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Source contributions to Devonian granite magmatism near the Laurentian border, New Hampshire and Western Maine, USA

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Abstract

Radiogenic isotope data (initial Nd, Pb) and elemental concentrations for the Mooselookmeguntic igneous complex, a suite of mainly granitic intrusions in New Hampshire and western Maine, are used to evaluate petrogenesis and crustal variations across a mid-Paleozoic suture zone. The complex comprises an areally subordinate monzodiorite suite [377±2 Ma; $\varepsilon_{\mathrm{Nd}}$ (at 370 Ma)=−2.7 to −0.7; initial ^{207}Pb/^{204}Pb=15.56–15.58] and an areally dominant granite [370±2 Ma; $\varepsilon_{\mathrm{Nd}}$ (at 370 Ma)=−7.0 to −0.6; initial ^{207}Pb/^{204}Pb=15.55–15.63]. The granite contains meter-scale enclaves of monzodiorite, petrographically similar to but older than that of the rest of the complex [389±2 Ma; $\varepsilon_{\mathrm{Nd}}$ (at 370 Ma)=−2.6 to +0.3; initial ^{207}Pb/^{204}Pb c. 15.58, with one exception]. Other granite complexes in western Maine and New Hampshire are c. 30 Ma older than the Mooselookmeguntic igneous complex granite, but possess similar isotopic signatures.

Derivation of the monzodioritic rocks of the Mooselookmeguntic igneous complex most likely occurred by melting of Bronson Hill belt crust of mafic to intermediate composition. The Mooselookmeguntic igneous complex granites show limited correlation of isotopic variations with elemental concentrations, precluding any significant presence of mafic source components. Given overlap of initial Nd and Pb isotopic compositions with data for Central Maine belt metasedimentary rocks, the isotopic heterogeneity of the granites may have been produced by melting of rocks in this crustal package or through a mixture of metasedimentary rocks with magmas derived from Bronson Hill belt crust.

New data from other granites in western Maine include Pb isotope data for the Phillips pluton, which permit a previous interpretation that leucogranites were derived from melting heterogeneous metasedimentary rocks of the Central Maine belt, but suggest that granodiorites were extracted from sources more similar to Bronson Hill belt crust. Data for the Redington pluton are best satisfied by generation from sources in either the Bronson Hill belt or Laurentian basement. Based on these data, we infer that Bronson Hill belt crust was more extensive beneath the Central Maine belt

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than previously recognized and that mafic melts from the mantle were not important to genesis of Devonian granite magma.

Keywords: Acadian; Appalachians; Bronson Hill belt; Central Maine belt; Granite; Geochemistry; Pb isotopes; Nd isotopes

1. Introduction

In the study of the histories of orogenic belts, granites are indispensable sources of information. Age relations, elemental and isotopic compositions, fabrics and three-dimensional forms provide evidence as to the dynamics of exhumed convergent plate margins and give pivotal clues to the identity of unexposed basement terranes. Thus, as long as geochemical contrasts between source materials are clear, regional-scale geochemical mapping may illuminate basement relations (Bennett and DePaolo, 1987; Ayuso and Bevier, 1991; Dorais and Paige, 2000). However, in areas like the northern Appalachians of New Hampshire and Maine, where end-member source compositions may bear considerable similarity to one another, detailed studies of individual precisely-dated plutonic complexes may be a more appropriate approach to provide the kind of information required.

In the northern Appalachians, the principal exposed basement source candidates are Laurentian (North American) and Avalonian (non-North American) continental crust, which exhibit strong contrasts in their Pb and Nd isotopic signatures (Ayuso and Bevier, 1991; Barr and Hegner, 1992; Whalen et al., 1994; Kerr et al., 1995). However, the nature of the basement beneath New Hampshire and western Maine is likely to be much more complex (Stewart et al., 1992), requiring assessment of additional source components, including various mantle reservoirs, Taconic arc crust, and mid-crustal metasedimentary rocks. The specific nature of the basement near the edge of the geophysically defined margin of North American continental crust is still rather poorly known. For this reason, our study of granite complexes in New Hampshire and western Maine is important because the magmas from which they crystallized potentially record information that directly addresses this uncertainty in basement terranes. There is abundant evidence for lower crust of circum-Gondwanan affinity across strike to the south of this boundary (Whalen et al., 1998; Tomascak et al., 1996), but whether the non-North American crust extends fully to the boundary with North American crust is a point of speculation.

In addition to questions about the details of tectonic assembly of a continental margin that was active for more than 100 Ma, the northern Appalachians present longstanding problems regarding the heat sources for the generation of abundant peraluminous granite bodies (DeYoreo et al., 1989; Chamberlain and Sonder, 1990; Brown and Solar, 1999). Furthermore, orogens control the mechanics of interactions between converging plates; thus, it is important to understand both weakening and hardening mechanisms. Syntectonic pervasive melt flow, episodic melt expulsion, ascent and emplacement, and crystallization of melt all affect the rheology and control the mechanical response to imposed stresses. For these reasons it is important to evaluate crustal melting and the relative contributions of mantle-derived and crustal-derived melts to upper crustal plutons. Geochemical tracers, particularly isotopic systems, yield important petrogenetic information.

The plutons studied are in part petrologically primitive (with potentially important mantle contributions). Confirming or ruling out mantle source components for these rocks, or indeed placing constraints on the volume of mantle contributions, will allow development of better-constrained tectonic models. In this study we use precise geochronology, isotope tracers and elemental geochemistry of plutonic rocks in order to more clearly define the nature of the crust beneath the boundary of the Bronson Hill and Central Maine belts of the northern Appalachians during the Devonian.

2. Geology and samples

The New Hampshire and Maine part of the northern Appalachians is divided into several tectonostratigraphic units defined by discrete northeast–southwest oriented tracts of deformed and metamorphosed rock (Fig. 1). The Central Maine belt (CMB) underlies much of the area; it is composed of a Lower Paleozoic sedimentary succession, deformed and metamorphosed at greenschist to upper amphibolite facies conditions, and intruded by Devonian plutons. The CMB is located between Ordovician rocks of the Bronson Hill belt (BHB) to the northwest and Neoproterozoic to Silurian rocks of the Avalon Composite terrane (ACT) to the southeast, from which it is separated by the dextral-transcurrent Norumbega shear zone system (NSZS).

The area of study covers part of the western side of the Central Maine belt where it is in contact with the Bronson Hill belt to the northwest (Figs. 1 and 2). The CMB comprises Siluro-Devonian metasedimentary rocks (metaturbidite) of the “Rangeley stratigraphic sequence” (Moench, 1971; Moench et al., 1995; Solar and Brown, 2001a), migmatites (Brown and Solar, 1998a, 1999; Solar and Brown, 2001b) and predominantly granitic plutons of various volumes and shapes (e.g., Moench et al., 1995; Brown and Solar, 1998b, 1999; Pressley and Brown, 1999). To the northwest, the CMB is bounded by a Devonian tectonite zone (Fig. 1; Solar and Brown, 2001a) across which the belt is juxtaposed against the BHB. The main deformation and metamorphism within the CMB were the result of Devonian Acadian orogenesis, whereas the main deformation and metamorphism within the BHB were the result of Ordovician Taconic orogenesis. However, both belts record Devonian metamorphism and deformation in the area of their contact, recorded by structures such as refolded folds found in the BHB rocks, but not in the adjacent CMB rocks, and the tectonite zone that includes the contact. Plutonism across the area was Devonian and late syntectonic (Solar et al., 1998), and may be concordant with, or discordant to, the regional metamorphic mineral fabrics (Brown and Solar, 1998b; Solar and Brown, 1999).

The penetrative deformation within the CMB is recorded by metamorphic mineral fabrics and regional-scale folds of the metasedimentary rock units consistent with bulk transpression during the Acadian orogeny (Solar and Brown, 2001a). Oblique (dextral) southeast-side up contraction of the belt was largely accommodated within the broad Central Maine belt shear zone system (Fig. 1; Brown and Solar, 1998a). Solar and Brown (1999, 2001a) and Brown and Solar (1998a,b, 1999) subdivided the region into kilometer-scale alternating NE–SW-trending structural zones of apparent flattening (AFZ in Fig. 2) and apparent constrictional finite strain as defined by the bulk rock fabrics, supported by the style and intensity of folds of the metasedimentary rock layers (tighter in the apparent flattening zones). The grade of Devonian regional metamorphism within the CMB ranges from greenschist to upper amphibolite facies; granulite facies assemblages occur in Massachusetts (Chamberlain and Robinson, 1989). In Maine and New Hampshire regional metamorphism occurred at low pressure; andalusite is abundant in rocks of suitable grade and composition. At the highest grade (upper sillimanite zone; e.g., Guidotti and Holdaway, 1993), anatectic migmatites are variably developed in metapelitic rocks (Solar and Brown, 2001b; Johnson et al., 2003). Contact metamorphic effects of pluton emplacement are local and have modified and variably overprinted the regional metamorphism (e.g., Solar and Brown, 1999, 2000; Guidotti and Johnson, 2002; Johnson et al., 2003).

Peraluminous granite bodies are widespread (Fig. 1), ranging from millimeter- to centimeter-scale leucosomes and meter-scale tabular- and cylinder-shaped bodies in migmatites (e.g., Brown and Solar, 1999; Solar and Brown, 2001b), to kilometer-scale composite plutons (Brown and Solar, 1998b). The Phillips and Redington plutons and the central lobe of the Lexington composite pluton (Fig. 1) have yielded ages of c. 404 Ma (U–Pb zircon, monazite), which are interpreted to record the age of crystallization (Solar et al., 1998; Brown and Pressley, 1999; see Appendix B). Schlieric granite and decimeter- to meter-scale tabular granite bodies within the migmatites crystallized synchronously with the c. 404 Ma plutons (Solar et al., 1998). The three-dimensional geometry of the granites, their relationship to the regional structure and the close association of smaller bodies, such as the Phillips pluton, with heterogeneous migmatite support a genetic relationship between deformation, granite ascent and pluton emplacement (Brown and

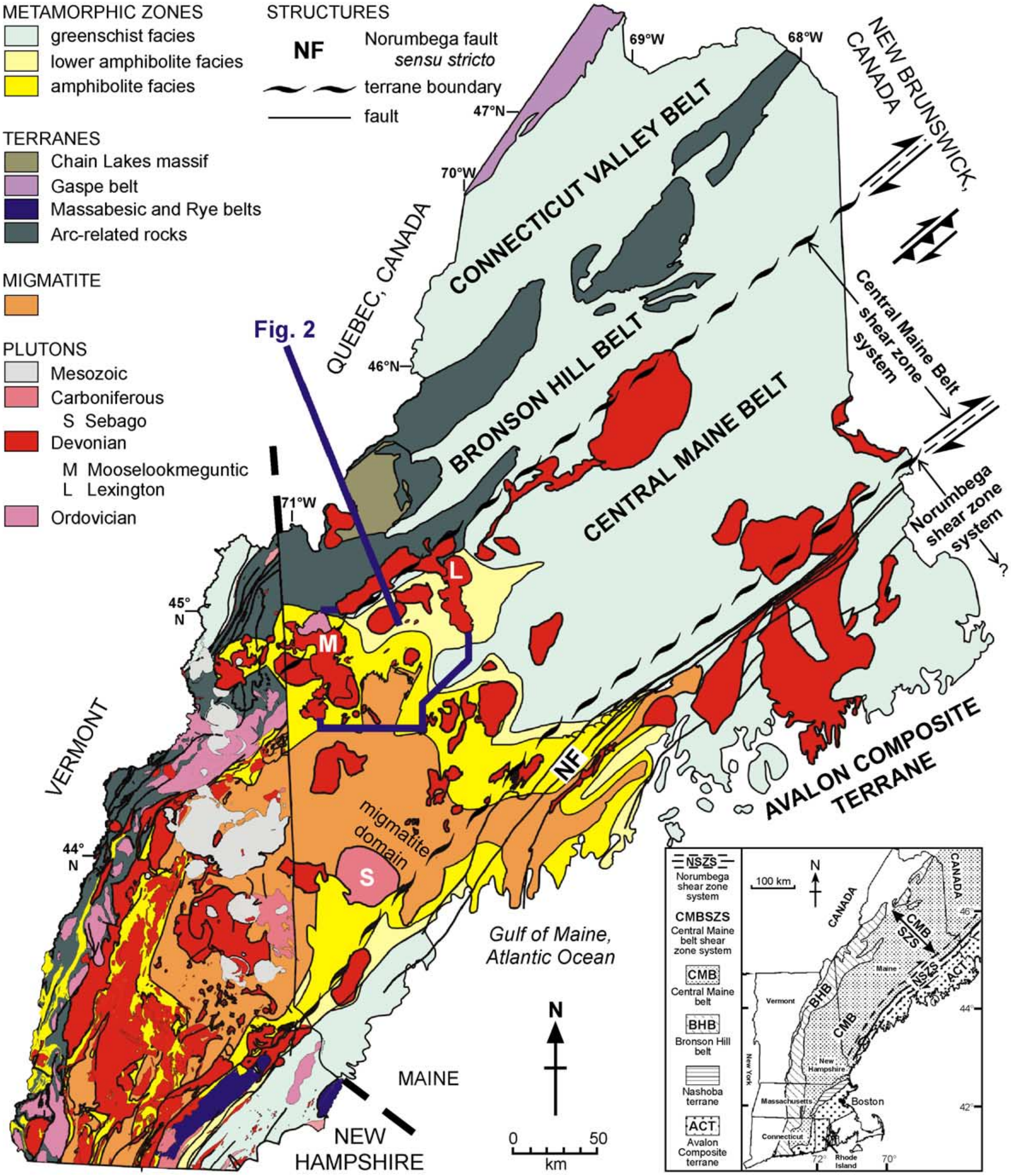

Fig. 1. Simplified geological map of Maine and New Hampshire, of the northeastern U.S.A. (see inset map for location), to illustrate the distribution of plutons, migmatite, metamorphic zones and principal terranes. Area shown in Fig. 2 is indicated. Modified after Lyons et al. (1997) and Solar and Brown (1999).

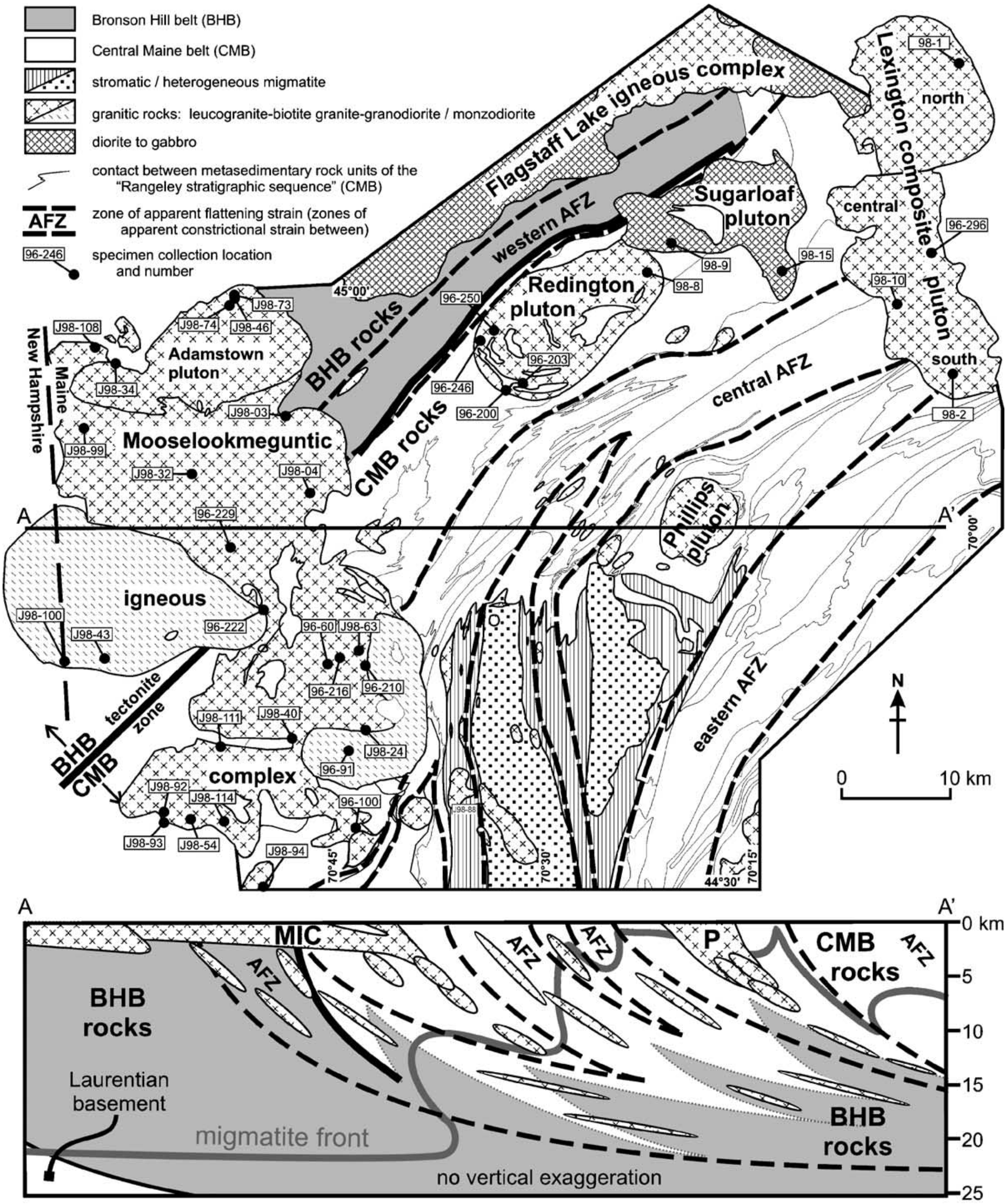

Fig. 2. Simplified geological map and schematic structure section of the area of study (see Fig. 1 for location) based upon the mapping of Solar and Brown (2001a), and Tian (2000). Abbreviations: MIC—Mooselookmeguntic igneous complex; P—Phillips pluton; BHB—Bronson Hill belt; CMB—Central Maine belt. The regional structure is illustrated as the alternating zones of apparent flattening strain (AFZ) and zones of apparent constrictional strain (ACZ). The tectonite zone in the northwest is coincident with the BHB-CMB boundary at the surface which is cross-cut by the MIC.

Solar, 1998a, 1998b, 1999; Pressley and Brown, 1999).

This study concentrates primarily on new data from the Mooselookmeguntic igneous complex (MIC) that straddles the CMB-BHB contact (Fig. 2). We also have reinvestigated samples of the Phillips pluton from Pressley and Brown (1999), and have made additional Pb isotope measurements on rocks from this body. Supporting new elemental and isotopic data from rocks of the nearby Redington, Sugarloaf and Lexington plutons are presented, although none of these bodies was examined in sufficient detail to permit petrogenetic interpretation. Comparison with published data from granite complexes in New Hampshire, which unfortunately do not include Pb isotope data, allow some wider implications to be drawn.

2.1. The Mooselookmeguntic igneous complex

The Mooselookmeguntic igneous complex (MIC) was previously mapped as petrographically distinct plutonic bodies, the Mooselookmeguntic and Umbagog plutons (Fig. 2; Moench et al., 1995). Considering the information currently available, we consider the MIC to consist of two principal types of rock: biotite granodiorite to quartz monzodiorite (herein referred to as the monzodiorite suite), biotite and two-mica granite to granodiorite (herein referred to as granite). Biotite monzodiorite to granodiorite enclaves, petrographically similar to rocks of the monzodiorite suite, occur in the granite. The monzodiorite suite dominates the southern and western portions of the complex (previously mapped as the Umbagog pluton). The enclaves in the MIC granite occur as multi-meter-scale blocks with petrographic character similar to the monzodiorite suite. Portions of both the monzodiorite suite and the granite lie to the north and south of the BHB-CMB contact. The Adamstown pluton in the north is distinct from the rocks that comprise the MIC and will not be discussed in this work.

Solar et al. (1998) reported crystallization ages for two MIC rocks: a U–Pb zircon age of 389±2 Ma for sample 96-216 (see Fig. 2), a granodiorite enclave (“biotite granite” in their publication), and a concordant U–Pb monazite age of 370±1 Ma for sample 96-210 of the MIC granite (“two-mica leucogranite” in their publication). Two samples from distinct parts of the MIC monzodiorite suite yield identical ages, slightly older than the granite (samples J98-40 and J98-100: c. 377 Ma on four concordant to 3% discordant U–Pb zircon fractions; see Appendices A and B; see Fig. 2 for location). This is equivalent to the U–Pb concordia upper intercept age of 378±2 Ma published by Moench and Aleinikoff (2002) for an alkali gabbro “border facies” of the monzodiorite suite.

2.2. The Phillips pluton

The Phillips pluton (Fig. 2) comprises petrographically distinct granodiorite and leucogranite with equivalent crystallization ages of 404±2 Ma (concordant U–Pb zircon and monazite; Solar et al., 1998; Pressley and Brown, 1999). This age is characteristic of a wide band of igneous bodies throughout Maine and New Hampshire (e.g., Bradley and Tucker, 2002), and of a variety of migmatites in the area of study, contributing to the thesis that metamorphism, granite production and regional deformation were functionally linked during this period (Solar et al., 1998).

2.3. Other granitic rocks

The Redington pluton (5 specimens), dominantly a porphyritic biotite granite, crops out within the CMB, with its northern boundary coincident with the tectonite zone that separates the BHB and CMB. The upper U/Pb intercept age of four zircon fractions from sample 96-246 is 408±5 Ma (Solar et al., 1998). Two subsequent concordant zircon fractions from sample 98-8 (see Fig. 2) suggest an age of c. 406 Ma is more accurate (see Appendix B).

The Sugarloaf pluton (2 specimens; Fig. 2) occupies a similar position to the Redington pluton with respect to the BHB-CMB contact. Mingled felsic-mafic rocks in outcrops of this body bear strong resemblance to large portions of the more mafic part of the adjacent Flagstaff Lake intrusive complex. The samples include gabbroic rock (98-15), the dominant rock type in outcrop, and subordinate material from a felsic pod (sample 98-9).

The Lexington composite pluton (5 specimens) comprises northern, central and southern portions, based partly on interpretation of the three-dimensional character of the pluton (Brown and Solar, 1998b), occurring east along strike from the main body of the MIC (Fig. 2). Rock types are primarily granite and granodiorite, based on normative composition, although one sample (98-10-2) is a gabbro enclave. All granite samples contain biotite and some contain two igneous micas (e.g., 98-2). The U–Pb zircon age determined by Solar et al. (1998; 404±2 Ma) is from sample 96-296-6, from the central portion of the pluton, and an identical zircon age has been measured from the southern lobe (sample 98-2: c. 403 Ma on two concordant fractions; see Appendix B). Interestingly, the northern part of the pluton has yielded a younger age (sample 98-1: c. 365 Ma on two concordant U–Pb zircon fractions; see Appendix B).

3. Analytical procedures

Major and trace element analyses (except Nd, Sm) were produced by XRF at Washington University following their standard procedures (R. Couture, analyst). Most samples for Sm–Nd isotope dilution analyses were prepared by flux fusion, Fe-coprecipitation, and cation exchange identically to Tomascak et al. (1996). Despite a Nd blank of c. 3 ng during the course of the study, the ratio of sample/blank for Nd was always greater than 500. Samples from the Redington, Lexington and Sugarloaf pluton were digested for two days in concentrated $HF+HNO_3$ in Paar Teflon bombs at 210 °C. Blanks for these preparations were <400 pg for Nd and <100 pg for Sm, and corrections were insignificant. Samples of alkali feldspar were isolated, cleaned and leached as detailed in Tomascak et al. (1996). The total Pb blank was 130–370 pg, of which 1–4 pg was introduced during loading. Using whole-rock Pb concentrations as a proxy for concentrations in alkali feldspar, a minimum of 200 ng Pb was processed for each sample, indicating that no significant blank correction was necessary.

Isotope ratio measurements carried out at the Isotope Geochemistry Laboratory, Department of Geology, University of Maryland, used a VG Sector 54 mass spectrometer, and methods described in Tomascak et al. (1996). Measured Nd isotope ratios were normalized to $^{146}Nd/^{144}Nd=0.72190$. Analyses of the La Jolla Nd standard during the study yielded a mean $^{143}Nd/^{144}Nd$ of 0.511844±16 (2σ; $n=10$), translating to an uncertainty of ±0.35 ε unit. To facilitate discussion of rocks with distinct crystallization ages, Nd isotope data in this work are calculated for the age of the youngest rocks, 370 Ma. Given the Sm/Nd of the samples, there is at most a 0.3 unit difference between ε_{Nd} (at 370 Ma) and the initial ε_{Nd} for the oldest samples.

A fractionation correction of 0.079±0.008% amu^{-1} was applied to the Pb isotope data, referenced relative to the updated recommended isotopic values of NBS Pb standard SRM-981 (Thirlwall, 2000). The Pb standard analyses collected throughout the study yielded a mean reproducibility of ±0.032% amu^{-1} (2σ; $n=16$) for ratios involving measurement of ^{204}Pb. To assess potential long-term, user-to-user reproducibility, a K-feldspar sample from Tomascak et al. (1996; SG-3-14: $^{206}Pb/^{204}Pb=18.467$, $^{207}Pb/^{204}Pb=15.622$, $^{208}Pb/^{204}Pb=38.256$) was hand-picked, cleaned and leached. The mean offset between results is ±0.046% amu^{-1} ($^{206}Pb/^{204}Pb=18.439$, $^{207}Pb/^{204}Pb=15.612$, $^{208}Pb/^{204}Pb=38.192$), similar to the reproducibility of replicate preparations of individual feldspar samples from this study (±0.025% amu^{-1}).

4. Geochemical results

4.1. Elemental data

The MIC monzodiorite suite and enclaves range from metaluminous to peraluminous, whereas all of the MIC granites are peraluminous (Table 1). Despite their c. 12 Ma age difference, compositions of samples from the monzodiorite suite and of the enclaves overlap almost completely, with the exception that the enclaves have lower Mg# (average of 48.6 versus 57.6). Contents of $Fe_2O_3^T$, MgO and CaO decrease with increasing SiO_2, and correlations are absent or poor between SiO_2 and Al_2O_3, Na_2O, or K_2O (Fig. 3). All of these samples show light rare earth element enrichment typical of crustal rocks ($^{147}Sm/^{144}Nd=0.1002$ to 0.1273; Table 2).

Table 1
Major (wt.%) and trace (ppm) elements in samples from this study

Pluton group	MIC enclave					MIC monzodiorite			
Sample number	96-216	J9832-2	J98-54	J98-93	J98-111-3	96-222	J98-43	J98-100	J98-63-2
Rock type	gdr	gdr	qtz mdr	mzdr	mdr	qtz mdr	qtz mdr	mzn	gdr
SiO_2	65.0	67.2	63.8	51.7	52.1	57.9	57.7	57.2	64.6
TiO_2	0.85	0.51	0.91	1.74	2.03	1.28	1.35	1.36	0.90
Al_2O_3	15.97	15.89	16.25	14.87	15.77	16.10	15.00	15.34	15.95
Fe_2O_3*	4.69	4.54	4.58	8.62	9.14	7.02	6.70	6.03	4.43
MnO	0.10	0.10	0.10	0.24	0.17	0.12	0.10	0.11	0.08
MgO	2.83	1.75	2.04	3.75	4.99	4.57	5.20	4.20	3.09
CaO	3.66	4.12	3.78	6.26	7.39	5.32	5.70	4.73	3.98
Na_2O	3.64	3.11	4.03	3.94	3.42	3.45	3.55	3.27	3.48
K_2O	2.43	1.90	3.28	2.86	2.18	2.56	3.50	5.46	2.58
P_2O_5	0.24	0.09	0.34	1.08	0.65	0.45	0.50	0.69	0.26
L.O.I.	0.47	0.39	0.35	0.43	0.48	0.47	0.37	0.38	0.42
Sum	99.90	99.59	99.45	98.50	98.31	99.22	99.68	98.77	99.77
Rb	196	145	105	117	79	193	177	234	120
Sr	437	185	480	994	1253	623	798	910	510
Ba	528	484	872	1187	1093	667	888	1297	730
Y	16.0	15.9	22.8	30.3	26.5	22.7	19.8	27.1	16.9
Zr	181	162	323	419	185	218	161	342	185
Nb	10.7	11.2	17.9	28.1	17.5	12.4	15.2	20.6	10.7
Sn	5.5	<4.2	3.8	6.3	<7.8	<4.1	<6.7	<6.8	<4.8
Pb	12.0	12.1	19.6	12.4	22.6	12.1	29.1	36.1	15.3
V	81.4	75.1	70.7	136.1	151.7	112.6	123.4	131.5	84.7
Cr	93.7	<21.7	22.9	<26.8	59.3	152.5	177.5	105.4	93.4
Ni	48.3	<4.2	13.3	13.1	25.9	73.3	113.6	57.4	45.4
Co	17.3	8.0	12.8	22.7	27.8	23.0	24.2	22.6	14.1
Zn	71.9	58.6	93.2	147.3	105.5	76.7	70.5	79.8	65.2
Ga	19.3	16.6	21.5	26.4	19.3	20.0	21.5	20.0	19.1
Nd	25.20	28.30	55.30	81.45	75.89	41.35	45.18	72.57	30.27
Sm	5.305	5.067	9.441	13.68	12.67	7.433	8.489	12.03	5.751
Mg#	54.5	43.3	46.9	46.3	52.0	56.3	60.6	58.0	58.0
A/CNK	1.05	1.08	0.95	0.71	0.74	0.89	0.75	0.77	1.01

Pluton group	MIC monzodiorite	MIC granite							
Sample number	J98-40	96-60	96-91	96-100	96-100-2	96-210	96-229	J98-03	J98-04
Rock type	gdr	gdr	gdr	grn	grn	grn	grn	grn	grn
SiO_2	67.0	71.8	69.6	71.6	73.8	72.5	71.9	74.8	72.7
TiO_2	0.81	0.27	0.32	0.30	0.14	0.18	0.30	0.19	0.27
Al_2O_3	15.35	15.23	15.98	15.10	14.12	14.95	14.81	13.29	14.49
Fe_2O_3*	3.86	1.64	2.03	2.11	0.92	1.29	1.82	1.55	1.77
MnO	0.07	0.04	0.04	0.08	0.04	0.06	0.04	0.07	0.05
MgO	2.38	0.55	0.88	0.43	0.23	0.44	0.52	0.47	0.49
CaO	3.02	2.36	3.13	1.51	0.77	1.48	1.67	1.30	1.36
Na_2O	3.25	4.42	3.87	4.21	3.98	3.89	3.66	3.24	3.46
K_2O	2.64	3.22	2.99	3.91	4.98	4.17	4.22	4.09	4.78
P_2O_5	0.21	0.10	0.13	0.28	0.13	0.12	0.17	0.04	0.17
L.O.I.	0.86	0.29	0.28	0.37	0.29	0.42	0.39	0.41	0.31
Sum	99.34	99.86	99.46	100.08	99.47	99.64	99.70	99.44	99.84

Table 1 (*continued*)

Pluton group	MIC monzodiorite	MIC granite							
Sample number	J98-40	96-60	96-91	96-100	96-100-2	96-210	96-229	J98-03	J98-04
Rock type	gdr	gdr	gdr	grn	grn	grn	grn	grn	grn
Rb	136	125	89	194	212	228	200	173	194
Sr	441	266	387	129	63	135	166	202	151
Ba	770	695	861	484	253	317	487	483	448
Y	17.8	6.7	6.3	21.3	9.2	11.8	12.1	14.2	9.2
Zr	147	123	154	187	81	82	156	111	138
Nb	11.4	8.2	5.7	22.4	10.4	12.8	11.1	13.2	9.6
Sn	4.3	3.5	3.4	9.2	5.5	6.7	7.9	6.1	<6.4
Pb	19.8	27.6	22.1	26.1	33.2	32.0	28.5	23.2	31.5
V	74.9	19.8	28.2	16.4	<5.1	13.3	18.2	14.1	12.8
Cr	69.5	21.9	29.1	16.4	17.3	19.7	<22.8	<14.4	<22.3
Ni	32.3	<5.6	<3.6	<4.4	<3.5	6.2	<4.0	<3.6	<3.6
Co	15.0	4.0	5.3	3.9	4.5	4.3	<5.0	4.6	<6.1
Zn	57.0	33.8	38.8	64.2	25.1	34.3	62.8	19.0	50.4
Ga	18.4	16.4	18.9	21.3	16.9	18.4	20.5	14.0	16.9
Nd	29.90	18.56	14.64	37.57	–	21.40	–	14.55	39.66
Sm	6.204	3.093	2.602	6.466	–	3.975	–	2.613	7.081
Mg#	55.0	39.9	46.2	28.8	33.1	40.3	36.1	37.5	35.4
A/CNK	1.12	1.01	1.04	1.09	1.06	1.10	1.09	1.10	1.09

Pluton group	MIC granite								
Sample number	J98-24	J98-32	J98-63-1	J98-88	J98-92-2	J98-94	J98-99	J98-108	J98-111-2
Rock type	grn	grn	gdr	gdr	gdr	gdr	grn	grn	gdr
SiO_2	73.4	74.2	75.3	74.8	71.5	72.6	74.3	73.6	72.2
TiO_2	0.12	0.11	0.08	0.06	0.47	0.28	0.11	0.21	0.41
Al_2O_3	14.90	14.42	14.02	14.38	14.60	15.21	14.47	14.14	14.95
Fe_2O_3*	0.96	0.80	0.55	0.47	2.90	1.84	0.96	1.15	2.51
MnO	0.02	0.03	0.02	0.01	0.05	0.06	0.04	0.05	0.04
MgO	0.32	0.29	0.13	0.04	0.80	0.56	0.26	0.29	0.85
CaO	1.14	1.06	1.15	0.89	1.65	2.30	0.53	0.91	1.99
Na_2O	3.46	4.09	4.49	4.90	4.06	4.68	3.51	3.31	4.09
K_2O	4.98	4.57	3.62	3.91	3.23	1.50	4.85	4.93	2.45
P_2O_5	0.15	0.14	0.13	0.09	0.12	0.18	0.20	0.14	0.04
L.O.I.	0.52	0.23	0.30	0.23	0.47	0.50	0.69	0.69	0.49
Sum	99.97	99.93	99.79	99.78	99.85	99.69	99.92	99.40	100.03
Rb	202	220	169	179	145	85	298	285	84
Sr	143	78	59	95	182	125	51	101	263
Ba	368	196	56	172	452	79	190	297	421
Y	12.0	8.2	10.3	6.4	41.5	10.7	9.8	11.7	14.2
Zr	60	73	44	27	231	133	56	97	242
Nb	9.5	8.4	9.9	6.9	21.2	7.5	14.3	10.5	13.7
Sn	6.7	5.8	7.6	6.9	6.7	<6.8	11.4	8.1	4.7
Pb	50.0	31.8	31.4	48.7	37.6	19.6	33.2	29.2	36.9
V	6.9	<5.1	4.8	<4.7	33.4	15.4	<6.3	6.4	25.3
Cr	<14.6	<16.4	<23.7	<14.2	<14.8	<14.6	<25.6	<14.8	<14.4
Ni	<3.4	<3.4	<3.2	<3.2	<7.2	<6.6	<3.4	<5.0	<4.9

(continued on next page)

Table 1 (*continued*)

Pluton group	MIC granite								
Sample number	J98-24	J98-32	J98-63-1	J98-88	J98-92-2	J98-94	J98-99	J98-108	J98-111-2
Rock type	grn	grn	gdr	gdr	gdr	gdr	grn	grn	gdr
Co	4.2	<3.7	<3.7	<5.6	4.2	<6.0	<6.2	<3.5	5.9
Zn	28.5	26.2	16.9	24.8	62.7	42.2	37.3	51.2	46.2
Ga	19.1	16.8	21.3	16.1	18.7	16.1	19.5	21.7	18.1
Nd	17.54	16.65	31.28	4.650	53.37	24.94	6.349	36.71	70.78
Sm	4.038	3.623	6.806	1.177	9.624	4.656	1.698	6.734	10.59
Mg#	39.8	41.8	31.9	14.4	35.3	38.1	34.9	33.3	40.1
A/CNK	1.13	1.06	1.05	1.03	1.11	1.13	1.21	1.14	1.15

Pluton group	MIC granite	Redington					Lexington north	Lexington south	Lexington central
Sample number	J98-114	96-200	96-203	96-246	96-250	98-8	98-1	98-2	96-296-2
Rock type	grn	grn	grn	grn	grn	grn	gdr	grn	grn
SiO_2	74.6	73.8	67.2	68.7	64.4	72.8	71.0	73.3	72.9
TiO_2	0.09	0.36	0.68	0.56	0.72	0.10	0.38	0.19	0.40
Al_2O_3	14.41	13.78	16.12	16.02	17.77	16.17	15.01	14.25	13.56
Fe_2O_3*	0.81	2.24	4.41	3.69	4.65	1.24	2.57	1.46	2.77
MnO	0.02	0.02	0.04	0.03	0.04	0.05	0.08	0.04	0.05
MgO	0.18	0.64	1.22	1.06	1.30	0.21	0.69	0.32	0.82
CaO	0.62	1.51	2.12	1.84	2.34	0.70	2.41	0.94	1.55
Na_2O	3.39	2.60	2.78	3.08	3.50	3.74	3.95	3.24	3.05
K_2O	5.13	3.84	4.12	3.86	4.26	4.04	3.71	5.51	3.97
P_2O_5	0.22	0.15	0.14	0.15	0.11	0.24	0.08	0.21	0.22
L.O.I.	0.56	0.74	0.78	0.87	0.66	0.66	0.37	0.51	0.48
Sum	100.04	99.71	99.57	99.90	99.74	99.91	100.2	99.96	99.80
Rb	243	123	139	144	138	–	143	287	172
Sr	54	124	168	149	196	–	215	70.5	156
Ba	104	580	750	590	990	–	495	197	272
Y	11.8	9.1	15.0	12.1	16.2	–	17.8	12.2	15.3
Zr	44	140	254	212	262	–	171	99.7	153
Nb	11.7	8.9	13.9	12.2	13.9	–	12.2	15.6	17.4
Sn	7.4	4.4	<5.1	<6.3	<6.3	–	<5.7	10	<5.7
Pb	38.0	26.2	30.6	33.0	32.3	–	23.5	37.1	36.3
V	<3.4	30	41.6	43.7	46.0	–	27.6	5.1	28.3
Cr	<17.7	23.9	18.1	23.9	32.1	–	<15.0	<14.8	15.5
Ni	<3.4	5.4	12.0	12.4	11.3	–	<3.8	<3.6	3.8
Co	<3.3	3.6	7.7	6.6	6.2	–	4.0	<4.8	8.3
Zn	34.7	44.8	80.2	70.1	77.5	–	44.3	40.5	55.5
Ga	20.2	16.3	20.7	18.6	22.3	–	18.3	16.1	15.4
Nd	15.73	32.61	52.83	52.34	66.71	8.943	29.42	22.44	33.70
Sm	3.930	5.659	9.357	9.077	11.47	2.460	5.138	4.708	6.423
Mg#	30.6	36.1	35.4	36.3	35.6	25.1	32.9	30.3	37.0
A/CNK	1.18	1.23	1.25	1.27	1.22	1.37	1.01	1.10	1.12

Fe_2O_3*=total Fe as Fe_2O_3; L.O.I.=loss on ignition at 600 °C; Mg#=100* molar MgO/(MgO+FeO), where FeO is estimated to be 0.9* total Fe; A/CNK= molar $Al_2O_3/(Na_2O+K_2O+CaO)$. Rock type (as defined by CIPW normative compositions): grn—granite; gdr—granodiorite; qtz mdr—quartz monzodiorite; mdr—monzodiorite; mzn—monzonite. <x=samples where element was below limit of accurate quantification. –=not determined.

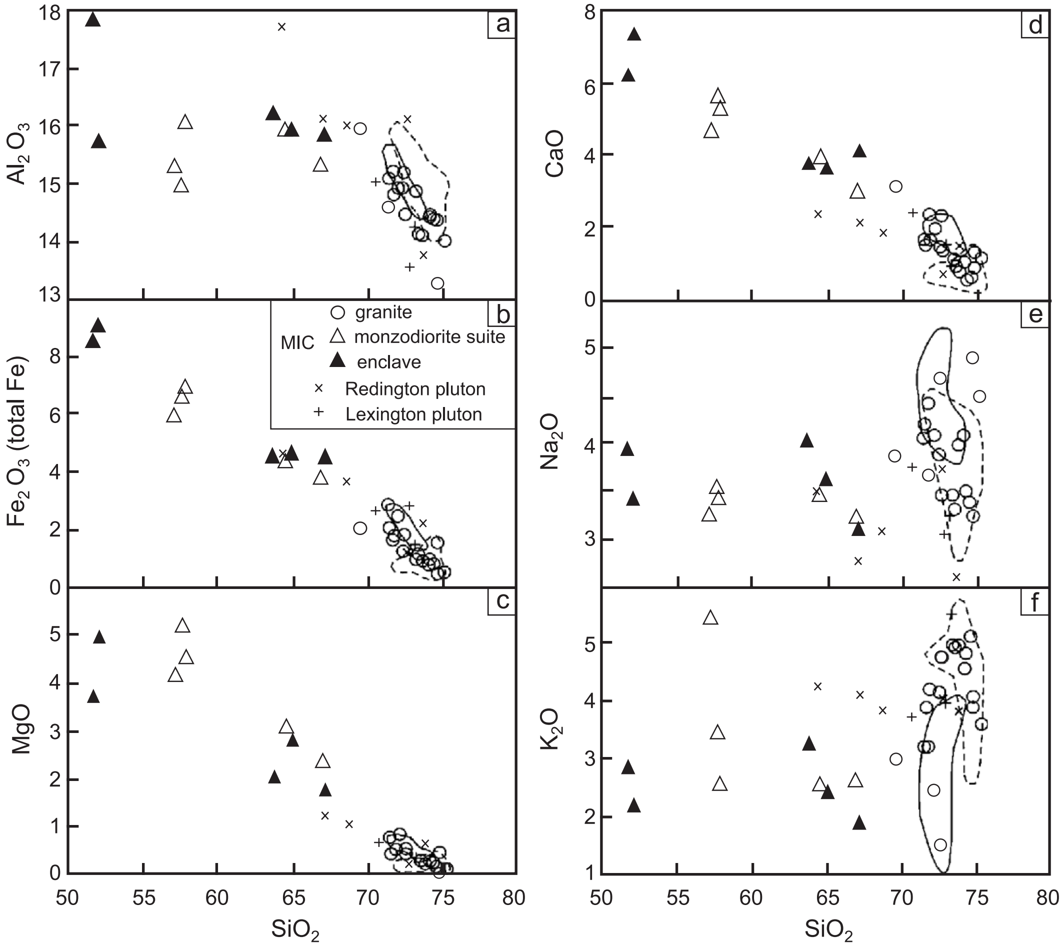

Fig. 3. SiO_2 versus major element variation diagrams: (a) Al_2O_3; (b) Fe_2O_3 (total Fe); (c) MgO; (d) CaO; (e) Na_2O; (f) K_2O (all in wt.%). Fields denote compositions of Phillips pluton granodiorites (solid line) and leucogranites (dashed line), after Pressley and Brown (1999).

The MIC granites have high SiO_2 concentrations (69–78 wt.%) and show internally coherent decreases in Al_2O_3, TiO_2, $Fe_2O_3^T$, MgO, CaO with increasing SiO_2, despite minimal spread (Fig. 3). The MIC granites show a substantial range in trace element content, particularly the trace alkaline earth Ba and the high field strength elements Y (Fig. 4), Nb and Zr. The MIC granites are depleted in transition metals such as Ni, Cr, V and Co, which reach moderate concentrations in the MIC monzodiorite suite. Although the majority of the MIC granites have Sm/Nd close to average upper crustal values, there is significant variability in the degree of fractionation ($^{147}Sm/^{144}Nd$=0.0905–0.1617; Table 2).

The Redington pluton samples have major element compositions distinct from the MIC granites, generally spanning the gap on Harker plots between the monzodioritic and granitic MIC samples (Fig. 3). They tend to have lower CaO and Na_2O contents and higher Al_2O_3 and $Fe_2O_3^T$ than rocks with comparable SiO_2. The samples are uniformly weakly evolved with respect to Rb/Sr and are enriched in Ba and compatible transition metals (V, Cr, Ni, Co) relative to MIC granites (Fig. 4).

The samples from each of the three lobes of the Lexington composite pluton have major and trace element concentrations that overlap the MIC granites, although with slightly lower Na_2O (Fig. 3). Together

Table 2
Nd isotope data for whole rocks and Pb isotope data for leached alkali feldspars

Pluton/ complex	Suite/rock type/location	Sample number	^{143}Nd/ ^{144}Nd^{a}	^{147}Sm/ ^{144}Nd	ε_{Nd} (at 370 Ma)	^{206}Pb/ ^{204}Pb^{b}	^{207}Pb/ ^{204}Pb^{b}	^{208}Pb/ ^{204}Pb^{b}
MIC	granite	96-60	0.512207(20)	0.1007	−3.9	18.265(1)	15.573(1)	37.932(2)
MIC	granite	96-91	0.512250(6)	0.1074	−3.4	18.273(2)	15.575(2)	37.921(5)
MIC	granite	96-100	0.512312(18)	0.1040	−2.0	18.269(2)	15.586(2)	37.962(6)
MIC	granite	replicate	–	–	–	18.263(2)	15.580(2)	37.937(5)
MIC	granite	96-210	0.512212(10)	0.1123	−4.3	18.395(1)	15.606(1)	38.085(2)
MIC	granite	J98-03	0.512286(31)	0.1086	−2.7	18.239(3)	15.548(2)	37.746(5)
MIC	granite	J98-04	0.512300(12)	0.1079	−2.4	18.222(2)	15.575(2)	37.917(5)
MIC	granite	J98-24	0.512141(10)	0.1392	−7.0	18.405(1)	15.621(1)	38.101(2)
MIC	granite	J98-32-1	0.512244(19)	0.1315	−4.6	18.293(1)	15.592(1)	38.014(2)
MIC	granite	replicate	–	–	–	18.289(1)	15.584(1)	37.999(3)
MIC	granite	J98-63-1	0.512192(23)	0.1315	−5.6	–	–	–
MIC	granite	J98-88	0.512378(17)	0.1530	−3.0	18.350(2)	15.606(2)	38.032(4)
MIC	granite	replicate	–	–	–	18.367(1)	15.626(1)	38.092(4)
MIC	granite	J98-92-2	0.512141(17)	0.1090	−5.6	18.242(3)	15.578(2)	37.927(6)
MIC	granite	J98-94	0.512405(40)	0.1129	−0.6	18.282(1)	15.568(1)	37.881(2)
MIC	granite	J98-99	0.512281(8)	0.1617	−5.3	–	–	–
MIC	granite	J98-108	0.512173(15)	0.1109	−5.0	18.278(1)	15.588(1)	38.016(3)
MIC	granite	J98-111-2	0.512258(20)	0.0905	−2.4	18.180(1)	15.550(1)	37.865(4)
MIC	granite	J98-114	0.512270(44)	0.1510	−5.0	18.360(1)	15.605(1)	38.011(2)
MIC	monzodiorites	96-222	0.512384(7)	0.1087	−0.7	18.281(1)	15.581(1)	37.907(3)
MIC	monzodiorites	J98-43	0.512325(7)	0.1136	−2.1	18.253(1)	15.572(1)	37.896(3)
MIC	monzodiorites	J98-100	0.512262(18)	0.1002	−2.7	18.296(1)	15.578(1)	37.958(2)
MIC	monzodiorites	J98-63-2	0.512345(12)	0.1149	−1.8	18.159(2)	15.562(1)	37.821(4)
MIC	monzodiorites	J98-40	0.512363(13)	0.1254	−1.9	18.175(1)	15.564(1)	37.845(2)
MIC	enclave	96-216	0.512329(24)	0.1273	−2.6	18.265(2)	15.576(2)	37.905(4)
MIC	enclave	J98-32-2	0.511910(15)	0.1082	−9.8	18.359(1)	15.603(1)	38.100(5)
MIC	enclave	J98-54	0.512271(14)	0.1032	−2.5	18.231(1)	15.584(1)	37.944(3)
MIC	enclave	J98-93	0.512412(10)	0.1015	0.3	18.267(3)	15.577(3)	37.920(7)
MIC	enclave	J98-111-3	0.512341(7)	0.1009	−1.0	–	–	–
Redington	granite	96-200	0.512134(17)	0.1093	−5.3	–	–	–
Redington	granite	96-203	0.512177(6)	0.1115	−4.6	18.161(1)	15.587(1)	38.024(3)
Redington	granite	96-250	0.512184(13)	0.1083	−4.3	18.150(1)	15.576(1)	37.989(3)
Redington	granite	98-8	0.512346(14)	0.1732	−4.5	18.162(6)	15.581(6)	38.008(13)
Redington	granite	96-246	0.512161(9)	0.1092	−4.8	18.159(1)	15.586(1)	38.015(2)
Lexington	north portion	98-1	0.512286(13)	0.1100	−2.8	18.066(1)	15.545(1)	37.925(2)
Lexington	central portion	98-10-1	0.512247(8)	0.1202	−4.0	18.201(1)	15.594(1)	38.051(2)
Lexington	central portion	96-296-2	0.512213(13)	0.1200	−4.7	18.185(1)	15.585(1)	38.042(2)
Lexington	central portion	98-10-2	0.512690(62)	0.1670	+2.4	–	–	–
Lexington	south portion	98-2	0.512225(16)	0.1321	−4.7	–	–	–
Sugarloaf	felsic pod	98-9	–	0.1994	–	–	–	–
Sugarloaf	gabbro	98-15	0.512709(15)	0.1941	+1.5	–	–	–
Phillips	leucogranite	PH-03	0.512224(12)^{c}	0.1695^{c}	−6.8^{c}	18.177(1)	15.583(1)	38.016(3)
Phillips	leucogranite	PH-04	0.512253(11)^{c}	0.1751^{c}	−6.5^{c}	18.194(1)	15.591(1)	38.029(2)
Phillips	leucogranite	PH-05	0.512222(10)^{c}	0.1789^{c}	−7.3^{c}	18.170(1)	15.567(1)	37.961(3)
Phillips	granodiorite	P-74a	0.512386(6)^{c}	0.1257^{c}	−1.6^{c}	18.213(2)	15.605(2)	38.050(4)
Phillips	granodiorite	PH-06	0.512431(9)^{c}	0.1242^{c}	−0.6^{c}	18.230(1)	15.609(1)	38.040(2)
Phillips	granodiorite	P-92	0.512333(6)^{c}	0.1104^{c}	−1.9^{c}	18.185(3)	15.562(2)	37.926(6)

MIC denotes the Mooselookmeguntic igneous complex.

–=not determined.

[a] Measured value, corrected for fractionation and blank; absolute 2σ within-run uncertainty on last digit(s) of individual analysis in parentheses.

[b] Same as a, but also corrected for blank.

[c] Data from Pressley and Brown (1999).

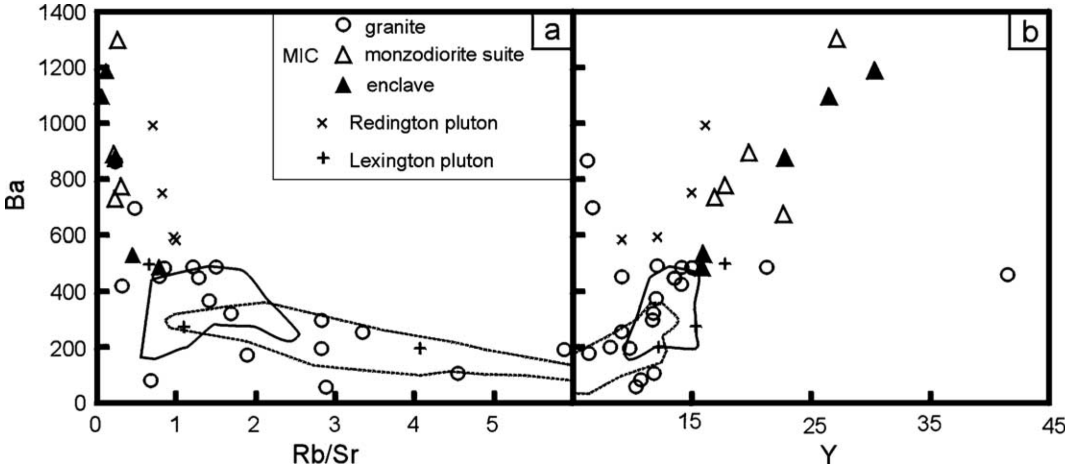

Fig. 4. (a) Rb/Sr versus Ba and (b) Y versus Ba variation diagrams (all concentrations in ppm). Fields denote compositions of Phillips pluton granodiorites (solid line) and leucogranites (dashed line), after Pressley and Brown (1999).

with the MIC granites, these are the only rocks studied that have Rb/Sr significantly greater than unity (Fig. 4).

4.2. Isotope data

Samples of the MIC monzodiorite suite ($\varepsilon_{\mathrm{Nd}}=-2.8$ to -0.7) and enclaves ($\varepsilon_{\mathrm{Nd}}=-2.8$ to 0.1, except for J98-32-2) span a similar, restricted range in initial Nd isotopic composition, whereas the granites are highly variable ($\varepsilon_{\mathrm{Nd}}=-7.0$ to -0.6) (Table 2). Enclave sample J98-32-2 contains the least radiogenic Nd ($\varepsilon_{\mathrm{Nd}}=-10.0$) of all of the samples analyzed. The Redington pluton samples have homogeneous initial Nd isotopic compositions, in the middle of the MIC granite range ($\varepsilon_{\mathrm{Nd}}=-5.3$ to -4.3). Samples from the felsic portions of the Lexington composite pluton have initial $\varepsilon_{\mathrm{Nd}}$ that overlap the MIC granite values (-5.0 to -2.8). The mafic sample from the central lobe of the Lexington pluton and the single Sugarloaf sample that was analyzed (a gabbro) yield $\varepsilon_{\mathrm{Nd}}$ values of +2.4 and +1.5, respectively.

Alkali feldspars from the MIC monzodiorite suite span a narrow Pb isotopic range, all within analytical uncertainty and overlapping the ratios of the enclaves, except sample J98-32-2, which has higher ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb (Fig. 5). Save for that one sample, the monzodiorite suite and enclaves have a mean ^{207}Pb/^{204}Pb of 15.574. The Pb isotopic compositions of the MIC granites span a large range that overlaps the data for the less evolved rocks and extends to higher ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb, and with a slightly higher mean ^{207}Pb/^{204}Pb of 15.583 (Fig. 5). The granite data occupy all three of the fields in ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb space from Ayuso and Bevier (1991), who distinguished northern, central and southern plutons. The MIC data show similar ^{206}Pb/^{204}Pb but slightly lower ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb, though still within uncertainty, to the Mooselookmeguntic granite feldspar reported by Ayuso and Bevier (1991).

The new Pb isotope data from the Phillips pluton are consistent with the three analyses from Pressley and Brown (1999): average compositions of granodiorites are slightly more radiogenic in uranogenic Pb than the leucogranites, although the samples overlap within uncertainty, with values equivalent to those of the MIC (Fig. 5). The Redington pluton initial Pb data are, like the whole-rock Nd initial isotopic compositions, tightly clustered, with a mean ^{207}Pb/^{204}Pb of 15.582, identical to the mean for the MIC granites (Fig. 5).

All samples from this study have initial Pb isotopic compositions that lie close to or below the two-stage growth curve of Stacey and Kramers (1975), advanced relative to their model ages. The rocks of this study all have ^{208}Pb/^{204}Pb typical of upper crustal

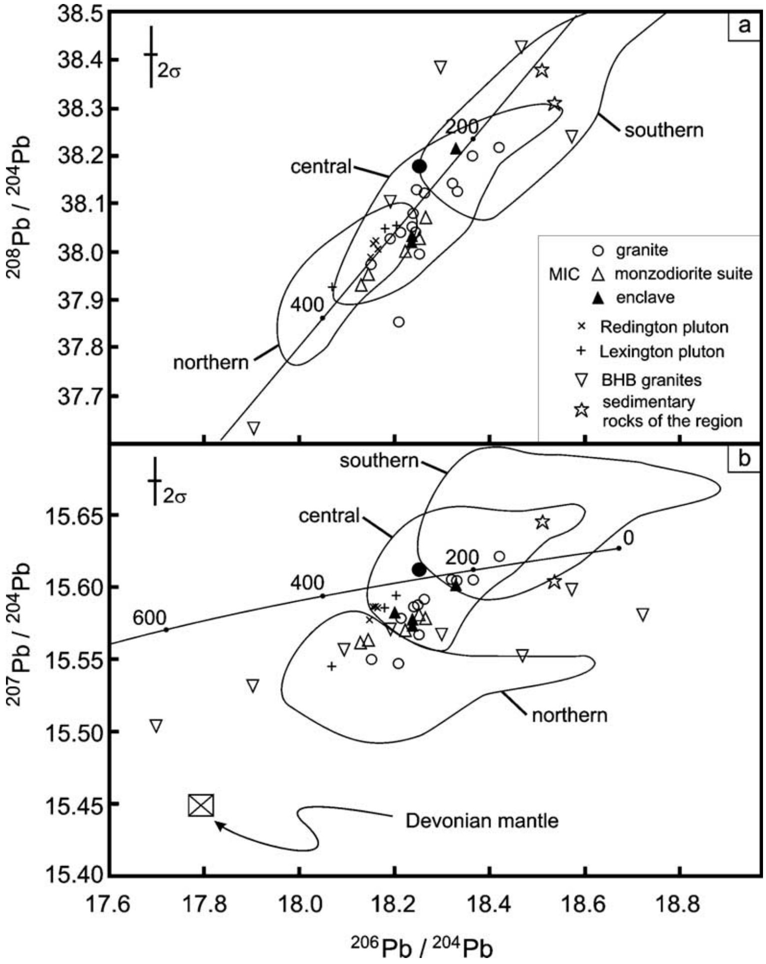

Fig. 5. Plots of Pb isotopic compositions of leached alkali feldspars from rocks of this study: (a) ^{206}Pb/^{204}Pb versus ^{208}Pb/^{204}Pb with the model two-stage curve of Stacey and Kramers (1975); (b) ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb with the Stacey and Kramers curve. Tics are all 200 Ma. Fields (northern, central, southern) from Ayuso and Bevier (1991) are based on geographic variability of Pb isotopes in the northern Appalachians. Bronson Hill belt granite data (inverted triangles) are from Moench and Aleinikoff (2002), on samples of pre-Devonian plutons. The filled circle is the Mooselookmeguntic granite feldspar datum from Ayuso and Bevier (1991). Age-corrected whole-rock data of Siluro-Devonian sedimentary rocks from Maine (star symbols) are from Krogstad (1993). The estimate of Devonian oceanic mantle is from Zartman and Doe (1981).

rocks with sources that have not experienced significant Th/U changes in their histories.

5. Discussion

5.1. Constraints on sources

Ayuso (1986) defined three distinct regions in Pb isotope space based on feldspar data from granites occupying different geographic areas in Maine (Fig. 5), interpreted to reflect influences of (primarily) Laurentian (with low ^{207}Pb/^{204}Pb at a given ^{206}Pb/^{204}Pb) and non-North American (Avalon-like or circum-Gondwanan, with high ^{207}Pb/^{204}Pb at a given ^{206}Pb/^{204}Pb) crustal sources. This approach has been fundamental to the use of Pb isotopes in probing the unexposed crust in Maine, but has limitations, particularly in assessing crust–mantle mixtures and in the specific identity of sources for samples with isotopic compositions that are neither clearly Laurentian nor clearly non-North American.

Traditionally, Nd and Pb data are viewed separately and give potentially complementary results based on differences in time-integrated parent/daughter ratios of source materials. Combining the two systems on one diagram (using $^{207}Pb/^{204}Pb$) permits more comprehensive assessment of possible sources of the plutonic rocks. Owing to the shorter half life of ^{235}U compared to ^{238}U, the most significant production of ^{207}Pb in the Earth took place in the Precambrian; since then the most significant changes in Pb isotopic compositions have been the steady increase in $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. As such, in areas where magmatic source components have significant time integrated differences in U/Pb, $^{207}Pb/^{204}Pb$ is a more powerful tracer of these components than $^{206}Pb/^{204}Pb$, which will vary considerably in mantle and crustal materials in response to small changes in U/Pb—changes that may be unrelated to the nature of source materials.

Of the known, potential, or anticipated sources of the magmas parental to plutons of this study, we discriminate mantle of two isotopically distinct types, three basement terranes, and a broad mid-crustal source that takes into account metasedimentary rocks that overlie the basement framework. These can be distinguished to varying extents based on their respective elemental and isotopic characteristics. We summarize the general distinguishing features of these components below.

Material source components from the mantle that have been called into prominence in the petrogenesis of other plutonic complexes in the northern Appalachians range from chemically homogeneous convecting upper mantle reflected in modern mid-ocean ridge basalts (MORB; e.g., Waight et al., 2001; Coish and Rogers, 1987) to subduction-modified lithospheric mantle (e.g., Arth and Ayuso, 1997; Whalen et al., 1996). Sources within the latter reservoir are characterized by specific trace element enrichment (large-ion lithophile elements) and depletion (high field strength elements), and by long-term decrease in Sm/Nd, yielding initial ε_{Nd} lower than the MORB range (<+8 to +10, present-day). The Pb isotopic composition of Paleozoic MORB has been estimated (Zartman and Doe, 1981), although this does not take into account the significant variability expected from analogy with modern MORB (e.g., White, 1993). An estimate of the variability of lithospheric mantle Pb was made by Pegram (1990), through analysis of Mesozoic tholeiites in eastern North America. The Mesozoic tholeiites show considerable, positively correlated variability in initial ε_{Nd} and $^{207}Pb/^{204}Pb$, with samples from in and near New England having the highest ratios for both systems, with average ε_{Nd} (at 370 Ma) c. +1.2 and average $^{207}Pb/^{204}Pb$ (corrected to 370 Ma) c. 15.63. The Nd initial isotopic compositions are consistent with data from mafic rocks in the Mount Ascutney complex in eastern Vermont (Foland et al., 1988).

The isotopic compositions of both Nd and Pb in Laurentian crustal materials are now well-established from studies in Maine (Ayuso et al., 1988) and in 'classic' Laurentian crustal massifs, such as at the Grenville front and Adirondacks (Fletcher and Farquhar, 1977; Daly and McLelland, 1991; McLelland et al., 1993; DeWolf and Mezger, 1994). In these rocks, ε_{Nd} (at 370 Ma) ranges from -10 to -4 and $^{207}Pb/^{204}Pb$ is characteristically <15.60, with the majority <15.56.

Continental crustal fragments accreted to North America throughout Paleozoic closure of Iapetus are thought to have circum-Gondwanan origins (Williams and Hatcher, 1983). Although it is not clear whether multiple accreted crustal basement terranes with slightly different initial isotopic characteristics can be defined (Whalen et al., 1996; Tomascak et al., 1999), the general nature of these terranes is well constrained, primarily from basement exposures in Atlantic Canada, but also from granitic plutons in the coastal region throughout the northern Appalachians. These non-North American ("Avalon-like") sources are characterized by high (juvenile) ε_{Nd} (at 370 Ma) (>−4) and radiogenic $^{207}Pb/^{204}Pb$ (>15.6) (Ayuso and Bevier, 1991; Barr and Hegner, 1992; Whalen et al., 1994; Kerr et al., 1995; Samson et al., 2000; Fig 6).

Studies of Bronson Hill belt (BHB) rocks in which both Nd and Pb isotopes were analyzed are lacking. Whalen et al. (1998) reported initial Nd and Pb isotope data for arc-related Mid- to Late Ordovician volcanic and plutonic rocks in the Miramichi belt in western New Brunswick. The granites in this part of the Taconic orogen (the age of which is perhaps as much as 15 Ma older than Taconic orogenesis in New Hampshire and Maine), have $^{207}Pb/^{204}Pb$ in the range

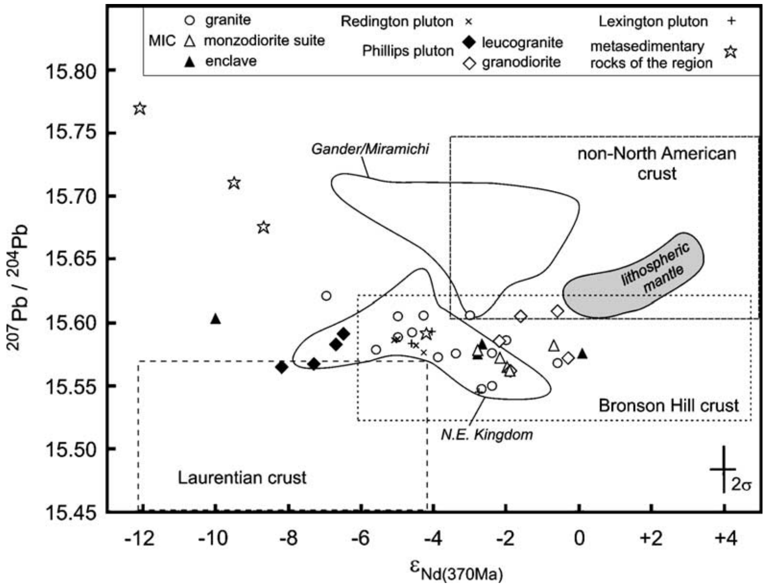

Fig. 6. Plot of whole-rock ε_{Nd} (at 370 Ma) versus initial $^{207}Pb/^{204}Pb$. Metasedimentary supracrustal rocks of the CMB (star symbols) are from Ayuso and Schulz (2003) and Arth and Ayuso (1997). White fields with italic labels define ranges of paired Nd, Pb data for granites in the northern Appalachians (Silurian to Devonian Gander zone and Ordovician Miramichi highlands plutons from New Brunswick: Whalen et al., 1996, 1998; Northeast Kingdom batholith, Vermont, granites: Arth and Ayuso, 1997). Shaded field represents compositions of mid-Atlantic tholeiites from the central and northern Appalachians (Pegram, 1990), an estimate of the lithospheric mantle at 370 Ma. Dashed rectangular fields show estimated ranges for basement terranes based on literature data from unpaired Nd, Pb samples (see text).

15.67 to 15.71, and ε_{Nd} (470 Ma) of -5.4 to $+0.2$. The coincidence of Nd and Pb isotope data from these rocks and Silurian to Devonian plutons in the same region (Whalen et al., 1994) suggests that the Pb in Ordovician granites may in large part not reflect arc basement sources, but rather significant contributions from lower- to mid-crustal metasedimentary rocks with strongly non-North American Pb.

Samson and Tremblay (1996) reported ε_{Nd} (at 450 Ma) in the range -5 to $+5$ for Ordovician volcanic rocks from Québec correlative with the BHB in Maine. Hingston (1992) presented Nd isotope data from mafic to felsic metavolcanic rocks in New Hampshire of estimated Ordovician age. These Nd data combined with initial Pb isotope data from 435 to 469 Ma granite plutons that intrude the BHB in New Hampshire (Moench and Aleinikoff, 2002), allow an estimate to be made for the nature of BHB crust. The Pb in these granites has low $^{207}Pb/^{204}Pb$ (<15.58). It should be stressed that the estimate of BHB isotopic composition used herein is based on data not from the same or even spatially equivalent samples. Furthermore, the data chosen from Moench and Aleinikoff (2002) show a large range in $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (although not $^{207}Pb/^{204}Pb$). Considering that these are single samples from large plutonic bodies, caution must be applied in their absolute interpretation, as they may not be uncompromised representatives of BHB sources.

Ordovician to Devonian metasedimentary rocks in the northern Appalachians have not been extensively studied with Pb isotopes, although there is a growing body of Nd isotope data. In general these rocks, which crop out in the CMB and BHB in the region between central Maine and eastern Vermont, show relatively unradiogenic initial Nd isotopic compositions, the majority are in the range ε_{Nd} (at 370 Ma) -12 to -4 (Ayuso and Schulz, 2003; Arth and Ayuso, 1997; Cullers et al., 1997; Pressley and Brown, 1999; Lathrop et al., 1996; Foland et al., 1988), which completely overlaps the Nd range for Laurentian crust at this time. Hence, Nd isotopes alone are not an effective discriminator between these two potential sources.

The small number of extant Pb isotope data for these kinds of metasedimentary rocks show an inverse correlation with Nd initial ratios, with low values of $^{207}Pb/^{204}Pb$ being present in samples with the highest ε_{Nd}. The Pb isotopic compositions have to be viewed carefully, because they were obtained from whole rocks and are calculated initial compositions which integrate measured U/Pb assumed to be applicable to these rocks. If the sources of the original sediments contained Laurentian (low ε_{Nd}, low $^{207}Pb/^{204}Pb$) and non-North American components (high ε_{Nd}, high $^{207}Pb/^{204}Pb$), a positive correlation would be expected in Pb–Nd space; however, the opposite is apparent based on the few literature data available for which both isotope systems were measured. This intriguing feature cannot be examined further without a greater abundance of Pb isotope data for samples where Nd isotopes have been determined.

5.1.1. Sources of the MIC monzodiorite suite and enclaves

Samples from the MIC monzodiorite suite have a combination of radiogenic initial Nd and unradiogenic initial Pb (low $^{207}Pb/^{204}Pb$), but both are homogeneous, especially compared to the scale of major element variation in these rocks (Fig. 6). Comparing the Nd–Pb relations of the MIC monzodiorite suite to lithospherically derived tholeiites from elsewhere in New England allows a comparison with a plausible enriched mantle source. Samples from the MIC monzodiorite suite consistently have both lower $^{207}Pb/^{204}Pb$ and lower ε_{Nd} than the tholeiites of Pegram (1990). The monzodiorite samples have significantly less radiogenic initial Nd and more radiogenic initial Pb than the Devonian MORB mantle. The absence of mafic rocks in the area with characteristic high ε_{Nd} (>+8) also does not support a depleted mantle source component for these magmas.

Samples from the MIC monzodiorite suite have fractionated Sm/Nd relative to normal mantle rocks and high Nd concentrations, resembling ordinary upper crustal rocks in this regard. However, this is not unusual among orogenic diorites (e.g., van de Flierdt et al., 2003; McCulloch and Woodhead, 1993; Liew et al., 1989), where source rocks have significant lower crustal components. Samples from the MIC monzodiorite suite have compatible element concentrations (V, Cr, Ni, Co) equivalent to diorites of similar SiO_2 content interpreted to have been generated exclusively by lower crustal melting (van de Flierdt et al., 2003), suggesting that a mantle component is not necessary in their petrogenesis. The estimated composition of BHB crust overlaps the Nd–Pb initial ratios of the MIC monzodiorite suite. Laurentian crust of mafic composition (e.g., Shaw and Wasserburg, 1984) is plausible as a basement source for the monzodiorite suite as well, but the scarcity of paired Nd–Pb data from them make it unfeasible to test this alternative.

Given the isotopic and elemental data, two models for the petrogenesis of the monzodiorite suite appear most probable: assimilation of Laurentian crustal material by melts derived from the enriched lithospheric mantle, or derivation from arc crust of the BHB. The isotopic compositions of the monzodiorite suite can be reproduced using either two component mixing calculations or assimilation-fractional crystallization (Fig. 7; details in Appendix C). However, the elemental contents of these rocks, in particular the compatible elements, are not consistent with significant input of mantle material. Additionally, although ε_{Nd} and SiO_2 are weakly anticorrelated (Fig. 8), as would be expected with a mantle-Laurentian crust mixture, the absence of trends between compatible element contents and Nd isotopes in samples of the MIC monzodiorite suite makes a mantle-mixing scenario less likely than derivation from a single source in the lower crust, specifically BHB crust. It is likely that mantle heat was required to produce large-scale melting of the mafic to intermediate, metaigneous lower crust, even if compelling evidence for mantle material involvement is lacking.

With the exception of sample J98-32-2, the MIC enclaves display isotopic and elemental characteristics indistinguishable from the monzodiorite suite, suggesting the groups may be related by a single petrogenetic process. The geochronology of neither the monzodiorite suite nor the enclaves has been investigated in detail. However, the apparent potential c. 12 Ma age difference between these two groups of rocks is consistent with variations in age populations seen in microgranitoid enclaves in of other granitic suites (e.g., Elburg, 1996). Compositions of the enclaves do not argue for significant interaction with their host granite, which is reasonable considering their age difference (c. 20 Ma) and likely thermal

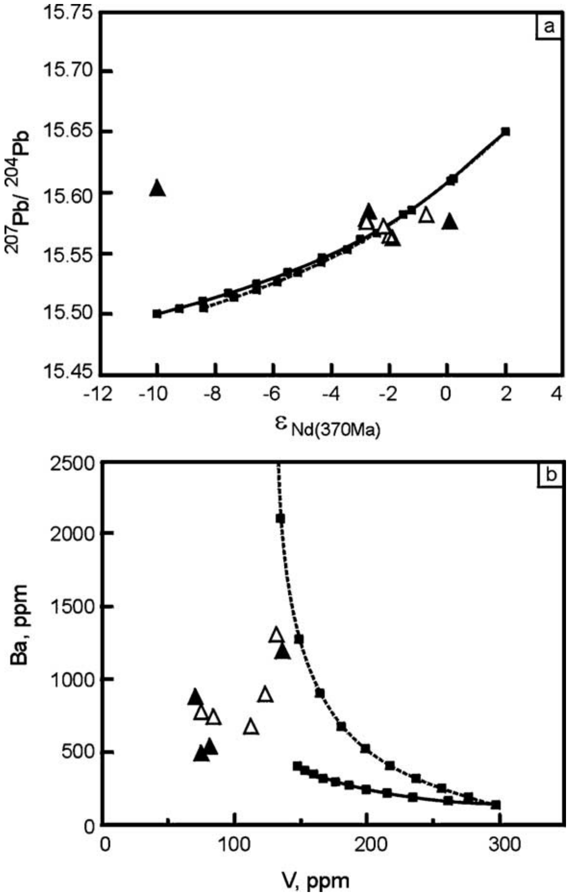

Fig. 7. Compositions of MIC monzodiorite suite and enclave samples: (a) whole-rock ε_{Nd} (at 370 Ma) versus initial $^{207}Pb/^{204}Pb$; (b) V versus Ba (ppm). Symbols as in Fig. 6. Also plotted are calculated two-component mixing (solid line; Langmuir et al., 1978) and assimilation-fractional crystallization (dashed line; DePaolo, 1988) curves, with 10% increments. In the mixing calculations (for details see Appendix C) enriched mantle is mixed with or assimilates felsic crust of Laurentian origin. Although the isotopic compositions of the MIC monzodiorite suite are generally consistent with derivation from a mantle-crust mixture, the compatible element signatures of these rocks are far lower than predicted using any plausible end members.

difference between the enclaves and their host magma. The enclave sample with much less radiogenic Nd (J98-32-2; $\varepsilon_{Nd}=-10.0$) most plausibly assimilated material with isotopic characteristics similar to CMB metasedimentary rocks.

5.1.2. Sources of the MIC granites

The MIC granites form an array in Pb–Nd space, such that samples with lower initial ε_{Nd} have slightly less radiogenic $^{207}Pb/^{204}Pb$ (Fig. 6). Despite coherent major and trace element trends in the MIC granite data, the significant variation in initial isotopic compositions of Nd without a strong deviation in Pb does not allow the granites to be derived from a single homogeneous source. The isotopic variation of these samples could be produced by magma of more mafic composition mixing with or assimilating evolved crust, or by melting of a heterogeneous package of crustal material.

If the spread in initial ε_{Nd} in the MIC granites was due to an assimilation process between a mantle/mafic lower crust component and a more siliceous mid-crustal (metasedimentary) component, the data should describe trends in ε_{Nd} versus SiO_2 (or other indicative major element) space, which are not evident (Fig. 8). Furthermore, the best estimate of an incompatible element enriched mantle component is unlike the high-ε_{Nd} end member of the granites.

The spread in initial ε_{Nd} could be produced by mixing compositionally similar yet isotopically distinct components. Evolved Laurentian crustal rocks have significantly lower ε_{Nd} than the MIC granites that have the most Laurentian-like Pb (i.e., lowest $^{207}Pb/^{204}Pb$). Our estimate of the Nd–Pb characteristics of BHB crust provides a possible lower-$^{207}Pb/^{204}Pb$ source component for the MIC granites, but does not appear to satisfy the lower initial ε_{Nd} of some samples.

Elemental and isotopic parameters of magma compositions can be approximated by an assimilation-fractional crystallization model wherein melts of BHB crust assimilate CMB metasedimentary material and undergo variable extents of crystallization (Fig. 9). Nevertheless, the data for certain elements (notably Ba and Nd; Fig. 9c,d) are sufficiently dispersed that they require either source heterogeneity or non-ideal behavior in the melt extraction process (e.g., retained residual K-feldspar and monazite).

These data do not rule out derivation of magmas from heterogeneous mid-crustal sources. The initial Nd and Pb isotopic compositions of the MIC granites form an array that is subparallel to that for metasedimentary rocks from the CMB in Maine and the Connecticut Valley belt in Vermont (Ayuso and Schulz, 2003; Arth and Ayuso, 1997) (Fig. 6). The granite data extend to lower $^{207}Pb/^{204}Pb$ and higher ε_{Nd} than the metasedimentary rock data. This could

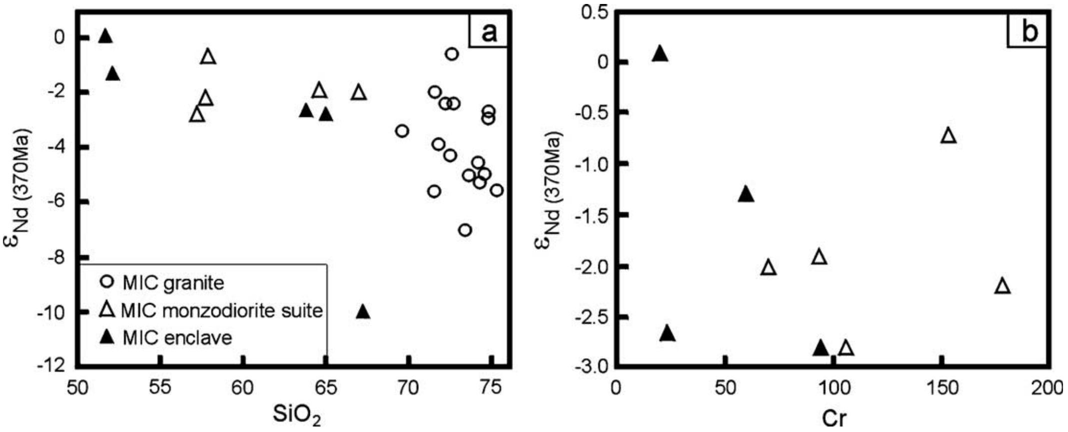

Fig. 8. (a) SiO_2 (wt.%) versus ε_{Nd} (at 370 Ma) for MIC samples. (b) Cr (ppm) versus $\varepsilon_{Nd(370\ Ma)}$ for MIC monzodiorite suite and enclave data. Lack of correlations among the samples of either the granite or monzodiorite suites argue against significant mixing between mafic and felsic components.

be a shortcoming of an inadequate data set for these potential source rocks. Indeed, variation in Nd and Pb isotopes with stratigraphic age has been observed in Appalachian sedimentary rocks and metamorphic equivalents, indicating higher ε_{Nd} and lower $^{207}Pb/^{204}Pb$ in the oldest rocks (Bock et al., 1996; Krogstad, 1993).

The low-$^{207}Pb/^{204}Pb$ MIC granite data overlap the MIC monzodiorite suite in Nd–Pb space. Although the geochronologic data suggest a >4 Ma gap in the timing of crystallization of these two groups of rocks, it is possible that their emplacement occurred as part of a continuous process that might be adequately defined only by a much larger number of age determinations. As discussed above, it would also be fortuitous to develop the minimal trends of the granite elemental compositions from a mixture of a more evolved crustal component and something equivalent to the MIC monzodiorite suite. Although no petrogenetic link between these two groups is apparent, it is worthwhile considering a thermal link.

The Nd–Pb isotope trend of the MIC granites overlaps that of the Northeast Kingdom batholith in Vermont (Arth and Ayuso, 1997; Fig. 6), a suite of Devonian plutons that intrude west across strike, within the Connecticut Valley belt, where the underlying crust is Laurentian. Arth and Ayuso interpreted the Northeast Kingdom batholith to have been derived substantively from igneous lower crust, consistent with our interpretation for the monzodiorite suite of the MIC. However, primitive segments of the Northeast Kingdom batholith have been interpreted as possessing mantle source components (Ayuso and Arth, 1992; Arth and Ayuso, 1997). Although a mantle source is not explicitly ruled out in our analysis of the MIC data, we favor the simpler interpretation, that BHB crust forms the low-$^{207}Pb/^{204}Pb$, high-ε_{Nd} source component to these magmas and that most of the Pb and Nd isotopic heterogeneity has been introduced through additions of metasedimentary material prior to final emplacement.

5.1.3. Sources of the other western Maine granitic rocks

The additional Pb isotope data from the Phillips pluton allow reinterpretation of the source for these rocks (Fig. 6). The interpretation that the leucogranites derive from melting of isotopically heterogeneous CMB metasedimentary rocks (Pressley and Brown, 1999) remains acceptable, given the limits on our understanding of Pb in these rocks.

The Phillips pluton granodiorites were interpreted to come from melting of Avalon-like crustal basement by Pressley and Brown (1999). Whereas these sources are consistent with ε_{Nd} of −2.0 to 0, the mean $^{207}Pb/^{204}Pb$ of 15.59 is not simply accounted for by such an end member. The data are more consistent with the granodiorites originating from a BHB source, which requires a modification of the crustal assembly

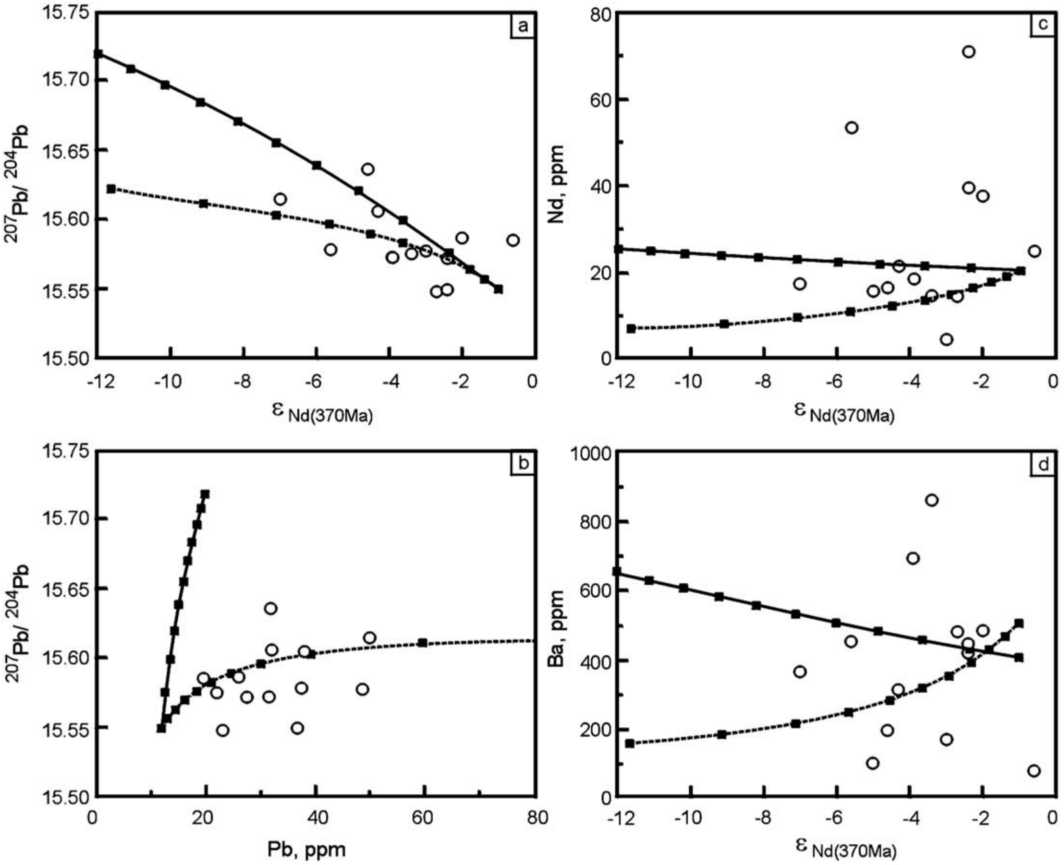

Fig. 9. Compositions of MIC granite samples: (a) whole-rock $\varepsilon_{\mathrm{Nd}}$ (at 370 Ma) versus initial ^{207}Pb/^{204}Pb; (b) Pb (ppm) versus initial ^{207}Pb/^{204}Pb; (c) $\varepsilon_{\mathrm{Nd}}$ (at 370 Ma) versus Nd (ppm); (d) $\varepsilon_{\mathrm{Nd(370\ Ma)}}$ versus Ba (ppm). Also plotted are calculated two-component mixing (solid line; Langmuir et al., 1978) and assimilation-fractional crystallization (dashed line; DePaolo, 1988) curves, with 10% increments. In the mixing calculations (for details see Appendix B) Bronson Hill belt crust partial melts are mixed with or assimilate Central Maine belt metasedimentary rock. The isotopic data permit either mechanism to have produced the samples, at moderate degrees of crystallization or mixing. The dispersion of Ba and Nd elemental data may reflect mineralogical heterogeneity of source materials or crustal assimilant, or entrained residual K-feldspar and monazite.

at depth as shown in interpretive cross-sections (Fig. 2). Viewed as a whole, we interpret the MIC and Phillips pluton data to require the extension of BHB crust farther into central Maine than previously interpreted. This suggests that examination of granites between the Phillips and Sebago plutons should delineate the transition between BHB and non-North American crust at depth.

The source of the Redington pluton was apparently more thoroughly homogenized than that of the MIC granites, or alternatively the magmas that make up the Redington pluton were homogenized after melt generation and possibly during emplacement (Fig. 6). The Nd–Pb relations of Redington pluton samples are satisfied either by derivation from the estimated BHB crust, Laurentian basement, or CMB metasedimentary rocks. Plutons interpreted to have a significant CMB-supracrustal source tend to show significant initial Nd isotope heterogeneity (e.g., Sebago pluton group 2 granites, Tomascak et al., 1996; Phillips pluton leucogranites, Pressley and Brown, 1999), and thus such sources are not favored for the Redington pluton. Although ^{207}Pb/^{204}Pb of the Redington pluton samples are high relative to most Laurentian samples, they are within the range, and hence potentially derived from this crustal source.

The significant differences in major and trace element composition between MIC granites and the Redington samples suggests a fundamental difference in the nature of the sources, although they share isotopic character.

Without paired Nd and Pb isotope data from the Lexington and Sugarloaf plutons detailed interpretation of their sources is precluded. Textures suggestive of magma mingling in the Sugarloaf pluton and the central lobe of the Lexington plutonic complex suggest petrogenetic processes that may be different from those for the other plutons of this study. Nevertheless, the positive $\varepsilon_{\mathrm{Nd}}$ values of the mafic portions of these mingled zones do not require mantle components, considering the nature of BHB crust. More detailed study of these rocks, as well as the Flagstaff Lake intrusive complex (Fig. 2), is an important next step toward investigating the potential for material input from mantle sources in this area during the Devonian.

The volume of melt generated to form the plutonic complexes in this study, the sources of which are interpreted to have been dominantly lower crustal metaigneous rocks, requires significant thermal input that is best satisfied by advection of thermal energy during lithospheric thinning and upwelling of the convecting asthenospheric mantle. Although material and thermal input from the mantle are commonly assumed to go hand in hand, certain areas of exposed lower crust bearing mantle intrusions show evidence for an absence of appreciable material contributions to melting overlying crust by these melts (e.g., Barboza et al., 1999).

6. Summary

Data presented for the Mooselookmeguntic igneous complex (MIC) in western Maine support the following inferences about melting in the crust in this area between c. 389 and 370 Ma. Earliest magmas, represented by the monzodiorite suite and enclaves in the MIC, were generated by melting Bronson Hill belt (BHB) crust of mafic to intermediate composition. The compositions are most consistent with derivation of these magmas from a single crustal source rather than a mixture of mantle and crust. Heterogeneity in initial Nd and Pb isotopic compositions of the MIC granites are most plausibly attributable to either melting of rocks in the Central Maine belt stratigraphic package or through assimilation of this material by magmas from intermediate to felsic BHB crust. The absence of isotope-element correlations indicates that metasedimentary-mafic lower crust (or crust–mantle) mixtures are not tenable.

Data from granites emplaced 10–15 Ma before the MIC also yield new insight on crustal architecture. New data for the Phillips pluton are consistent with derivation of the leucogranites from CMB sources whereas the granodiorites are best considered to have originated in BHB crust. The geochemistry of the Redington pluton suggests sources in either BHB crust or Laurentian crust. Collectively, we interpret the data to indicate that BHB crust extended southeastward to significant distance beyond the exposed limit of BHB exposure and that, at least in this part of the orogen, direct material contributions from mantle sources were not important (see Fig. 2, structure section).

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2004.04.059.

Appendix B

U and Pb isotope data for zircon samples from this study

Sample number	Sample weight (mg)	Pb (ppm)	U (ppm)	Pb_{com} (pg)	^{206}Pb/^{204}Pb[a]	^{206}Pb/^{238}U[b]	^{207}Pb/^{235}U[b]	^{207}Pb/^{206}Pb[b]	^{206}Pb/^{238}U age (Ma)	^{207}Pb/^{235}U age (Ma)	^{207}Pb/^{206}Pb age (Ma)
J98-40	0.015	14.82	235.8	2.1	6200	0.05919 (14)	0.4418 (16)	0.05413 (14)	371	372	377
J98-40	0.029	14.14	227.1	2.4	10,060	0.05811 (16)	0.4338 (14)	0.05414 (8)	364	366	378
J98-100	0.028	11.49	150.8	2.6	6351	0.06077 (16)	0.4536 (15)	0.05414 (12)	380	380	377
J98-100	0.018	43.47	583.8	1.0	37,470	0.06009 (14)	0.4485 (10)	0.05413 (4)	376	376	377
98-8	0.003	48.66	810.1	0.8	10,480	0.06446 (16)	0.4870 (14)	0.05479 (10)	403	403	404
98-8	0.002	120.4	2028	1.5	11,090	0.06418 (14)	0.4855 (12)	0.05486 (10)	401	402	407
98-1	0.004	21.65	353.8	2.0	2514	0.05782 (18)	0.4285 (30)	0.05375 (36)	362	362	361
98-1	0.006	47.49	786.7	1.2	14,260	0.05852 (14)	0.4346 (12)	0.05385 (8)	367	366	365
98-2	0.013	85.08	1446	2.7	26,960	0.06395 (16)	0.4832 (12)	0.05480 (6)	400	400	404
98-2	0.002	79.40	1247	5.1	2125	0.06401 (28)	0.4831 (26)	0.05474 (18)	400	400	402

Analyses of 1–21 clear, colorless to pale brown, prismatic to needle-like grains for each sample. Blanks: Pb=2 pg; U=0.2 pg.

[a] Measured value, uncorrected.

[b] Corrected for spike contribution, instrumental mass fractionation, blank and estimated initial Pb content; absolute 2σ within-run uncertainty on last digit(s) of individual analysis in parentheses.

Appendix C. Details of calculations

The fractional crystallization model for the MIC monzodiorite suite and enclaves assumes a residual mineralogy of 60% plagioclase, 30% clinopyroxene, and 10% amphibole, and uses a mass ratio of assimilated to fractionated material (r) of 0.5. The starting material is enriched lithospheric mantle with V=300 ppm, Ba=140 ppm, Nd=8 ppm, and Pb=6 ppm. These parameters are estimated from the Mesozoic tholeiite data of Pegram (1990) and from the compilations of McDonough and Sun (1995) and Sun and McDonough (1989). This starting magma assimilates Laurentian crust with V=150 ppm, Ba=400 ppm, Nd=11 ppm, and Pb=20 ppm. This composition is estimated from lower crustal averages of Shaw et al. (1986) and Rudnick and Fountain (1995). Isotopic characteristics of the end members are discussed in the text.

The fractional crystallization model for MIC granites assumes a residual mineralogy of 45% plagioclase, 25% amphibole, 15% K-feldspar, 15% biotite, and 0.1% monazite, and uses r=0.2. The composition of the starting material, average Bronson Hill belt crust, has Ba=500 ppm, Nd=20 ppm, and Pb=12 ppm. These parameters are estimated from data in Leo (1985), Hingston (1992), and Kim and Jacobi (1996). This starting magma assimilates Central Maine belt crust, with Ba=660 ppm, Nd=25 ppm, and Pb=20 ppm. Compositional features are consistent with data from western Maine Siluro-Devonian metasedimentary rocks (Solar and Brown, 2001b). Isotopic characteristics of the end members are discussed in the text.

Mineral distribution coefficients for the calculations come from a variety of sources in order to attempt to best match the estimated magma compositions. These sources include Bacon and Druitt (1988), Bea et al. (1994), Brenan et al. (1995), Ewart and Griffin (1994), Luhr and Carmichael (1980), Mahood and Hildreth (1983), Nash and Crecraft (1985), and Sisson (1994). Bulk distribution coefficients calculated from these references, using the assemblages above, were V=1.1; Nd=0.46 (using basalt/andesite coefficients), 1.6 (using rhyolite coefficients); Ba=0.26 (mafic), 1.7 (felsic); Pb=0.61 (mafic), 0.40 (felsic).

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