Whole-rock chemical and Sm-Nd isotopic composition of a Late Proterozoic metasedimentary sequence in Ganderia: Kellys Mountain, Bras d'Or terrane, Nova Scotia, Canada

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ABSTRACT

The relationship between low-grade metasedimentary and high-grade paragneissic Precambrian rock units in the Bras d'Or terrane of central Cape Breton Island is a long-standing geological problem. Whole-rock geochemical and Nd isotopic data from representative components of these units in the Kellys Mountain area, the Glen Tosh formation and Kellys Mountain Gneiss, show strong similarity. Major and trace element characteristics suggest that protolith sediments for both units were wackes derived from felsic igneous sources and deposited at an active continental margin. Samarium-Nd isotopic data in combination with previously published detrital zircon ages show that the sediments contained an ancient (ca. 2 Ga) end-member of recycled continental crust mixed with a juvenile component of Late Neoproterozoic age. The similarities suggest that the rocks represent the same sedimentary unit at different grades of metamorphism, implying a major crustal break under the area of mixed dioritic and granitic rocks that separates the gneissic and lower grade rocks.

RÉSUMÉ

Le lien entre les unités lithologiques précambriennes métasédimentaires faiblement métamorphisées et celles paragneissiques fortement métamorphisées du terrane Bras d'Or et du centre de l'île du Cap Breton est un problème géologique de longue date. Les données isotopiques du Nd et géochimiques sur roche totale d'éléments représentatifs de ces unités dans le secteur du mont Kellys, la formation de Glen Tosh et le gneiss du mont Kellys révèlent une similarité prononcée. Les caractéristiques des éléments majeurs et des éléments traces laissent supposer que les sédiments protolithiques des deux unités étaient des wackes provenant de sources ignées felsiques qui se sont déposés le long d'une marge continentale active. Les données isotopiques du samarium-néodyme combinées avec les datations sur zircon détritique précédemment publiées révèlent que les sédiments comportaient un membre extrême ancien (environ 2 Ga) de croûte continentale recyclée mélangée avec un jeune élément de l'époque du Néoprotérozoïque tardif. Les similarités notées permettent de penser que les roches constituent la même unité sédimentaire à des niveaux différents de métamorphisme, ce qui suppose une rupture crustale majeure sous le secteur des roches dioritiques et granitiques mixtes séparant les roches gneissiques et moins métamorphisées.

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INTRODUCTION

Kellys Mountain is a northeast-trending ridge of crystalline rocks surrounded by unconformably overlying Carboniferous sedimentary rocks. It is one of several such blocks which characterize the Bras d'Or terrane of central Cape Breton Island (e.g., Raeside and Barr 1990; Keppie *et al.* 1998). All of these blocks are dominated by metasedimentary, in some areas gneissic, rocks, intruded by varied granitic and dioritic rocks with ages of ca. 580–550 Ma (Raeside and Barr 1990; Keppie *et al.* 1998). Based on tectonic history, age, and isotopic data, these characteristic components of the Bras d'Or terrane, like similar units in the Brookville terrane of southern New Brunswick (White and Barr 1996), are now interpreted to be part of Ganderia (Fig. 1 inset), a peri-Gondwanan continental fragment of probable Amazonian provenance (e.g., Hibbard *et al.* 2007; van Staal *et al.* 2009; van Staal and Barr 2012). Only southernmost Cape Breton Island (Mira terrane, Fig. 1) and northern mainland Nova Scotia are interpreted to be part of Avalonia (Fig. 1 inset). Northernmost Cape Breton Island, known as the Blair River Inlier (Fig. 1), is interpreted to be part of Laurentia (Fig. 1 inset).

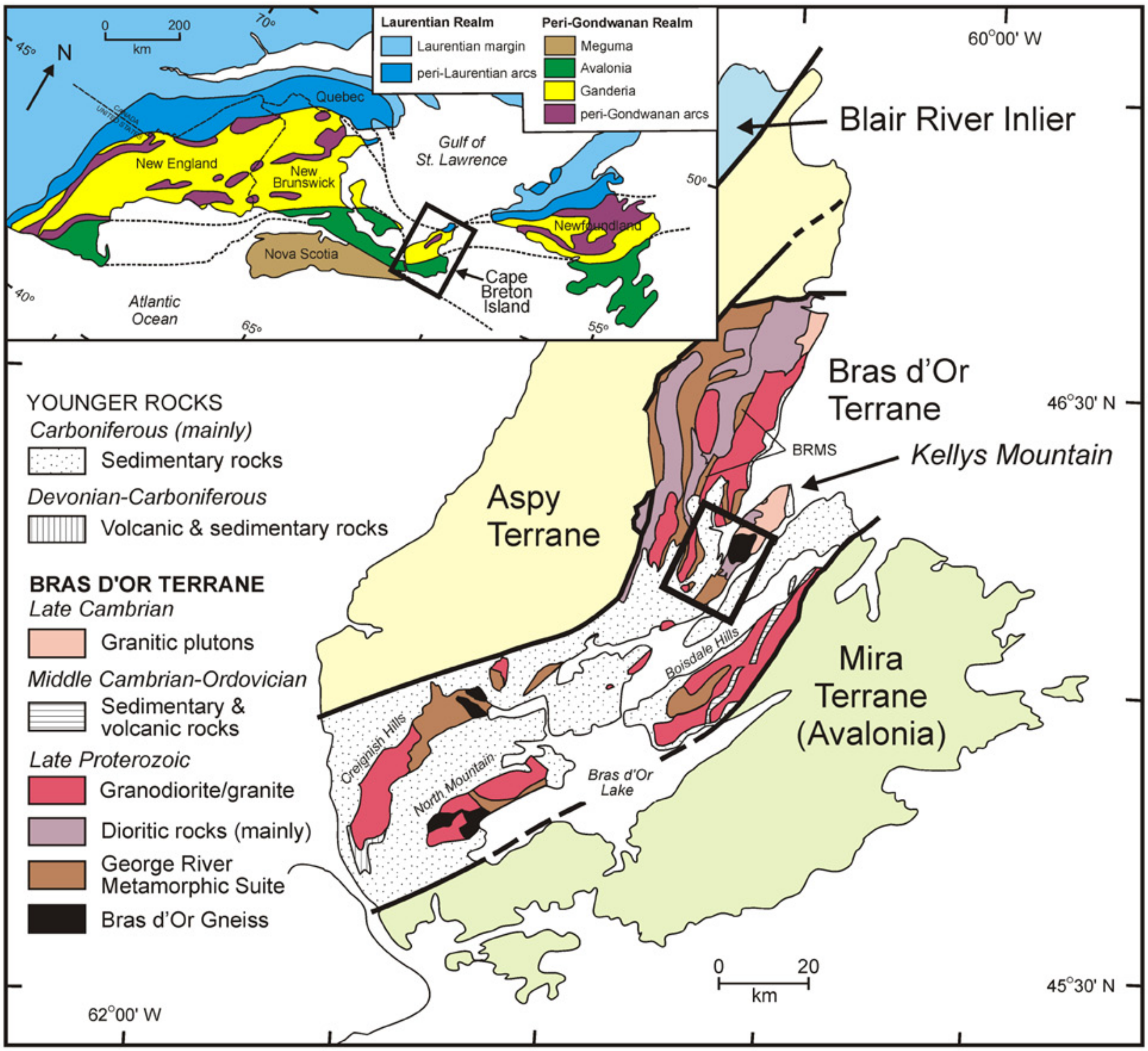

Figure 1. Simplified geological map of the Bras d'Or terrane after Raeside and Barr (1990) showing the location of the Kellys Mountain area. Black box outlines the area shown in Figure 2. Inset map shows components of the northern Appalachian orogen after Hibbard *et al.* (2006). Abbreviation: BRMS, Barachois River Metamorphic Suite.

In addition to the larger questions such as the relationship of these rocks to units of similar age in adjacent Avalonia and their original position within Rodinia (e.g., Barr and White 1996; Keppie *et al.* 1998; Keppie *et al.* 2000; Barr *et al.* 2003), a long-standing uncertainty has been the relationship between the lower grade units, collectively termed the George River Metamorphic Suite in the Bras d'Or terrane and the Green Head Group in southern New Brunswick, and the gneissic units, collectively known as the Bras d'Or Gneiss and Brookville Gneiss in the Bras d'Or and Brookville terranes, respectively. Where observed, contacts between these units in both Bras d'Or and Brookville terranes are Carboniferous and older faults that range from ductile to brittle, and hence several interpretations of their relative depositional ages have been proposed: (i) the gneissic rocks form the basement beneath the low-grade metasedimentary units (e.g., Nance 1987); (ii) the gneissic rocks are the high-grade metamorphic equivalent of the lower grade units (e.g., Milligan 1970); and (iii) the gneissic rocks are younger than the low-grade units (Wardle 1978; Bevier *et al.* 1990; White and Barr 1996).

The present study was undertaken to try to resolve the fundamental question of the relationship between the metasedimentary and gneissic rocks by comparing whole-rock major-element, trace-element, and Sm-Nd isotopic composition of clastic units in the George River Metamorphic Suite to that of paragneissic components of the Bras d'Or Gneiss.Kellys Mountain was selected for this study because both the gneissic and lower grade metasedimentary units are well exposed in that area, and field relations are relatively well understood (Barr *et al.* 1982; Jamieson 1984; Raeside and Barr 1990).

GEOLOGICAL BACKGROUND

Kellys Mountain Gneiss

Gneissic rocks form the central core of Kellys Mountain, surrounded and intruded by dioritic and granitic rocks (Fig. 1). As described by Jamieson (1984), the gneiss is mainly medium- to coarse-grained cordierite-bearing migmatitic paragneiss consisting of cordierite–biotite–K-feldspar–plagioclase–quartz with accessory tourmaline, apatite, and opaque minerals (Fe-Ti oxides). K-feldspar is stable, muscovite is present only as a retrograde mineral, garnet is very rare, and cordierite occurs in both mesosome and leucosome. The paragneiss locally contains areas of tonalitic to granodioritic orthogneiss, as well as amphibolite sheets, likely originally mafic dykes. The foliation in the gneissic rocks generally trends north-northwest with steep dip (Fig. 2; Jamieson 1984).

The degree of migmatization increases toward the centre of the gneiss, away from the exposed contacts with the surrounding plutonic rocks. Based on mineral assemblages and absence of prograde muscovite, Jamieson (1984) inferred that peak metamorphic conditions occurred at 100–350 MPa and 580–700°C. The age of metamorphism is constrained by U-Pb dating of titanite from amphibolite in the gneiss, which gave an age of 496 ± 5 Ma (Dunning *et al.* 1990), and by similar ca. 495 Ma $^{40}Ar/^{39}Ar$ dates from hornblende, muscovite, and biotite in both the gneiss and amphibolite sheets in the gneiss (Keppie and Dallmeyer 1989; Reynolds *et al.* 1989). Metamorphic monazite separated from the gneiss yielded nearly concordant data, with a $^{206}Pb/^{238}U$ age of 515 ± 1 Ma, interpreted to date the time of migmatization (Keppie *et al.* 1998). Attempts to constrain the protolith age of the gneiss were unsuccessful, as single- and multi-grain zircon analyses are moderately to highly discordant, with $^{207}Pb/^{206}Pb$ ages ranging between 843 and 1700 Ma (Keppie *et al.* 1998). The data scatter about a chord between 657 and 1840 Ma, but the discordant nature of the data and their scatter indicate that the zircons have several generations of growth and (or) Pb loss, making it difficult to interpret the significance, if any, of the chord.

Glen Tosh Formation

Lower grade metasedimentary rocks (described below) form the southwestern part of Kellys Mountain, separated from the gneissic rocks by dioritic and granitic rocks (Fig. 2). Similar rocks occur north of Big Hill and in scattered outcrops farther north, and all of these rocks, including those in the southwestern part of Kellys Mountain, were assigned by Raeside and Barr (1990, 1992) to the Barachois River Metamorphic Suite, a component of the George River Metamorphic Suite (Figs. 1, 2). According to Raeside and Barr (1992), the Barachois River Metamorphic Suite is composed mainly of semipelitic and mafic lithologies, with metamorphic grade that ranges from upper-amphibolite to subgreenschist facies. The highest grade rocks occur in the north where the suite is surrounded by the 555–565 Ma plutons of the southeastern Cape Breton Highlands. Although Raeside and Barr (1990, 1992) interpreted the gneissic rocks of the northern outcrop areas of the Barachois River suite as being correlative with lower grade phyllite and greenschist in the southern Cape Breton Highlands and with metasiltstone in the Big Hill and Kellys Mountain areas, that relationship is uncertain. Hence the new informal name Glen Tosh formation is introduced here for the low-grade, mainly metasedimentary, rocks in the Kellys Mountain-Big Hill area (Fig. 2).

In contrast to other areas of the George River Metamorphic Suite which include carbonate as well as clastic rocks, the rocks in the Glen Tosh formation are psammitic and semi-pelitic, consisting dominantly of sutured quartz and feldspar, with variable but generally small (<10%)

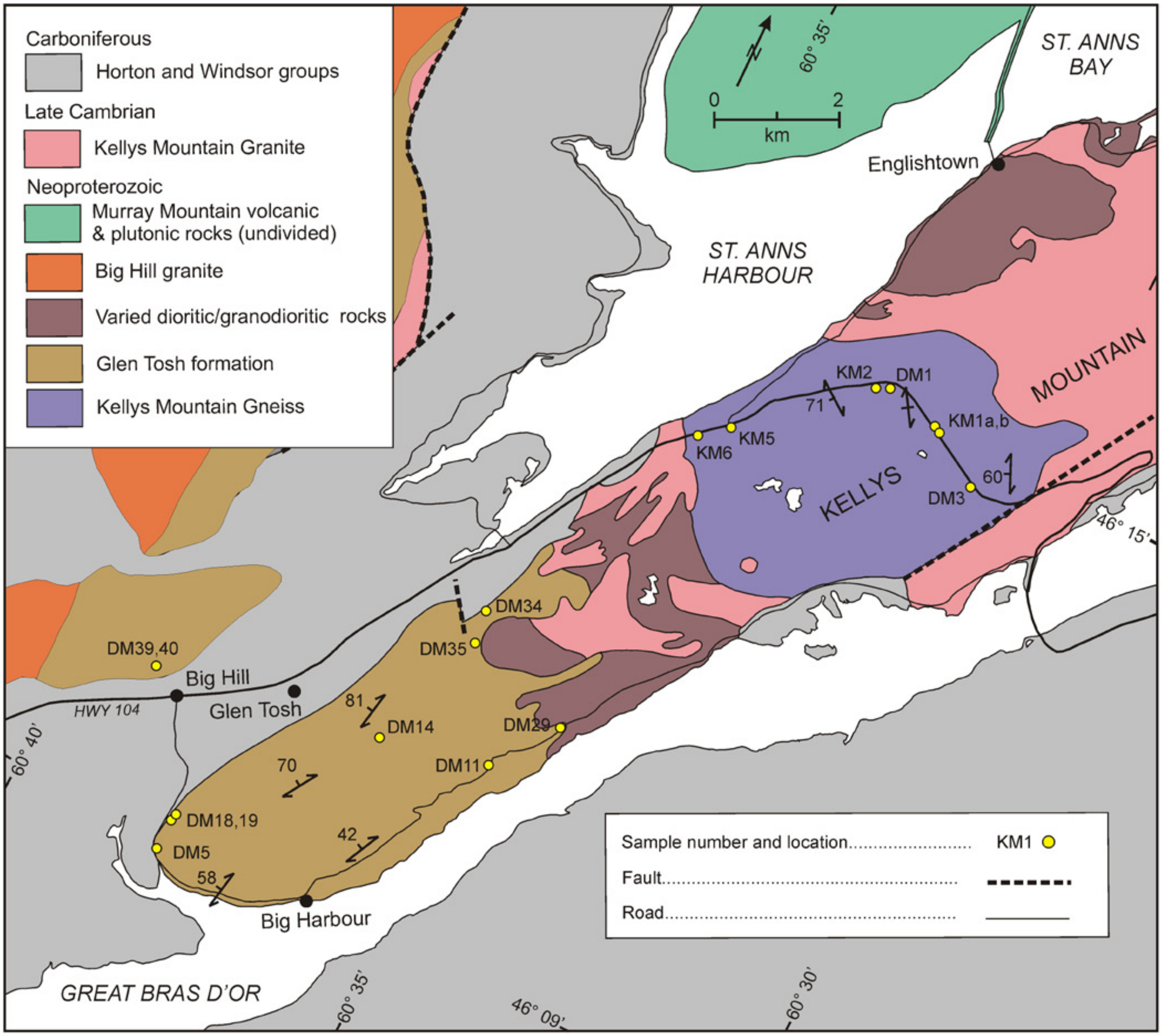

Figure 2. Geological map of the southwestern part of the Kellys Mountain peninsula after Barr *et al.* (1992) showing sample locations. Representative foliation orientations are shown in the Kellys Mountain Gneiss and Glen Tosh formation (this study).

amounts of biotite and muscovite, with accessory apatite, tourmaline, and opaque minerals. Grain size is variable and may represent variation in clast size in the original wacke protolith. Cordierite appears to be common in many of the rocks, though in most cases is completely retrograded to pinite or sericite making it difficult to be certain in rocks that have been completely retrograded. Extremely large cordierite porphyroblasts up to 10 cm in length now pseudomorphed by pinite/sericite are present in muscovite-rich rocks from the extreme southwestern part end of the study area. Ragged andalusite grains were noted in a few samples, where it is at least partly altered to sericite, and garnet also is present in a few samples. In rocks showing the greatest level of alteration, chlorite and epidote are common.

Bedding is difficult to distinguish in most places but the rocks have a well-defined foliation that trends uniformly north-northeast with moderate to steep dips to west-northwest. In thin section the foliation is defined by aligned muscovite and biotite that wraps around cordierite porphyroblasts. Furthermore, within cordierite porphyroblasts, muscovite and biotite grains have a random or reticulated alignment. The discordance between fabrics internal and external to the porphyroblasts indicates that cordierite growth predated the last phase of foliation development. Where the psammitic/pelitic rocks of the Glen Tosh formation are intruded by the dioritic and granitic rocks, they are contact metamorphosed and less foliated. In these contact metamorphic rocks cordierite has overgrown early ragged andalusite porphyroblasts.

These various relationships suggest the following series of events. Early somewhat random muscovite and biotite growth (with garnet and andalusite in rocks of suitable composition) followed by peak regional metamorphism produced cordierite porphyroblasts up to 10 cm in suitable (though rare) compositions. Peak deformation (and foliation development) postdated peak regional metamorphism. Subsequent intrusion of diorite and granite produced pronounced contact metamorphic effects including renewed cordierite growth (over early andalusite) and recrystallization of the matrix to produce a more granoblastic texture. The ages of these events are uncertain but Dallmeyer and Keppie (1993) reported a metamorphic muscovite cooling age of ca. 550 Ma from metapsammitic rocks in the Big Hill area, likely providing a minimum age for the metamorphism.

Mafic dykes occur rarely in the Glen Tosh formation, and are of dioritic and lamprophyric composition (Gates 2011). Their age is uncertain but they may be related to Cambrian extensional igneous activity in the Boisdale Hills to the south (Fig. 1; Gates 2011).

Plutonic Rocks

Barr *et al.* (1982) divided plutonic rocks of the Kellys Mountain area into two main units, leucogranite (now termed Kellys Mountain Granite; Fig. 2), which forms most of the northeastern part of the mountain, and a more varied but less extensive dioritic unit that includes quartz diorite, tonalite, diorite, granodiorite, quartz monzonite, and hornblendite. The dioritic suite occurs mainly in the area between the gneissic and psammitic units of the Glen Tosh formation. The dioritic suite is intruded by the Kellys Mountain Granite, which yielded a U-Pb (zircon) age of 498 ± 2 Ma (Barr *et al.* 1990). The dioritic suite may be significantly older, based on its similarity to varied dioritic, tonalitic, and granitic units dated at ca. 560 Ma elsewhere in the Bras d'Or terrane (e.g., Raeside and Barr 1990; Dunning *et al.* 1990). However, the close physical association between the dioritic suite and leucogranite is also suggestive of a co-magmatic relationship. More geochronology is needed to resolve this uncertainty.

GEOCHEMISTRY

Seventeen samples were selected for whole-rock chemical analysis, 10 from the Glen Tosh formation and 7 from the Kellys Mountain Gneiss (Tables 1, 2, 3). Analyticial methods are described in Appendix A. The Glen Tosh formation samples include cordierite phyllite, quartz metawacke, and 8 more typical metawacke samples (Table 1). The gneissic samples include 6 typical paragneiss samples and one sample with higher plagioclase and biotite contents (Table 1). The metawacke and typical paragneiss samples show considerable similarity in whole-rock chemical characteristics (Fig. 3a-g). The metawacke samples range in SiO_2 from 67.4 to 72.0 weight % (69.1–73.4 weight % calculated volatile-free) and the paragneissic samples from 67.1 to 72.8 % (68.4–73.7% calculated volatile-free). Other major element components overlap in both units, although the gneissic rocks tend to be lower in Fe and higher in CaO and K_2O (Fig. 3b, d, f). The gneissic samples also tend to have lower volatile content (Fig. 3g). The quartz metawacke sample has higher SiO_2 and lower Al_2O_3. The cordierite phyllite and plagioclase-biotite paragneiss samples have similar low SiO_2 (about 60%) and both have high Al_2O_3, reflecting their more pelitic compositions. Although element mobility during metamorphism may have affected the chemical compositions of these rocks, such consistency between petrography and chemistry suggests that the changes have not been substantial.

Trace element compositions are also similar between the Kellys Mountain Gneiss and Glen Tosh formation metawacke samples, as illustrated in Fig. 4. Data from the majority of samples are closely similar to the average North American Shale Composite (Gromet *et al.* 1984), as shown in Fig. 4a, further evidence for limited post-depositional chemical changes. However, the typically more mobile elements such as Cs, Rb, Ba, and Sr show more variability, suggesting that some changes may have occurred. The plagioclase-biotite paragneiss sample has higher Rb, Ba, Th, and Nb than any of the other samples, metawacke sample DM91-40 has high Sr, and DM91-34 has low Cs, Rb, and Ba compared to most other samples (Fig. 4a). Sample DM91-40 has abundant accessory apatite compared to the other samples but is otherwise similar (Table 1). Rare-earth element patterns in the majority of samples, both gneiss and metawacke, also show patterns similar to the North American Shale Composite (Fig. 4b). Exceptions are cordierite phyllite sample DM91-19 and metawacke sample DM91-34 which have low and erratic light REE, sample DM91-40 which has high heavy REE, and plagioclase-biotite paragneiss sample DM91-01 which has high light REE (Fig. 4b). On the more commonly used chondrite-normalized REE plot (Fig. 4c) all of the samples show elevated light REE, relatively flat heavy REE, and a strong negative Eu anomaly, a pattern typical of many felsic igneous rocks. The differences in a few samples

Table 1. Petrographic descriptions of analyzed samples*.

Sample	Rock type	Petrographic Description
Glen Tosh formation		
DM91-5	metawacke	relict uneven (sedimentary) texture with larger (0.5 mm) grains in f.g. (ca. 0.05 mm) matrix of Qz-Or (dusty); some Ms-rich patches; minor Bt, accessory Op, Ep, Ap; trellis-like arrangement of Ms in 2 foliations.
DM91-11	quartz metawacke	similar to DM91-5, though more clearly defined single foliation; more Bt than DM91-5; pronounced relict uneven sedimentary texture with polycrystalline Qz and Pl grains up to 1.5 mm in f.g. (0.05 mm) groundmass.
DM91-14	metawacke	Qz-Or (dusty)-Bt-Ms-Chl with scattered skeletal Grt; finer and more even grained (0.25 mm to ca. 0.05 mm) than DM91-5.
DM91-18	metawacke or metasiltstone	f.g. (0.25–0.05 mm) Qz-Or (dusty)-Ms-Bt/Chl; acccessory Op-ap.
DM91-19	Crd phyllite	large (up to 1 cm) sericitized cordierite(?) porphyroblasts in strongly foliated very even fine grained (0.05 mm) matrix of Ms-Qz-Or-Chl with accessory Op - Ap.
DM91-29	metawacke	banded (bedded?) chloritized and sericitized metawacke consisting of Qz-Or (dusty)-Ser-Chl plus accessory Op and Ap; banding (bedding) evident as subtle variation in grain size; maximum grain size in coarser bands, 0.25 mm; maximum grain size in finer bands, 0.1 mm grains; foliation not recognizable.
DM91-34	metawacke	chaotically uneven texture, with larger (>1 mm) quartz eyes (both single grains and multigrain aggregates) in a v.f.g. (<<0.05 mm) matrix of Qz-Chl-Ser; accessory Op - Ap; foliation not recognizable.
DM91-35	metawacke	banded uneven meta-sedimentary texture similar to DM91-29; finer grained bands more noticeably pelitic (more biotite/muscovite) than DM91-29; f.g. (0.05–0.3 mm) quartz in Ms-Bt rich matrix with sporadic ragged and partly sericitized andalusite (and/or cordierite); foliation weak/absent.
DM91-39	metawacke	non-foliated f.g. wacke consisting of Qz-Or(dusty)-Bt/Chl and ragged Ms grains; accessory Op - Ap; c.g. (0.1–0.25 mm) and more sutured than other metawacke samples; Ms flakes up to 0.5 mm.
DM91-40	metawacke or metasiltstone	even grained relict f.g. (0.05–0.1 mm) sedimentary texture, with Qz-Or(dusty)-Bt with minor Ms and accessory Op and Ap; no visible foliation.
Kellys Mountain Gneiss		
DM91-01	Bt-Pl gneiss	m.g. (0.1–0.5 mm), decussate, Pl(An37)-Qz (An37)-Bt-Mcl gneiss; some myrmekite; mineralogical banding but no obvious foliation (alignment) of Bt.
DM91-03	Sil-Crd-Bt-Mcl-Pl gneiss	granoblastic-lepidoblastic(domainal) m.g. (0.25–1 mm) gneiss; Qz-Pl(An35)-Bt-Crd-Sil-Ms-Tur-Op-Ap.
KM10-1a	Crd-Bt-Pl-Qz gneiss	very similar to DM91-3; granoblastic-lepidoblastic(domainal) m.g.(0.25–1 mm) gneiss containing Qz-Pl-Crd-Bt-Ms-Mcl-Op; Crd is partly sericistized; Ms present as randomly oriented ragged flakes.
KM10-1b	And-Bt-Ms-Mcl-Pl gneiss	m.g. (0.25–1 mm) Qz-Pl-Mcl-Bt-Ms gneiss with ragged partly altered And (or perhaps Crd) grains, and scattered needles of Sil; some myrmekite.
KM10-2	Grt-And-Bt-Pl gneiss	granoblastic-lepidoblastic(domainal) f.g.-m.g. (0.1–1 mm) gneiss; Qz-Pl-Bt with scattered skeletal Grt and And porphyroblasts.
KM10-5	Ms-Bt-Mcl-Pl gneiss	granoblastic m.g. (0.25–0.5 mm) gneiss rich in Qz-Pl-Mcl, and 1 mm clots of f.g. (0.1 mm) Bt and Ms.
KM10-6	Ms-Bt-Mcl-Pl gneiss	granoblastic m.g. (0.5–1 mm) gneiss like KM10-5 but with less Bt-Ms; ser in Fpr and Chl after Bt.

*Mineral abbreviations: And, andalusite; Ap, apatite; Bt, biotite; Chl, chlorite; Crd, cordierite; Ep, epidote; Fpr, feldspar; Grt, garnet; Mcl, microcline; Ms, muscovite; Op, opaque mineral; Or, orthoclase; Pl, plagioclase; Qz, quartz; Ser, sericite; Sil, sillimanite; Tur, tourmaline. Other abbreviations: f.g., fine-grained; m.g., medium-grained.

Table 2. Whole-rock chemical analyses* of samples from Kellys Mountain area.

Sample	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^T$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni	V	Hf	Cs	Ta	Co	Be	U	Sn	Mo	Au
Glen Tosh formation																																		
DM91-05	72.00	0.75	12.91	4.82	0.06	1.15	1.14	2.83	2.32	0.10	1.26	99.39	546	100	185	33	293	15	15	1	14	49	21	11	106	7.7	4.9	1.5	66	1	2.6	2	0.1	2.2
DM91-11	76.60	0.64	10.23	4.10	0.09	1.51	1.58	2.18	1.69	0.09	0.89	99.63	283	84	141	23	186	13	10	3	13	50	15	21	75	5.2	4.7	1.6	72	2	1.9	2	0.1	1.8
DM91-14	71.20	0.68	12.31	5.39	0.12	2.23	1.10	2.84	1.98	0.12	1.65	99.62	298	100	166	28	206	13	11	2	14	78	45	24	94	6.2	4.4	1.3	61	2	2.5	2	0.1	3.0
DM91-18	67.40	0.73	14.29	6.11	0.12	2.63	1.03	2.87	2.39	0.15	2.35	100.13	366	115	159	35	209	15	14	1	17	76	66	19	104	6.3	6.1	1.4	42	2	2.1	3	0.1	2.2
DM91-19	60.70	0.87	17.83	7.65	0.10	2.63	0.82	2.50	3.55	0.15	2.81	99.70	581	143	160	27	157	16	11	1	21	85	14	40	133	4.4	6.3	1.3	34	2	1.8	4	0.1	0.5
DM91-29	66.70	0.55	14.46	5.53	0.12	1.78	2.11	3.17	2.32	0.11	1.98	98.90	368	105	410	34	180	11	11	2	18	73	43	16	88	5.6	3.1	1.0	37	2	1.8	3	0.1	1.0
DM91-34	67.00	0.93	14.94	5.21	0.12	2.23	1.25	3.68	1.68	0.11	2.31	99.52	300	54	211	34	241	16	14	6	18	87	19	29	119	6.4	2.5	1.3	40	2	2.4	3	0.2	0.5
DM91-35	68.00	0.56	14.65	5.19	0.10	2.33	1.23	1.75	3.17	0.08	2.20	99.29	495	145	208	30	171	13	12	1	16	86	26	18	77	5.4	8.3	1.2	42	2	2.5	2	0.2	1.6
DM91-39	67.80	0.69	14.86	5.34	0.11	2.06	1.63	2.70	2.73	0.13	1.94	100.05	540	86	158	34	219	14	14	2	18	74	5	18	98	6.3	2.5	1.1	40	2	2.4	3	0.2	0.5
DM91-40	68.00	0.75	14.56	5.00	0.13	1.95	2.23	3.71	2.38	0.16	0.97	99.85	383	96	163	44	303	15	13	25	16	96	15	13	82	8.2	4.4	1.5	50	2	3.0	3	0.6	0.5
Kellys Mountain Gneiss																																		
DM91-01	59.70	0.80	17.22	5.89	0.14	2.77	3.17	3.60	4.37	0.15	1.17	99.15	1164	158	195	34	243	17	18	1	20	74	83	21	109	7.3	6.3	1.4	50	2	2.2	3	3.7	6.9
DM91-03	69.10	0.65	14.31	5.19	0.09	2.34	2.18	2.14	2.40	0.11	1.51	100.01	419	150	138	27	146	15	11	2	17	55	2	27	89	4.5	9.1	1.8	56	2	2.1	3	0.6	2.2
KM10-01A	69.10	0.51	15.26	4.09	0.12	1.86	1.63	2.75	3.08	0.13	1.47	100.12	646	128	193	34	187	13	14	1	18	59	8	10	51	5.8	6.1	1.3	60	3	2.8	2	0.6	0.7
KM10-01B	67.10	0.57	15.81	4.62	0.12	1.35	1.56	3.33	3.53	0.11	1.45	99.66	708	127	192	36	198	14	14	3	19	65	37	10	63	5.4	5.4	1.5	68	3	2.7	3	1.2	0.5
KM10-02	68.90	0.61	13.14	4.95	0.15	2.40	2.14	2.85	2.62	0.11	0.73	98.68	502	102	121	29	169	14	12	2	16	80	26	23	82	5.0	3.3	1.4	58	2	2.4	3	0.7	1.3
KM10-05	72.80	0.73	12.30	4.31	0.06	1.46	1.39	2.59	2.99	0.09	0.83	99.56	517	114	116	22	205	14	10	2	15	60	7	15	80	5.9	4.3	1.5	73	1	1.8	2	0.2	0.5
KM10-06	70.90	0.46	14.08	3.68	0.07	1.23	1.58	3.52	3.53	0.10	0.67	99.90	483	117	143	28	183	15	11	1	16	56	23	11	61	5.2	7.5	1.8	79	2	2.3	3	0.2	1.0

*Acme Analytical Lab, Vancouver, BC (Appendix A). $Fe_2O_3^T$ is total Fe as Fe_2O_3. LOI is loss on ignition at 1000°C. Major element oxides and LOI are in weight %. Trace elements are in ppm.

Table 3. Rare-earth element analyses* of samples from Kellys Mountain area.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Glen Tosh formation														
DM91-05	36.50	75.90	9.03	32.50	6.60	1.37	5.74	0.96	5.64	1.12	3.29	0.50	3.44	0.51
DM91-11	28.80	64.20	7.32	26.00	5.11	0.98	4.27	0.70	4.10	0.81	2.38	0.40	2.44	0.37
DM91-14	31.30	68.00	7.69	28.20	5.80	1.20	5.13	0.83	4.68	0.94	2.83	0.41	2.84	0.43
DM91-18	34.20	70.90	8.79	32.90	7.13	1.31	6.33	1.06	6.25	1.27	3.70	0.58	3.80	0.56
DM91-19	21.00	55.20	5.60	20.30	4.66	1.04	4.56	0.81	4.97	0.95	2.68	0.40	2.72	0.40
DM91-29	34.80	72.40	8.54	31.40	6.67	1.33	6.17	0.98	5.58	1.14	3.36	0.51	3.40	0.53
DM91-34	21.90	47.10	6.39	25.90	6.25	1.25	5.76	1.01	6.00	1.20	3.53	0.52	3.52	0.52
DM91-35	33.20	70.40	8.33	30.70	6.18	1.19	5.60	0.88	5.22	1.03	3.02	0.46	3.13	0.46
DM91-39	36.00	77.50	9.25	32.80	6.70	1.39	6.09	1.02	5.87	1.23	3.45	0.51	3.57	0.54
DM91-40	34.70	75.40	9.04	33.00	7.24	1.53	7.16	1.23	7.55	1.54	4.40	0.67	4.42	0.66
Kellys Mountain Gneiss														
DM91-01	47.40	101.40	11.47	41.50	8.23	1.42	6.83	1.10	6.37	1.22	3.34	0.49	3.19	0.50
DM91-03	31.30	65.70	7.73	27.70	5.65	1.12	4.98	0.79	4.77	0.92	2.71	0.41	2.59	0.39
KM10-01A	37.30	80.00	9.40	34.20	6.90	1.26	6.22	1.00	5.65	1.13	3.38	0.51	3.42	0.50
KM10-01B	37.30	81.20	9.53	34.00	7.13	1.37	6.54	1.06	6.12	1.25	3.76	0.56	3.80	0.56
KM10-02	34.20	75.90	8.36	29.50	5.83	1.22	5.38	0.87	5.02	0.97	2.91	0.42	2.96	0.43
KM10-05	30.80	64.50	7.33	25.80	4.86	1.16	4.32	0.69	4.03	0.80	2.32	0.35	2.39	0.35
KM10-06	34.80	74.10	8.39	29.00	5.74	1.16	5.32	0.87	5.08	1.05	3.08	0.46	3.03	0.45

*Acme Analytical Lab, Vancouver, BC (Appendix A). Data are in ppm.

as seen in Fig. 4b are also apparent, but more muted due to the relatively compressed scale of the diagram.

On a chemical classification diagram of Herron (1988), all of the samples plot in or near the wacke field (Fig. 5a). They plot in or near the active continental margin field on the depositional setting diagram (Fig. 5b) of Roser and Korsch (1986). Both the TiO_2-Zr and TiO_2-Ni diagrams indicate that the sediments are derived from felsic igneous sources (Fig. 5c and d), and the sediments are relatively immature (Fig. 5d). The low Ni that characterizes all of the samples compared to the North American Shale Composite (Fig. 4a) is consistent with derivation from felsic sources (Fig. 5d).

Sm and Nd isotopic data were obtained from 4 samples from the Kellys Mountain Gneiss and 5 samples from the Glen Tosh Formation (Table 4). The Nd isotope data are expressed following the ε-notation, after correction for the effect of in situ decay of ^{147}Sm, assuming a 650 Ma depositional age. Epsilon values calculated at 500 Ma, the minimum estimate for the age of metamorphism, are also given for comparison (Table 4). The $\varepsilon_{Nd(650)}$ show a range from -9.0 to -1.5 but no consistent differences between the two sets of samples; the range of values for the Glen Tosh formation (-9.0/-1.5) is broadly similar to that of the Kellys Mountain Gneiss samples (-7.1/-1.6) (Fig. 6). All but two samples (DM-91-03 and DM-91-11) provide consistent T_{DM} model ages (DePaolo 1981) of ca. 1.4 Ga, interpreted to reflect the average provenance age of the detrital components, without any specific geological significance. Two samples, DM-91-03 (Glen Tosh formation) and DM-91-11 (Kellys Mountain Gneiss) depart markedly from the rest of the samples in having distinctly less radiogenic Nd isotope composition ($\varepsilon_{Nd(650)}$ = -9.0 and -7.1) and older model ages (1.88 Ga and 1.75 Ga, respectively) that point to a much higher contribution of Early Proterozoic ultimate (bearing in mind the possibility of multiple, "cannibalistic" recycling) sources of the sediments. In contrast, the other samples are all characterized by relatively radiogenic Nd isotope signatures (mildly negative epsilon values) pointing to the relatively significant involvement of "juvenile" components in the source(s) of the detritus.

DISCUSSION

The chemical and Sm-Nd isotopic similarity between the gneissic (Kellys Mountain Gneiss) and metawacke (Glen Tosh formation) samples is consistent with the interpretation that they represent the same sedimentary unit at different grades of metamorphism. If they represent two unrelated units, or units of different age, then the sediment sources in both cases were similar.

The subordinate presence, in both units, of samples containing a major component with an old crustal residence age (T_{DM} = 1.75–1.88 Ga) is an important similarity. It is consistent with the minimum age of ca. 1.84 Ga indicated by the upper intercept age provided by detrital zircons

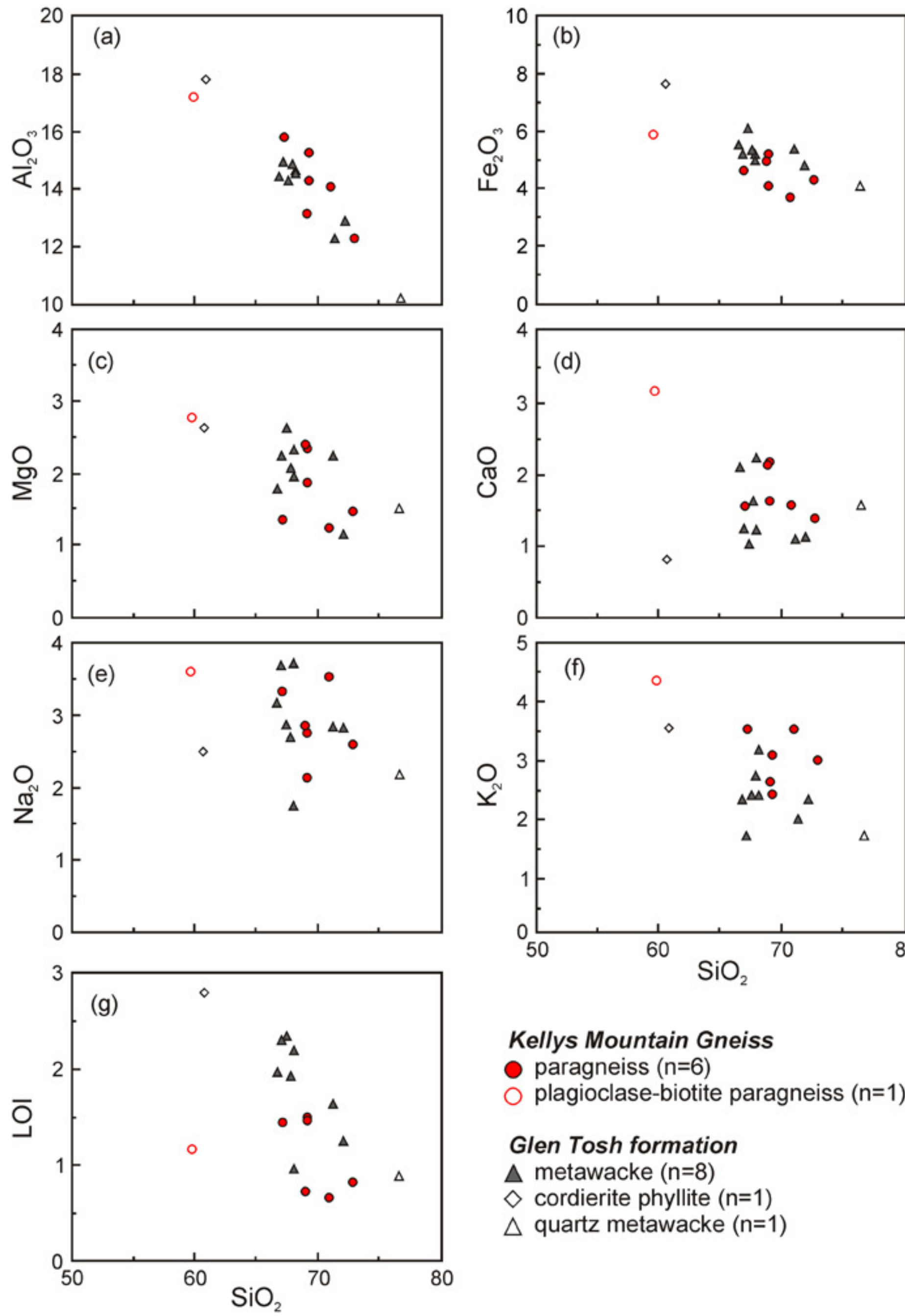

Figure 3. Major element oxides and loss-on-ignition (LOI) plotted against SiO_2 to illustrate chemical characteristics of samples from the Kellys Mountain Gneiss and Glen Tosh formation. Data are in weight % from Table 2.

analysed by Keppie *et al.* (1998) in three samples of Kellys Mountain Gneiss. Because these U-Pb data were based on multigrain analyses (their Table 1, p. 230), it is tentatively suggested that the chord drawn in the concordia plot might represent both a lead loss trajectory and a two-component mixing line between an old (>1.8 Ga) component and a Late Proterozoic (ca. 0.65–0.70 Ga) component. The apparent scarcity of young subconcordant zircons of ca. 0.70–0.65 Ga age (their Fig. 7; p. 228) could reflect the fact that the juvenile component implied by the mildly negative ε_{Nd} isotope signature corresponds to zircon-poor material (e.g., relatively mafic or intermediate volcanic rocks). This interpretation is supported by the occurrence of ca. 0.69 Ga euhedral zircon grains with high Th/U ratios in a

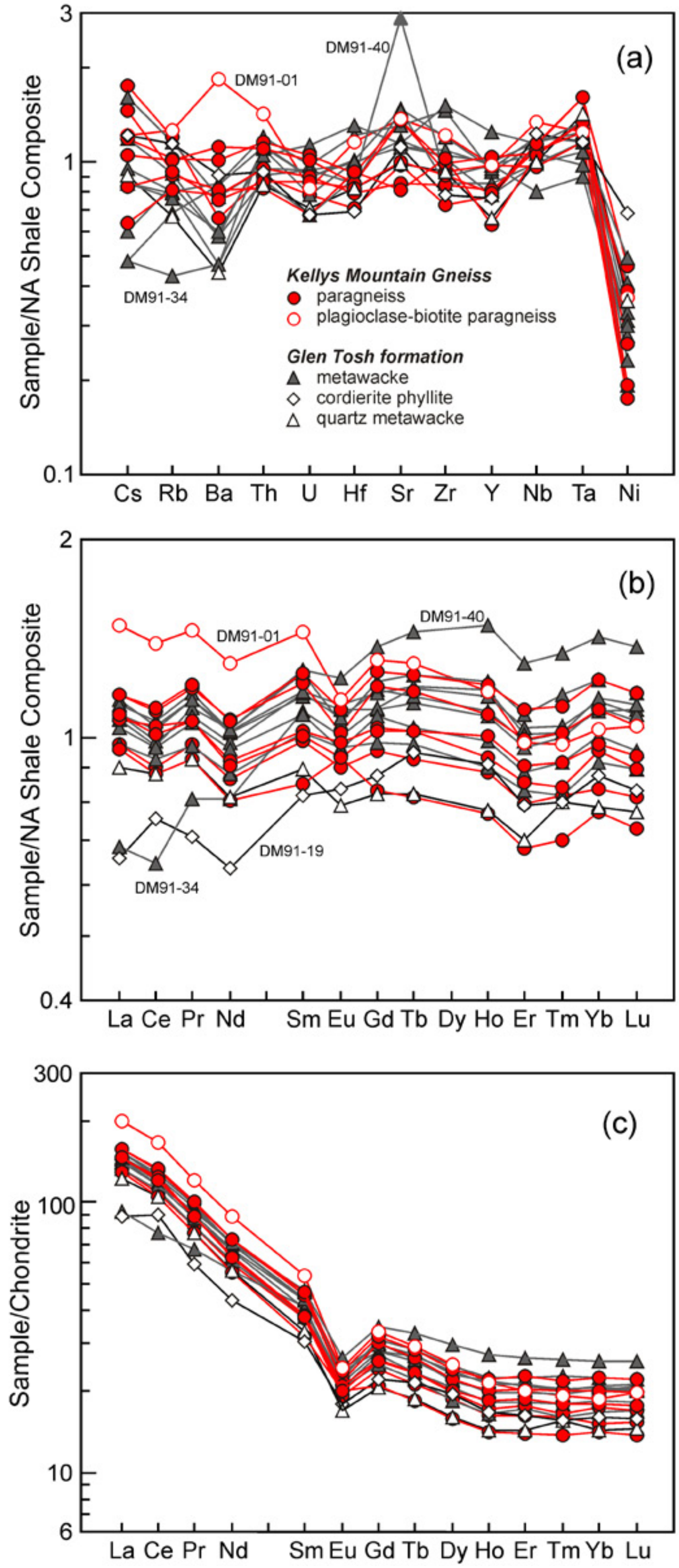

Figure 4. Trace element characteristics of samples from the Kellys Mountain Gneiss and Glen Tosh formation (data from Tables 2 and 3). (a) Selected elements normalized against the North American Shale Composite from Gromet *et al.* (1984). (b) Rare-earth elements normalized against the North American Shale Composite from Gromet *et al.* (1984). (c) Rare-earth elements normalized against chondrite data from Sun and McDonough (1989).

pelitic paragneiss of inferred volcanogenic origin (Keppie *et al.* 1998, p. 228) in the Creignish Hills (Fig. 1). Such high Th/U ratios are typical of zircon derived from either mafic or alkaline igneous rocks. However, most chemical characteristics are consistent with a dominantly felsic source (Fig. 5c, d).

In summary, Sm-Nd isotope data are consistent with a composite derivation of detrital components having fed the sedimentary basin or basins in which the protoliths of both the Kellys Mountain Gneiss and Glen Tosh formation were deposited. These sediments contained an ancient (ca. 2 Ga) end-member of recycled continental crust mixed with a juvenile component of Late Neoproterozoic age. However, major and trace element data indicate that the sedimentary protoliths were relatively immature and dominated by felsic igneous material, likely derived from an eroding active continental margin of still uncertain age.

The tectonic events that led to the near-juxtaposition of the Glen Tosh formation and Kellys Mountain Gneiss, parts of originally the same or similar sedimentary basins, remain enigmatic. On Kellys Mountain, the gneissic and lower grade rocks occur a few kilometres from one another, separated by plutonic rocks that intruded both. The U-Pb ages of 496 ± 5 Ma from titanite in an amphibolite layer in the paragneiss (Dunning *et al.* 1990), and ca. 495 Ma $^{40}Ar/^{39}Ar$ (cooling) dates from hornblende, muscovite, and biotite in both the amphibolite and gneiss (Keppie and Dallmeyer 1989; Reynolds *et al.* 1989) indicate that post-metamorphic uplift was occurring in the Late Cambrian. Early to mid-Cambrian metamorphism is suggested by a nearly concordant $^{206}Pb/^{238}U$ age of 515 ± 1 Ma for monazite from the Kellys Mountain Gneiss reported by Keppie *et al.* (1998), although they preferred the interpretation (consistent with their data from Creignish Hills and North Mountain) that the metamorphic age was 550 Ma and partially reset during granite emplacement. If so, then the metamorphic muscovite cooling age of ca. 550 Ma from the Glen Tosh formation at Big Hill reported by Dallmeyer and Keppie (1993) supports the interpretation that low- and high-grade metamorphism was synchronous in the Late Neoproterozoic.

The high-temperature and low-pressure metamorphic events in the Bras d'Or terrane have been attributed to a within-plate extensional regime that affected a pre-existing active continental margin, but the reason for the scattered

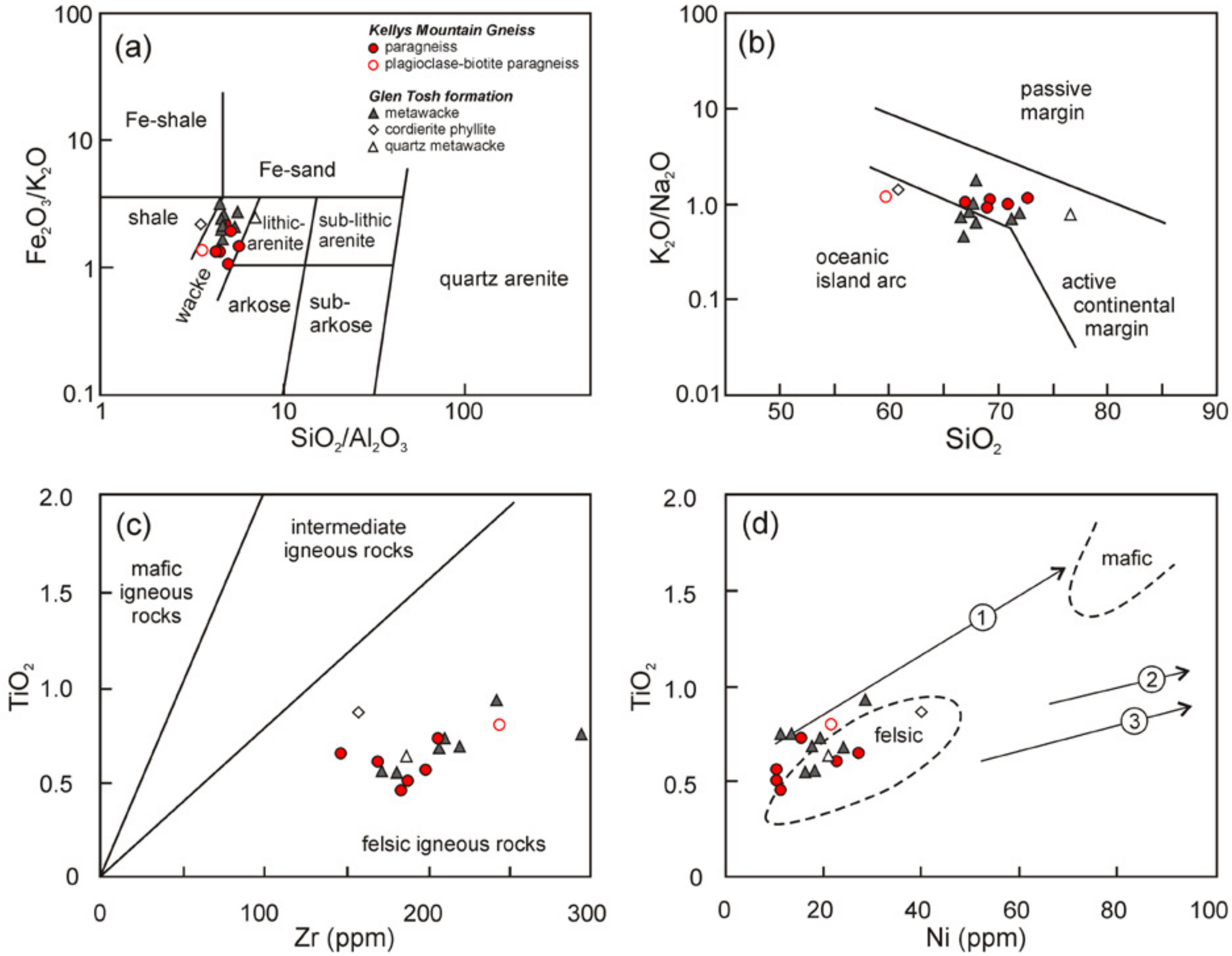

Figure 5. Chemical data for samples from the Kellys Mountain Gneiss and Glen Tosh formation plotted on chemical discrimination diagrams for sedimentary rocks. (a) Chemical classification diagram using Fe_2O_3/K_2O vs SiO_2/Al_2O_3 with fields from Herron (1988). (b) Depositional tectonic setting discrimination diagram using K_2O/Na_2O vs SiO_2 (in weight %) with fields from Roser and Korsch (1986). (c) Provenance discrimination diagram using TiO_2 (in weight %) vs Zr (in ppm) with fields from Hayashi *et al.* (1997). (d) Provenance discrimination diagram using TiO_2 (in weight %) vs Ni (in ppm) with fields from Floyd *et al.* (1989). Trends in (d) are for (1) magmatogenic greywacke, (2) mature recycled mudstone, and (3) mature recycled sandstone.

Table 4. Sm-Nd isotopic data*.

Sample	Rock type	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	$\varepsilon_{(0)}$	$\varepsilon_{(650)}$	T_{DM} (Ga)
Glen Tosh formation									
DM-91-11	quartz metawacke	4.77	25.0	0.1151	0.511831	2	-15.8	-9.0	1.88
DM-91-14	metawacke	5.49	28.9	0.1151	0.512142	3	-9.7	-2.9	1.40
DM-91-18	metawacke	6.82	32.4	0.1271	0.512269	3	-7.2	-1.5	1.36
DM-91-29	metawacke	6.86	33.1	0.1255	0.512258	2	-7.5	-1.5	1.36
DM-91-35	metawacke	6.08	30.5	0.1206	0.512190	2	-8.8	-2.5	1.40
Kellys Mountain Gneiss**									
DM-91-03	paragneiss	5.25	27.1	0.1170	0.511936	2	-13.7	-7.1	1.75
KM-10-01A	paragneiss	6.60	33.4	0.1194	0.512231	5	-8.0	-1.6	1.32
KM-10-02	paragneiss	5.92	30.4	0.1178	0.512128	2	-10.0	-3.4	1.46
KM-10-06	paragneiss	5.65	29.7	0.1149	0.512158	3	-9.4	-2.6	1.37

*See Appendix A for analytical methods. Sm and Nd are in ppm. **See Table 1 for detailed rock names.

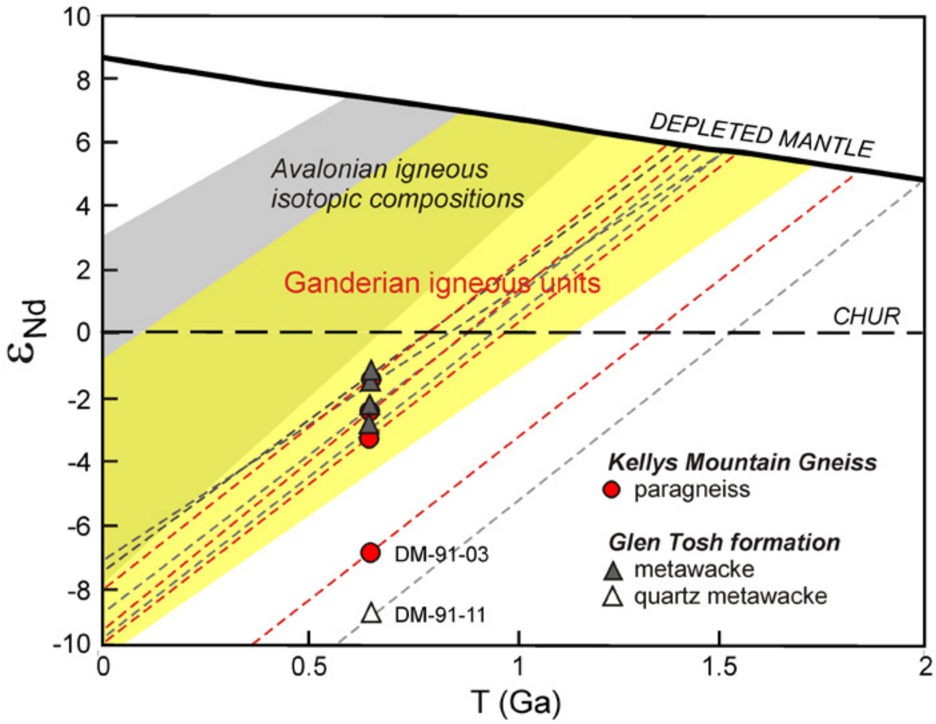

Figure 6. Plot of ε_{Nd} against time, with ε_{Nd} values calculated at 650 Ma (Table 4). The dashed lines are ε_{Nd} evolution lines, grey for metawacke samples and red for paragneiss samples. Grey shaded area indicates isotopic evolution of Neoproterozoic igneous samples from Avalonia (estimated from Murphy 2002) and overlapping yellow shaded area encloses the field for Neoproterozoic igneous samples in Ganderia estimated from Samson *et al.* (2000).

distribution of the high-grade rocks and their tectonic juxtaposition with more widespread low-grade rocks such as the Glen Tosh formation remains enigmatic. They could represent ca. 500 Ma core complexes disrupted by subsequent tectonic episodes. Extension in the Bras d'Or terrane, as indicated by within-plate volcanic rocks in the Boisdale Hills, has been attributed to the detachment of the Ganderian microcontinental block from Gondwana (e.g., van Staal and Barr 2012).

CONCLUSIONS

The petrographic, major and trace element, and Sm-Nd isotopic data presented here strongly support the interpretation that the Glen Tosh formation and Kellys Mountain Gneiss represent the same sedimentary protoliths, now at different metamorphic grades. Given the similarities among equivalent units elsewhere in the Bras d'Or terrane, it is likely that this is the case everywhere. However, the reason for the contrasting metamorphic histories and subsequent tectonic juxtaposition remains uncertain.

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Editorial responsibility: David P. West

APPENDIX A

Analytical methods

Major and trace elements were analyzed at Acme Analytical Laboratories Ltd., Vancouver, British Columbia. Major elements were determined by X-ray fluorescence after $LiBO_2$ fusion. Rare earth and refractory elements were determined by ICP Mass Spectrometry following lithium metaborate / tetraborate fusion and nitric acid digestion of a 0.2 g sample. A separate 0.5 g split was digested in Aqua Regia and analysed by ICP Mass Spectrometry to obtain precious and base metal data.

Sm-Nd isotope analyses were done by Isotope Dilution Thermal Ionization Mass Spectrometry (ID-TIMS) techniques. First, ca. 30 mg of powder samples were decomposed by fusion in an induction furnace with $LiBO_2$ as a fluxing agent, as described by Le Fèvre and Pin (2005), and the resulting melt was dissolved in 1.25M HCl. Then, Sm and Nd were separated from matrix elements and from each other by a procedure adapted from Pin and Santos Zalduegui (1997) combining cation-exchange and extraction chromatography techniques. Sm concentrations were measured with a ^{149}Sm-enriched tracer and an upgraded VG54E mass spectrometer in the single collector mode (Clermont-Ferrand), while Nd concentrations and $^{143}Nd/^{144}Nd$ isotope ratios were determined concomitantly with a ^{150}Nd-enriched tracer and a Triton TIMS machine operated in the static multicollection mode (GIS Laboratory, Nîmes). Two measurements of the standard of the Japan Geological Survey JNdi-1 made along with the samples provided $^{143}Nd/^{144}Nd$ ratios of 0.512102 +/- 2 and 0.512099 +/- 3, respectively, the mean of which corresponds to a value of 0.511843 for the La Jolla standard (Tanaka *et al.* 2000).