Geological Society of America
Memoir 197
2004

Oxygen-isotope constraints on terrane boundaries and origin of 1.18–1.13 Ga granitoids in the southern Grenville Province

William H. Peck*
Department of Geology, Colgate University, Hamilton, New York 13346, USA
John W. Valley
Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA
Louise Corriveau
Natural Resources Canada, Geological Survey of Canada, GSC-Québec, 880 Chemin Ste-Foy, Room 840, Québec City, Québec G1S 2L2, Canada
Anthony Davidson
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A OE8, Canada
James McLelland
Department of Geology, Colgate University, Hamilton, New York 13346, USA
David A. Farber
Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA

ABSTRACT

Granitic rocks related to 1.18 to 1.13 Ga anorthosite-mangerite-charnockite-granite plutonism stitch three terranes in the southwestern Grenville Province (Adirondack Highlands–Morin terrane, Frontenac terrane, Elzevir terrane). Because of the refractory nature of zircon (Zrn), analysis of oxygen-isotope ratios of dated igneous zircon from these rocks allows calculation of δ^{18}O values of original magmas even if the rocks were subjected to late magmatic assimilation, postmagmatic alteration, or metamorphism. Documented variability in δ^{18}O(Zrn) for these granitic rocks corresponds to their geographic location. Seven plutons from the central Frontenac terrane (Ontario) have a high average δ^{18}O(Zrn) = 11.8 ± 1.0‰, which corresponds to δ^{18}O magma values of 12.4–14.3‰. In contrast, twenty-seven other plutons and dikes of this suite (New York, Ontario, and Québec) average δ^{18}O(Zrn) = 8.2 ± 0.6‰, with a typical igneous range of 8.6 to 10.3‰ for δ^{18}O magma values. High δ^{18}O values in the Frontenac terrane are some of the highest magmatic oxygen-isotope ratios recognized worldwide, but these plutons are not unusual with respect to whole-rock chemistry or radiogenic isotope compositions. Such high δ^{18}O values can result from mixing between paragneiss (δ^{18}O ≈ 15‰) and hydrothermally altered basalts and/or oceanic sediments (δ^{18}O ≈ 12‰) in the source region. We propose that high-δ^{18}O, hydrothermally altered basalts and sediments were subducted or underthrust to the base of the Frontenac terrane during closure of an ocean basin between the Frontenac terrane and the Adirondack Highlands at or prior to 1.2 Ga.

Keywords: anorthosite suite, Grenville Province, oxygen isotopes, zircon

*E-mail: wpeck@mail.colgate.edu.

Peck, W.H., Valley, J.W., Corriveau, L., Davidson, A., McLelland, J., and Farber, D.A., 2004, Oxygen-isotope constraints on terrane boundaries and origin of 1.18–1.13 Ga granitoids in the southern Grenville Province, *in* Tollo, R.P., Corriveau, L., McLelland, J., and Bartholomew, M.J., eds., Proterozoic tectonic evolution of the Grenville orogen in North America: Boulder, Colorado, Geological Society of America Memoir 197, p. 163–182.

INTRODUCTION

In the southwestern Grenville Province different criteria that have been used to identify crustal scale subdivisions include structural style (e.g., Davidson, 1984), ages of igneous suites (e.g., Easton, 1986; Corriveau, 1990; Friedman and Martignole, 1995; McLelland et al., 1996; Corriveau and van Breemen, 2000), age of peak metamorphism (e.g., Mezger et al., 1992, 1993; McLelland et al., 1993), peak metamorphic conditions (e.g., Bohlen et al., 1985; Anovitz and Essene, 1990; Valley et al., 1990; Streepey et al., 1997), and cooling rates (e.g., Mezger et al., 1991; Cosca et al., 1992; Martignole and Reynolds, 1997). Integrated geological and geophysical studies derived from the Lithoprobe project (Carr et al., 2000; Corriveau and Morin, 2000; Martignole et al., 2000) and detailed studies across individual shear zones (e.g., Mezger et al., 1992; van der Pluijm et al., 1994; Busch et al., 1997; Cureton, et al., 1997) also constrain histories of the assembly and cooling of midcrustal blocks.

We use oxygen-isotope compositions of zircons from 1.18 to 1.13 Ga granitic plutons to investigate terrane boundaries in the Allochthonous Monocyclic Belt of the southwestern Grenville Province (Rivers et al., 1989; Fig. 1). Such "mapping" of the lower crust is achieved by isotopic analysis of whole rocks from Phanerozoic plutons (e.g., Solomon and Taylor, 1989), but analysis of zircon is necessary for igneous oxygen-isotope ratios to be determined precisely and accurately in high-grade (commonly polymetamorphic) rocks. Weakly (or para-) magnetic, nonmetamict igneous zircons are systematically recoverable from granitic plutons, and preserve primary igneous oxygen-isotope ratios through conditions ranging from hydrothermal alteration to high-grade metamorphism (e.g., Valley et al., 1994; Gilliam and Valley, 1997; King et al., 1997; 1998; Peck and Valley, 1998; Peck et al., 1999; see Valley, 2003). Their refractory nature allows zircon to "see past" common postmagmatic oxygen-isotope exchanges that affect whole-rock and mineral oxygen-isotope ratios in many orogenic belts. The plutons studied intruded within a similar time span into three major subdivisions of the Allochthonous Monocyclic Belt, spanning >300 km (east to west), and crossing two previously proposed terrane boundaries (Fig. 1). A focus of this study is two anorthosite-mangerite-charnockite-granite (AMCG) suites, namely the 1.16 to 1.13 Ga Morin AMCG suite in the Morin terrane (Québec) (Martignole and Schrijver, 1970; Doig, 1991), and the ca. 1.15 Ga Marcy AMCG suite (Adirondack Highlands) (McLelland and Chiarenzelli, 1990; Clechenko et al., 2002; McLelland et al., 2002). We also examined two suites coeval with AMCG plutonism, namely the 1.17 to 1.16 Ga Chevreuil suite in the Central Metasedimentary Belt (Québec) (Corriveau and van Breemen, 2000) and the 1.18 to 1.15 Ga Frontenac suite in the Central Metasedimentary Belt (Ontario) (Davidson and van Breemen, 2000). Oxygen-isotope ratios of magmas that formed these plutons were determined by analysis of igneous zircon (Valley et al., 1994; this study), allowing recognition of regional domains in the oxygen-isotope ratio of the lower crust (the inferred pluton source region).

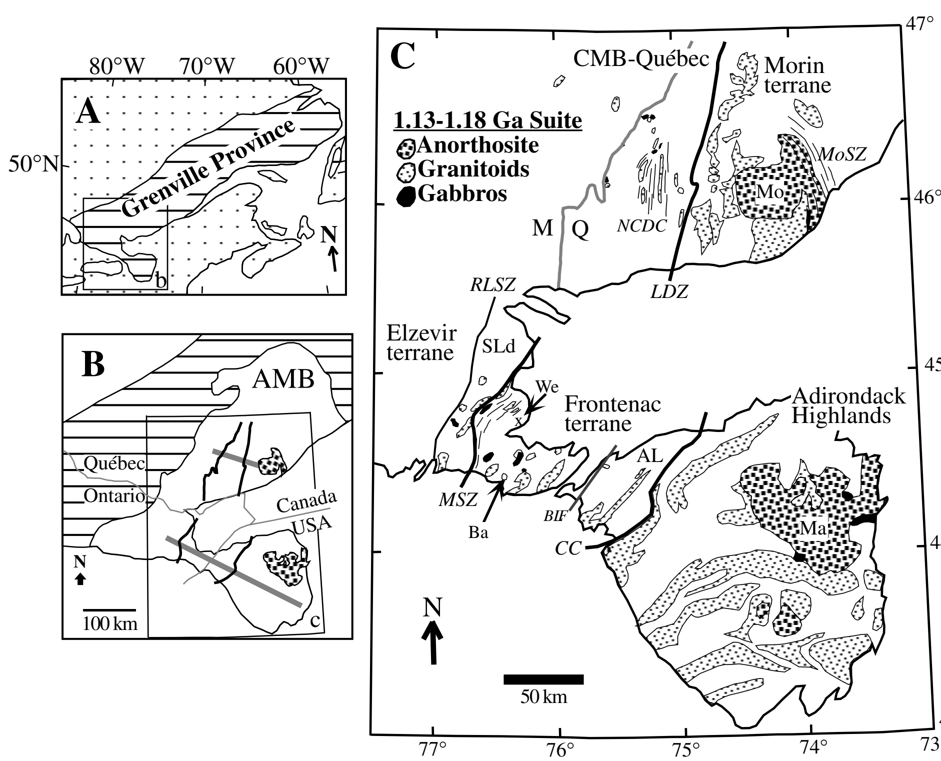

Figure 1. (A) Location of the study area within the Grenville Province. (B) Location map and subdivisions of the Allochthonous Monocyclic Belt (AMB) of the Grenville Province (after Rivers et al., 1989; Davidson, 1995; McLelland et al., 1996; Corriveau et al., 1998). (C) Detail of B. AL—Adirondack Lowlands (Frontenac terrane); Ba—Battersea pluton; BLF—Black Lake fault; CC—Carthage-Colton mylonite zone; CMB-Québec—Central Metasedimentary Belt of Québec; LDZ—Labelle deformation zone; M—marble domain; MSZ—Maberly shear zone; Ma—Marcy anorthosite massif; Mo—Morin anorthosite massif; MoSZ—Morin shear zone; Nominingue-Chénéville deformation zone; Q—quartzite domain of the CMB-Québec; RLSZ—Robertson Lake shear zone; NCDZ—SLd—Sharbot Lake domain of the Elzevir terrane; We—location of the 1.08 Ga Westport pluton. Locations of the oxygen-isotope transects are shown in gray in B.

REGIONAL GEOLOGY

The study area includes the Adirondack Highlands and the Morin terrane (Fig. 1), which are interpreted as 1.3 to 1.25 Ga arc-related rocks accreted to the Laurentian margin ca. 1.2 Ga (1.19 Ga in Wasteneys et al., 1999; 1.22 Ga in Corriveau and van Breemen, 2000). In this model the Central Metasedimentary Belt of Québec and Ontario (subdivided in Ontario into the Elzevir and Frontenac terranes) is the southeastern Laurentian margin at 1.2 Ga (present-day coordinates, Fig. 1). AMCG suite and contemporaneous 1.18 to 1.13 Ga granitic plutons intrude all of these terranes.

Adirondack Highlands

The Adirondack Highlands (Fig. 1) are primarily metaplutonic rocks, dominated by the AMCG suite and minor juvenile metasedimentary rocks ($\varepsilon_{Nd} \sim 1.3$; Daly and McLelland, 1991). The Marcy anorthosite was emplaced at 1.15 ± 0.01 Ga, which is also the age of associated charnockite and mangerite bodies (McLelland and Chiarenzelli, 1990; Clechenko et al., 2002; McLelland et al., 2002). The AMCG suite was overprinted by the granulite-facies Ottawan event at 1.09 to 1.03 Ga (7–8 kilobars, 675–800 °C; Bohlen et al., 1985; McLelland et al., 1996), followed by slow cooling (1–3 °C/m.y.; Mezger et al., 1991). Some rocks near contacts of AMCG plutons preserve low $\delta^{18}O$ values caused by interaction with heated meteoric water during contact metamorphism, indicating that these plutons intruded at relatively shallow depths (<10 km, Valley and O'Neil, 1982; Morrison and Valley, 1988; Clechenko and Valley, 2003). The Adirondack Highlands are bounded on the northwest by the Carthage-Colton mylonite zone (Geraghty et al., 1981).

Frontenac Terrane

The Frontenac terrane of the Central Metasedimentary Belt in Ontario and New York (Fig. 1, C) is made up of metaigneous and metasedimentary rocks, and is bounded on the southeast by the Carthage-Colton mylonite zone (Geraghty et al., 1981). Other lithologic breaks in the Frontenac terrane include the Black Lake fault in New York (Fig. 1, C), which marks the eastern limit of the ca. 1.16 Ga olivine diabase Kingston dike swarm (Davidson, 1995; Carl and deLorraine, 1997). Especially important to this study is a suite of ca. 1.21 Ga calc-alkaline plutons in New York (the Antwerp-Rossie suite), which is interpreted as indicating westward subduction under the eastern Frontenac terrane at this time (Wasteneys et al., 1999).

The Adirondack Lowlands of New York (Fig. 1) are included as part of the Frontenac because of similarities in rock types, magmatic crystallization ages, and timing of metamorphism (Wasteneys et al., 1999). The Adirondack Lowlands experienced amphibolite-facies conditions (640–680 °C, 6–7 kilobars; Bohlen et al., 1985; Kitchen and Valley, 1995), while peak conditions reached the granulite facies in Ontario (Streepey et al., 1997) prior to 1.18–1.16 Ga (McLelland et al., 1993; Mezger et al., 1993; Corfu and Easton, 1997). Metamorphism was broadly coeval with intrusion of monzonite, syenite, granite, and gabbro plutons of the Frontenac suite (van Breemen and Davidson, 1988; Marcantonio et al., 1990; McLelland et al., 1996; Davidson and van Breemen, 2000). In Ontario peak metamorphic conditions predated emplacement of Frontenac suite plutons, which intruded at lower pressures than peak conditions (Anovitz and Essene, 1990; Cosca et al., 1992; Wasteneys, 1994).

The Frontenac terrane is separated from the Sharbot lake domain of the Elzevir terrane on the northwest by the southeast-dipping Maberly shear zone (Fig. 1, C), a locally mylonitic zone of high strain (Corfu and Easton, 1997; Davidson and van Breemen, 2000). Highly strained rocks in the Frontenac hangingwall extend up to15 km southeast of the Maberly shear zone, and are intruded by syntectonically emplaced Frontenac suite plutons.

Sharbot Lake Domain

The Elzevir terrane is divided into several domains (Easton, 1992) that are interpreted as parts of an attenuated (and rifted) marginal basin developed at the edge of pre-Grenvillian Laurentia (e.g., Pehrsson et al., 1996; Smith et al., 1997), or as amalgamated volcanic arc terranes (Carr et al., 2000). The Sharbot Lake domain is the southeasternmost of these divisions (Fig. 1, C; Corfu and Easton, 1997; Davidson and van Breemen, 2000), and is separated from the rest of the Elzevir terrane by the extensional Robertson Lake shear zone (Fig. 3, C).

The metavolcanic and plutonic rocks and associated carbonate metasedimentary rocks of the Sharbot Lake domain are deformed and variably metamorphosed from upper greenschist to granulite facies, reaching 650–700 °C and 8 kilobars near the Maberly shear zone (see Streepey et al., 1997, and references therein). Country rocks are intruded by granitic, monzonitic, and gabbroic rocks of the 1.18–1.15 Ga Frontenac suite (Fig. 1, C; Corfu and Easton, 1997; Davidson and van Breemen, 2000), which are not metamorphosed and are deformed only in the immediate footwall of the Maberly shear zone.

Morin Terrane

The granulite-facies Morin terrane (Fig. 1, C) is dominated by a central anorthosite massif, with voluminous mangerite and monzonite, and minor jotunite and gabbro of the Morin AMCG suite (Martignole and Schrijver, 1970). This magmatism is dated at 1.16 to 1.13 Ga (Emslie and Hunt, 1990; Doig 1991; Friedman and Martignole, 1995; van Breemen and Corriveau, 1995). The Morin terrane is bounded to the west by the Labelle deformation zone, along which high strain occurred between 1.17 and 1.07 Ga (Zhao et al., 1997; Martignole and Friedman, 1998; Corriveau and van Breemen, 2000). Preserved metamorphic conditions are 650–775 °C and 6–7 kilobars for the region (Indares and Martignole, 1990), and were followed by slow cooling (Martignole and Reynolds, 1997). High-grade, deformed metasedimentary rocks occur as inclusions in undeformed Morin AMCG suite rocks (e.g., Martignole and Schrijver, 1970).

Central Metasedimentary Belt (Québec)

The Central Metasedimentary Belt of Québec (Fig. 1, C) is subdivided into a western marble-rich domain (referred to as the marble domain) and an eastern quartzite-rich domain (referred to as the quartzite domain) (Corriveau et al., 1998), interpreted as northern extensions of the Elzevir and Frontenac terranes of Ontario, respectively. Granulite-facies felsic gneiss complexes with mixed volcanic and plutonic protoliths (magmatic age ca. 1.4 Ga; Wodicka et al., this volume) occur within both domains and contain evidence for peak metamorphism at ca. 1.2–1.19 Ga (Corriveau and van Breemen, 2000; ~950 °C and ~10 kilobars, Boggs and Corriveau, this volume). These gneiss complexes were intruded by undeformed commingled dioritic and monzonitic dikes of the 1.17–1.16 Ga Chevreuil suite, while the synkinematic monzonitic, dioritic, and gabbroic sheetlike plutons of this suite were preferentially emplaced into the metasedimentary domains and their deformation zones (Corriveau et al., 1998; Corriveau and Morin, 2000; Corriveau and van Breemen, 2000). In these zones, gneissic host records a metamorphic overprint at 650 °C and 6 kilobars in the western marble domain and 750 °C and 8 kilobars in both the eastern marble and the quartzite domains (Perkins et al., 1982; Indares and Martignole, 1990; Kretz, 1990; Boggs, 1996). These metamorphic conditions resulted from intraplate reactivation at ca. 1.17–1.16 Ga (the ages of monazite, titanite, and syntectonic pegmatite; Friedman and Martignole, 1995; van Breemen and Corriveau, 1995; Corriveau and van Breemen, 2000). Syntectonic Chevreuil suite plutons were emplaced coevally with early members of the Morin AMCG suite to the east (Corriveau and van Breemen, 2000).

AMCG Suite and Contemporaneous Plutonism in the Monocyclic Belt

Because the emplacement style and volume of AMCG suite and contemporaneous plutonic rocks vary across the area, correlation of these rocks between lithotectonic terranes is possible only through precise U-Pb zircon geochronology of rocks that include syenite, monzonite, granite, charnockite, mangerite, and jotunite, and have been the foci of numerous igneous petrology and geochemistry studies (e.g., Buddington, 1939; Heath and Fairbairn, 1969; Martignole and Schrijver, 1970; Barton and Doig, 1977; Ashwal and Wooden, 1983; Shieh, 1985; Wu and Kerrich, 1986; Morrison and Valley, 1988; Lumbers et al., 1990; Marcantonio et al., 1990; McLelland and Whitney, 1990; Valley et al., 1990, 1994; Daly and McLelland, 1991; Doig, 1991; Emslie and Hegner, 1993; McLelland et al., 1993; Owens et al., 1993; Eiler and Valley, 1994; Rockow, 1995; Davidson and van Breemen, 2000; Peck and Valley, 2000). These granitoids have A-type, subalkalic to alkalic chemistries (Irvine and Baragar, 1971), alkali-calcic to calc-alkaline Peacock (1931) indexes, show little iron enrichment in AFM diagrams, are metaluminous (Shand, 1951), have flat heavy rare earth element patterns, and plot as within-plate granites on tectonic discrimination diagrams (e.g., Pearce et al., 1984). These characteristics contrast with those of other A-type granitic rocks that are more subalkalic with respect to $K_2O + Na_2O$ versus SiO_2 (Irvine and Baragar, 1971), and have alkali-calcic or alkalic Peacock indexes (e.g., Anderson, 1983). Neodymium isotope ε_{Nd} values of 1.5 to 2.9, depleted mantle Nd model ages of 1.3 to 1.5 Ga, and initial $^{87}Sr/^{86}Sr$ ratios of 0.704 to 0.705 indicate that these rocks underwent little interaction with Archean crust.

The origin of AMCG suite granitoids is controversial. Many studies indicate that they are not comagmatic with contemporaneous anorthosite, and were likely formed by partial melting of lower crust by anorthosite parent magma (see Ashwal, 1993). This contrasts with interpretations that these granitic rocks are related to anorthosite parent magmas or differentiates (e.g., Frost et al., 2002). In the Central Metasedimentary Belt of Québec, easterly dipping seismic reflectors are interpreted as images of AMCG suite–related monzonite and gabbro sheets that extend from the Moho to the surface along listric high-strain zones (Corriveau and Morin, 2000).

OXYGEN-ISOTOPE METHODS

Minerals and whole-rock powders were analyzed for $\delta^{18}O$ by laser fluorination at the University of Wisconsin, and all data are given in Table 1 or Peck (2000). Oxygen was liberated from mineral separates (Table 1; Appendixes 1–5) by heating with a CO_2 laser in the presence of BrF_5 (see Valley et al., 1995) so that small sample sizes (1–4 mg) can be analyzed with high precision and accuracy, typically better than ±0.1‰. The zircons analyzed are from the same zircon separate used for U-Pb age determination (McLelland, et al., 1988; Emslie and Hunt, 1990; Marcantonio et al., 1990; McLelland and Chiarenzelli, 1990; Chiarenzelli and McLelland, 1991; Corriveau and van Breemen, 2000; Davidson and van Breemen, 2000). Zircons were soaked in cold HF to dissolve or identify radiation damage, and were hand-picked for purity. On the 29 days of mineral analysis, 120 aliquots of garnet standard (UWG-2; Valley et al., 1995) were analyzed. UWG-2 had an average $\delta^{18}O$ = 5.75 ± 0.13‰ (1 s.d. reported, 1 s.e. = 0.01‰) relative to Vienna Standard Mean Ocean Water (VSMOW). This is within the error of the published laboratory average for UWG-2 of 5.74 ± 0.15‰ (n = 1081, 1 s.e. = 0.005‰; Valley et al. 1995). The daily precision of UWG-2 averaged 0.07 ± 0.04‰. Thirty-eight zircon samples were analyzed in duplicate, and reproducibility (half the difference of two analyses) averaged 0.07 ± 0.05‰. The mineral analyses were adjusted by the amount that daily UWG-2 values deviated from 5.8‰, its accepted value (based on $\delta^{18}O$(NBS-28) = 8.59; Valley et al., 1995). This adjustment averaged 0.10‰, and was always <0.30‰.

Whole-rock powders (Appendixes 1–4) were analyzed using an airlock sample chamber where individual samples were heated and reacted with BrF_5 (Spicuzza et al., 1998). Whole-rock powders are typically reactive with BrF_5 at room temperature, so they were isolated from the lasing chamber with a gate valve, and moved into the lasing chamber only when residual BrF_5 was removed. On the 16 days of whole-rock powder analysis, 63 aliquots of powdered UWG-2 were analyzed; they averaged 5.83 ± 0.15‰ (ls.e. = 0.02‰), and daily precision averaged 0.06 ± 0.02‰. Thirty out of 150 whole-rock powders were duplicated, and reproducibility averaged 0.06 ± 0.05‰. The whole-rock analyses were adjusted by the amount that daily UWG-2 values deviated from 5.8‰, and this adjustment averaged 0.11‰ (maximum adjustment = 0.30‰).

OXYGEN ISOTOPE RESULTS

Whole-rock (WR) $\delta^{18}O$ values from all granitic rocks, except those from the central Frontenac terrane, range from ~7 to 13‰ (Table 1; Appendixes 1–4; Fig. 2). These oxygen-isotope ratios are typical of the high end of variation seen in common granitic rocks (e.g., Taylor and Sheppard, 1986). Granitic rocks in the Frontenac terrane have $\delta^{18}O$(WR) = 9 to 16‰ (Shieh, 1985; Marcantonio et al., 1990; this study), a range much higher than reported igneous values from granitic rocks (see Taylor and Sheppard, 1986). Gabbros from the Central Metasedimentary Belt of Québec range from ~7 to 11‰ (Appendix 2; Fig. 3). The gabbro plutons have $\delta^{18}O$(WR) values comparable to those of gabbros related to AMCG suite plutonism in the Adirondack Highlands (6.8 ± 0.3‰, n = 16; Valley et al., 1994).

There is good correlation between SiO_2 and $\delta^{18}O$(WR) values for granitic rocks of each terrane (Fig. 2). Correlation is best in the Adirondack Highlands, the Morin terrane, and the marble domain (results are not plotted for the Frontenac terrane and the Sharbot Lake domain because of the small number of whole-rock analyses). Eiler and Valley (1994) also showed that individual AMCG plutons in the Adirondack Highlands have a better correlation between SiO_2 and $\delta^{18}O$ than is seen in the complete data set for Adirondack granitic rocks, reflecting

TABLE 1. OXYGEN ISOTOPE ANALYSES OF MAGMATIC ZIRCONS FROM 1.18 TO 1.13 GA GRANITOIDS, SOUTHERN GRENVILLE PROVINCE

	Pluton	Sample #	SiO_2 wt%	Zircon sat. *T* (°C)	Zircon mag.	$\delta^{18}O$ zircon	$\delta^{18}O$ zircon	Average zircon	$\delta^{18}O$ cal. WR	$\delta^{18}O$ aver. WR	Age (Ma)
1	Snowy Mountain dome	AM86-7	58.5	730	M-2	8.05	—	8.05	9.37	—	>1130 A
2	Schroon Lake	9.23.85.7	69.2	890	M-2	8.19	—	8.19	9.23	10.23	1125 ± 10 A
3	Hermon granite	DF178	n.d.	~850	NM5	8.34	—	8.34	9.34	—	1149 ± 26 B
4	Edwardsville Syenite	AM87-5	61.5	850	NM-2	11.18	11.03	11.11	12.41	14.57	1164 ± 4 C
5	Battersea	LH86-63	66.1	900	NM0	11.18	11.11	11.15	12.55	13.40	1168 ± 3 D
6	Perth Road	LH87-64	61.0	860	MN0	13.09	12.93	13.01	14.35	13.80	1166 ± 3 D
7	Lyndhurst	LH87-31	68.3	720	MN0	11.11	10.72	10.92	12.97	13.60	1166 ± 3 D
8	South Lake	86DM9c	60.1	870	NM1	11.20	11.06	11.13	12.43	12.48*	1162 ± 3 E
9	Crow Lake	LH87-30	63.6	860	NM0	13.64	13.38	13.51	14.92	15.70	1176 ± 2 D
10	Beales Mills	95DM53	64.2	870	NM3	11.88	11.83	11.86	13.14	14.00	1164 ± 2 F
11	North Crosby	93DM131a	54.4	750	NM0	7.90	7.89	7.90	9.23	9.13	1157 ± 3 F
12	Bennett Bay	93DM19	55.1	630	NM0	7.90	8.03	7.97	9.31	10.01	1162 ± 3 F
13	Silver Lake	93DM20	68.1	840	NM 0.5	6.79	6.81	6.80	7.71	9.25†	1161 +3/–2 F
14	Oso	92DM152	50.0	770	NM0	7.64	—	7.64	8.65	8.58	1154 ± 2 F
15	Grey Valley	96MR43	66.2	860	NM-2	8.49	8.28	8.39	9.44	9.82	n.d.
16	Western Mangerite	96MR21	71.7	870	NM-2	9.41	9.34	9.38	10.53	11.25	n.d.
17	Maskinongé	CQA925A	n.d.	~850	M2	8.36	8.35	8.36	9.36	—	1164 ± 3 H
18	Maskinongé (dike)	CQA925b	n.d.	~850	M2	8.03	8.22	8.13	9.13	—	1168 ± 3 H
19	Mangerite dike	EC84-246	57.1	840	—	9.77	9.60	9.65	10.47	—	1146 +7/–6 I
						9.76	9.64				
						9.69	9.49				
20	Chevreuil	CQA1085	66.1	850	M2	9.31	9.16	9.23	10.31	11.64	1166 ± 2 H
21	Roches	CQA008	62.1	840	M1	7.35	7.51	7.43	8.46	10.34	1166 +8/–4 H
22	Granitic dike	CQA3565B	n.d.	~850	M1	8.80	8.91	8.86	9.86	—	1161 ± 3 H
23	Ecorses	96FN1	57.4	920	NM2	8.26	8.13	8.19	9.04	9.28	n.d.

Note: All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Zircon mag. indicates magnetic (M) or nonmagnetic (NM) at a particular side tilt (e.g. 2°) of the Frantz Isodynamic Separator. Calculation of zircon saturation temperature follows the method of Watson and Harrison (1983); an average value of ~850 °C is assumed when whole-rock chemistry is not available. Age and geochemistry references: A—Chiarenzelli and McLelland (1991); B—Carl and Sinha (1992); C—McLelland et al. (1993); D—Marcantonio et al. (1990); E—van Breemen and Davidson (1988); F—Davidson and van Breemen (2000); G—Corfu and Easton (1997); H—Corriveau and van Breemen (2000 and personal communication); I—Emslie and Hunt (1990). WR—whole-rock sample; *whole-rock sample 86DM96; †whole-rock sample 94DM29; n.d.—not determined.

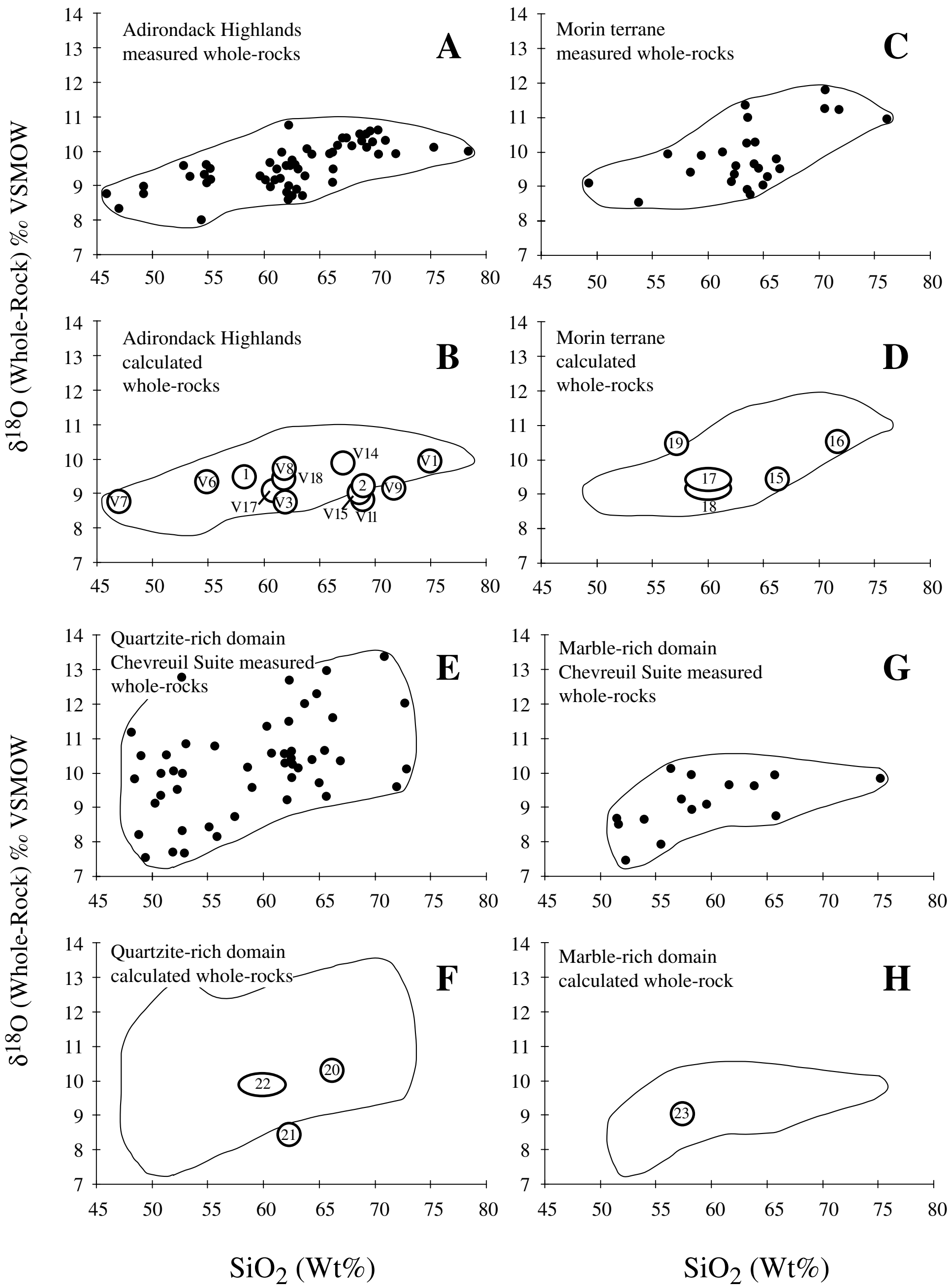

Figure 2. Weight percent SiO_2 versus $\delta^{18}O$ for whole-rock samples (measured or whole-rock values calculated from $\delta^{18}O$ zircon) for 1.13 to 1.18 Ga granitic rocks from the Adirondack Highlands (A and B), Morin terrane (C and D), and Central Metasedimentary Belt of Québec (E–H). Samples with a "V" prefix are from Valley et al. (1994). Adirondack whole-rock $\delta^{18}O$ and SiO_2 data are from Eiler and Valley (1994) and Valley et al. (1994). Calculated whole-rock $\delta^{18}O$ values for samples 17, 18, and 22 (Table 1) are placed to indicate approximate SiO_2 values. Results are not plotted for the Frontenac terrane and the Sharbot Lake domain because of the small number of whole-rock analyses.

pluton-to-pluton variability in assimilants and crystallization histories. This improved correlation is also seen in our data sets, where correlation of $\delta^{18}O$ and SiO_2 for individual plutons is better than for all data taken together from each terrane (not plotted; see Appendixes 1–4). Chevreuil suite granitic rocks of the quartzite domain have the most variation in $\delta^{18}O$(WR), and have high $\delta^{18}O$ values for SiO_2 contents below 60% (Fig. 2, E).

Oxygen-isotope ratios of zircon (Table 1) follow a similar relationship to whole-rock values from terrane to terrane (Fig. 2). For all granitic rocks except those of the Frontenac terrane, $\delta^{18}O$(Zrn) is elevated compared to the values in most igneous rocks, but relatively consistent at 7.4–9.6‰. In the Frontenac terrane, $\delta^{18}O$(Zrn) in granitic rocks ranges from 6.8 to 13.5‰. Zircon from the Lacordaire gabbro has a $\delta^{18}O$ of 6.4‰, which compares well to zircons from two gabbro bodies in the Adirondack Highlands ($\delta^{18}O$ = 6.8 and 6.0‰; Valley et al., 1994). Quartz from the Battersea pluton (Fig. 1, Frontenac terrane) ranges from 13.9 to 14.9‰, and biotite ranges from 9.7 to 10.7‰. In the Perth Road pluton (Fig. 1, Frontenac terrane), $\delta^{18}O$(Qtz) ranges from 14.7 to 17.4‰.

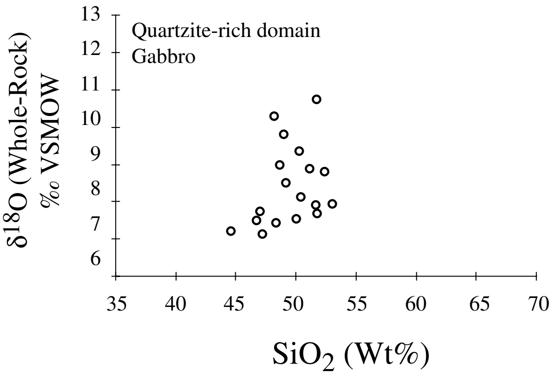

Figure 3. Weight percent SiO_2 versus $\delta^{18}O$ for whole-rock samples of 1.7 Ga gabbros from the quartzite domain of the Central Metasedimentary Belt (Québec).

DISCUSSION AND INTERPRETATIONS

Oxygen-Isotope Ratios of Whole Rocks

Correlation between $\delta^{18}O$(WR) and SiO_2 (Fig. 2) is consistent with magmatic differentiation that would cause both $\delta^{18}O$(WR) and SiO_2 to rise as these rocks evolve. This correlation was described in the Adirondack Highlands for granitic rocks from the AMCG suite (Fig. 2, A), and was interpreted as preservation of premetamorphic igneous variation in whole-rock $\delta^{18}O$ values (Eiler and Valley, 1994). In general, we interpret correlation of $\delta^{18}O$ and SiO_2 in other Grenville terranes studied as indicating overall preservation of igneous values in whole rocks as well. Correlation of $\delta^{18}O$ with differentiation indexes is expected from closed-system fractional crystallization, but can explain only a few tenths per mil of the observed variation (e.g., closed-system fractionation at 800 °C would elevate whole-rock $\delta^{18}O$ values by ~0.8‰ for a 20% increase in SiO_2). The observed correlation of SiO_2 and $\delta^{18}O$(WR) could result from contamination by supracrustal material with high $\delta^{18}O$, or from assimilation fractional crystallization (AFC) processes, which would increase the $\delta^{18}O$ of igneous rocks as they differentiate (e.g., Taylor and Sheppard, 1986). In addition to the consistency with AFC models, good petrologic and isotopic evidence for preservation of igneous $\delta^{18}O$ values and against resetting by exchange with metamorphic fluids is documented in the Adirondack Highlands and in the Frontenac and Morin terranes (e.g., Valley and O'Neil, 1984; Shieh, 1985; Morrison and Valley, 1988; Valley et al., 1990, 1994; Peck and Valley, 2000).

Chevreuil suite granitic rocks of the quartzite domain have the most variation in $\delta^{18}O$(WR) with respect to SiO_2 content (Fig. 4, A). This could be caused either by higher $\delta^{18}O$ values of potential assimilants or by the tectonic setting of these plutons. These plutons were synkinematically emplaced as sheets into the Nominingue-Chénéville deformation zone (Corriveau and van Breemen, 2000), and high $\delta^{18}O$ values at low SiO_2 contents may reflect extensive interaction with supracrustal materials facilitated by the active tectonic environment of the deformation zone and the large surface area:volume ratios of these plutons. Common field observation of calc-silicate, skarn, and quartzite xenoliths and the absence of biotite-bearing and quartzofeldspathic xenoliths (which are abundant country rocks) point toward efficient assimilation of country rocks that have lower melting temperatures. High and variable $\delta^{18}O$(WR) for the Chevreuil suite cannot be explained by some country rocks with unusually high $\delta^{18}O$ values; none of the country rocks analyzed in the quartzite domain has an unusual $\delta^{18}O$ value compared to the values of supracrustal rocks elsewhere in the Grenville Province (e.g., Taylor, 1969; Shieh and Schwarcz, 1978; Shieh, 1985; Wu and Kerrich, 1986; Marcantonio et al., 1990; Peck, 2000; Appendixes 1, 2, and 5). This conclusion is supported by oxygen-isotope ratios of vertically layered mafic intrusions associated with the Chevreuil suite in the quartzite domain (Fig. 3). The gabbro plutons show a similar large variation in $\delta^{18}O$ as well as relatively high $\delta^{18}O$ values at low SiO_2 contents, implying similar contamination styles (albeit during different differentiation histories and at different absolute $\delta^{18}O$ values).

Preservation of Igneous Oxygen-Isotope Ratios in Zircons

Zircon is an excellent "reference mineral" from which to estimate oxygen-isotope ratios of metaigneous rocks, inasmuch as low-magnetism, low-radiation-damage zircon retains igneous oxygen-isotope ratios during metamorphism and hydrothermal alteration (Valley et al., 1994; Gilliam and Valley, 1997; King et al., 1997, 1998; Peck and Valley, 1998; Peck et al., 1999; Peck et al., 2003; Valley, 2003). Also, zircon is a high-temperature liquidus phase in many igneous rocks, is refractory, is resistant to recrystallization, and can be dated by U-Pb methods. Inheritance (determined by U-Pb) is uncommon in our zircons, consistent with the alkaline chemistry of many of the plutons, which would promote dissolution of any inherited zircon (Watson and

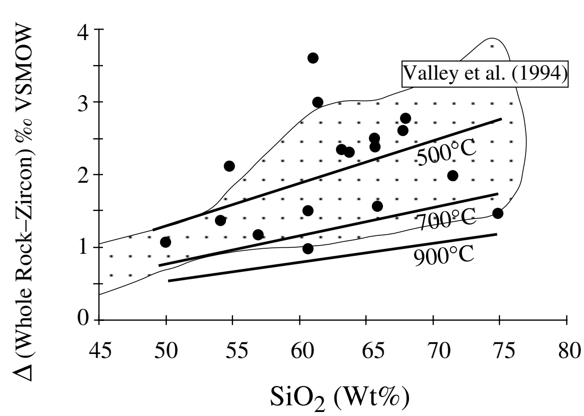

Figure 4. Fractionation between $\delta^{18}O$ (whole rock) and $\delta^{18}O$ (zircon) against SiO_2 for anorthosite-suite granitic rocks. Isotherms are shown, as is the field of data from Valley et al. (1994).

Harrison, 1983); hence zircon is ideal for this regional study of igneous oxygen-isotope geochemistry. Under anhydrous experimental conditions, Watson and Cherniak (1997) determined oxygen diffusion rates that are slow enough to be prohibitive of appreciable intermineral oxygen exchange during geological time (tens of m.y.) at <900 °C. Experiments using free H_2O ("wet" experiments) showed faster oxygen diffusion. When extrapolated to geologic temperatures (e.g., 600 °C), these experimental rates are seven orders of magnitude faster than those in anhydrous experiments. Closure temperatures calculated from "wet" experiments are 500–600 °C for average zircon sizes and slow cooling rates.

Studies of zircon from Adirondack rocks were designed to test the rapid diffusion rates inferred from wet experiments. Thus far, wet experiments do not describe oxygen-isotope systematics of zircons studied from metamorphic rocks (e.g., detrital zircons in quartzite preserve premetamorphic oxygen-isotope values through ~700 °C metamorphism; Valley et al., 1994; Peck and Valley, 1998; Peck et al., 2003). Zircons from orthogneiss do not show the oxygen-isotope zoning caused by slow cooling that wet experiments predict. Given a cooling rate of 2 °C/m.y. after granulite-facies metamorphism, zircons from Adirondack orthogneiss would develop a 0.6 to 0.8‰ fractionation between the smallest and largest sizes analyzed if the wet experiments applied (Peck et al., 1999, 2003). No systematic fractionation is observed between large and small zircon sizes in our samples, indicating that oxygen diffusion rates are significantly slower than that predicted by wet experiments and supporting the interpretation that magmatic oxygen-isotope compositions are preserved in zircon.

Oxygen-Isotope Systematics between Whole Rocks and Zircons

Zircons from our granitic rocks have oxygen-isotope ratios that are broadly consistent with the lower range of measured whole-rock values. Both our data (Table 1) and data from Valley et al. (1994) have variable Δ(WR-Zrn), with some values that are consistent with magmatic temperatures and others that are ~1.0–1.5‰ higher (Fig. 4). High values of $\delta^{18}O$(WR) may indicate assimilation of country rock after zircon crystallization or low-temperature alteration (especially of feldspars) and elevation of $\delta^{18}O$(WR). Fractionations with zircon were calculated after the method of Valley et al. (1994, 2003).

The fractionation between calculated whole-rock $\delta^{18}O$ values (CWRs; Table 1; Fig. 2) and zircon is determined using normative minerals from each rock and published oxygen-isotope fractionation factors. The temperature used for calculating intermineral fractionations is the zircon saturation temperature of Watson and Harrison (1983), which is 750–900 °C for these rocks (Table 1). Calculation of whole-rock $\delta^{18}O$ values from normative minerals versus modal mineralogy (e.g., Valley et al., 1994) does not vary significantly, and the former is a better proxy for $\delta^{18}O$ of the silicate melt (e.g., Matthews et al., 1994). The zircon saturation temperature, an estimate of the temperature at which zircon began to crystallize, is a minimum estimate for zircon crystallization. A range in temperature of 200 °C for zircon crystallization in a granitic melt would raise the $\delta^{18}O$(CWR) only ~0.5‰. Calculated whole-rock $\delta^{18}O$ values fall within the lower envelope of whole-rock data (Fig. 2), which supports the interpretation that zircon retains its igneous $\delta^{18}O$ values during the final stages of assimilation or alteration of these plutons.

High-$\delta^{18}O$ Plutons of the Frontenac Terrane

Oxygen-isotope ratios for whole-rock powders of Frontenac suite granitic rocks from the central Frontenac terrane average ~14‰ (Shieh, 1985; Marcantonio et al., 1990; this study), which is ~4‰ higher than those for other contemporaneous granitic rocks in this study (Figs. 5–7). In both the north-

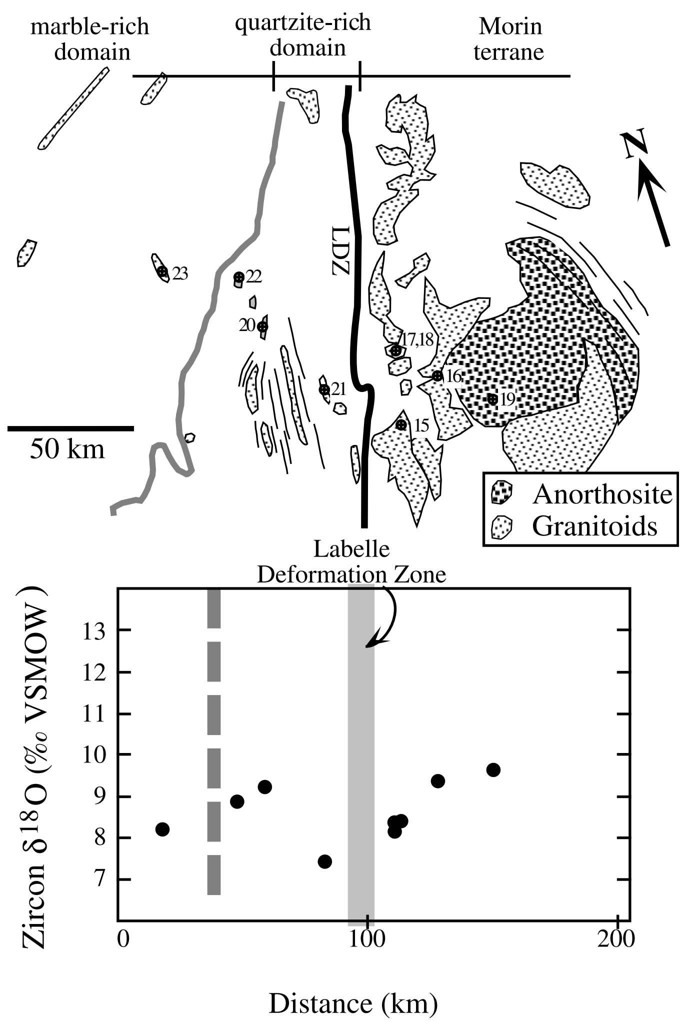

Figure 5. Transect of 1.13–1.18 Ga granitic rocks across the Morin terrane and the Central Metasedimentary Belt (Québec), showing $\delta^{18}O$ (zircon) values as a function of distance perpendicular to terrane boundaries. LDZ—Labelle deformation zone. Numbers refer to plutons in Table 1.

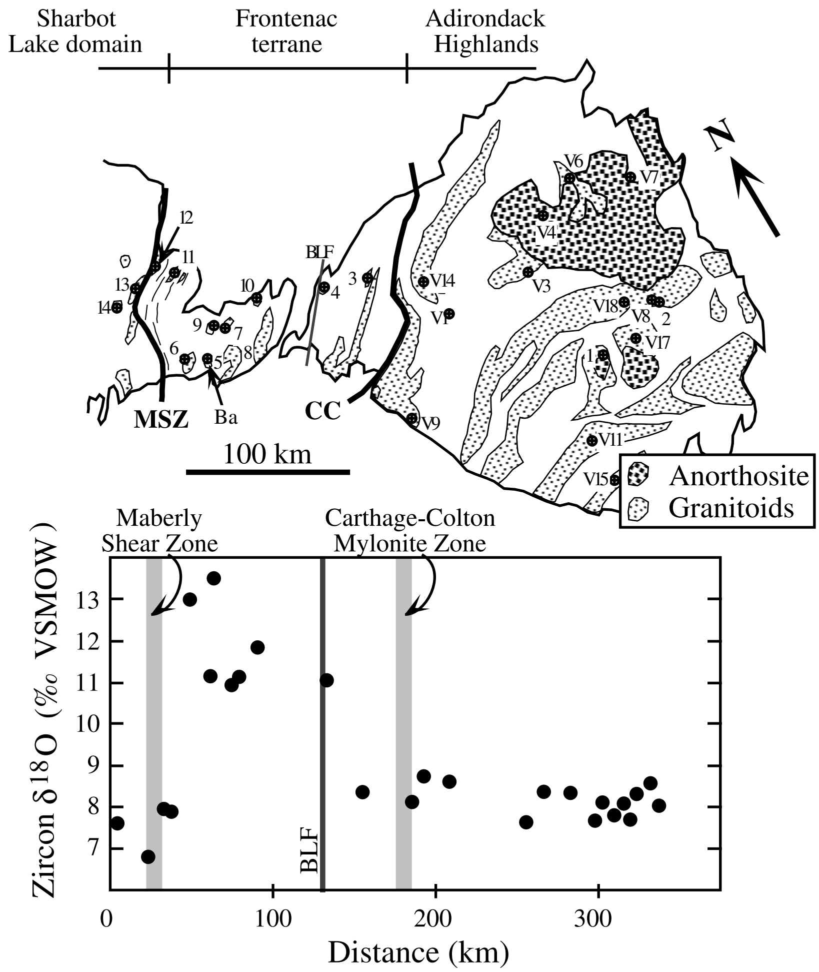

Figure 6. Transect of 1.13–1.18 Ga granitic rocks across the Adirondack Highlands, the Frontenac terrane, and the Sharbot Lake domain (Elzevir terrane), showing $\delta^{18}O$ (zircon) values as a function of distance perpendicular to terrane boundaries. Ba—location of the Battersea pluton; BLF—Black Lake fault; CC—Carthage-Colton mylonite zone; MSZ—Maberly shear zone. Numbers refer to plutons in Table 1.

western Frontenac terrane (Ontario) and the eastern Frontenac terrane (New York), some granitic rocks have lower $\delta^{18}O$ values (i.e., Figs. 3, 6, 11, and 12). The unusually high $\delta^{18}O$ values of some granites from the Frontenac terrane were first recognized by Shieh (1985), who interpreted them as partial melts of metagreywackes or volcanogenic metasedimentary rocks in order to explain both their metaluminous chemistries and their high $\delta^{18}O$. Marcantonio et al. (1990) concluded that the Nd- and Sr-isotope systematics of these plutons could be explained by a mixture of melts derived from depleted mantle and pelitic sedimentary material. They interpreted the unusual oxygen-isotope ratios of these rocks as indicating interaction with high-$\delta^{18}O$, marble-derived CO_2-rich fluids, in effect decoupling radiogenic and stable-isotope systematics. CO_2-rich fluids are necessary for their model because the only reservoirs they considered were melts from depleted mantle, pelitic metasedimentary rocks, and marble. If isotope systems were not decoupled in their calculation, the large amount of marble needed for the high $\delta^{18}O$ values of the plutons would be apparent in lower Si and higher Ca compositions of the granitic rocks (shifting CaO and SiO_2 by ~10 wt%). The strontium-isotope ratio of Grenville marble (Hauer, 1995) is also inconsistent with the composition of these plutons (Marcantonio et al., 1990).

If CO_2-magma interaction was important, the process occurred at depth, and/or the magma was subsequently well mixed. Because CO_2 solubility in granitic magmas is extremely low at crustal pressures, CO_2-magma interaction implies diffusion of CO_2 with high $\delta^{18}O$ values into the magma, and continuous escape of CO_2 in order to shift the magma $\delta^{18}O$. In-filtrating water cannot appreciably change the $\delta^{18}O$ of granitic magmas because of its slow diffusion across the magma–country rock interface (see Taylor and Sheppard, 1986). This applies for CO_2 diffusion as well, but CO_2-magma exchange is even more unlikely given the very low solubility of CO_2 in granitic melts.

The high $\delta^{18}O$ values from the Frontenac terrane require derivation of the granitic rocks from high-$\delta^{18}O$ source materials. These plutons preserve igneous oxygen-isotope fractionations between coexisting minerals (Δ[Qtz–Fsp] = 1.0–1.7‰) and have no correlation between $\delta^{18}O$(WR) and pluton size (Shieh, 1985). Shieh (1985) found no gradients in $\delta^{18}O$(WR) with respect to contacts with high-$\delta^{18}O$ country rock, an obser-

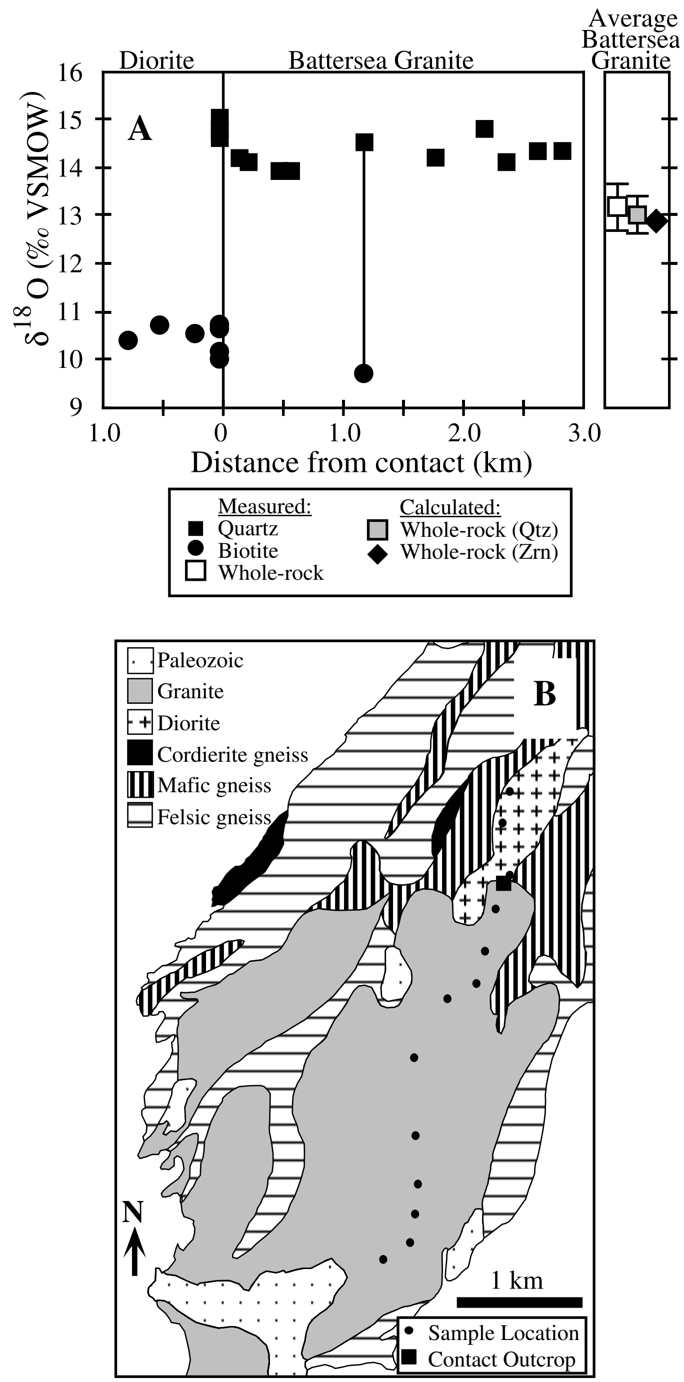

Figure 7. Transect of the Battersea pluton (Frontenac terrane), showing $\delta^{18}O$ (quartz) values in granite and $\delta^{18}O$ (biotite) in adjacent diorite (A). Geology (B) is from Currie and Ermanovics (1971). The average whole-rock $\delta^{18}O$ values calculated in equilibrium with quartz and zircon (shown on right side of figure) agree well with the average measured $\delta^{18}O$ (whole rock) (from Shieh, 1985).

vation confirmed by traverses across the plutons. Quartz $\delta^{18}O$ values do not vary with location in the Battersea granite (Fig. 7) and in Perth Road plutons (Appendix 5), and homogeneity of $\delta^{18}O$ within these plutons supports the absence of interaction with exposed rocks or metamorphic fluids to explain high $\delta^{18}O$ values (Shieh, 1985).

Interaction with exposed country rocks cannot explain the high $\delta^{18}O$ values in the Frontenac terrane, because younger plutons emplaced in the same country rocks have lower $\delta^{18}O$ values (e.g., zircons from the 1.08 Ga Westport pluton [Fig. 1] have $\delta^{18}O$ = 8.1‰, compared to the 11.0–13.5‰ zircons from the high-$\delta^{18}O$ Frontenac plutons). Granitic rocks of the same age emplaced into similar rocks in adjacent terranes have moderate $\delta^{18}O$(WR) values (8–11‰; e.g., Shieh and Schwarcz, 1978; Wu and Kerrich, 1986; Eiler and Valley, 1994). Given the homogeneity of $\delta^{18}O$(WR) and $\delta^{18}O$(Qtz) on the pluton scale, igneous oxygen-isotope fractionations, and high $\delta^{18}O$(Zrn), we interpret the $\delta^{18}O$ values of the Frontenac terrane plutons as inherited from parental materials of the plutons.

The high $\delta^{18}O$(Zrn) of some granitic plutons in the Frontenac terrane (11.81 ± 1.04‰, n = 7) correlates neither with other geochemistry nor with emplacement style. $\delta^{18}O$(Zrn) for the Adirondack Highlands is 8.10 ± 0.36 (n = 13; Valley et al., 1994), and other samples (from Ontario and Québec) have an average of 8.37 ± 0.83‰ (n = 12). This bimodal distribution between the central Frontenac terrane and other terranes reflects neither whole-rock chemistry nor other isotope systems such as Sr and Nd (Heath and Fairbairn, 1969; Barton and Doig, 1977; Ashwal and Wooden, 1983; Marcantonio et al., 1990; Daly and McLelland, 1991; Doig, 1991; Emslie and Hegner, 1993; McLelland et al., 1993). For example, ε_{Nd} values for AMCG granitic rocks (from the Adirondack Highlands) average 2.3 ± 0.7 (n = 5; McLelland et al., 1993), which is indistinguishable from the 2.0 ± 0.5 (n = 5; Marcantonio et al., 1990) of Frontenac terrane samples. The neodymium-isotope compositions of Adirondack granitic rocks are consistent with mixing between melts derived from mantle and paragneiss (Fig. 8). The values for Adirondack samples fall between those for average Frontenac metasedimentary rocks and ca. 1.15 Ga mantle-derived melts, suggesting a 30/70 mixture of the two. Because of the large variability in Frontenac ε_{Nd} values for metasediments, the mixing line does not pass precisely through all measured values. Some Adirondack metasedimentary rocks have higher ε_{Nd} values (+1.3, McLelland et al., 1996) than average Frontenac paragneiss. The high $\delta^{18}O$ values of some Frontenac granitic rocks, however, cannot be explained by mixing between 1.15 Ga mantle-derived melts (Fig. 8, M) and metasedimentary rocks.

We propose that the source materials for Frontenac granitic rocks with high $\delta^{18}O$ had Mesoproterozoic mantle extraction ages, but that these source materials had a different low temperature history than the source materials for other contemporaneous granitic rocks. Basalt derived from depleted mantle has a

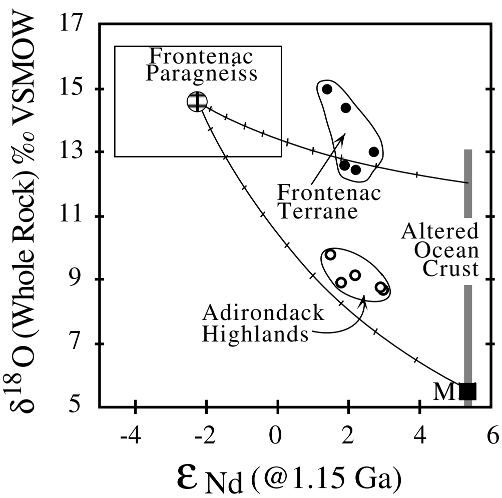

Figure 8. $\delta^{18}O$ (whole rock) versus ε_{Nd} at 1.15 Ga for anorthosite-mangerite-charnockite-granite-related granitic rocks from the Frontenac terrane and Adirondack Highlands, average paragneiss from the Frontenac terrane, melt from unaltered mantle (M—source of MORB, mid-ocean ridge basalt), and melts of ocean crust which underwent low-temperature hydrothermal alteration and/or juvenile oceanic sediments (Shieh, 1985; Muehlenbachs, 1986; Marcantonio et al., 1990; McLelland et al., 1993). Frontenac samples are consistent with mixing between melts of altered ocean crust and paragneiss. The box is ± 1 standard deviation.

$\delta^{18}O$ of ~5.5‰, but hydrothermal alteration on the seafloor is known to change the $\delta^{18}O$ to a higher or lower value, depending on the temperature of alteration (Muehlenbachs, 1986). Seawater alteration at temperatures lower than ~250° will raise $\delta^{18}O$ values, whereas at temperatures higher than ~250°, it will lower $\delta^{18}O$, and basalts altered at intermediate temperatures are essentially unchanged. Strontium-isotope ratios are commonly affected by hydrothermal alteration on the seafloor, but Nd isotopes show only minor shifts (e.g., McCulloch et al., 1980). Melts of metasedimentary rocks and hydrothermally altered basalt (and/or immature, juvenile oceanic sediments) may therefore explain radiogenic and stable isotope results. For example, Sr isotope ratios of Grenville marbles (0.705 to 0.706; Hauer, 1995) do not differ sufficiently from depleted mantle values to cause a large shift in the Sr-isotope ratios of basalt during hydrothermal alteration. The upper mixing line (Fig. 8) is between a hypothetical low-temperature altered basalt-oceanic sediment ($\delta^{18}O$ ~12‰) and Frontenac paragneiss. Frontenac granitic rocks correspond to ~20–30% paragneiss contribution. The Perth Road and Crow Lake plutons have the highest $\delta^{18}O$ values, and may represent mixing between an extremely high-$\delta^{18}O$ component (~15‰) and paragneiss. Hydrothermally altered ocean crust and associated sediments provide a geochemically consistent end-member that accounts for the O-, Sr-, and Nd-isotope compositions of the granitic rocks, does not involve marble, and utilizies little paragneiss so that plutons remain metaluminous. Hydrothermally altered ocean crust has an average oxygen-isotope ratio of ~6‰ (Muehlenbachs, 1986), so the absence of high $\delta^{18}O$ values in adjacent terranes does not imply that hydrothermally altered ocean crust is not present, but implies only that crust under the central Frontenac terrane may have contained more remnants of the upper (high-$\delta^{18}O$) portions of a subducted slab.

TECTONIC IMPLICATIONS

The presence of the AMCG suite and coeval plutons in the Adirondack Highlands, Frontenac terrane, Sharbot Lake domain, Morin terrane, and Central Metasedimentary Belt (Québec) indicates that these crustal blocks were juxtaposed by ca. 1.18 Ga (McLelland et al., 1996; Corriveau et al., 1998; Corriveau and van Breemen, 2000). These plutons have similar trace element patterns, Nd- and Sr-isotope ratios, and depleted mantle Nd model extraction ages that do not correlate with another geochemistry or location. Oxygen-isotope ratios are the only apparent difference among the plutons.

High-$\delta^{18}O$ plutons, as in the central Frontenac terrane, do not exist near the margins of the terrane. The easternmost anomalously high-$\delta^{18}O$ pluton in the Frontenac terrane is the Edwardsville syenite (Fig. 6, #4). To the east, the Hermon granite (Fig. 6, #3) has $\delta^{18}O$(Zrn) = 8.3‰, isotopically identical to the AMCG granitoid suite in the Adirondack Highlands. The westernmost high-$\delta^{18}O$ body is the Perth Road pluton (Fig. 6, #6); the two lower-$\delta^{18}O$ plutons in the western Frontenac terrane (#11 and #12) were synkinematically intruded into the western Frontenac terrane and deformed by the Maberly shear zone (Davidson and van Breemen, 2000). The similarity in oxygen-isotope ratios between these deformed plutons and those in the structurally underlying Sharbot Lake domain may indicate that the normal-$\delta^{18}O$ granitic rocks are derived from the footwall (Sharbot Lake domain) (Fig. 5). An alternate explanation is that the deformation zone at the margin of the Frontenac terrane was a magma conduit (as proposed in Québec by Corriveau et al., 1998, and Corriveau and Morin, 2000), tapping a source region different from that of the undeformed high-$\delta^{18}O$ Frontenac plutons.

The high-$\delta^{18}O$ Edwardsville syenite is on the eastern side of the Black Lake fault, but has a $\delta^{18}O$(Zrn) identical to plutons in the central Frontenac terrane. This could indicate that the Edwardsville syenite is derived from the same basement as the high-$\delta^{18}O$ plutons in Ontario. Furthermore, basement of the Adirondack Highlands may have extended from the Carthage-Colton mylonite zone under the eastern Frontenac terrane in New York as far as the Hermon granite, which could have been derived from Adirondack Highlands material at depth under the Adirondack Lowlands at ca. 1.15 Ga.

The new oxygen-isotope data are consistent with subduction and storage of ocean crust beneath the Frontenac terrane before 1.18–1.13 Ga. In the tectonic model of Wasteneys et al.

(1999, modified from McLelland et al., 1996), the Frontenac terrane is the trailing margin of the ca. 1.35 to 1.22 Ga Elzevir arc, and west-dipping subduction of ocean crust beneath the Frontenac terrane gave rise to the calc-alkaline ca. 1.21 Ga Antwerp-Rossie suite of the Adirondack Lowlands (Fig. 9). Alternatively, Elzevir subduction from the west could also have been a source of ocean crust in the lower crust of the Frontenac terrane. Collision of the Frontenac terrane with the Adirondack Highlands began after ca. 1.21 Ga Antwerp-Rossie suite plutonism but before generation of the ca. 1.17 Ga Rockport granite and the Hyde School gneiss. Docking and imbrication were accompanied by metamorphism and magmatism. In Québec, collision with the Morin terrane occurred at 1.22 to 1.21 Ga, as manifested by ca. 1.20 to 1.19 Ga metamorphism and anatexis (Corriveau and van Breemen, 2000). The 1.17 to 1.16 Ga Chevreuil suite monzonites of the Central Metasedimentary Belt (Québec)

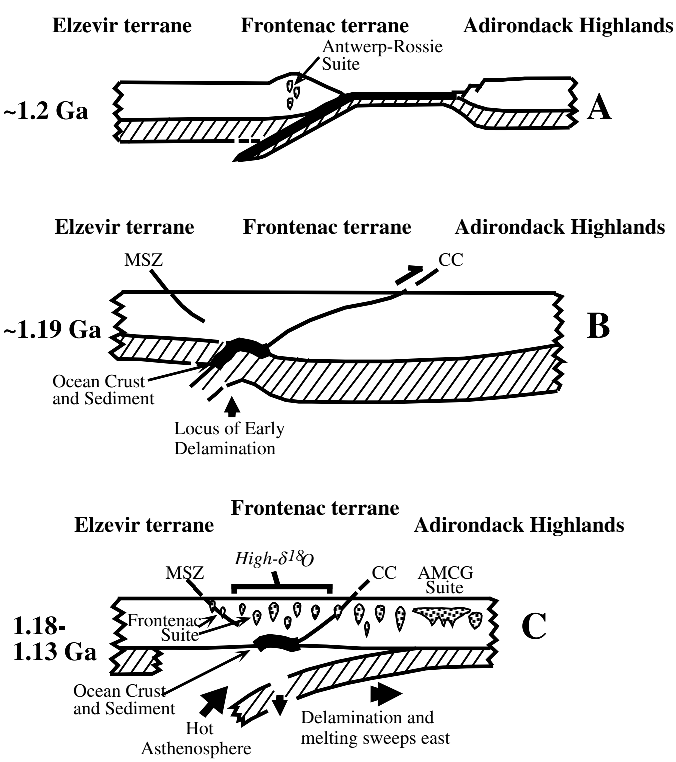

Figure 9. Cartoon (after Wasteneys et al., 1999) of the plate tectonic configuration of subduction and underplating at ca. 1.2 Ga during generation of the calc-alkaline Antwerp-Rossie suite (A), during initial collision of the Frontenac terrane and Adirondack Highlands (B), and during 1.18 to 1.13 Ga anorthosite suite and coeval plutonism (C). Plutonism at 1.18 to 1.13 Ga is interpreted as resulting from postorogenic delamination of lithospheric mantle that progressed to the east, along with decompression melting, ponding of basaltic magmas at the base of the crust, and anatexis of the lower crust to produce granitic magmas (see McLelland et al., 1996). The location of high-$\delta^{18}O$ plutons is consistent with underplating or thrusting of hydrothermally altered ocean crust at the base of the Frontenac terrane before ca. 1.15 Ga. AMCG—anorthosite-mangerite-charnockite-granite; CC—Carthage-Colton mylonite zone; MSZ—Maberly shear zone.

are interpreted as indicating syntectonic intrusion, as are the ca. 1.16 Ga elongate plutons in the Maberly shear zone in the western Frontenac terrane (Corriveau and van Breemen, 2000; Davidson and van Breemen, 2000).

If hydrothermally altered ocean crust was present in the lower crust of the Frontenac terrane during generation of granitic rocks at 1.15 Ga, it was likely either subducted and underplated or underthrust as the orogen closed (Fig. 9). If westward subduction, which caused Antwerp-Rossie plutonism, also subducted hydrothermally altered ocean crust to the base of the Frontenac crust at ca. 1.21 Ga, localization of the Antwerp-Rossie suite in the Frontenac terrane (New York) and high-$\delta^{18}O$ granitic rocks were linked by the geometry of subduction before collision of the Adirondack Highlands–Morin terrane block (Fig. 9). Whatever the direction of subduction, the Central Metasedimentary Belt (Québec) may expose crust that was not underplated because it was farther inboard from the subduction zone than the Frontenac terrane (Ontario). This interpretation is consistent with the lack of juvenile 1.2 Ga Nd model ages in lower crustal xenoliths within the 1.07 Ga Rivard dike in the Central Metasedimentary Belt of Québec (Amelin et al., 1994).

CONCLUSIONS

Zircons preserve the magmatic oxygen-isotope compositions of the high-$\delta^{18}O$ AMCG suite and related granitoid plutons in the Allochthonous Monocyclic Belt of the southern Grenville Province. A traverse from the eastern Adirondacks to the western Frontenac terrane shows pronounced steps of $\delta^{18}O$ in the central Frontenac terrane (Fig. 9). The high-$\delta^{18}O$ plutons of the Frontenac terrane are interpreted as resulting from the melting of a large component of high-$\delta^{18}O$ hydrothermally altered ocean crust and sediments subducted and underplated near the Moho. The lack of gradients in $\delta^{18}O$ on the pluton scale (Fig. 7) and the high $\delta^{18}O$ of zircon indicate that high-$\delta^{18}O$ Frontenac plutons acquired their $\delta^{18}O$ values deep in the crust, and that they were well mixed before crystallization.

The extension of the Frontenac terrane northward along strike in the Central Metasedimentary Belt (Québec) is interpreted to be the quartzite domain, which lacks the distinctive high-$\delta^{18}O$ granitic rocks of Ontario (Fig. 5). A discontinuity along strike in the lower crust of the Frontenac terrane is inferred to reflect differences in location relative to the continental margin in Ontario versus Québec. This discontinuity along strike could also have been caused by the geometry between the Frontenac-quartzite domain block and adjacent terranes, in that subduction and underplating of hydrothermally altered ocean crust and sediments occurred under the Frontenac terrane in Ontario, but not under the extension in Québec.

Basement mapping using stitching plutonic suites can have great utility in delineating exotic crustal blocks, even where there are difficulties in recognizing terrane boundaries. This approach is possible only if the primary, igneous geochemistry of plutonic suites can be rigorously constrained. In this case, analysis of oxygen-isotope ratios in zircon has allowed the inference of large masses of high-δ^{18}O hydrothermally altered basalts and metasedimentary rocks under part of the Frontenac terrane. The analysis of dated zircons to map the δ^{18}O values of magmatic source regions has not been applied previously in Precambrian rocks, and will likely assist in delineation of terrane boundaries and discontinuities in the lower crust of other polymetamorphic orogens.

APPENDIX 1. OXYGEN ISOTOPE RATIOS FROM THE MORIN TERRANE, SOUTHERN GRENVILLE PROVINCE

Pluton	Sample number	SiO_2 wt%	δ^{18}O whole rock	Average whole rock	Other
AMCG suite granitoids					
Grey Valley	CQA877	63.3	11.31, 11.47	11.39	
	CQA878	70.7	11.82	11.82	
	CQA883	70.6	11.31	11.31	
	CQA891	62.7	9.60	9.60	
	CQA928	65.1	9.06	9.06	
	96MR43	66.2	9.82	9.82	Garnet 7.94
					Quartz 11.11, 11.14
Southeastern Mangerite	95MR40	63.7	8.72, 8.87	8.80	
	95MR60	63.3	10.24	10.24	
	95MR62	63.4	10.25	10.25	
	95MR69	64.0	10.30	10.30	
	95MR71	53.6	8.54	8.54	
	95MR72	59.3	9.88	9.88	
	95MR1	58.3	9.52, 9.32	9.42	
	95MR125	56.3	10.00, 9.89	9.95	
Western Mangerite	95MR32	63.6	11.00	11.00	
	95MR35	65.2	9.31, 9.25	9.28	
	95MR81	49.2	9.08	9.08	
	95MR85	76.1	10.93, 11.01	10.97	
	95MR87	66.3	9.55	9.55	
	95MR88	64.4	9.55	9.55	
	96MR21	71.7	11.20, 11.30	11.25	
Janet	CQA1172	64.2	9.61, 9.69	9.65	
	CQA1176	63.6	8.92	8.92	
	CQA1178	62.3	9.37	9.37	
	CQA1181	62.1	9.16	9.16	
Maskinongé	CQA925A				Hornblende 7.75
Mangerite dike	EC84-246	57.1			Quartz 12.95, 12.58
					Garnet 8.78, 8.97, 8.76
					Clinopyroxene 8.52, 8.77
Granitic country rock					
	95MR12		9.90	9.90	
	95MR36		6.65	6.65	
	95MR127		7.26	7.26	
	95MR154		5.69	5.69	
	95MR161		13.68	13.68	
	CQA920	74.5	7.38	7.38	
	CQA921	77.9	7.76, 7.77	7.76	
	98MR7	75.1	8.99, 8.64	8.81	Zircon (NM2) 7.62, 7.43
	98MR6	76.5	8.37	8.37	
	98MR5	77.4	8.26	8.26	

Note: All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). AMCG—anorthosite-mangerite-charnockite-granite. Zircon magnetism indicates magnetic (M) or nonmagnetic (NM) at a particular side tilt (e.g. 2°) of the Frantz Isodynamic Separator. Sample locations are given in Peck (2000).

APPENDIX 2. OXYGEN ISOTOPE RATIOS FROM THE QUARTZITE-RICH DOMAIN OF THE CENTRAL METASEDIMENTARY BELT—QUÉBEC, SOUTHERN GRENVILLE PROVINCE

Pluton	Sample number	SiO_2 wt%	$\delta^{18}O$ whole rock	Average whole rock	Other
Chevreuil suite granitoids					
Armstrong	CQA953	60.7	10.62	10.62	
	CQA1062	70.8	13.40	13.40	
	CQA1067	53.1	10.90	10.90	
	CQA1068	65.6	9.36	9.36	
	CQA1071	52.6	12.77, 12.83	12.80	
	CQA3498a	48.9	8.15, 8.26	8.20	
	CQA3526a	52.2	9.55	9.55	
	CQA3544	62.3	12.71	12.71	
	CQA3547	55.6	10.82	10.82	
	CQA3558	49.0	10.54	10.54	
	CQA4064	52.7	10.02	10.02	
Chreveuil	CQA1085	66.1	11.64	11.64	Hornblende 9.64
	CQA1086d	63.6	12.04	12.04	
	CQA1087	52.6	8.34	8.34	
	CQA1901	60.3	11.23, 11.54	11.38	
	CQA1902	61.9	10.59	10.59	
	CQA3313	51.3	10.52	10.52	
Gagnon	CQA939	64.8	12.31	12.31	
	CQA961	58.9	9.59	9.59	
	CQA964	55.8	8.15	8.15	
	CQA968	72.0	9.61	9.61	
	CQA1372a	66.9	10.39	10.39	
	CQA1951	63.0	10.17	10.17	
	CQA1953	65.6	13.00	13.00	
	CQA1965	72.6	12.05	12.05	
	CQA2206a	48.1	11.20	11.20	
	CQA2200a	62.5	10.28	10.28	
	CQA2647	52.9	7.66, 7.69	7.68	
	CQA2648	64.3	10.40	10.40	
	CQA2651	62.4	10.65	10.65	
	CQA2958	49.4	7.56	7.56	
	CQA3500	51.9	10.08	10.08	
Roches	CQA008	62.1	10.32, 10.36	10.34	Hornblende 7.37
	CQA019	72.8	10.14	10.14	
	CQA023	51.8	7.71	7.71	
	CQA349	65.0	9.77, 9.72	9.74	
	CQA355	62.1	9.20, 9.25	9.22	
	CQA557	55.0	8.45	8.45	
St. Francois	CQA1091a	62.4	10.43	10.43	
	CQA1097b	50.7	9.38	9.38	
	CQA1455a	62.5	9.91	9.91	
Sept Freres	CQA2076a	62.3	11.51	11.51	
Serpent	CQA1022	48.3	9.84	9.84	
	CQA4107	50.8	9.99	9.99	
Sucrerie	CQA134	53.0	7.62	7.62	
	CQA136	58.6	10.10, 10.27	10.18	
	CQA198	57.4	8.75	8.75	
	CQA207	65.4	10.69	10.69	
Unnamed	CQA2605a	50.2	9.16	9.16	
Chevreuil suite gabbros					
Diable	CQA1369a	53.2	9.11	9.11	
	CQA1398a	54.1	9.02	9.02	
	CQA1398b	50.0	8.17	8.17	
	CQA1399a	52.5	8.77	8.77	
	CQA1399b	49.4	8.09	8.09	
	CQA1402a	50.5	9.80	9.80	
	CQA1573a	52.1	8.09	8.09	
	CQA1573b	48.5	7.52	7.52	
Buchesi	CQA1100	49.3	7.24	7.24	
	CQA1105	50.3	7.60	7.60	

APPENDIX 2. ***Continued***

Pluton	Sample number	SiO_2 wt%	$\delta^{18}O$ whole rock	Average whole rock	Other
	CQA1806a	49.0	7.84	7.84	
Hydroplane (gab. dike)	CQA2584a	49.1	8.51	8.51	
	CQA2589a	50.4	8.09, 8.16	8.12	
Har-ha-kon	CQA1799	48.6	9.01	9.01	
	CQA1800a	51.1	8.90	8.90	
Lacordaire	CQA1348a	48.1	10.29	10.29	
	CQA1420a	53.0	7.95	7.95	
	CQA1421a	47.2	7.13	7.13	
	CQA1425a	47.0	7.73	7.73	
	CQA1426a	48.4	7.44	7.44	
	CQA1433a	51.7	7.68	7.68	
	CQA2159a	50.1	7.55	7.55	
	CQA2597a	51.7	10.75, 10.74	10.75	
	CQA1427				Zircon (M1) 6.29, 6.59 Hornblende 6.54, 6.47
Country rocks					
Tonalite (BND, 1220 Ma)	CQA3565A				Zircon (M1) 6.36, 6.30 Hornblende 6.45
Pelite	CQA4021a		14.75	14.75	
Pelite	CQA1499		15.85, 15.85	15.85	
Pelite	CQA750	14.52	14.52		
Tonalites (BND)	CQA1659W		10.06, 9.93	9.99	
Tonalites (BND)	CQA4945A2	12.26	12.26		
Tonalites (BND)	CQA4945A2	12.75	12.75		
Tonalites (BND)	CQA5063	9.85	9.85		
Tonalites (BND)	CQA4960	8.77	8.77		
Al-rich facies (BND)	CQA1659H	8.56	8.56		
Al-rich facies (BND)	CQA4957	8.93	8.93		
Al-rich facies (BND)	CQA4961A	8.41	8.41		
Later intrusive					
Diable (1077 Ma)	CQA1369a	53.2	9.11	9.11	Zircon (M2) 7.55, 7.35 Hornblende 7.11

Note: BND—Bondy Gneiss Dome. All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Zircon magnetism indicates magnetic (M) or nonmagnetic (NM) at a particular side tilt (e.g. 2°) of the Frantz Isodynamic Separator. Sample locations are given in Peck (2000).

APPENDIX 3. OXYGEN ISOTOPE RATIOS FROM THE MARBLE-RICH DOMAIN OF THE CENTRAL METASEDIMENTARY BELT—QUÉBEC, SOUTHERN GRENVILLE PROVINCE

Pluton	Sample number	SiO_2 wt%	$\delta^{18}O$ whole rock	Average whole rock
Chevreuil suite granitoids				
Polonais	CQA1603a	63.8	9.61, 9.73	9.67
Henn	CQA1606	51.6	8.54	8.54
	CQA1607	52.2	7.48	7.48
Baskatong	CQA1161a	61.6	9.69	9.69
	CQA1162	58.1	9.98	9.98
	CQA1167	56.3	10.15	10.15
Ecorses	CQA1116a	58.2	8.97	8.97
	CQA1122	65.9	8.75	8.75
	CQA1126	65.6	9.96, 9.96	9.96
	CQA1127	75.2	9.86	9.86
	CQA1129	51.4	8.70	8.70
	CQA1135a	55.4	7.96	7.96
	CQA1151a	59.5	9.03, 9.15	9.09
	CQA1152	54.0	8.66	8.66
	96FN1	57.4	9.19, 9.36	9.28

Note: All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Sample locations are given in Peck (2000).

APPENDIX 4. OXYGEN ISOTOPE RATIOS OF WHOLE ROCKS FROM FRONTENAC AND ELZEVIR TERRANES, SOUTHERN GRENVILLE PROVINCE

Lithology/pluton	Sample number	$\delta^{18}O$ whole rock	Average whole rock
Frontenac terrane			
Hermon granite	DF178	14.56	14.56
Edwardsville syenite	AM87-5	13.40	13.40
Battersea	LH86-63	13.80	13.80
Perth Road	LH87-64	13.60	13.60
Lyndhurst	LH87-31	12.36,12.59	12.36
South Lake	86DM9c	15.70	15.70
Crow Lake	LH87-30	13.80,14.19	13.80
Beales Mills	95DM53	7.90,7.89	7.90
Elzevir terrane			
Silver Lake	93DM20	9.25	9.25
Oso	92DM152	8.58	8.58

Note: All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Sample locations are given in Peck (2000).

APPENDIX 5. OXYGEN ISOTOPE RATIOS OF MINERALS FROM THE BATTERSEA AND PERTH ROAD PLUTONS, FRONTENAC TERRANE, SOUTHERN GRENVILLE PROVINCE

Lithology/pluton	Sample number	$\delta^{18}O$ quartz	Average quartz	$\delta^{18}O$ biotite	Average biotite
Battersea pluton					
Diorite	96BP1	13.91, 13.84	13.88		
Granite	96BP9	14.93, 14.76	14.85		
Granite	96BP10	14.91, 14.94	14.93		
Granite	96BP11	14.21, 14.10	14.16		
Granite	96BP13	14.22, 14.08	14.15		
Granite	96BP14	13.77, 13.94	13.86		
Granite	96BP15	14.45	14.45		
Granite	96BP16	14.29, 14.08	14.19		
Granite	96BP17	14.78	14.78		
Granite	96BP18	14.05, 14.20	14.13		
Granite	96BP19	14.15, 14.43	14.29		
Granite	96BP20	14.31, 14.18	14.25		
Granite	96BP8-A	14.65, 14.64	14.64		
Granite	96BP8-B	14.64	14.64		
Granite	96BP8-C	14.94	14.94		
Granite	96BP8-C			10.63	10.63
Granite	96BP8-D	14.57	14.57		
Diorite	96BP8-E			10.61	10.61
Diorite	96BP8-F			10.67	10.67
Diorite	96BP8-G			10.64	10.64
Diorite	96BP8-H			10.62	10.62
Granite	96BP8-J	13.86	13.86		
Diorite	96BP2			10.67	10.67
Diorite	96BP3			10.42	10.42
Diorite	96BP6			10.12, 10.13	10.12
Diorite	96BP4			10.52	10.52
Granite	96BP15			9.98	9.98
Granite	96BP12			9.69, 9.74	9.71
Diorite	96BP7			10.16, 9.68	9.92
Perth Road pluton					
Syenite	96PR19	16.43, 16.62	16.52		
Granitic gneiss	96PR10	16.91, 16.91	16.91	13.24, 13.63	13.43
Syenite	96PR18	16.14, 16.26	16.20		
Syenite	96PR17	16.82	16.82		
Monzonite	96PR9	14.28, 14.86	14.57		
Granitic gneiss	96PR12	17.00	17.00		

APPENDIX 5. *Continued*

Lithology/pluton	Sample number	$\delta^{18}O$ quartz	Average quartz	$\delta^{18}O$ biotite	Average biotite
Granitic gneiss	96PR3	17.24	17.24		
Granitic gneiss	96PR4	17.45	17.45		
Granitic gneiss	96PR1	14.80, 15.03	14.92		
Granitic gneiss	96PR2	14.76	14.76		
Monzonite	96PR5	14.87, 15.04	14.96		
Monzonite	96PR8	14.75	14.75		
Monzonite	96PR9	15.19	15.19		
Granitic gneiss	96PR14	17.09	17.09		
Granitic gneiss	96PR15	16.77	16.77		
Granitic gneiss	96PR16	16.49	16.49		
Syenite	96PR20	16.35	16.35		
Syenite	96PR21	15.77, 16.08	15.93		
Syenite	96PR22	16.71	16.71		
Granitic gneiss	96PR13			14.89	14.89
Diorite	96PR6				
	Hornblende = 8.77, 8.87				
	Plagioclase = 11.72, 11.67				
Granitic gneiss	96PR23	17.36, 17.22	17.29		
Granitic gneiss	96PR24	16.89	16.89		
Granitic gneiss	96PR25	17.18	17.18		
Granitic gneiss	96PR26	16.85	16.85		
Granitic gneiss	96PR27	17.71	17.71		
Granitic gneiss	96PR31	16.53	16.53		
Granitic gneiss	96PR32	17.25	17.25		
Granitic gneiss	96PR33	16.65	16.65		
Granitic gneiss	96PR34	16.49	16.49		
Granitic gneiss	96PR35	16.61	16.61		
Monzonite	96PR37	16.89	16.89		

Note: All oxygen isotope ratios are given in standard per mil (‰) notation relative to Vienna Standard Mean Ocean Water (VSMOW). Sample locations are given in Peck (2000).

ACKNOWLEDGMENTS

This work was supported by grants from the National Science Foundation (EAR96-28260), the Department of Energy (93ER14389), and the University of Wisconsin, Department of Geology and Geophysics. Otto van Breemen was instrumental in establishing the geochronology of zircon samples from Ontario and Québec. We thank Mike Spicuzza for assistance in the stable isotope laboratory; Brian Hess for making thin sections; Mike DeAngelis, Chris Frederickson, and Myongsun Kong for their assistance in the field; and James Carl, Don Davis, and Ron Emslie for providing samples. Phil Brown, Guoxiang Chi, Clark Johnson, and Brad Singer offered helpful comments on an early version of the manuscript. Detailed reviews by Margaret Streepey and an anonymous reviewer are gratefully acknowledged. This is Geological Survey of Canada contribution 2002068.

REFERENCES CITED

Amelin, Y., Corriveau, L., and Morin, D., 1994, Constraints on the evolution of Grenvillian lithosphere from Nd-Sr-Pb clinopyroxene and garnet and U-Pb zircon study of pyroxenite and mafic granulitic xenoliths: Reston, Virginia, United States Geological Survey, Circular 1107, p. 5.

Anderson, J.L., 1983, Proterozoic anorogenic granite plutonism of North America, *in* Medaris, L.G., et al., eds., Proterozoic geology: Selected papers from an international Proterozoic symposium: Boulder, Colorado, Geological Society of America Memoir 161, p. 133–154.

Anovitz, L.M., and Essene, E.J., 1990, Thermobarometry and pressure-temperature paths in the Grenville Province of Ontario: Journal of Petrology, v. 31, p. 197–241.

Ashwal, L.D., 1993, Anorthosites. Berlin, Springer-Verlag, 422 p.

Ashwal, L.D., and Wooden, J.L., 1983, Sr and Nd isotope geochronology, geologic history, and origin of the Adirondack Anorthosite: Geochimica et Cosmochimica Acta, v. 47, p. 1875–1885.

Barton, J.M., and Doig, R., 1977, Sr-isotopic studies of the origin of the Morin Anorthosite Complex, Quebec, Canada: Contributions to Mineralogy and Petrology, v. 61, p. 219–230.

Boggs, K., 1996, Retrograde cation exchange in garnets during slow cooling of mid crustal granulites and the P-T-t trajectories from the Mont-Laurier region, Grenville Province, Quebec [M.S. thesis]: Chicoutimi, Université du Québec à Chicoutimi, 333 p.

Bohlen, S.R., Valley, J.W., and Essene, E.J., 1985, Metamorphism in the Adirondacks, 1: Petrology, pressure, and temperature: Journal of Petrology, v. 26, p. 971–992.

Buddington, A.F., 1939, Adirondack igneous rocks and their metamorphism: Boulder, Colorado, Geological Society of America Memoir 7, 354 p.

Busch, J.P., Mezger, K., and van der Pluijm, B.A., 1997, Suturing and extensional reactivation in the Grenville orogen, Canada: Geology, v. 25, p. 507–510.

Carl, J.D., and deLorraine, W.F., 1997, Geochemical and field characteristics of metamorphosed granitic rocks, NW Adirondack Lowlands, New York: Northeastern Geology and Environmental Science, v. 19, p. 276–301.

Carl, J.D., and Sinha, A.K., 1992, Zircon U-Pb age of Popple Hill Gneiss and a Hermon-type granite gneiss, northwest Adirondack Lowlands, New York: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 11.

Carr, S., Easton, R.M., Jamieson, R.A., and Culshaw, N.G., 2000, Geologic transect across the Grenville orogen of Ontario and New York: Canadian Journal of Earth Sciences, v. 37, p. 193–216.

Chiarenzelli, J., and McLelland, J., 1991, Age and regional relationships of granitoid rocks of the Adirondack Highlands: Journal of Geology, v. 99, p. 571–590.

Clechenko, C.C., and Valley, J.W., 2003, Oscillatory zoning in garnet from the Willsboro Wollastonite Skarn, Adirondack Mts, New York: A record of shallow hydrothermal processes preserved in a granulite facies terrane, Journal of Metamorphic Geology, v. 21, p. 771–784.

Clechenko, C., Valley, J.W., Hamilton, M.A., McLelland, J., and Bickford, M.E., 2002, Direct U-Pb dating of the Marcy Anorthosite, Adirondacks, NY, USA: Twelfth Annual V.M. Goldschmidt Conference: Geochimica et Cosmochimica Acta, v. 66, p. A144.

Corfu, F., and Easton, R.M., 1997, Sharbot Lake terrane and its relationships to Frontenac terrane, Central Metasedimentary Belt, Grenville Province: New insights from U-Pb geochronology: Canadian Journal of Earth Sciences, v. 34, p. 1239–1257.

Corriveau, L., 1990, Proterozoic subduction and terrane amalgamation in the southwestern Grenville Province, Canada: Evidence from ultrapotassic to shoshonitic plutonism: Geology, v. 15, p. 614–617.

Corriveau, L., and Morin, D., 2000, Modeling 3D architecture of western Grenville from surface geology, xenoliths, styles of magma emplacement, and Lithoprobe reflectors: Canadian Journal of Earth Sciences, v. 37, p. 235–251.

Corriveau, L., and van Breemen, O., 2000, Docking of the Central Metasedimentary Belt to Laurentia in geon 12: Evidence for the 1.17–1.16 Ga Chevreuil intrusive suite and host gneisses, Quebec: Canadian Journal of Earth Sciences, v. 37, p. 253–269.

Corriveau, L., Rivard, B., and van Breemen, O., 1998, Rheological controls on Grenvillian intrusive suites: Implications for tectonic analysis: Journal of Structural Geology, v. 20, p. 1191–1204.

Cosca, M.A., Essene, E.J., Kunk, M.J., and Sutter, J.F., 1992, Differential unroofing within the Central Metasedimentary Belt of the Grenville Orogen: Constraints from $^{40}Ar/^{39}Ar$ thermochronology: Contributions to Mineralogy and Petrology, v. 110, p. 211–225.

Cureton, J.S., van der Pluijm, B.A., and Essene, E.J., 1997, Nature of the Elzevir–Mazinaw domain boundary, Grenville Orogen, Ontario: Canadian Journal of Earth Sciences, v. 7, p. 976–991.

Currie, K.L., and Ermanovics, I.F., 1971, Geology of the Loughborough Lake region, Ontario, with a special emphasis on the origin of granitoid rocks: Geological Survey of Canada Bulletin 199, 71 p.

Daly, J.S., and McLelland, J., 1991, Juvenile Middle Proterozoic crust in the Adirondack Highlands, Grenville Province, northeastern North America: Geology, v. 19, p. 119–122.

Davidson, A., 1984, Tectonic boundaries within the Grenville Province of the Canadian Shield: Journal of Geodynamics, v. 1, p. 433–444.

Davidson, A., 1995, A review of the Grenville orogen in its North American type area: AGSO [Australian Geological Survey Organisation] Journal of Australian Geology and Geophysics, v. 16, p. 3–24.

Davidson, A., and van Breemen, O., 2000, The age and extent of the Frontenac plutonic suite in the Central Metasedimentary Belt, Grenville Province, Ontario: Radiogenic Age and Isotope Studies Report 13, Ottawa, Ontario, Geological Survey of Canada Current Research 2000–F.

Doig, R., 1991, U-Pb zircon dates of Morin anorthosite suite rocks, Grenville Province, Québec: Journal of Geology, v. 99, p. 729–738.

Easton, R.M., 1986, Geochronology of the Grenville Province, *in* Moore, J.M., Davidson, A., and Baer, A.J., eds., The Grenville Province: St. John's, Newfoundland, Geological Association of Canada Special Paper 31, p. 127–173.

Easton, R.M., 1992, The Grenville Province and the Proterozoic history of central and southern Ontario, *in* Geology of Ontario: Sudbury, Ontario Geological Survey Special Paper 4, Part 1, p. 715–904.

Eiler, J.M., and Valley, J.W., 1994, Preservation of premetamorphic oxygen isotope ratios in granitic orthogneiss from the Adirondack Mountains, New York, USA: Geochimica et Cosmochimica Acta, v. 58, p. 5525–5535.

Emslie, R.F., and Hegner, E., 1993, Reconnaissance isotopic geochemistry of anorthosite-mangerite-charnockite-granite (AMCG) complexes, Grenville Province, Canada: Chemical Geology, v. 106, p. 279–298.

Emslie, R.F., and Hunt, P.A., 1990, Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville Province: Journal of Geology, v. 98, p; 213–231.

Friedman, R.M., and Martignole, J., 1995, Mesoproterozoic sedimentation, magmatism, and metamorphism in the southern part of the Grenville Province (western Quebec): U-Pb geochronological constraints: Canadian Journal of Earth Sciences, v. 32, p. 2103–2114.

Frost, C.D., Frost, B.R., Bell, J.M., and Chamberlain, K.R., 2002, The relationship between A-type granites and residual magmas from anorthosite: Evidence from the northern Sherman batholith, Laramie Mountains, Wyoming, USA: Precambrian Research, v. 119, p. 45–71.

Geraghty, E.P., Isachsen, Y.W., and Wright, S.F., 1981, Extent and character of the Carthage-Colton Mylonite Zone, northwest Adirondacks, New York: Rockville, Maryland, U.S. Nuclear Regulatory Commission Technical Report NUREG/CR-1865.

Gilliam, C.E., and Valley, J.W., 1997, Low $\delta^{18}O$ magma, Isle of Skye, Scotland: Evidence from zircons: Geochimica et Cosmochimica Acta, v. 61, p. 4975–4981.

Hauer, K.L., 1985, Protoliths, diagenesis, and depositional history of the Upper Marble, Adirondack Lowlands, New York [Ph.D. thesis]: Oxford, Ohio, Miami University, 281 p.

Heath, S.A., and Fairbairn, H.W., 1969, Sr^{87}/Sr^{86} ratios in anorthosites and some associated rocks, *in* Isachsen, Y., ed., Origin of anorthosites and related rocks: Albany, New York State Museum Memoir 18, p. 99–110.

Indares, A., and Martignole, J., 1990, Metamorphic constraints on the tectonic evolution of the allochthonous monocyclic belt of the Grenville Province, western Quebec: Canadian Journal of Earth Sciences, v. 27, p. 371–386.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.

King, E.M., Barrie, C.T., and Valley, J.W., 1997, Hydrothermal alteration of oxygen isotope ratios in quartz phenocrysts, Kidd Creek Mine, Ontario: Magmatic values are preserved in zircon: Geology, v. 25, p. 1079–1082.

King, E.M., Valley, J.W., Davis, D.W., and Edwards, G.R., 1998, Oxygen isotope ratios of Archean plutonic zircons from granite-greenstone belts of the Superior Province: Indicator of magmatic source: Precambrian Research, v. 92, p. 365–385.

Kitchen, N., and Valley, J.W., 1995, Carbon isotope thermometry in marbles of the Adirondack Mountains, New York: Journal of Metamorphic Geology, v. 13, p. 577–594.

Kretz, R., 1990, Biotite and garnet compositional variation and mineral equilibria in Grenville gneisses of the Otter Lake area, Quebec: Journal of Metamorphic Geology, v. 8, p. 493–506.

Lumbers, S.B., Heaman, L.M., Vertolli, V.M., and Wu, T.-W., 1990, Nature and timing of Middle Proterozoic magmatism in the Central Metasedimentary Belt, Grenville Province, Ontario, *in* Gower, C.F., et al., eds., Mid-Proterozoic Laurentia-Baltica: St. John's, Newfoundland, Geological Association of Canada Special Paper 38, p. 243–276.

Marcantonio, F., McNutt, R.H., Dickin, A.P., and Heaman, L.M., 1990, Isotopic evidence for the crustal evolution of the Frontenac Arch in the Grenville Province of Ontario, Canada: Chemical Geology, v. 83, p. 297–314.

Martignole, J., and Friedman, R., 1998, Geochronological constraints on the last stages of terrane assembly in the central part of the Grenville Province: Precambrian Research, v. 92, p. 145–164.

Martignole, J., and Reynolds, P., 1997, $^{40}Ar/^{39}Ar$ thermochronology along a western Quebec transect of the Grenville Province, Canada: Journal of Metamorphic Geology, v. 15, p. 283–296.

Martignole, J., and Schrijver, K., 1970, Tectonic setting and evolution of the Morin anorthosite, Grenville Province, Quebec: Geological Society of Finland Bulletin, v. 42, p. 165–209.

Martignole, J., Calvert, A.J., Friedman, R., and Reynolds, P., 2000, Crustal evolution along a seismic section across the Grenville Province (western Quebec): Canadian Journal of Earth Sciences, v. 37, p. 291–306.

Matthews, A., Palin, J.M., Epstein, S., and Stolper, E.M., 1994, Experimental study of $^{18}O/^{16}O$ partitioning between crystalline albite, albitic glass, and CO_2 gas: Geochimica et Cosmochimica Acta, v. 58, p. 5255–5266.

McCulloch, M.T., Gregory, R.T., Wasserburg, G.J., and Taylor, H.P., 1980, A neodymium, strontium, and oxygen isotopic study of the Cretaceous Samail Ophiolite and implications for the petrogenesis and seawater-hydrothermal alteration of oceanic crust: Earth and Planetary Sciences Letters, v. 46, p. 201–211.

McLelland, J., and Chiarenzelli, J., 1990, Isotopic constraints on the emplacement age of the Marcy anorthosite massif, Adirondack Mountains, New York: Journal of Geology, v. 98, p. 19–41.

McLelland, J., and Whitney, P., 1990, Anorogenic, bimodal emplacement of anorthositic, charnockitic, and related rocks in the Adirondack Mountains, New York, *in* Stein, H.J., and Hannah, J.L., eds., Ore-bearing granite systems: Petrogenesis and mineralizing processes: Boulder, Colorado, Geological Society of America Special Paper 246, p. 301–315.

McLelland, J., Chiarenzelli, J., Whitney, P., and Isachsen, Y., 1988, U-Pb zircon geochronology of the Adirondack Mountains and implications for their geologic evolution: Geology, v. 16, p. 920–924.

McLelland, J., Daly, J.S., and Chiarenzelli, J., 1993, Sm-Nd and U-Pb isotopic evidence for juvenile crust in the Adirondack Lowlands and implications for the evolution of the Adirondack Mts.: Journal of Geology, v. 101, p. 97–105.

McLelland, J., Daly, J.S., and McLelland, J.M., 1996, The Grenville orogenic cycle (ca. 1350–1000 Ma): An Adirondack perspective: Tectonophysics, v. 265, p. 1–28.

McLelland, J.M., Hamilton, M.A., Bickford, M.E., Clechenko, C., and Valley, J.W., 2002, SHRIMP II Geochronology of the Adirondack AMCG suite, II: Granitoids, gabbros, and crosscutting dikes: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 271.

Mezger, K., Rawnsley, C.M., Bohlen, S.R., and Hanson, G.N., 1991, U-Pb garnet, sphene, monazite, and rutile ages: Implications for the duration of metamorphism and cooling histories, Adirondack Mts., New York: Journal of Geology, v. 99, p. 415–428.

Mezger, K., van der Pluijm, B.A., Essene, E.J., and Halliday, A.N., 1992, The Carthage-Colton mylonite zone (Adirondack Mountains, New York): The site of a cryptic suture in the Grenville Orogen? Journal of Geology, v. 100, p. 630–638.

Mezger, K., Essene, E.J., van der Pluijm, B.A., and Halliday, A.N., 1993, U-Pb geochronology of the Grenville orogen of Ontario and New York: Constraints on ancient crustal tectonics: Contributions to Mineralogy and Petrology, v. 114, p. 13–26.

Morrison J., and Valley, J.W., 1988, Contamination of the Marcy anorthosite massif, Adirondack Mountains, N.Y.: Petrologic and isotopic evidence: Contributions to Mineralogy and Petrology, v. 98, p. 97–108.

Muehlenbachs, K., 1986, Alteration of the ocean crust and the ^{18}O history of seawater, *in* Valley J.W., Taylor, H.P., and O'Neil, J.R., eds., Stable isotopes in high temperature geological processes: Reviews in Mineralogy, v. 16, p. 425–444.

Owens, B.E., Rockow, M.W., and Dymek, R.F., 1993, Jotunites from the Grenville Province, Quebec: Petrological characteristics and implications for massif anorthosite petrogenesis: Lithos, v. 30, p. 57–80.

Peacock, M.A., 1931, Classifications of igneous rock series: Journal of Geology, v. 39, p. 65–67.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretations of granitic rocks: Journal of Petrology, v. 25, p. 956–983.

Peck, W.H., 2000, Oxygen Isotope Studies of Grenville Metamorphism and Magmatism [Ph.D. thesis]: Madison, University of Wisconsin, 320 p.

Peck, W.H., and Valley, J.W., 1998, Oxygen diffusion in zircon: Quartz-zircon disequilibrium in Grenville quartzites: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 317.

Peck, W.H., and Valley, J.W., 2000, Large crustal input to high $\delta^{18}O$ anorthosite massifs of the southern Grenville Province: New evidence from the Morin Complex, Quebec: Contributions to Mineralogy and Petrology, v. 139, p. 402–417.

Peck, W.H., Valley, J.W., and McLelland, J., 1999, Slow oxygen diffusion in zircon during cooling of Adirondack orthogneiss: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. 103.

Peck, W.H., Valley, J.W., and Graham, C.M., 2003, Slow oxygen diffusion rates in igneous zircons from metamorphic rocks: American Mineralogist, v. 88, p. 1003–1014.

Pehrsson, S., Hanmer, S., and van Breemen, O., 1996, U-Pb geochronology of the Raglan gabbro belt, Central Metasedimentary Belt, Ontario: Implications for an ensialic marginal basin in the Grenville Orogen: Canadian Journal of Earth Sciences, v. 33, p. 691–702.

Perkins, D., Essene, E.J., Marcotty, L.A., 1982, Thermometry and barometry of some amphibolite-granulite facies rocks from the Otter Lake area, southern Quebec: Canadian Journal of Earth Sciences, v. 9, p. 1759–1774.

Rivers, T., Martignole, J., Gower, C.F., and Davidson, A., 1989, New tectonic divisions of the Grenville Province, Southeast Canadian Shield: Tectonics, v. 8, p. 63–84.

Rockow, M.W., 1995, Petrogenesis of the jotunite unit at the Morin Complex, Grenville Province, Quebec: A field, mineralogical and chemical study [Ph.D. thesis]: St. Louis, Missouri, Washington University, 477 p.

Shand, S.J., 1951, Eruptive Rocks: New York, John Wiley and Sons, 360 p.

Shieh, Y., 1985, High-^{18}O granitic plutons from the Frontenac Axis, Grenville Province of Ontario, Canada: Geochimica et Cosmochimica Acta, v. 49, p. 117–123.

Shieh Y., and Schwarcz, H.P., 1978, The oxygen isotope composition of the surface of the Canadian Shield: Canadian Journal of Earth Sciences, v. 15, p. 1773–1782.

Smith, T.E., Holm, P.E., Dennison, N.M., and Harris, M.J., 1997, Crustal assimilation in the Burnt Lake metavolcanics, Grenville Province, southeastern Ontario, and its tectonic significance: Canadian Journal of Earth Sciences, v. 34, p. 1272–1285.

Solomon, G.C., and Taylor, H.P., Jr., 1989, Isotopic evidence for the origin of Mesozoic and Cenozoic granitic plutons in the northern Great Basin: Geology, v. 17, p. 591–594.

Spicuzza, M.J., Valley, J.W., and McConnell, V.S., 1998, Oxygen isotope analysis of whole rock via laser fluorination: An air-lock approach: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 80.

Streepey, M.M., Essene, E.J., and van der Pluijm, B.A., 1997, A compilation of thermobarometric data from the metasedimentary belt of the Grenville Province, Ontario and New York State: Canadian Mineralogist, v. 35, p. 1237–1247.

Taylor, H.P., 1969, Oxygen isotope studies of anorthosites, with particular reference to the origin of bodies in the Adirondack Mts., NY, *in* Isachsen, Y., ed., Origin of anorthosites and related rocks: Albany, New York State Museum Service Memoir 18, p. 111–134.

Taylor, H.P., and Sheppard, S.M.F., 1986, Igneous Rocks, I: Processes of isotopic fractionation and temperature systematics, *in* Valley, J.W., et al., eds., Stable isotopes in high temperature geological processes: Reviews in Mineralogy, v. 16, p. 227–271.

Valley, J.W., 2003, Oxygen isotopes in zircon, *in* Hanchar, J., and Hoskin, L., eds., Zircon: Reviews in Mineralogy and Geochemistry, v. 53, p. 343–385.

Valley, J.W., and O'Neil, J.R., 1982, Oxygen isotope evidence for shallow intrusion of Adirondack anorthosite: Nature, v. 300, p. 497–500.

Valley, J.W., and O'Neil, J.R., 1984, Fluid heterogeneity during granulite facies metamorphism in the Adirondacks: Stable isotope evidence: Contributions to Mineralogy and Petrology, v. 85, p. 158–173.
Valley, J.W., Bohlen, S.R., Essene, E.J., and Lamb, W., 1990, Metamorphism in the Adirondacks, II: The role of fluids: Journal of Petrology, v. 31, p. 555–596.
Valley, J.W., Chiarenzelli, J.R., and McLelland, J.M., 1994, Oxygen isotope geochemistry of zircon: Earth and Planetary Science Letters, v. 126, p. 187–206.
Valley, J.W., Kitchen, N., Kohn, M.J., Niendorf, C.R., and Spicuzza, M.J., 1995, UWG-2, a garnet standard for oxygen isotope ratios: Strategies for high precision and accuracy with laser heating: Geochimica et Cosmochimica Acta, v. 59, p. 5523–553.
Valley, J.W., Bindeman, I.N., and Peck, W.H., 2003, Empirical calibration of oxygen isotope fractionation in zircon: Geochimica et Cosmochimica Acta, Clayton Volume, v. 67, p. 3257–3266.
van Breemen, O., and Corriveau, L., 1995, Evolution of the Central Metasedimentary Belt in Quebec, Grenville orogen: U-Pb geochronology: International Conference on Tectonics and Metallogeny of Early/Mid Precambrian Orogenic Belt, Precambrian 1995, École Polytechnique de Montrége, Montreal, Program with Abstracts, p. 137.
van Breemen, O., and Davidson, A., 1988, U-Pb zircon ages of granites and syenites in the Central Metasedimentary Belt, Grenville Province, Ontario: Radiogenic Age and Isotope Studies Report 2: Ottawa, Ontario, Geological Survey of Canada Paper 88-2, p. 45–50.
van der Pluijm, B.A., Mezger, K., Cosca, M.A., and Essene, E.J., 1994, Determining the significance of high-grade shear zones by using temperature-time paths, with examples from the Grenville orogen: Geology, v. 22, p. 743–746.
Wasteneys, H.A., 1994, U-Pb geochronology of the Frontenac Terrane, Central Metasedimentary Belt, Grenville Province, Ontario: Geological Association of Canada–Mineralogical Association of Canada, Program with Abstracts, v. 19, p. 18.
Wasteneys, H., McLelland, J., and Lumbers, S., 1999, Precise zircon geochronology in the Adirondack Lowlands and implications for revising plate tectonic models of the Central Metasedimentary Belt and Adirondack Mountains, Grenville Province, Ontario and New York: Canadian Journal of Earth Sciences, v. 36, p. 967–984.
Watson, E.B., and Cherniak, D.J., 1997, Oxygen diffusion in zircon: Earth and Planetary Science Letters, v. 148, p. 527–544.
Watson, B., and Harrison, M., 1983, Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types: Earth and Planetary Science Letters, v. 64, p. 295–304.
Wu, T., and Kerrich, R., 1986, Combined oxygen isotope-compositional studies of some granitoids from the Grenville Province of Ontario, Canada: Implications for source regions: Canadian Journal of Earth Sciences, v. 23, p. 1412–1432.
Zhao, X., Ji, S., and Martignole, J., 1997, Quartz microstructures and c-axis preferred orientations in high-grade gneisses and mylonites around the Morin anorthosite (Grenville Province): Canadian Journal of Earth Sciences, v. 34, p. 819–832.

Manuscript Accepted by the Society August 25, 2003

Printed in the USA