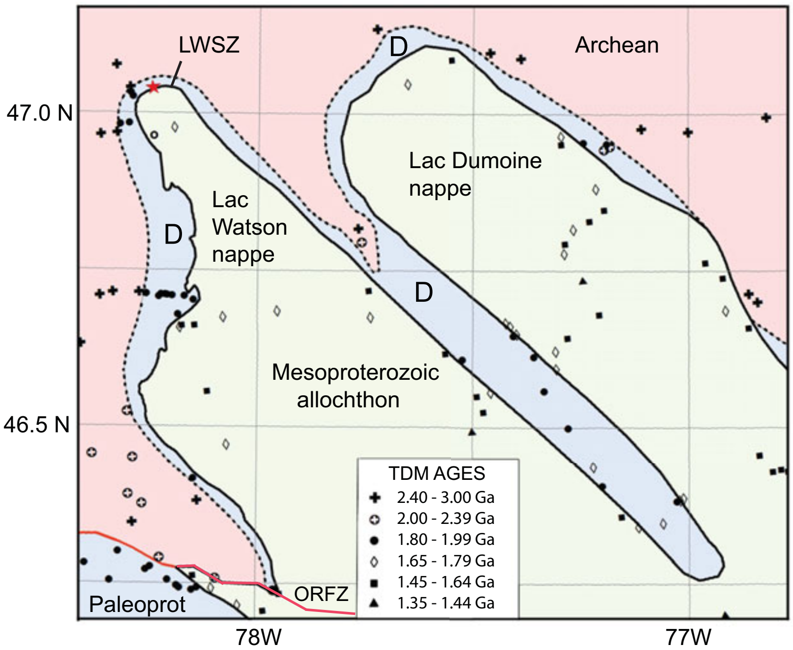

Figure 3. (Colour online) Map of the Lac Watson – Lac Dumoine nappes showing the proposed location of the ABT = Lac Watson Shear Zone (LWSZ) and Palaeoproterozoic duplex (D). ORFZ = Ottawa River Fault Zone. Red star = retrogressed eclogite. Modified after Dickin *et al.* (2012).

et al. 2004). Hence, referring to these rocks as monocyclic relative to the Grenville Orogeny can be misleading.

The location of the Rosseau eclogites near a shear zone of equivalent structural level to the Muskoka Shear Zone (Fig. 2) prompts us to reconsider the identity of these boundaries. Based on the association of eclogites with zones of deep crustal exhumation, we propose that the Muskoka Shear Zone represents the principal locus of Ottawan tectonic convergence, and hence the local expression of the ABT. However, this raises questions about the more northerly trajectories of the ABT previously proposed by other workers (e.g. Ketchum & Davidson, 2000; Rivers *et al.* 2002; Culshaw *et al.* 2016) and also by us (e.g. Dickin, Moretton & North, 2008).

To answer this question, we need to examine the structure of the ABT where it is known with more confidence, such as the Lac Watson area in western Quebec (Fig. 3). This area corresponds to the question mark of Rivers *et al.* (1989) shown in Figure 1, but was subsequently the subject of a detailed study by Indares & Dunning (1997). In this region, these authors mapped three structural decks with distinct lithologies, of which the lower one is Archaean in age, while the upper two are Proterozoic. They found retrogressed eclogite close to a major shear zone between the middle and upper decks, termed the Lac Watson Shear Zone (LWSZ; Fig. 3). Hence the Lac Watson Shear Zone is regarded as the local expression of the ABT, forming the footwall to the Mesoproterozoic allochthon in this area.

Subsequently, Herrell, Dickin & Morris (2006) showed that the middle deck of this stack had Palaeoproterozoic TDM model ages between 1.8 and 2 Ga, and referred to it as a structural duplex. This duplex was argued to represent parautochthonous crust that was entrained onto the base of the main allochthon by downward propagation of the basal décollement of the thrust sheet. This duplex structure was then shown by Dickin *et al.* (2012, 2014) to be of widespread distribution around the Lac Watson and Lac Dumoine thrust sheets (D, Fig. 3).

We propose here that the Mesoproterozoic allochthon in the Parry Sound area is underlain by a similar duplex structure that can be identified by Nd isotope mapping. However, the crustal structure in the Parry Sound area is more complex than at Lac Watson, because the Parry Sound domain itself represents a fourth structural deck on top of the main allochthonous thrust sheet (as proposed by Culshaw *et al.* 1997). In addition, the lower structural decks in the Parry Sound area have younger crustal formation ages than the Lac Watson area because the more southerly crustal units around Parry Sound were generated outboard of the Archaean craton during the Proterozoic eon.

As a result, the lower deck in the Parry Sound area is predicted to have Penokean TDM ages (1.8–2 Ga), as identified further north by Dickin & McNutt (1989), while the duplex is proposed to have Labradorian TDM ages (1.65–1.79 Ga). Finally, the main allochthon in the Parry Sound region is proposed to have Pinwarian TDM ages (1.45–1.64 Ga), as recently proposed by Dickin & North (2015). The ages of these orogenic events (based on U–Pb dating) have been defined elsewhere in the Mid Continent (Van Schmus, 1980) and the Grenville Province (Gower, Scharer & Heaman, 1992; Tucker & Gower, 1994). In addition, zircon ages in these ranges have recently been obtained by U–Pb analysis of quartzite and metaplutonic units from the Algonquin area (Culshaw *et al.* 2016).

3. Sampling and analytical techniques

The objective of Nd isotope mapping is to characterize the protolith age (crustal formation age) of large areas of crust as an indication of the geological relationships between highly metamorphosed lithotectonic terranes. The protolith age is one of the most fundamental features of a crustal terrane, but clearly there are other events in the geological history of terranes that are also indicative of relationships between them.

Another feature that may characterize lithotectonic terranes and domains is their magmatic/plutonic history. In the SW Grenville Province, the most widely distributed igneous crystallization event occurred around 1.45 Ga (Slagstad *et al.* 2004, 2009, and references therein). Rocks with U–Pb ages corresponding to this event are found in most of the lithotectonic domains shown in Figure 2, except for the monocyclic belt in the SE corner. Some older U–Pb ages are also found in the northern part of the study area (Nadeau & van Breemen, 1998, and references therein). However, these U–Pb ages are much too thinly scattered to be used to map the complexly deformed terrane boundaries in this region. In contrast, Nd isotope analysis represents a cost-effective technique for mapping lithotectonic terrenes, based on the robustness of Nd isotope signatures in highly metamorphosed terranes (e.g. Dickin, 2000). This method allows very high spatial resolution, which is unmatched by any other geological age discriminant.

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 arc crust. Previous studies have shown that granitoids of this type have Nd isotope signatures that are consistent and predictable, allowing reliable estimates to be made 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 primitive arc 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 arc crust. In contrast to granitoid rocks, sampling of mafic gneisses was avoided as far as possible, 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 weathered, veined or migmatized material, and careful attention was given to obtaining a fine powder representative of the whole rock. Sm–Nd analysis followed our established procedures. After a 4-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 ± 0.000012 (2σ), and an average value of 0.51185 ± 2 (2σ 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 % (1σ) respectively, leading to an analytical uncertainty on each model age of *c.* 20 Myr (2σ), based on empirical experience over several years of analysing duplicate dissolutions. Uncertainties deriving from the Nd mantle model are discussed below.

4. Results

New Nd data for nearly 70 samples from the Parry Sound region are presented in Table 1, where they are used to calculate TDM ages using the depleted mantle model of DePaolo (1981). As discussed by Dickin *et al.* (2016), this yields formation ages for crustal terranes in the SW Grenville Province that are very well supported by U–Pb dating (Slagstad *et al.* 2004, 2009). Samples are grouped in Table 1 according to the new structural domains proposed in this study, and are shown on a coloured map in Figure 4, where new data points from Table 1 are numbered, whereas published data points are unnumbered (Dickin & McNutt 1989, 1990; Dickin, Moretton & North, 2008 Slagstad *et al.* 2009; ; Dickin *et al.* 2010; Moore & Dickin, 2011; Dickin & North, 2015). However, two published analyses are included in Table 1 because of their strategic location in the newly recognized Proudfoot klippe (see below).

In Figure 4, our four proposed structural decks of the gneiss belt are coloured as follows: blue = Palaeoproterozoic parautochthon; violet = tectonic duplex; green = Mesoproterozoic allochthon; yellow = Parry Sound domain. The main allochthon is coloured in two shades of green to distinguish the segment underlying Parry Sound from the Muskoka segment. These two segments have the same range of model ages (to be demonstrated below) and are believed to have originally been a single thrust sheet that was later broken, so that the more southeasterly Muskoka terrane overrode the northwesterly terrane (Nobel – Ahmic – Upper Rosseau – Upper Go Home domains).

Parry Sound domain is the most significant lithotectonic unit in the study area because of its abundance of mafic rocks. These rocks give rise to a large positive gravity anomaly, up to 35 mGal higher than the surrounding crust (Lindia, Thomas & Davidson, 1983). This dense crustal unit locally depressed the underlying allochthon, protecting it from erosion and causing it to be preserved as an almost complete ring around Parry Sound domain (green in Fig. 4). The exception to this is the NE side of Parry Sound domain where it abuts nearly against the Powassan batholith. This plutonic body forms most of the large southerly salient of the parautochthon in Figure 4. Based on its negative gravity anomaly, the Powassan batholith probably acted as a buoyant object, pushing the overlying allochthon upwards so that it was removed by erosion.

To the west of Parry Sound domain, a proposed new location for the ABT divides the old Shawanaga domain into two parts. The eastern part is made up largely of the Nobel gneiss (Connare & McNutt, 1985), and this new unit is therefore termed the Nobel domain (Fig. 4). On the shores of Georgian Bay, the new boundary follows the same trajectory as the ABT proposed by Culshaw *et al.* (2004*a*, *b*) on the Parry Sound and Naiscoot map sheets (P3550, P3549) along the south side of the Shawanaga pluton.

As a result of detailed new sampling, the ABT is now defined on Highway 69 by a clear step in TDM ages (±1.65 Ga) that coincides with the boundary mapped by Culshaw (2004*a*). The boundary passes to the east of an outcrop of coronitic metagabbro (large green star in Fig. 4) that was dated to 1152 ± 2 Ma by Heaman & LeCheminant (1993). This shows that this coronitic metagabbro is not located in the main allochthon, but its underlying duplex. Hence, the two metabasic rock suites believed by Ketchum & Davidson (2000) to be separated by the ABT are actually separated by the sole thrust of the duplex, which we call the Duplex Boundary (dashed line in Fig. 4). Although the Duplex Boundary is not the principal locus of deep crustal exhumation corresponding to the ABT, it is still a zone of significant crustal shortening, as indicated in Figure 3, where the Palaeoproterozoic duplex overrides Archaean basement by at least 200 km.

The ABT was not mapped to the north of Highway 69 by Culshaw *et al.* (2004*a*). However, we trace it northwards on the west side of Parry Sound domain in Figure 4, where it passes close to two retrogressed eclogite outcrops (red stars),

Table 1. Nd isotope data

Map#	Field#	YNAD 83	XNAD 83	Nd ppm	Sm ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	TDM Ga
Parautochthonous Huntsville and Go Home windows								
1	HU12	5019027	637483	35.6	6.07	0.1032	0.511725	1.81
2	DW10	5020010	640490	40.9	7.42	0.1096	0.511807	1.81
3	HU1	5017274	640988	66.0	12.47	0.1142	0.511837	1.85
4	DW7	5022670	645780	32.2	5.55	0.1041	0.511779	1.76
5	DW6	5021060	647790	36.4	7.14	0.1184	0.511955	1.73
6	DW5	5017110	650250	34.0	5.97	0.1060	0.511735	1.85
7	DW1	5024310	650650	20.5	4.14	0.1221	0.511967	1.79
8	DW4	5019930	650960	46.0	8.12	0.1067	0.511840	1.71
9	DW3	5024350	652650	31.5	6.51	0.1247	0.511955	1.86
10	GH9	4951020	610588	28.3	6.45	0.1379	0.512105	1.88
11	GH14	4954406	610035	22.8	4.85	0.1287	0.511998	1.87
							Mean	1.81
Shawanaga/Algonquin/Rosseau duplex								
12	CG10	5042576	557762	43.9	8.97	0.1234	0.512020	1.72
13	BN7	5052159	642266	57.5	9.58	0.1006	0.511740	1.75
14	BN3	5049760	645893	19.2	2.91	0.0913	0.511667	1.71
15	AP6	5049590	657060	26.8	3.93	0.0881	0.511613	1.73
16	AH29	5049842	615334	47.8	9.02	0.1140	0.511917	1.72
17	AH31	5046043	617989	34.3	6.19	0.1091	0.511866	1.72
18	BN15	5045699	637618	39.1	7.56	0.1168	0.511925	1.76
19	NO8	5038752	628798	42.2	8.62	0.1236	0.512067	1.65
20	BN12	5038620	641742	30.4	5.22	0.1037	0.511807	1.71
21	D5	5033500	657100	55.8	11.19	0.1213	0.512031	1.66
22	NO5	5032187	631519	32.7	6.31	0.1168	0.511946	1.72
23	NO4	5031489	637879	34.4	7.21	0.1267	0.512054	1.73
24	NO9	5029795	627587	51.2	9.77	0.1154	0.511919	1.74
25	D3	5029600	651700	62.2	11.98	0.1165	0.511963	1.69
26	NO10	5028281	629602	119.3	20.77	0.1052	0.511767	1.79
27	NO3	5027170	638870	17.2	2.89	0.1012	0.511767	1.73
28	NO11	5027011	633592	13.6	2.04	0.0904	0.511654	1.72
29	NO1	5024422	631612	55.4	11.38	0.1241	0.512002	1.77
30	NO2	5024016	633193	24.2	4.41	0.1104	0.511891	1.70
31	HU18	5022556	642753	85.5	13.25	0.0936	0.511760	1.63
32	HU19	5022516	654055	36.8	6.37	0.1048	0.511858	1.66
33	HU17	5021054	638029	17.2	2.94	0.1035	0.511836	1.66
34	HU21	5017280	654235	67.7	11.52	0.1030	0.511842	1.65
35	DW11	5014867	642832	52.8	8.86	0.1015	0.511756	1.74
36	HU20	5014484	654359	49.4	7.98	0.0977	0.511766	1.68
37	HU23	5013370	659774	9.5	1.74	0.1105	0.511843	1.77
38	HU9	5012856	651296	22.4	3.86	0.1044	0.511846	1.67
39	HU22	5011261	661187	62.8	12.09	0.1164	0.511906	1.78
40	DW13	5011070	651251	6.4	1.17	0.1110	0.511870	1.74
41	RS7	5007698	617877	47.6	10.30	0.1307	0.512128	1.68
42	RS10	5006755	623288	39.8	8.03	0.1220	0.512004	1.72
							Mean	1.71
Mesoproterozoic allochthon								
Nobel domain								
43	CG11	5041883	558474	25.1	5.17	0.1245	0.512123	1.57
44	CG12	5040645	559648	29.1	5.24	0.1089	0.512004	1.51
45	CG18	5037326	560151	30.4	5.38	0.1068	0.511948	1.56
46	CG9	5037490	562935	45.3	9.91	0.1322	0.512195	1.58
47	CG7	5034925	565530	52.9	9.89	0.1130	0.512008	1.56
48	CG4	5031790	567935	54.0	10.34	0.1157	0.512018	1.59
49	CG2	5030415	561770	39.7	7.84	0.1195	0.512103	1.52
50	WW4	5065902	575246	32.6	5.39	0.1000	0.511895	1.54
51	WW6	5066310	573306	50.0	9.88	0.1195	0.512065	1.58
52	WW9	5065895	571645	36.2	6.22	0.1040	0.511873	1.62
53	WW11	5054200	567219	25.1	5.17	0.1245	0.512123	1.57
							Mean	1.56
Ahmic and Upper Rosseau domains								
54	AH21	5060561	604215	22.1	4.74	0.1296	0.512160	1.59
55	AH24	5058294	604903	39.1	8.30	0.1283	0.512211	1.48
56	AH27	5053397	608078	30.0	3.96	0.0796	0.511602	1.64
57	AH30	5045181	616313	46.0	7.64	0.1004	0.511980	1.43
58	RS1	5012398	605435	12.9	2.12	0.0994	0.511904	1.52
59	RS2	5005015	604650	47.6	8.40	0.1066	0.511901	1.62
							Mean	1.55
Muskoka terrane								
60	HU4	5013231	639494	47.7	9.27	0.1174	0.512121	1.45
61	HU2	5013859	641520	11.4	2.71	0.1439	0.512304	1.61
62	HU5	5013992	642471	48.2	9.37	0.1176	0.512017	1.62
63	HU8	5010717	650010	40.9	8.16	0.1207	0.512045	1.63

Table 1. Continued

Map#	Field#	YNAD 83	XNAD 83	Nd ppm	Sm ppm	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	TDM Ga
64	HU24	5010418	656526	56.5	11.36	0.1216	0.512147	1.49
65	HU25	5009292	655363	69.4	14.11	0.1228	0.512090	1.60
							Mean	1.57
Bethune and Proudfoot klippen								
66	BN4	5044151	643730	46.4	8.44	0.1099	0.511944	1.61
67	BN5	5046761	639960	70.6	15.59	0.1334	0.512251	1.50
68	BN6	5049005	639172	68.8	12.53	0.1101	0.511900	1.68
Pub	BL8	5063100	634600	6.5	1.16	0.1070	0.512017	1.46
Pub	AP12	5065850	638000	15.1	3.67	0.1467	0.512314	1.65
							Mean	1.58

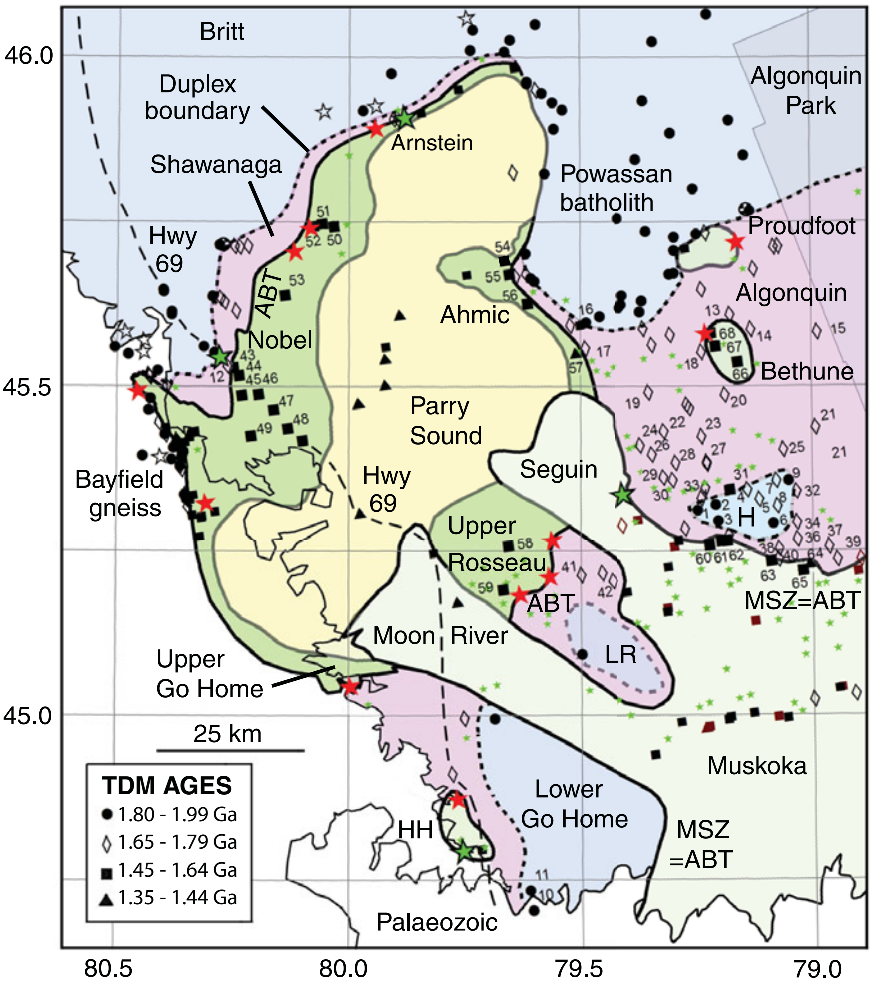

Figure 4. (Colour online) Map of the Parry Sound region showing proposed new tectonic structure, including the Palaeoproterozoic parautochthon (blue), duplex (violet), Mesoproterozoic allochthon (greens) and Parry Sound klippe (yellow). ABT = Allochthon Boundary Thrust. Domain abbreviations: HH = Honey Harbour; LR = Lower Rosseau; H = Huntsville. Stars = metabasic: red = eclogite; green = coronitic olivine metagabbro (large, dated; small, undated); open = Sudbury diabase equivalent, from Ketchum & Davidson (2000).

as expected for its role as a crustal-scale ramp. It is also well constrained in the vicinity of Arnstein (Fig. 4), where it passes close to another mapped eclogite body.

To the south of Parry Sound domain, the Lower Go Home and Lower Rosseau tectonic windows have been known for some time (e.g. Davidson, 1995). However, it is notable that a young TDM age in the southern part of Go Home domain (Dickin & McNutt, 1990) is located within a ring-shaped outcrop of anorthosite bodies that is associated at its northern end with a retrogressed eclogite pod. Anorthosite bodies are characteristic in this region of major terrane boundaries (Davidson, Nadeau & Culshaw, 2012), and the association with retrogressed eclogite also implies crustal exhumation on a thrust zone. Hence these rock types provide strong evidence that this lithotectonic unit (HH = Honey Harbour domain, Fig. 4) represents another tectonic klippe of the allochthon.

The affinity of the surrounding gneisses in the Lower Go Home domain is not yet properly understood. The klippe may be surrounded by a tectonic duplex (violet colour in

Fig. 4), but two new samples yield TDM ages >1.9 Ga (nos 10, 11 in Fig. 4), suggesting that the tectonic window reaches through to the underlying parautochthon (blue colour). This is consistent with the polycyclic metamorphic history of the Lower Go Home domain, as noted by Culshaw *et al.* (1997).

A tectonic window was proposed in the Huntsville region by Davidson (1995), but abandoned in later work (e.g. Ketchum & Davidson, 2000). However, two factors prompted us to re-examine this proposal. Firstly, there is a lack of granulite-facies gneisses in the immediate vicinity of Huntsville, although these are seen in the surrounding domains (Nadeau, 1991). Secondly, a similar gap is observed in the distribution of coronitic olivine metagabbro (Ketchum & Davidson, 2000), as shown in Figure 4. This petrological evidence for a tectonic window at Huntsville is supported by the new Nd data (Fig. 4), with several TDM ages >1.8 Ga characteristic of the Palaeoproterozoic parautochthon. Additional evidence for old protolith ages in the Huntsville domain comes from a 1714 + 123/− 71 Ma upper intersection age for zircon cores from the Hillside granitic orthogneiss (Nadeau & van Breemen, 1998). This unit was collected as sample #7 in the present study, with a TDM age of 1.79 Ga (Table 1). The observation of many horizontal foliation directions to the E and NE of Huntsville (Lumbers & Vertoli, 1996) is consistent with the existence of a structural dome. This area is also characterized by a large number of sub-horizontally oriented straight gneisses (Nadeau, 1991). Hence we suggest that the ABT was originally located almost immediately above the present land surface in this area.

We also propose the existence of two additional outliers of allochthonous rocks (tectonic klippen) to the east of Parry Sound domain, located within Bethune and Proudfoot townships (Fig. 4). When combined with the units discussed above, these form a series of NW-directed allochthonous terranes at 30–40 km intervals, including two large nappes (Moon River and Seguin) flanked by smaller klippen on either side (Honey Harbour and Bethune–Proudfoot) (Fig. 4). The distribution of these klippen reflects late Grenvillian corrugation of the thrust sheet (Rivers & Schwerdtner, 2015; Culshaw *et al.* 2016). However, the greater degree of preservation of the Moon River and Seguin nappes is attributed to the dominant role of the Parry Sound domain in down-buckling the local crust, giving them more protection against uplift and erosion.

A consequence of this new structural model is that the Algonquin domain to the east is now recognized as an expression of the tectonic duplex (Fig. 4). Therefore, far from being a thick crustal slice, as proposed by Culshaw *et al.* (2016), Algonquin domain is inferred to be a quite thin-skinned unit that comprises a corrugated sub-horizontal thrust sheet. This implies that Algonquin domain could be perforated by additional tectonic windows and carry additional allochthonous klippen that have not yet been mapped.

5. Discussion

The ranges of model age data for the main structural domains proposed above are summarized in the form of stacked histograms and probability density curves in Figure 5, where the three main structural decks are distinguished using the same colours as in Figure 4. It is important to emphasize that these sample suites are geographically defined. However, based on the boundaries identified above, the distribution of Nd model ages in each of these terranes can be examined in order to understand their geological history.

The oldest model age suite is found in the Palaeoproterozoic Parautochthon, using a data compilation previously discussed by Dickin, Moretton & North (2008). The data form a tight symmetrical distribution of model ages with a frequency maximum at 1.9 Ga (Fig. 5a). This distribution is consistent with crustal extraction as a juvenile arc terrane shortly before the 1.85 Ga Penokean orogeny, and it validates our use of the depleted mantle model of DePaolo (1981) to calculate Nd crustal formation ages.

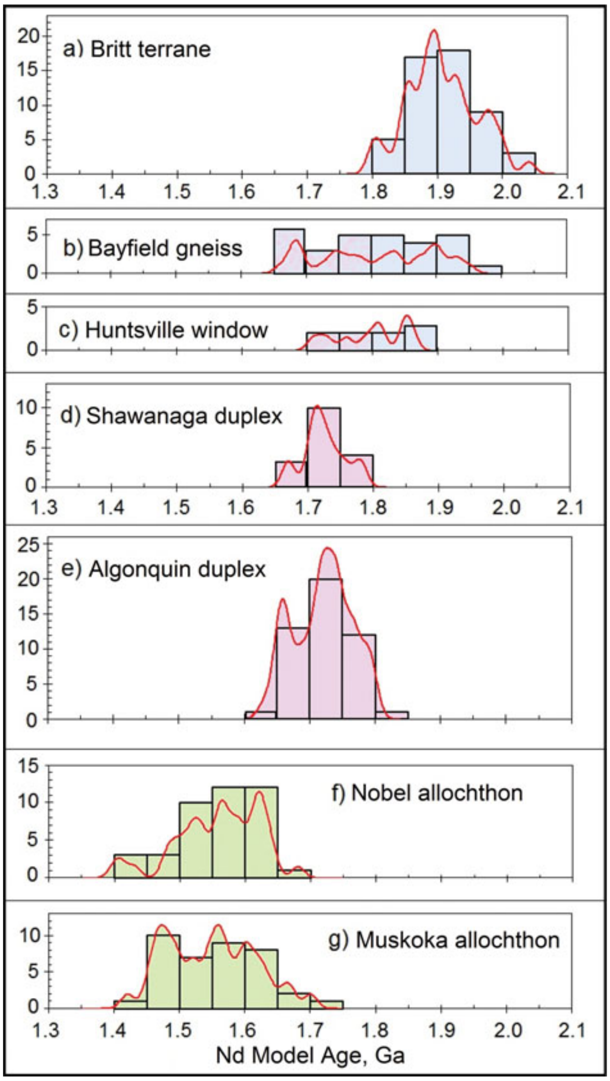

Figure 5. (Colour online) Histograms and probability density curves for TDM model ages of lithotectonic units of the Parry Sound region from Table 1 and published data (Dickin & McNutt, 1990; Dickin, Moreton & North, 2008; Slagstad *et al.* 2009; Dickin *et al.* 2010; Moore & Dickin, 2011; Dickin & North, 2015).

The youngest Nd model age suite, seen in the allochthon, includes data from Table 1, Dickin, Moretton & North (2008), Slagstad *et al.* (2009), Dickin *et al.* (2010) and Dickin & North (2015). These suites, from the Muskoka terrane (Fig. 5g) and the Nobel and Ahmic domains (Fig. 5f), have similar age ranges from *c.* 1.4 to 1.7 Ga. The lower end of this distribution is consistent with the widespread 1.45 Ga magmatic event in the study area (Slagstad *et al.* 2004), but model ages >1.55 Ga are suggestive of incorporation of a small fraction of Palaeoproterozoic crustal material. This can be explained by the development of an ensialic arc on the older continental margin, in which mixing of older and younger components occurred (Dickin & McNutt, 1990; Slagstad *et al.* 2009).

Samples from the Shawanaga and Algonquin duplexes (Table 1; Dickin & McNutt, 1990; Dickin, Moretton & North, 2008; Moore & Dickin, 2011) form an intermediate model age peak around 1.7 Ga (Fig. 5d, e). Some U–Pb crystallization ages similar to this value are known to the north of the study area (Corrigan, Culshaw & Mortensen, 1994). However, due to the large amount of crust that has been cut out by Grenvillian thrusting, it is not known whether the 1.7 Ga Nd model ages in the duplex are indicative of a discrete 1.7 Ga crustal formation event that occurred on the continental margin, or a mixture of 1.9 Ga and 1.5 Ga components in an ensialic arc.

It is notable that the three domains with the largest sample suites, comprising Britt, Algonquin and Muskoka domains (Fig. 5a, 5e, 5g), have minimal overlap in TDM ages. This supports the interpretation of these three domains as distinct structural decks, juxtaposed by Grenvillian tectonism from an originally wider continental margin (e.g. Dickin & McNutt, 1990; Slagstad *et al.* 2009). However, because the thrust stack was generated by oblique telescoping of the older margin, it is expected that the allochthon and the underlying duplex will both gradually get older to the NE (compare TDM ages in Fig. 4 with Fig. 3). This can explain why some ages within the Bethune and Proudfoot klippen (Table 1) are slightly over the normal range of ages seen in the Muskoka and Nobel domains to the south and west.

Nd data for the Bayfield gneiss assemblage (Culshaw *et al.* 1994) to the west of the ABT on Georgian Bay tell a more complex story (Fig. 5b). These rocks have been recognized by all workers as parautochthonous, but were found by Dickin & North (2015) to have TDM ages as low as 1.65 Ga. As a result, Dickin and North interpreted them as magmatically reworked parautochthon. However, the interfingering of reworked and less-reworked Palaeoproterozoic gneisses in this area may result from the near-coincidence of the Shawanaga and Muskoka shear zones on Georgian Bay. This would likely have resulted in local imbrication of the tectonic duplex, whose magmatically reworked Nd signatures reflect a more outboard origin than the earlier continental margin recognized in the parautochthon. This local imbrication may explain the location of eclogite pods in the footwall of the ABT in this vicinity, whereas elsewhere they are located in the hangingwall.

The range of TDM ages in the Huntsville window (Table 1; Fig. 5c) shows that it has model ages slightly younger than the parautochthonous Britt domain, but older than the Bayfield assemblage (Fig. 5b). This is expected if the Huntsville window represents a southerly equivalent of Britt domain, which experienced moderate Mesoproterozoic magmatic reworking, but less than the crustal segment that later formed the duplex. In fact, two rocks from within the perimeter of the Huntsville window (samples 5 and 8; Table 1) have significantly younger TDM ages than the other samples. These could be attributed to a greater degree of magmatic reworking of the protoliths, but alternatively these rocks could sample a sliver of the duplex that has been preserved in this locality on top of the parautochthon. The inferred sub-horizontal attitude of the ABT in this area is consistent with the ramp–flat structural model of Dickin *et al.* (2014).

6. Tectonic synthesis

These new interpretations of the tectonic structure of the Parry Sound region are put into the wider context of the SW Grenville Province in Figure 6a. This map shows the somewhat unique influence of Parry Sound domain in loading down the allochthon, but it also shows the repetitive distribution of allochthonous nappes and klippen, with an approximate spacing of 30–40 km. Rivers & Schwerdtner (2015) proposed that the Muskoka Shear Zone can be traced eastwards to form the nappe-shaped Wallace sub-domain. We have shown this structure in Figure 6a (marked ‘W’), However, their proposed trajectory must be modified on the eastern side of the Wallace nappe due to Nd evidence for a large salient of parautochthonous Palaeoproterozoic rocks in this vicinity.

The distribution of lithotectonic domains in Figure 6a leads us to extend the mapping of late Grenvillian fold axes previously summarized by Schwerdtner & Van Berkel (1991) and recently updated by Schwerdtner *et al.* (2016). Blue lines in Figure 6a indicate synforms occupied by nappes and klippen, whereas red lines indicate antiforms partially breached by windows. These features show good parallelism except in the vicinity of Parry Sound, and possibly the Powassan batholith, which seem to have acted as rigid blocks, resisting NE–SW compression and causing the fold axes to form a fan-shaped pattern.

The unique influence of the Parry Sound domain in down-loading the allochthon can be seen on a cross-section (Fig. 6b), which cuts across the Parry Sound and Rosseau domains along the anticlinal fold axis X–X (Fig. 6a). This cross-section follows close to the Lithoprobe 31 reflection profile (White *et al.* 1994), which therefore provides detailed evidence for the crustal structure along this section (see also Strong, 2015). As discussed by Dickin *et al.* (2014), the reflection profile shows that the ABT was down-warped under the Parry Sound domain, returning towards the surface in the Lower Rosseau domain, which forms a structural dome (Lumbers & Vertoli, 2000). This dome appears to consist of a parautochthonous core that is surrounded by a rim of the duplex (Fig. 4). Hence, in the cross-section in Figure 6b, the duplex is shown as a continuous sheet under the footwall of the allochthon, whose main ramp corresponds to the Muskoka Shear Zone.

We comment finally on the possible timing of movement on the shear zones discussed in this study. Early work by van Breemen *et al.* (1986) pointed to *c.* 1150 Ma ages for movement on the Parry Sound Shear Zone (PSSZ, Fig. 2). This age was confirmed by Krogh & Kwok (2005) and Marsh *et al.* (2012), who showed that this was also the date of metamorphism on the Twelve Mile Bay Shear Zone (TMBSZ; Fig. 6a). The latter forms the footwall to Parry Sound domain on its southern side, where it overlies the Upper Go Home domain (Fig. 4).

Hence we suggest that the Parry Sound domain was first emplaced onto what is now the main allochthon in the 1190 – 1150 Ma Shawinigan event (Rivers, 1997). However, Parry Sound domain was transported further to the NW during the main 1080–1040 Ma Ottawan event. This is demonstrated by the *c.* 1090 Ma U–Pb ages on a subset of the eclogite bodies (stars in Fig. 6a) dated by Marsh & Culshaw (2014). The chemistry of these zircons indicates growth within an eclogite assemblage, interpreted to date high-pressure metamorphism of these rocks immediately before major uplift on the ABT crustal-scale ramp.

Metamorphism on the Shawanaga Shear Zone (approximately following our Duplex Boundary) is mostly associated with late extensional tectonics (*c.* 1020 Ma; Ketchum & Krogh, 1998). However, this motion must have been preceded by NW-directed thrusting, since the duplex has younger TDM ages than the parautochthon, indicative of a more outboard origin. The age of this NW-directed thrusting is not well constrained, but 1035 Ma monazite ages in Britt domain (Jamieson, Culshaw & Corrigan, 1995) suggest that it occurred a few Ma earlier, possibly around 1040 Ma.

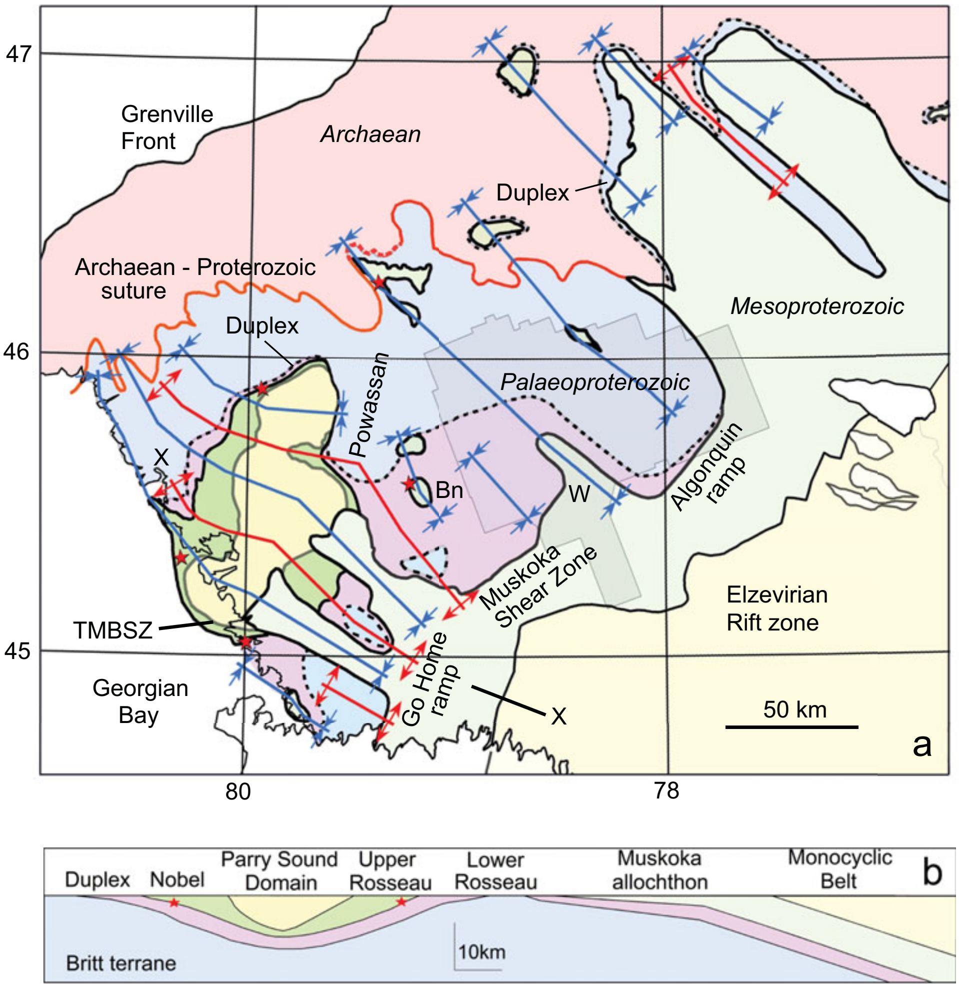

Figure 6. (Colour online) (a) Proposed new tectonic map of the SW Grenville Province. Bn = Bethune klippe; W = Wallace subdomain; TMBSZ = Twelve Mile Bay Shear Zone; red lines = antiformal fold axes; blue lines = synformal fold axes; red stars = retrogressed eclogites dated by Marsh & Culshaw (2014). X–X = line of section. (b) Cross-section along line X–X with no vertical exaggeration. Red stars = retrogressed eclogites.

This northward younging of U–Pb ages was summarized by Culshaw *et al.* (1997), and is consistent with progressive down-cutting of the basal décollement over time. It is comparable with the progressive down-cutting of Himalayan thrusting over the past 20 Ma (DeCelles *et al.* 2001).

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