Geology

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Geology 2010;38;151-154
doi: 10.1130/G30342.1

Notes

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ABSTRACT

Geochemical and Nd isotopic data from mafic and newly discovered ultramafic rocks in the Adirondack Lowlands suggest widespread enrichment of the lithospheric mantle under the Grenville Province. Incompatible element abundances and previously published Hf $T_{DM\,(zircon)}$ (depleted mantle model age) and Nd T_{DM} ages from rocks of the anorthosite-mangerite-charnockite-granite suite in the Adirondack Highlands document similar enrichment in the lower crust and its strong influence on subsequent magmatic events throughout the Ontario-Quebec-Adirondack segment of the Grenville Province. Likely the consequence of long-lived (ca. 1.4–1.2 Ga) northwest-directed subduction along the southeast edge of Laurentia (previously proposed Andean margin), this enrichment is similar to that associated with the vast (>240,000 km²) ultrapotassic province of the western Churchill Province. Enrichment of the lithospheric mantle beneath orogenic belts is a predictable and important differentiation process that has operated on Earth for at least the past 3 b.y.

ENRICHMENT BENEATH OROGENIC BELTS? A GRENVILLIAN EXAMPLE

Although subduction-related arc magmatism and resulting collisional orogenesis are well documented in the crust of orogenic belts, the impact on the underlying lithospheric mantle is relatively little known. Because orogenesis is preceded by the subduction of altered oceanic crust and sediment, and the ascent of derived magmas and volatiles, long-lived subduction events should leave a permanent geochemical and isotopic signature in the lithospheric mantle and lower crust of the overriding plate. However, can such enrichment influence the geochemistry of melts generated millions of years later over broad areas beneath the continents?

The Grenville orogen, one of the world's largest Precambrian (ca. 1.0–1.3 Ga) orogenic belts, extends from Baltica through the Canadian Maritimes, along the spine of the Appalachians, into Mexico and beyond. Originally defined in Canada (Fig. 1A) by the K-Ar studies of Stockwell (1968), rocks of the Grenville Province have been variably affected by several orogenic events preceding the Grenvillian orogeny (Rivers, 2008). This orogeny followed one of the Earth's major episodes of crustal growth (Condie, 1998), and led to the final assembly of Rodinia. Hanmer et al. (2000) and Rivers and Corrigan (2000) argued for the development of an Andean-type margin in the Ontario-Quebec-Adirondack segment of the orogen that formed along the leading edge of

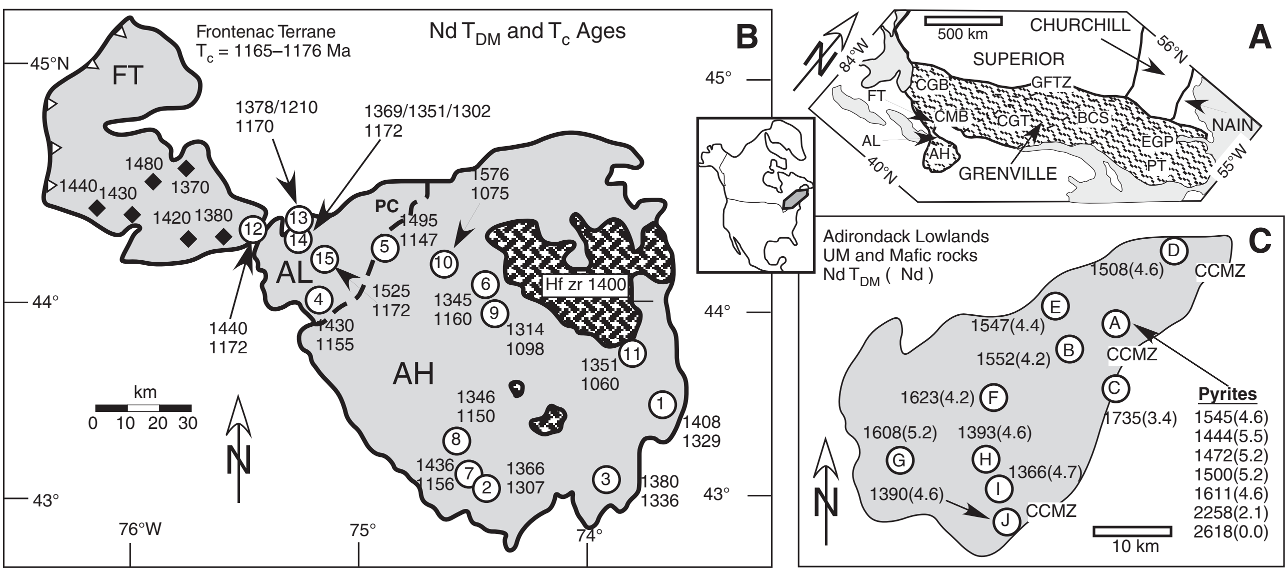

Figure 1. A: General location and subdivisions of Grenville Province (after McLelland et al., 1996). AH—Adirondack Highlands; AL—Adirondack Lowlands; BCS—Baie Comeau segment; CGB—Central Gneiss Belt; CGT—Central Granulite terrane; CMB—Central Metasedimentary Belt; EGP—Eastern Grenville Province; GFTZ—Grenville Front tectonic zone; PT—Pinware terrane. B: Neodymium T_{DM} (depleted mantle model) ages across part of the Grenville orogen including Frontenac terrane (FT), AL, and AH. PC—location of Pyrites Complex; T_c—Time of crystallization. Nd T_{DM} model ages and time of crystallization are given for AH (circles 1–11; Daly and McLelland, 1991) and AL (circles 12–15; McLelland et al. 1993). Data (diamonds) within Frontenac terrane are from Marcantonio et al. (1990). Checkered pattern—massif anorthosite bodies. Average Hf T_{DM} age from zircons of anorthosite-mangerite-charnockite-granite suite of 1400 Ma is shown in box (Bickford et al., 2008). Carthage Colton mylonite zone is shown as a dashed line. C: Enlarged (2.5×) inset (circles A–J) shows new data from mafic and ultramafic rocks in AL (this study). CCMZ—Carthage Colton mylonite zone; UM—ultramafic.

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Laurentia from ca. 1400 to 1200 Ma. If so, the underlying lithospheric mantle and lower crust of this area should be strongly influenced by subduction-related metasomatic processes.

We report Nd (T_{DM}) (depleted mantle model ages) and trace element geochemistry for mafic and previously unrecognized ultramafic rocks from the Adirondack Lowlands. While model ages determined from mafic-ultramafic rocks are generally not well constrained because of their low slope on Nd evolution diagrams (Dickin and McNutt, 2007), these rocks have geochemical traits and Nd evolution pathways similar to granitic rocks previously analyzed in the Adirondacks (Daly and McLelland, 1991; McLelland et al., 1993). They provide direct evidence of a widespread event or events that have influenced the isotopic systematics and trace element geochemistry of igneous rock suites subsequently intruded throughout the area, including the voluminous anorthosite-mangerite-charnockite-granite (AMCG) suite. Thus, these rocks offer a window into enrichment processes in the upper lithospheric mantle and lower crust that influenced the composition of subsequent intrusive events for ~300 m.y.

ULTRAMAFIC ROCKS IN THE ADIRONDACK LOWLANDS

The Adirondack Mountains are ~100 × 150 km domical uplift of the Grenville basement rocks in northern New York (Fig. 1). Separated into the Adirondack Lowlands and Highlands along the Carthage Colton mylonite zone, they are respectively equivalent to the Central Metasedimentary Belt and Central Granulite terrane, primarily exposed in eastern Ontario and Quebec. The area, and the Central Granulite terrane in particular, is extensively intruded by rocks of the 1150–1170 Ma AMCG and younger granitoids (McLelland et al., 1996).

The Adirondack Lowlands consist of a highly deformed supracrustal sequence dominated by shallow-water pure and siliceous marbles and pelitic gneisses metamorphosed and intruded by a variety of igneous rocks during the Shawinigan orogeny (Heumann et al., 2006). Although ultramafic rocks are exceedingly rare, several dismembered and highly intruded amphibolite belts occur. At Pyrites, New York, a small (~1 km^2) exposure of cumulate ultramafic rocks occurs within a ~15-km-long belt of amphibolite and hornblendite (Pyrites Complex; Fig. 1C). The amphibolite at Pyrites is in structural contact with marbles and pyritic pelitic gneisses. Elsewhere in the Adirondack Lowlands these supracrustal rocks are crosscut by igneous rocks that have been dated at ca. 1210 Ma (Wasteneys et al., 1999), and therefore must be older.

Within the ultramafic rocks at Pyrites decimeter to meter-scale compositional (pyroxenite and peridotite) and textural layering is at an angle to steep foliation trends in enveloping supracrustal rocks. A coarse-grained (to 3 cm) phlogopite-rich lamprophyre dike, as much as 1.5 m wide, cuts sharply across the aforementioned cumulate layering. The ultramafic rocks, with the exception of remnant augite and chromite, are composed of hydrous, secondary magnesium-rich silicates including talc, tremolite, phlogopite, chlorite, and serpentine.

Ultramafic and associated mafic rocks from Pyrites contain 33.7–52.1 wt% SiO_2 and have MgO concentrations of 12.4–33.3 wt% (see Table DR2 in the GSA Data Repository [1]). Chromium and Ni concentrations are typical of mantle rocks, with concentrations to 5440 and 1588 ppm, respectively. When normalized to primitive mantle, large ion lithophile element (LILE) concentrations, including Cs, Rb, Ba, Th, U, Pb, and the light rare earth elements are considerably elevated (Fig. 2). In contrast, high field strength elements such as Nb, Ta, P, and Ti exhibit pronounced negative anomalies. This geochemical signature is shared by all members of the suite, including the crosscutting lamprophyre dike.

A suite of dismembered amphibolites and metagabbros from throughout the Adirondack Lowlands (Lowlands mafic rocks) is geochemically similar, but has flatter and higher rare earth element concentrations and lacks a pronounced Ti anomaly (Fig. 2). Their relationship to ultramafic rocks of the Pyrites Complex is unknown; however, they most likely represent highly disrupted fragments of oceanic crust derived from enriched mantle like that exposed at Pyrites.

NEODYMIUM SYSTEMATICS OF LOWLANDS ULTRAMAFIC AND MAFIC ROCKS

Samples from the Pyrites Complex and from mafic rocks (amphibolites and metagabbros) throughout the Adirondack Lowlands, including one Highlands sample (Dana Hill metagabbro) have ε_{Nd} at 1210 or 1365 Ma values that range from +0.0 to +5.5 (inset, Fig. 1C; Table DR3). Neodymium T_{DM} ages range from

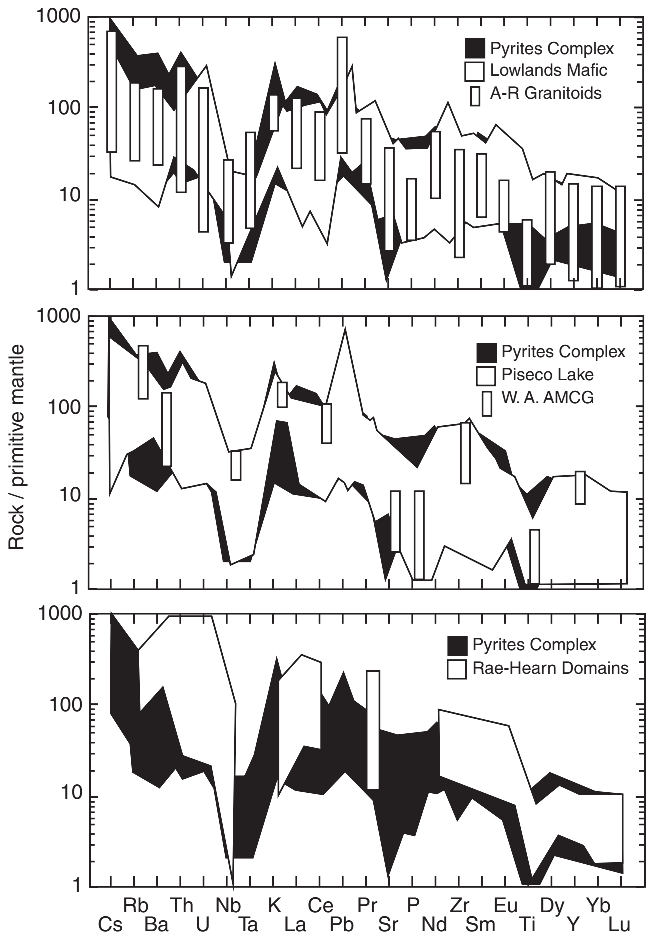

Figure 2. Primitive mantle normalized (Sun and McDonough, 1989) incompatible element abundances of Adirondack metaigneous suites mentioned in this study. Upper diagram shows Pyrites Complex, granitoids of West Canada Creek (R. Price, 2008, personal commun.) and Piseco Lake areas (Chiarenzelli's data, and D. Valentino, 2008, personal commun), and granites of western Adirondack anorthosite-mangerite-charnockite-granite (W-A AMCG) suite (Whitney, 1992). Middle diagram shows Pyrites Complex, Adirondack Lowlands amphibolites and gabbros, and granitoids of Antwerp-Rossie suite (Regan's data). Lower diagram shows minettes of the Rae-Hearne craton (Cousens et al., 2001) and the Pyrites Complex.

[1]GSA Data Repository item 2010030, Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

1366 to 1735 Ma (average 1510 Ma), with the exception of altered lamprophyre and metagabbro samples that yield unrealistically old ages (2260 and 2620 Ma) and have shallow slopes. Excluding disturbed samples (PLAMP and PGAB), rocks from the Pyrites Complex yield a Sm-Nd isochron of 1442 ± 120 Ma, and individual T_{DM} ages fall within error of this age. Similarly, a Sm-Nd isochron (Fig. 3) including amphibolites and metagabbros (Lowlands mafic rocks) and rocks of the Pyrites Complex yields an age of 1443 ± 170 Ma and is constrained between the arrays of Quebecia (ca. 1530 Ma; Dickin and Higgins, 1992) and the juvenile crust of Ontario's Central Metasedimentary Belt (ca. 1270 Ma; Dickin and McNutt, 2007). The crystallization age of the Pyrites Complex is assumed to be 1365 Ma, the oldest reported igneous age (juvenile tonalites) in the Adirondacks (McLelland and Chiarenzelli, 1990). Three samples of Balmat mafic rocks crosscut supracrustal rocks and are likely part of the 1210 Ma Antwerp-Rossie suite (Wasteneys et al., 1999). They are shown separately for comparison (Figs. 3 and 4).

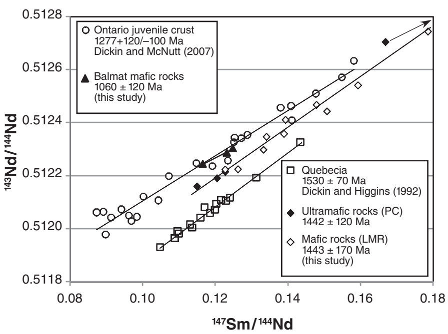

Figure 3. Sm-Nd isochron plot showing whole-rock samples of Pyrites Complex (filled diamonds) and Adirondack Lowlands mafic rocks (open diamonds), Quebecia (Dickin and Higgins, 1992), Ontario juvenile crust (Dickin and McNutt, 2007), and mafic rocks cutting the Adirondack Lowlands supracrustal sequence near Balmat (this study). Regression lines that correspond to calculated isochron ages are shown for reference.

The Nd isotopic evolution paths for the Pyrites Complex and Lowlands mafic rocks show substantial overlap (Fig. 4). At the time of crystallization, ε_{Nd} values for the Lowlands mafic rocks are below the depleted mantle curve of DePaolo (1981), suggesting derivation from an enriched mantle source or crustal contamination. Primitive compositions, incompatible element trends, lack of systematic variation in ε_{Nd} or T_{DM} relative to SiO_2 content, inferred oceanic origin, and positive ε_{Nd} values suggest that the Pyrites Complex is likely a sample of this mantle.

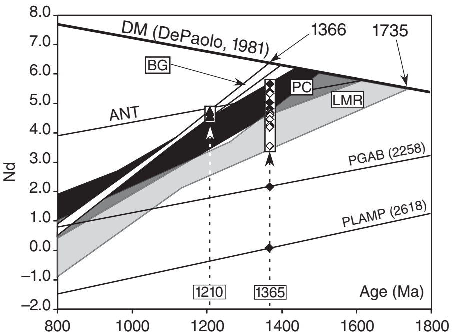

Figure 4. Nd isotopic evolution paths for mafic and ultramafic rocks of the Adirondack Lowlands. Two samples of the Pyrites Complex (PLAMP and PGAB) with extensive alteration have unrealistically old model ages and shallow slopes; one sample of amphibolite at Antwerp (ANT) shares similar slope. Circles (open—LMR; filled—PC) show individual crossing points at estimated ages 1210 and 1365 Ma. PC—Pyrites Complex; BG—Balmat Gabbros; LMR—Lowlands mafic rocks; DM—depleted mantle.

ENRICHMENT OF YOUNGER IGNEOUS ROCK SUITES

Numerous granitic intrusive suites ranging in age from 1050 to 1350 Ma occur in the Adirondacks (McLelland et al., 1988). Primitive mantle normalized incompatible element concentrations from granitic rocks in the Adirondack Highlands (Whitney, 1992; ca. 1150–1170 Ma AMCG suite), and calc-alkaline arc rocks in the Lowlands (Wasteneys et al., 1999; ca. 1210 Ma) have been plotted for comparative purposes (Fig. 2). They are remarkably similar to those of the Pyrites Complex and Lowlands mafic rocks both in scale and pattern with enriched LILEs and negative Nb, Ta, P, and Ti anomalies. Several studies have been conducted on the Nd isotopic systematics of a variety of felsic igneous rock suites ranging in age from 1075 to 1366 Ma in the Adirondack Highlands and Lowlands and adjacent areas of the Frontenac terrane in Ontario (Fig. 1A; Marcantonio et al., 1990; Daly and McLelland, 1991; McLelland et al., 1993). With few exceptions, these rocks have positive ε_{Nd} values (average +3), Nd T_{DM} ages of 1302–1576 Ma (average 1381–1412 Ma), and show no correspondence between SiO_2 content (~55–75 wt%) and Nd T_{DM} ages (Fig. 1B; Tables DR1 and DR4). These parameters limit the amount of older continental crust that was involved in the generation of these melts, as local supracrustal gneisses have ε_{Nd} values of –2.5 to –6.1 and T_{DM} of ca. 1790–2075 Ma (Marcantonio et al., 1990; Daly and McLelland, 1991).

Work by Bickford et al. (2008) on the Lu-Hf ratios of zircon separated from AMCG rocks (McLelland et al., 1988) yields similar Hf model ages (T_{DM}) of ca. 1400 Ma, consistent with Nd model ages (Daly and McLelland, 1991). Any model for the origin of these rocks must take into account their arc-like geochemical anomalies, enriched Nd and Hf isotopic systematics, and nearly identical and restricted range of Hf and Nd T_{DM} model ages of mafic and felsic metaigneous rocks of wide compositional range in Adirondacks (Table DR4).

The geochemistry and isotopic systematics of felsic and mafic metaigneous rocks in the Adirondack Highlands and Lowlands are similar to those derived from enriched mantle above subduction zones. The concentrations of incompatible elements and Nd isotopes in Adirondack felsic rocks are consistent with derivation, in part, from enriched mantle material like that exposed at Pyrites (Fig. 2). However, mantle, enriched or not, cannot have produced the vast volume of felsic melt associated with 1150–1170 Ma AMCG suite. McLelland et al. (1993) proposed, on the basis of Nd systematics, that juvenile tonalitic lower crust (ca. 1300–1365 Ma) like that exposed in the southern and eastern Adirondacks (ε_{Nd} = +5 at 1365 Ma), or more widely as the Dysart–Mount Holly granitoids (Rivers and Corrigan, 2000), was the source of AMCG rocks. Other potential sources include 1400–1500 Ma crust of the mid-continent granite-rhyolite province, and 1370–1450 Ma arc plutons exposed near Mauricie, Quebec (Rivers and Corrigan, 2000; Hanmer et al., 2000).

We consider that enrichment of depleted mantle began in the Grenville Province after 1.45 Ga, consistent with the age of Andean-type arc magmatism (1.4–1.2 Ga) proposed by Hanmer et al. (2000). Subsequently both the geochemistry and Nd and Hf systematics of mafic and felsic melts over ~300 m.y. was influenced by enriched mantle and juvenile lower crust underlying much of the Ontario-Quebec-Adirondack segment of the Grenville Province. Rocks of the widespread AMCG suite (ca. 1.15 Ga), formed by staging of vast volumes of basaltic magma that melted the base of the crust, reflect the geochemical and isotopic characteristics of their source(s). If so, how extensive is this area of enriched lithosphere? It likely includes the entire Central Granulite terrane with its massive volume of AMCG plutons. To the northwest, AMCG rocks of the appropriate age, Nd model ages, and geochemical trends extend across 350 km from the western boundary of the Frontenac terrane (Fig. 1A; Marcantonio et al., 1990) to the Adirondack Highlands. Similar geochemical trends are apparent in AMCG rocks farther to the south in the Hudson Highlands (M.L. Gorring, 2009, personal commun.).

ORIGIN OF THE ENRICHMENT

One mechanism for enriching the mantle and overlying lower crust is the widespread permeation of subduction-derived melts over prolonged periods or episodes of enhanced subduction (Condie, 1998). In Figure 2, the range in incompatible element concentrations (normalized to primitive mantle) of the Pyrites Complex is plotted against that of Paleoproterozoic (T_c = 1830 Ma) ultrapotassic rocks of the Christopher Island Formation in the western Churchill Province, subarctic Canada, from Cousens et al. (2001). These minette dikes and flows range from 41 to 72 wt% SiO_2 and, despite their range in SiO_2 content, they have a remarkable uniformity in Nd systematics (ε_{Nd} at 1830 Ma = –9 to –7; T_{DM} = 2.67–3.15 Ga). They are derived from an enriched mantle reservoir developed via flat subduction under a broad area of the western Churchill Province (>240,000 km^2) between the Rae and Hearn domains during the Neoarchean (Cousens et al., 2001). Several sets of older dikes and flows within the same Nd isotopic envelope attest to the long-lived influence of the enriched mantle on magmatism that spans nearly a billion years and a wide compositional spectrum.

The Grenville orogenic cycle resulted in the final assembly of Rodinia, one of the world's supercontinents; preceding this, a vast volume of oceanic crust was subducted beneath the leading edge of Laurentia from ca. 1400 to 1200 Ma. This event left a profound geochemical overprint on the overlying lithospheric mantle and lower crust that served as source material for subsequent igneous events ranging from mafic to felsic, including the voluminous AMCG suite. A similar enrichment event is recognized in ca. 3.0 Ga igneous rocks of the Pilbara craton of Western Australia (Smithies et al., 2004), in the western Churchill Province in Arctic Canada (Cousens et al., 2001), the Jurassic dolerites of the Ferrar Group (Morrison and Reay, 1995), and in Miocene–Pliocene igneous rocks in the Sierra Nevada (Cousens et al., 2008). The pervasive geochemical modification of the lithospheric mantle and lower crust appears to be a significant differentiation process operative in orogenic belts over at least the past 3 b.y. This enrichment has influenced the chemistry and isotopic systematics of subsequent magmatism in orogenic belts regardless of composition, tectonic origin, or ultimate source of the igneous rocks over hundreds of millions of years.

ACKNOWLEDGMENTS

We thank Rachel Price, David Valentino, and the 2008 Lowlands Keck Project (William Peck, Bruce Selleck, and Martin Wong) for sharing geochemical data.. J.M. McLelland, J.A. Donaldson, and three critical reviewers read the manuscript and improved its accuracy and clarity: their time and effort are greatly appreciated. We also thank St. Lawrence University, Carleton University, Curtin University of Technology and the James S. Street Fund for their financial support.

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Manuscript received 24 April 2009
Revised manuscript received 3 September 2009
Manuscript accepted 10 September 2009

Printed in USA