Late Proterozoic (ca. 930 Ma) extension in eastern Laurentia

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ABSTRACT

The northwest-dipping Carthage-Colton shear zone, located near the eastern margin of the Grenville province in northern New York, separates the Adirondack Lowlands of the Metasedimentary Belt from the Adirondack Highlands of the Granulite Terrane. Published U/Pb sphene ages are 1156–1103 Ma in the Lowlands and 1050–982 Ma in the Highlands, indicating an ∼100 m.y. offset in metamorphic ages across the boundary. Our reported hornblende ^{40}Ar-^{39}Ar ages are ∼1060 Ma in the Lowlands and ∼950 Ma in the Highlands. This confirms the offsets in sphene ages across the Carthage-Colton shear zone and indicates an average cooling rate in both the Lowlands and the Highlands of 1°–2°/m.y. over ∼100 m.y. Biotite ^{40}Ar-^{39}Ar ages from this study yield no apparent age difference, thus approximating the time of final Carthage-Colton shear-zone extension. These ^{40}Ar-^{39}Ar data suggest that extensional motion along the Carthage-Colton shear zone occurred between 950 and 920 Ma, postdating the latest recorded compressional activity between 1060 and 1030 Ma and orogenic collapse between 1045 and 1030 Ma in the Metasedimentary Belt. Extensional motion occurring at least 100 m.y. after the last compressional event is probably not related to orogenic collapse, but rather may be related to another, as yet undefined, extensional event in eastern Laurentia during Late Proterozoic time.

Keywords: extension, geochronology, Grenville province, Laurentia.

INTRODUCTION

Synorogenic to postorogenic extension has now been widely documented in many of the major mountain belts of the world, and it is considered to be a common feature defining the late stages of orogenic evolution in Phanerozoic mountain belts (Dewey, 1988). However, several hypotheses have been proposed for the origin of this extension, ranging from orogenic collapse to the influence of mantle plumes causing crustal thinning and subsequent extension to incipient rifting due to far-field stresses (Dewey, 1988; Hoffman, 1989; Tollo and Hutson, 1996). The exposed roots of ancient orogens are ideal for studies focused on extension and its relationship to orogenic activity at mid-crustal levels, a region that is difficult to observe in much younger Phanerozoic mountain belts.

Studies have shown evidence for extensional activity that followed orogenesis in the ca. 1.1 Ga Grenville province of northeastern North America (van der Pluijm and Carlson, 1989; Mezger et al., 1991b; Culshaw et al., 1994; Busch and van der Pluijm, 1996; McLelland et al., 1996). The Grenville orogeny is of particular interest because it is defined by nearly worldwide deformation ca. 1.1 Ga and is thought to represent the final stages of assembly of the Proterozoic supercontinent, Rodinia (Dalziel, 1991; Hoffman, 1991; Moores, 1991). The existence of this supercontinent is supported by available paleomagnetic data that suggest that Rodinia survived as a supercontinent until 750 Ma, when eastern Gondwana separated from the western margin of Laurentia (Moores, 1991). This was followed by the opening of the Iapetus ocean on the eastern margin of Laurentia ca. 600 Ma (Williams and Hiscott, 1987). Studies of postorogenic extension in the Grenville province may provide information on the transition between the stable configuration of Rodinia and extensional events that may signal the earliest hints of instability of the supercontinent. Information about the timing of this extension and the nature of the motion can give insights into the driving mechanisms of continental extension and any link that it may have with instabilities that are associated with supercontinents, mantle plumes, or gravitationally induced spreading.

REGIONAL GEOLOGY

In New York and Ontario, the Grenville province comprises a series of southeast-dipping crustal slices bounded by shear zones representing propagation from the hinterland toward the Grenville Front during a series of northwest-directed thrusting events that define Grenville orogenesis (Easton, 1992). These separate lithotectonic belts (the Gneiss Belt, the Metasedimentary Belt, and the Granulite Terrane, after Wynne-Edwards, 1972) are distinguished by their unique geological and geophysical characteristics as well as by distinct

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Data Repository item 2000100 contains additional material related to this article.

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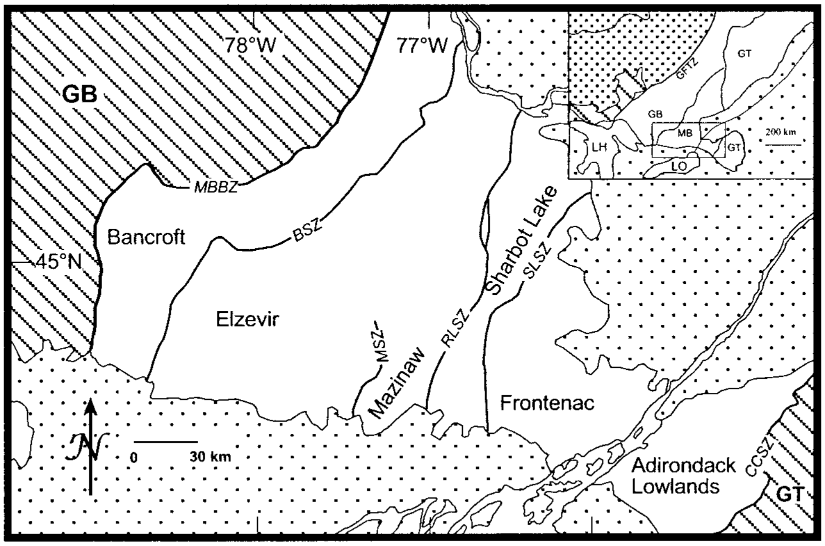

Figure 1. Subdivisions of the Grenville province in northeastern North America. Patterned areas are Gneiss Belt (GB) and Granulite Terrane (GT), and white area is the Metasedimentary Belt (MB). MBBZ—Metasedimentary Belt boundary zone; BSZ—Bancroft shear zone; MSZ—Mooroton shear zone; RLSZ—Robertson Lake shear zone; SLSZ—Sharbot Lake shear zone; CCSZ—Carthage-Colton shear zone. Stippled pattern marks approximate location of Paleozoic cover. Inset shows generalized region of study area.

differences in their geochronological histories (Fig. 1). The Gneiss Belt, in the foreland of the Grenville orogen, is primarily composed of reworked Archean and Proterozoic metasedimentary and intrusive rocks that are separated by dominantly ductile shear zones and have been metamorphosed from upper amphibolite to granulite facies conditions (Ketchum et al., 1998). The Gneiss Belt is considered to be an allochthonous belt juxtaposed against the margin of the pre-Grenvillian Laurentian craton (Davidson, 1995). This belt is separated from the southeastern portion of the North American Grenville province by the Metasedimentary Belt boundary zone, which is a diffuse, northwest-directed thrust zone (McEachern and van Breemen, 1993). Lithologic units in the Metasedimentary Belt represent marine metasedimentary rocks (marbles and quartzites), volcanic rocks, and intrusive rocks that may be separated into domains that are distinguished by distinct geochronological histories as well as by different geological characteristics (Davidson, 1986). The Elzevir terrane (comprising the Elzevir and Mazinaw domains) is characterized by abundant metavolcanic rocks and is thought to represent a volcanic arc or a backarc basin that was separate from other terranes in the Metasedimentary Belt and tectonically placed in its current position (Condie and Moore, 1977). Other domains in the Metasedimentary Belt contain packages of marine metasedimentary rocks and abundant intrusive suites. The Elzevir terrane is separated from the Frontenac terrane (comprising the Sharbot Lake domain, the Frontenac domain, and the Adirondack Lowlands) by the Robertson Lake shear zone (Easton, 1992; Busch et al., 1997). Southeast-dipping shear zones in the Metasedimentary Belt commonly show both brittle and ductile structures, in contrast to the dominantly ductile behavior observed in the Gneiss Belt region (McEachern and van Breemen, 1993).

The Grenville orogeny in North America is defined by multiple stages of compressional activity and extension associated with orogenic collapse. Early periods of deformation from 1250 to 1190 Ma are thought to represent arc-continent collision during closure of the Elzevir backarc basin to the Laurentian margin and are referred to as the Elzevirian orogeny, the first part of the Grenville orogenic cycle (Moore and Thompson, 1980; Windley, 1986). The Elzevirian orogeny is associated with high-grade metamorphism throughout much of the Metasedimentary Belt, although metamorphic grade is locally as low as greenschist facies (Carmichael et al., 1978; Streepey et al., 1997). In general, the Adirondack Lowlands and the Frontenac terrane reached their peak metamorphism to amphibolite and low-pressure granulite facies, respectively, at this time. Another pulse of thrusting and extension occurred from 1060 to 1030 Ma, representing the classic Grenville orogeny (e.g., Davidson, 1995). This is commonly thought to represent a continent-continent collision which, following recent Rodinia reconstructions, is most likely a collision between Laurentia and Amazonia (Bond et al., 1984; Dalziel, 1991). These two events comprise the Grenville orogenic cycle and are associated with widespread anorthosite-mangerite-charnockite granite (AMCG) magmatism and granitoid emplacement throughout the Metasedimentary Belt and the Adirondack Highlands (van Breemen and Davidson, 1988; McLelland et al., 1988).

Deformation in the Metasedimentary Belt is localized along the shear zones that bound domains. These zones of high strain commonly have complex histories and, in some cases, have been reactivated as extensional structures late in the history of the region (Busch et al., 1997). With the exception of the northwest-dipping Carthage-Colton shear zone at the eastern edge of the Metasedimentary Belt, these shear zones dip to the southeast. Some, such as the Robertson Lake shear zone, have brittle structures overprinting earlier ductile deformation (Busch et al., 1996). Complex deformational histories preclude a straightforward structural analysis of shear zones to determine their history and tectonic significance. More recently, with the advances in high-precision geochronology, multidisciplinary approaches combining structural, petrologic, and geochronologic data have been successful in unraveling the metamorphic and cooling history of this ancient orogenic belt (e.g., van der Pluijm et al., 1994).

There are distinct differences in U/Pb metamorphic sphene ages across the Metasedimentary Belt; a major discontinuity occurs across the Robertson Lake shear zone. Metamorphic sphenes from the Elzevir terrane and the Bancroft domain are 1020–1060 Ma, whereas sphene ages from the Sharbot Lake and Frontenac domains indicate that peak regional metamorphism occurred more than 100 m.y. earlier, from about 1180 to 1160 Ma (Mezger et al., 1993). The similarities in metamorphic sphene ages of the Bancroft domain and Elzevir terrane imply that the two were juxtaposed at or before 1020–1060 Ma, and the marked difference in metamorphic ages across the Robertson Lake shear zone suggests that it is a major tectonic boundary. There appears to be a ca. 50 m.y. younging in metamorphic sphene ages from the western Frontenac domain to the eastern Adirondack Lowlands. There is a major discontinuity in sphene ages across the Carthage-Colton shear zone, where the Adirondack Highlands, with sphene ages of ca. 1050–1030 Ma, record their latest regional metamorphism nearly 100 m.y. after

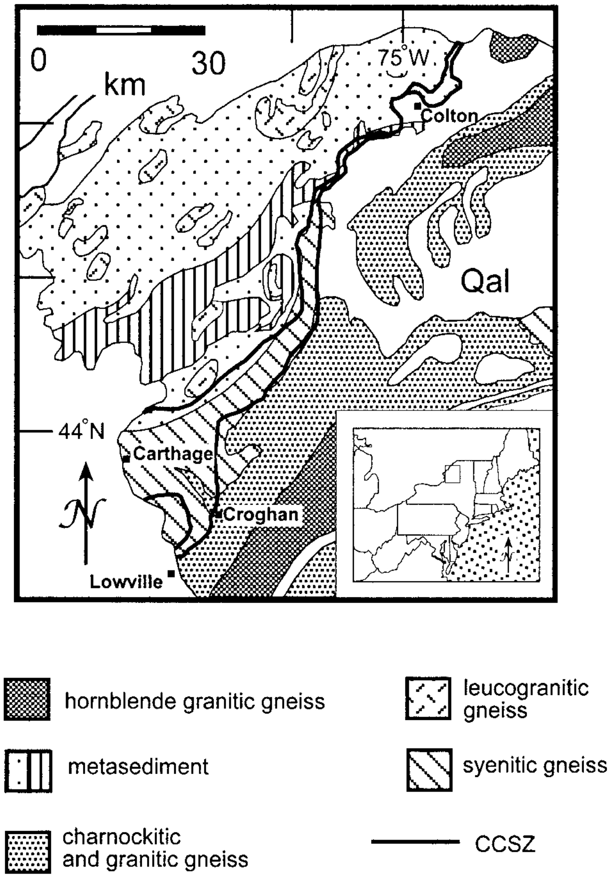

Figure 2. Generalized geologic map of the northwest Adirondacks. The Carthage-Colton shear zone (CCSZ) is shown by heavy black lines. Qal—approximate location of Quaternary alluvium in the Highlands. After McLelland and Isachsen (1986) and Geraghty et al. (1981). Inset shows approximate location of study area in northern New York State.

rocks from the adjacent Adirondack Lowlands (McLelland et al., 1988; Mezger et al., 1991a, 1992).

The use of ^{40}Ar-^{39}Ar thermochronology reveals detailed differences in the unroofing history across the Metasedimentary Belt. It has proven to be a useful tool in assessing late motion across some shear zones in this region. Extensional motion across the Bancroft shear zone has been constrained by sphene ages of ca. 1040 Ma within the shear zone (Mezger et al., 1991b). This movement is commonly attributed to orogenic collapse occurring contemporaneously with final thrusting in the Grenville orogen. Hornblende ages in the Bancroft domain, however, are on the order of 50 m.y. younger than those in the Elzevir domain (the hanging-wall block of the Bancroft shear zone; Cosca et al., 1995). This suggests differential unroofing related to extensional motion along the Bancroft shear zone. There is a major discontinuity in hornblende and biotite ^{40}Ar-^{39}Ar ages across the Robertson Lake shear zone, with cooling ages in the Elzevir terrane $\sim$50 m.y. younger than the Frontenac terrane. Typical hornblende ages (closure temperature, $T_c \cong 500$ °C) in this area are ca. 940 Ma in the footwall Elzevir terrane and ca. 1000 Ma in the hanging-wall Robertson Lake domain (Cosca et al., 1991, 1992). Biotite ages ($T_c \cong 300$ °C) are ca. 900 Ma in the Elzevir terrane and 970 Ma in the Robertson Lake domain (Busch and van der Pluijm, 1996). Across the southeast-dipping Robertson Lake shear zone, this discontinuity in ages is evidence of normal motion that must have occurred after 900 Ma to juxtapose the crustal levels exposed at the present-day surface.

This paper focuses on the cooling history of the Carthage-Colton shear zone, the northwest-dipping boundary at the eastern edge of the Metasedimentary Belt in New York. It shares common features with the Robertson Lake shear zone in southern Ontario in that it juxtaposes two terranes that have distinct regional metamorphic ages. However, a transition from plastic to brittle deformation in the Carthage-Colton shear zone is unclear, and ambiguous shear-sense indicators make the use of geochronology necessary to understand the timing and sense of motion across this boundary. The Carthage-Colton shear zone is located in northwestern New York and separates upper amphibolite facies metasedimentary rocks of the Adirondack Lowlands, the eastern edge of the Frontenac domain in the Metasedimentary Belt, from the granulite facies, predominantly metaigneous rocks of the Adirondack Highlands in the Granulite Terrane (Fig. 2). This zone has been correlated with the Labelle shear zone in Quebec. Major rock types of the Adirondack Highlands include hornblende granitic gneisses, syenitic gneisses, anorthosites, and charnockitic granitoids, which range in age from 1350 Ma to ca. 1120 Ma (McLelland et al., 1988; Emslie and Hunt, 1990; Chiarenzelli and McLelland, 1993; Davidson, 1995).

The northeast-trending Carthage-Colton shear zone is exposed over $\sim$110 km. It ranges from less than 3 m in width to greater than 5 km in the southern portion of the area near Carthage (Fig. 2). The Carthage-Colton shear zone is characterized by a locally intense mylonitization grading into a very well developed, northwest-dipping foliation and down-dip lineations plunging about 30°. Shear-sense indicators can give conflicting results, but the majority suggest a northwest-side-down sense of motion. Despite many field studies (Geraghty et al., 1981; Hall, 1984; Wiener et al., 1984; Heyn, 1990), the tectonic significance of the Carthage-Colton shear zone remains enigmatic. Geraghty et al. (1981) suggested that the Carthage-Colton shear zone represents a fold-thrust nappe and is therefore not a significant tectonic boundary, whereas others have proposed that the Carthage-Colton shear zone represents a major suture at the eastern edge of the Metasedimentary Belt (e.g., Martignole, 1986; Windley, 1986; Mezger et al., 1992).

Because shear-sense indicators in the Carthage-Colton shear zone have yielded ambiguous results, there have been attempts to delineate the timing and sense of movement along this fault by integrating geochronologic data with structural data. Mezger et al. (1991a) found significant differences in metamorphic ages recorded between the Lowlands and the Highlands. Zircon and garnet U/Pb ages suggest peak metamorphism in the Lowlands ca. 1170–1130 Ma. However, sphenes and garnets in the Highlands preserve metamorphic ages of ca. 1030–1050 Ma. Because garnet, monazite, and sphene in the Lowlands do not record this later event, it has been suggested that ca. 1050 Ma, the Lowlands were either laterally separated from the Highlands or protected from the subsequent metamorphism by being at structurally higher levels (Mezger et al., 1992).

In this study we analyze hornblende and biotite by the ^{40}Ar-^{39}Ar method to better understand the timing of extension across the Carthage-Colton shear zone. Using these data in conjunction with a large, preexisting base of structural and geochronologic data in the Metasedimentary Belt and the Gneiss Belt to the west provides insights on the timing and nature of extension within the Grenville orogen.

TABLE 1. MAJOR MINERAL ASSEMBLAGES*

	Rock type	Quartz	Biotite	Feldspar	Pyroxene	Amphibole	Garnet	Other
GV696–81	phl schist		X	X (minor)				ilm
LB93	bt schist	X	X	X		X		chl, zc, py, ap
PP596–60	grt-bt-sill gneiss	X	X	X			X	rt, py, ilm, ap, chl
SE596–49	amphibolite	X	X	X		X		py, zc, chl
CN596–56	hbl granite	X	X	X	X	X		zc
LB596–31b	bt schist	X	X	X		X		chl
HM95	grt-bt gneiss	X	X	X			X	sil, ms, rt, chl
A136	hbl granite	X	X	X		X		zc, ilm
A129	amphibolite	X	X	X		X		chl
A128	amphibolite	X	X	X				zc, ilm, ap
A112	amphibolite	X	X	X		X		py, zc, chl
A142	hbl granite	X	X	X		X		ilm, py

*Mineral abbreviations: ap—apatite; bt—biotite; chl—chlorite; hbl—hornblende; grt—garnet; ilm—ilmenite; py—pyrite; zc—zircon; rt—rutile; sil—sillimanite.

ANALYTICAL TECHNIQUES

Electron Microbeam Analyses

Polished thin sections were examined under a standard petrographic microscope to determine their suitability for microprobe analyses. We examined 60 thin sections, and 20 were chosen for electron microbeam analysis. A scanning electron microscope equipped with a backscattered electron imager, a secondary electron imager, and energy-dispersive analysis was used to further characterize the samples. A Cameca Camebax electron microprobe analyzer with a backscattered electron imager was used to determine quantitative mineral chemistry using wavelength-dispersive analysis. Standard electron microprobe operating conditions were an accelerating voltage of 15 kV and a sample current of 10 nA with a point beam. Micas were analyzed with the beam rastered over a 9 μm^2 area to minimize the loss of mobile elements. Standard scanning electron microscope operating conditions were an accelerating voltage of 15 kV and a sample current of 10 nA.

Argon Analyses

Hornblendes and biotites for ^{40}Ar-^{39}Ar analysis were initially selected by examination of polished thin sections with a standard petrographic microscope, and samples that contained chlorite alteration, either optically or under a scanning electron microscope, were excluded. In addition, splits of separated biotites were analyzed using a Scintag X-ray diffractometer to evaluate the possibility of submicroscopic chlorite interlayers or other impurities. We selected three samples containing hornblende and 15 biotite-bearing samples for argon analysis. Hornblendes were separated using standard magnetic separation techniques and were handpicked under a binocular microscope. Average grain sizes used for argon analysis were 1–3 mm. Biotite samples were crushed, sieved, and washed in deionized water, and pure biotite grains were handpicked under a binocular microscope. Sieved biotites ranging from 200 to 700 μm were selected for argon analysis; most samples were 300–400 μm. Samples were packaged at the University of Michigan Radiogenic Isotope Geochemistry Laboratory and irradiated at University of Michigan's Ford Phoenix reactor. Neutron flux gradients were monitored with samples of the standard Mmhb-1 using an age of 520.4 Ma (Samson and Alexander, 1987). Samples were step-heated using an argon-ion laser. The beam was defocused to uniformly heat the grains and the laser power was increased incrementally after each step until complete fusion. Individual steps consisted of heating for 60 s followed by 2 min of gas purification using two 10 1/s SAES getters (ST101 alloy) and a liquid N_2 cold finger. Argon isotopic ratios were measured with a VG 12OOS mass spectrometer. Extraction line blanks were run after every six steps. Blank values were 4×10^{-12} mL STP for mass 40 and below 3×10^{-13} mL STP for masses 36–39. The measurement of ^{37}Ar was affected by the time lag between irradiation and sample analysis; therefore, some ^{37}Ar values are small or negative numbers. Duplicates and occasionally triplicates were run to determine reproducibility among analyses and constrain grain to grain variability. Plateaus were defined by 50% or more of the total ^{39}Ar released in three or more consecutive steps and where the ages of the steps overlap at 2 σ error. Plateau ages were calculated as the inverse variance weighted mean of ages from the steps in the plateau.

RESULTS

Mineral Chemistry

Hornblendes and biotites were selected from a variety of rock types, including hornblende granite gneisses, garnet-biotite gneisses, biotite schists, and biotite-bearing amphibolites (Table 1). Sample locations are available in the GSA Data Repository (Table DR1[1]). Compositions of hornblende samples analyzed for ^{40}Ar-^{39}Ar dating are listed in Table 2, and compositions of biotite samples are listed in Table 3. The annite component of the biotites analyzed ranges from 33% to 56%. The Mg# [Mg/(Mg + Fe) × 100] of hornblendes in the Lowlands range from 43 to 55, whereas hornblendes in the Highlands have an average Mg# of 28.

TABLE 2. REPRESENTATIVE HORNBLENDE COMPOSITIONS

	A112	A142	A125
Wt% oxide			
SiO_2	41.74	40.92	42.90
TiO_2	1.12	1.31	1.20
Al_2O_3	12.17	10.05	10.88
Cr_2O_3	0.00	0.00	0.05
FeO	19.10	25.17	15.84
MgO	7.98	5.46	10.73
MnO	0.49	0.51	0.36
CaO	11.56	10.76	12.06
BaO	0.06	0.08	0.02
K_2O	1.27	1.84	1.40
Na_2O	1.49	2.06	1.20
F	0.14	1.45	0.39
Cl	0.03	0.49	0.06
Total	97.15	100.10	97.09

^{40}Ar-^{39}Ar Results

When combined with diffusion data for minerals, the ^{40}Ar-^{39}Ar system is widely used as a thermochronometer. The argon closure temperature of minerals is dependent on parameters that include diffusion length scale and regional cooling rate (Dodson, 1973; Harrison et al., 1979; Berger and York, 1981a, 1981b; McDougall and Harrison, 1989; Snee et al., 1988). However, laboratory and field studies have constrained the closure tempera-

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[1] GSA Data Repository item 2000100, supplemental tables, is available on the Web at http://www.geosociety.org/pubs/ft2000.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; editing@geosociety.org.

TABLE 3. REPRESENTATIVE BIOTITE COMPOSITIONS

	PP596–60	GV696–81	LB93	HM95	SE596–49	CN596–56	LB596–31b	A136	A128	A129	A142	A112
Wt% oxide												
SiO_2	36.29	39.45	40.30	36.18	39.82	35.40	40.90	37.74	35.18	36.46	34.73	39.53
TiO_2	5.33	0.84	4.07	4.23	3.82	1.18	3.84	3.62	3.09	2.93	2.58	4.45
Al_2O_3	14.56	14.46	14.67	15.33	12.75	15.39	13.95	14.11	15.81	14.98	15.53	14.36
Cr_2O_3	0.08	0.00	0.00	0.00	0.03	0.05	0.04	0.05	0.04	0.16	0.01	0.03
FeO	13.73	2.81	16.13	21.67	24.13	24.56	15.45	17.11	16.99	13.56	19.73	16.80
MnO	0.10	0.03	0.10	0.16	0.23	0.23	0.29	0.40	0.09	0.09	0.12	0.23
MgO	14.08	25.83	13.57	11.92	8.97	14.46	14.50	12.54	13.63	15.92	11.12	13.48
BaO	3.57	0.16	0.16	0.00	0.16	0.06	0.01	0.01	0.00	0.49	0.07	0.15
CaO	0.04	0.00	0.04	0.03	0.05	0.24	0.03	0.12	0.10	0.01	0.14	0.05
Na_2O	0.06	0.08	0.07	0.06	0.04	0.04	0.07	0.08	0.09	0.14	0.04	0.03
K_2O	9.83	10.63	9.99	7.47	9.74	2.29	10.48	9.55	9.30	9.12	9.13	9.92
F	0.86	0.23	0.36	0.39	0.72	0.30	0.39	1.15	0.58	0.81	0.38	0.27
Cl	0.01	0.05	0.08	0.04	0.67	0.26	0.16	0.14	0.03	0.03	0.03	0.08
O = F	0.36	0.10	0.15	0.16	0.30	0.13	0.16	0.48	0.25	0.34	0.16	0.12
O = Cl	0.00	0.01	0.02	0.01	0.15	0.06	0.03	0.03	0.01	0.01	0.01	0.02
Total	98.18	94.44	99.37	97.29	100.67	94.29	99.89	96.10	94.67	94.35	93.45	99.26

ture of Fe-rich biotite as ~300 °C and hornblende as ~500 °C in slowly cooled terranes (<5 °C/m.y.), and these values are assumed as the argon closure temperatures in this study (McDougall and Harrison, 1989).

Locations and ^{40}Ar-^{39}Ar spectra of hornblendes and biotites analyzed are shown in Figure 3 and argon data are in Table DR-2 (see footnote 1). Ages were calculated using decay constants recommended by Steiger and Jäger (1977). Two of the hornblendes analyzed were from the Lowlands, and one was from the Highlands. Hornblende plateau ages are 1055 and 1065 Ma in the Lowlands and 950 Ma in the Highlands to the east of the Carthage-Colton shear zone (Fig. 3).

We analyzed 15 biotite samples in this study. Four of these biotite samples, all from the Highlands, yield spectra that are characterized by well-behaved plateaus, but integrated and plateau ages from these samples are older than the well-defined age of amphibolite facies metamorphism. The presence of excess argon, which is normally related to a high partial pressure of argon during the cooling of minerals through their closure temperatures, is a well-known phenomenon in biotites (Roddick et al., 1980; Renne, 1995; Ruffet et al., 1995). Saddle-shaped spectra are produced if the apparent age of each increment of gas decreases to a minimum age, and then systematically increases for the remainder of the release of ^{39}Ar (Lanphere and Dalrymple, 1971). However, biotites often do not show saddle-shaped spectra but almost always yield plateaus, which implies complete mixing of the ^{40}Ar components. In areas that do not have a significant database of geochronologic ages, ^{40}Ar-^{39}Ar analyses of biotite can be difficult to interpret and must be used cautiously. However, the temperature-time history of the Grenville province is sufficiently well constrained that biotite ages can be interpreted within the existing framework of ages. Four biotites with integrated and plateau ages that are well in excess of the age of peak metamorphism reflect clearly unreasonable ages and have therefore been excluded in the regional interpretation.

There are 11 biotite samples from the Highlands and Lowlands that are characterized by flat plateaus that yield geologically meaningful ages (Fig. 3). Two samples, A136 and A142, do not display plateaus. Only a total gas age is reported for these samples, which should be considered as an approximation to the cooling age of the biotite. Seven samples were analyzed from the Lowlands, in the region between Carthage and Colton. Ages from these samples range from 892 to 964 Ma. Peak metamorphic temperatures in both the Lowlands and Highlands have been well constrained from 650 °C to greater than 750 °C (Bohlen et al., 1985; Edwards and Essene, 1988; Streepey et al., 1997), so all hornblende and biotite ages reported in this study are cooling ages. Four samples analyzed from the Highlands, ranging from 3 to ~10 km east of the Carthage-Colton shear zone, gave ages ranging from 919 Ma in the southern region near the town of Fine to 937 Ma just east of Colton (Fig. 3).

DISCUSSION

Temperature-time paths in the Adirondacks have been well characterized for the early history of the region (Mezger et al., 1991a, 1992), but have not been assembled for the younger, cooler history of the Lowlands and Highlands. Summary temperature-time paths for the Lowlands and Highlands are shown in Figure 4. These trajectories are constructed by plotting the closure temperature of individual minerals versus the age determined by the U/Pb method (for zircon, monazite, sphene, and rutile) and by the ^{40}Ar-^{39}Ar method (for hornblende and biotite). In constructing these curves for the Lowlands and Highlands, all ages are plotted and envelopes have been drawn around the data points to illustrate the overall cooling path. Metamorphic zircons, with $T_{c} > 800$ °C, record the timing of regional metamorphism in both the Lowlands and the Highlands between 1150 and 1176 Ma (McLelland et al., 1988). The common early history of the Lowlands and the Highlands was characterized by rapid initial cooling. The cooling rate decreased moderately (~5 °C/m.y.) through the timing of monazite closure, as recorded in the Lowlands. Monazite ages ($T_{c} \cong 700$ °C) converge around 1140 Ma, whereas a monazite age in the Highlands is 1030 Ma (Mezger et al., 1991a).

An ~100 m.y. offset in ages across the Carthage-Colton shear zone continues through sphene closure to lead diffusion and hornblende closure to argon diffusion. Sphene ages converge at about 1130 Ma in the Lowlands and 1030 Ma in the Highlands (Mezger et al., 1991a, 1992). In the time interval between the closure of sphene in the U/Pb system and the closure of hornblende in the ^{40}Ar-^{39}Ar system, the entire region was cooling slowly at ~2 °C/m.y. This slow, protracted cooling rate was maintained for ~100 m.y. in the Highlands and at least 200 m.y. in the Lowlands. Hornblende ages maintain the 100 m.y. offset seen in the higher temperature minerals and are ca. 1030 Ma in the Lowlands and 950 Ma in the Highlands. However, at the time of biotite closure, ca. 920 Ma, ages across the Carthage-Colton shear zone are the same in both the Lowlands and the Highlands.

Since ages are relatively older in the hanging wall (Lowlands) than the footwall (Highlands) of the northwest-dipping Carthage-Colton shear zone, extensional motion must have occurred to juxtapose these two terranes. Because biotites on both sides of the Carthage-Colton shear zone are within the same range

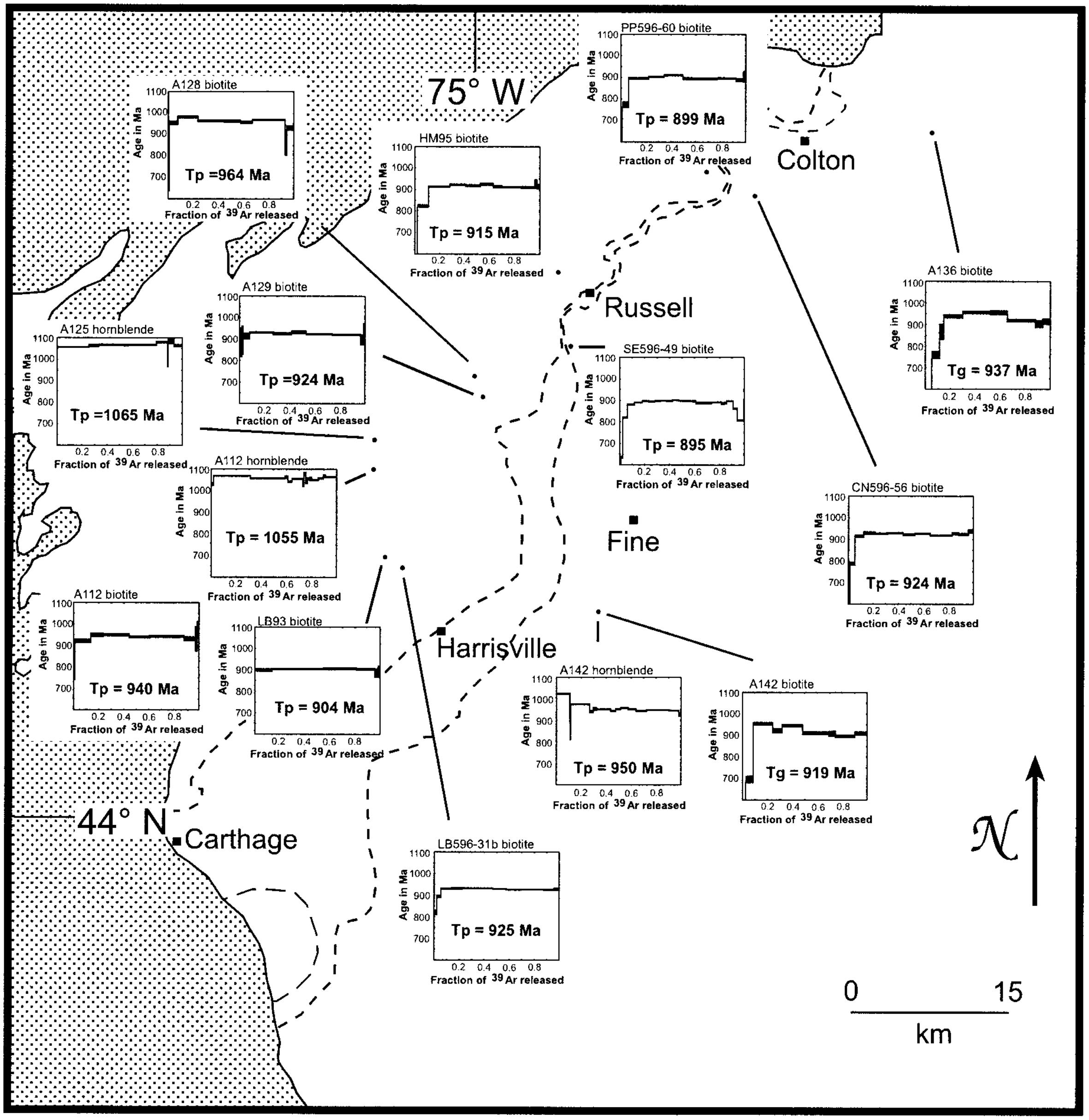

Figure 3. Release patterns and locations for all hornblende and biotite samples analyzed by the ^{40}Ar-^{39}Ar method in this study and their resulting plateau ages and 1 σ errors. Two biotite samples, A136 and A142, did not plateau; ages given are integrated total gas ages and should be considered an approximation to the actual cooling age of the biotite. Hornblende ages are 1066–1055 Ma in the Lowlands and 950 Ma in the Highlands. Biotite ages in the Lowlands range from 899 to 964 Ma while biotite ages in the Highlands range from 895 to 937 Ma.

of ages, in contrast to hornblende ages, extensional motion on the Carthage-Colton shear zone must have occurred between the time of hornblende closure in the Highlands and the time of biotite closure, ca. 930 Ma. An illustration of the ages of samples plotted against distance from the shear zone clearly shows an offset in sphene and hornblende ages and effectively shows the lack of offset in the biotite ages (Fig. 5). Systematic differences in ages as a function of distance from the shear zone may represent flexure of the crust caused by faulting, but no clear distribution has been shown with these data.

Therefore, we propose that ^{40}Ar-^{39}Ar analyses of hornblende and biotite constrain the termination of extensional motion in this eastern portion of the Grenville province. In contrast, ages obtained across other extensional shear zones in the Metasedimentary Belt, like the Bancroft and Robertson Lake shear zones, do not constrain the timing of latest extensional motion. Biotites across the Robertson Lake shear zone, to the west, record an ~70 m.y. offset in ages across the zone (Busch et al., 1996) and show that extensional activity must have continued after ca. 900 Ma. In addition, synthetic brittle structures overprint ductile deformation in the Robertson Lake shear zone, supporting continued extension at shallow crustal levels (Busch and van der Pluijm, 1996). This may imply that extensional shear zones in the Metasedimentary Belt vary in significance and that shear zones such as the Robertson Lake shear zone may record a more protracted extensional history.

It has been proposed that some extensional motion in the Grenville province may be related to orogenic collapse of overthickened crust, a feature common in many modern mountain belts (Dewey, 1988). There seems to be clear evidence for synorogenic extension across several of the shear zones in the Metasedimentary Belt ca. 1045 Ma (Mezger et al., 1991b; Busch et al., 1997). However, the prolonged nature of extension in this part of the Grenville province implies more than a single mechanism. It has been suggested that an early period of extension was so rapid that it was undetected by minerals with high closure temperatures, such as garnet and monazite, and that the errors on these ages allow for short periods of rapid uplift (McLelland et al., 1996). It is unlikely that extension due solely to synorogenic collapse can sustain itself for more than 150 m.y. Work in major extensional regimes such as the Basin and Range Province in western North America suggests that the shift between contractional tectonics and crustal-scale extension occurs over time scales of less than ~50 m.y. (Wernicke, 1992). The history of extension in the eastern Grenville province is therefore probably more complex than normal faulting due to the collapse and spreading of an overthickened crust.

There have been other hypotheses proposed to explain Grenville extension. Hoffman (1989) suggested the presence of a mantle upwelling underneath the supercontinent Rodinia during its final assembly between 1.3 and 1.0 Ga. An upwelling of hot asthenospheric material could drive extension through mantle delamination. A model of extension due to mantle delamination in this region has been proposed by others, e.g., McLelland et al. (1996), who suggested that the Carthage-Colton shear zone represents a low-angle detachment fault similar to those that have developed in the Basin and Range Province. In this model, the Adirondack Highlands represent the exposed core of the orogen that has undergone rapid uplift through extensional motion across faults such as the Carthage-Colton shear zone.

Recent paleogeographic reconstructions show the time of ca. 900 Ma to be relatively quiescent in northeastern Laurentia (Weil et al., 1998). Apart from some minor magmatic activity in Labrador (e.g., Rivers, 1997), the observed extensional motion in the eastern Grenville does not appear to have been accompanied by major pulses of magmatism. This motion may be related to the instability of the supercontinent Rodinia, which requires that extensional motion ca. 930 Ma should also be documented in the adjacent Amazon craton and in other areas in the Grenville orogen. Understanding the complete cooling history of the Ontario-New York segment of the Grenville orogen should further elucidate the significance of a ca. 930 Ma extensional event in Laurentia.

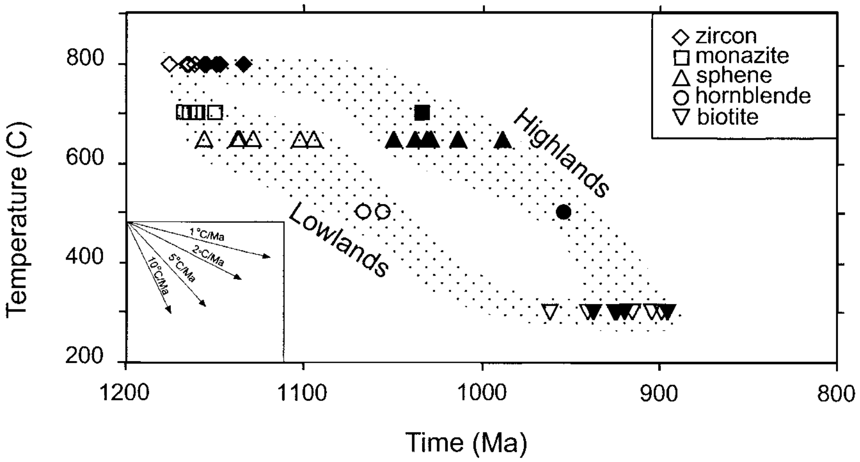

Figure 4. Generalized temperature-time paths for Adirondack Lowlands and Highlands. Curves are constructed by plotting closure temperatures of minerals versus ages they yield, both by U-Pb analyses (zircon data are from McLelland et al., 1988; monazite, sphene, and rutile data are from Mezger et al., 1991a, 1992, 1993) and by the ^{40}Ar-^{39}Ar method (hornblende and biotite). Open symbols represent ages from the Lowlands, and closed symbols are ages from the Highlands. Differences in cooling rates between hornblende and biotite closure are noted for both the Lowlands and the Highlands. The region is characterized by rapid initial cooling (~8 °C/m.y.) that decreases to about 1.5 °C/m.y. for the period of time between sphene and hornblende closure. Slow cooling continues in the Lowlands through biotite closure, but cooling rates increase to about 4 °C/m.y. in the Highlands between the time of hornblende closure and biotite closure.

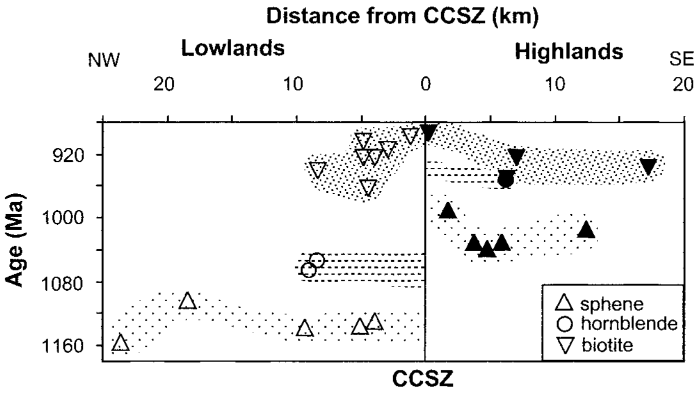

Figure 5. Distance versus age plot for sphene, hornblende, and biotite. The location of the Carthage-Colton shear zone (CCSZ) is shown as a solid black line at 0 km. Data are projected from the surface to the dipping plane of the CCSZ. Envelopes are drawn around data points. Open symbols are ages from the Lowlands and closed symbols represent ages from the Highlands. Sphene ages are from Mezger et al. (1991a).

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REFERENCES CITED

Berger, G.W., and York, D., 1981a, ^{40}Ar/^{39}Ar dating of the Thanet gabbro, Ontario: Looking through the metamorphic veil and implications for paleomagnetism: Canadian Journal of Earth Sciences, v. 18, p. 266–273.

Berger, G.W., and York, D., 1981b, Geothermometry from ^{40}Ar/^{39}Ar dating experiments: Geochimica et Cosmochimica Acta, v. 45, p. 795–811.

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

Bond, G.C., Nickeson, P.A., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345.

Busch, J.P., and van der Pluijm, B.A., 1996, Late orogenic, plastic to brittle extension along the Robertson Lake shear zone: Implications for the style of deep-crustal extension in the Grenville orogen, Canada: Precambrian Research, v. 77, p. 41–57.

Busch, J.P., van der Pluijm, B.A., Hall, C.M., and Essene, E.J., 1996, Listric normal faulting during postorogenic extension revealed by ^{40}Ar/^{39}Ar thermochronology near the Robertson Lake shear zone, Grenville Orogen, Canada: Tectonics, v. 15, p. 387–402.

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.

Carmichael, D.M., Moore, J.M., Jr., and Skippen, G.B., 1978, Isograds around the Hastings metamorphic ''low,'' *in* Currie, A.L., and Mackasey, W.O., eds., Toronto '78 field trips guidebook: Toronto, Ontario, Geological Association of Canada, p. 325–346.

Chiarenzelli, J.R., and McLelland, J.M., 1993, Granulite facies metamorphism, palaeo-isotherms, and disturbance of the U-Pb systematics of zircon in anorogenic plutonic rocks from the Adirondack Highlands: Journal of Metamorphic Geology, v. 55, p. 59–70.

Condie, K.C., and Moore, J.M., 1977, Geochemistry of Proterozoic volcanic rocks from the Grenville province, eastern Ontario, *in* Baragar, W.R.A., Coleman, L.C., and Hall, J.M., eds., Volcanic regimes in Canada: Geological Association of Canada Special Paper 16, p. 149–168.

Cosca, M.A., Sutter, J.F., and Essene, E.J., 1991, Cooling and inferred uplift/erosion history of the Grenville orogen, Ontario: Constraints from ^{40}Ar-^{39}Ar thermochronology: Tectonics, v. 10, p. 959–977.

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.

Cosca, M.A., Essene, E.J., Mezger, K., and van der Pluijm, B.A., 1995, Constraints on the duration of tectonic processes: Protracted extension and deep-crustal rotation in the Grenville orogen: Geology, v. 23, p. 361–364.

Culshaw, N.G., Ketchum, J.W.F., Wodicka, N., and Wallace, P., 1994, Deep crustal extension following thrusting in the southwestern Grenville province, Ontario: Canadian Journal of Earth Sciences, v. 31, p. 160–175.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and east Antarctica–Australia as a conjugate rift pair—Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601.

Davidson, A., 1986, New interpretations in the southwest Grenville province, *in* Moore, J.M., Davidson, A., and Baer, A.J., eds., The Grenville province: Geological Association of Canada Special Paper 31, p. 61–74.

Davidson, A., 1995, A review of the Grenville orogen in its North America type area: Journal of Australian Geology and Geophysics, v. 16, p. 3–24.

Dewey, J.F., 1988, Extensional collapse of orogens: Tectonics, v. 7, p. 1123–1139.

Dodson, M.H., 1973, Closure temperature in cooling geochronological and petrological systems: Contributions to Mineralogy and Petrology, v. 40, p. 259–274.

Easton, R.M., 1992, The Grenville province and the Proterozoic history of central and southern Ontario, *in* Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, G.M., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, p. 719–904.

Edwards, R.L., and Essene, E.J., 1988, Pressure, temperature, and C-O-H fluid fugacities across the amphibolite-granulite transition, northwest Adirondack Mountains, New York: Journal of Petrology, v. 29, p. 39–72.

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.

Geraghty, E.P., Isachsen, Y.W., and Wright, S.F., 1981, Extent and character of the Carthage-Colton mylonite zone, northwest Adirondacks, New York: U.S. Nuclear Regulatory Commission, NUREG/CR-1865,83 p.

Hall, P.C., 1984, Some aspects of deformation fabrics along the Highland/Lowland boundary, northwest Adirondacks, New York State [Master's. dissert.]: State University of New York, Albany, 124 p.

Harrison, T.M., Armstrong, R.L., Naeser, C.W., and Harakal, J.E., 1979, Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia: Canadian Journal of Earth Sciences, v. 16, p. 400–410.

Heyn, T., 1990, Tectonites of the northwest Adirondack Mountains, New York: Structural and metamorphic evolution [Ph.D. dissert.]: Ithaca, New York, Cornell University, 203 p.

Hoffman, P.F., 1989, Speculations on Laurentia's first Gigayear (2.0 to 1.0 Ga): Geology, v. 17, p. 135–138.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwana inside-out?: Science, v. 252, p. 1409–1412.

Ketchum, J.W.F., Heaman, L.M., Krogh, T.E., Culshaw, N.G., and Jamieson, R.A., 1998, Timing and thermal influence of late orogenic extension in the lower crust: A U-Pb geochronological study from the southwest Grenville orogen, Canada: Precambrian Research, v. 89, p. 25–45.

Lanphere, M.A., and Dalrymple, G.B., 1971, A test of the ^{40}Ar/^{39}Ar age spectrum technique on some terrestrial materials: Earth and Planetary Science Letters, v. 12, p. 359–372.

Martignole, J., 1986, Some questions about crustal thickening in the central part of the Grenville province, *in* Moore, J.M., Davidson, A., and Baer, A.J., eds., The Grenville province: Geological Association of Canada Special Paper 31, p. 327–339.

McDougall, I., and Harrison, T.M., 1989, Geochronology and thermochronology by the ^{40}Ar/^{39}Ar method: New York, Oxford University Press, 212 p.

McEachern, S.J., and van Breemen, O., 1993, Age of deformation within the Central Metasedimentary Belt boundary thrust zone, southwest Grenville orogen: Constraints on the collision of the mid-Proterozoic Elzevir terrane: Canadian Journal of Earth Sciences, v. 30, p. 1155–1165.

McLelland, J., and Isachsen, Y., 1986, Synthesis of geology of the Adirondack Mountains, New York and their tectonic setting within the southwestern Grenville Province, *in* Moore, J.M., Davidson, A., and Baer, A.J., eds., The Grenville Province: Geological Association of Canada Special Paper, 31, p. 75–94.

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

Mezger, K., Rawnsley, C.M., Bohlen, S.R., and Hanson, G.N., 1991a, U-Pb garnet, sphene, monazite, and rutile ages: Implications for the duration of high-grade 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., 1991b, Synorogenic collapse: A perspective from the middle crust: Science, v. 254, p. 695–698.

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 orogeny of Ontario and New York: Constraints on ancient crustal tectonics: Contributions to Mineralogy and Petrology, v. 114, p. 13–26.

Moore, J.M., Jr., and Thompson, P.H., 1980, The Flinton Group: A late Precambrian metasedimentary succession in the Grenville province of eastern Ontario: Canadian Journal of Earth Sciences, v. 17, p. 1685–1707.

Moores, E.M., 1991, Southwest United States–East Antarctica (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428.

Renne, P.R., 1995, Excess ^{40}Ar in biotite and hornblende from the Noril'sk 1 intrusion, Siberia: Implications for the age of the Siberian Traps: Earth and Planetary Science Letters, v. 131, p. 165–176.

Rivers, T., 1997, Lithotectonic elements of the Grenville province: Review and tectonic implications: Precambrian Research, v. 86, p. 117–154.

Roddick, J.C., Cliff, R.A., and Rex, D.C., 1980, The evolution of excess argon in alpine biotites—A ^{40}Ar-^{39}Ar analysis: Earth and Planetary Science Letters, v. 48, p. 185–208.

Ruffet, G., Feraud, G., Balevre, M., and Kienast, J., 1995, Plateau ages and excess argon in phengites: A ^{40}Ar-^{39}Ar laser probe study of Alpine micas (Sesia Zone, Western Alps, northern Italy): Chemical Geology, v. 121, p. 327–343.

Samson, S.D., and Alexander, E.C., 1987, Calibration of the interlaboratory ^{40}Ar-^{39}Ar dating standard, Mmhb–1: Chemical Geology: Isotope Geoscience Section, v. 66, no. 1–2, p. 27–34.

Snee, L.W., Sutter, J.F., and Kelly, W.C., 1988, Thermochronology of economic mineral deposits: Dating the stages of mineralization at Panasquiera, Portugal, by high-precision ^{40}Ar/^{39}Ar age spectrum techniques on muscovite: Economic Geology, v. 83, p. 335–354.

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

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.

Tollo, R.P., and Hutson, F.E., 1996, 700 Ma rift event in the Blue Ridge Province of Virginia: A unique time constraint on pre-Iapetan rifting of Laurentia: Geology, v. 24, p. 59–62.

van Breemen, O., and Davidson, A., 1988, U-Pb zircon ages of granite and syenites in the Central Metasedimentary Belt, Grenville province, Ontario, *in* Radiogenic ages and isotopic studies—Report 2: Geological Survey of Canada Special Paper 88–2, p. 45–50.

van der Pluijm, B.A., and Carlson, K.A., 1989, Extension in the Central Metasedimentary Belt of the Ontario Grenville: Timing and tectonic significance: Geology, v. 17, p. 161–164.

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.

Weil, A.B., Van der Voo, R., Mac Niocaill, C., and Meert, J.G., 1998, The Proterozoic supercontinent Rodinia: Paleomagnetically derived reconstructions for 1100–800 Ma: Earth and Planetary Science Letters, v. 154, p. 13–24.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C–2, p. 553–581.

Wiener, R.W., McLelland, J.M., Isachsen, Y.W., and Hall, L.M., 1984, Stratigraphy and structural geology of the Adirondack Mountains, New York, *in* Bartholomew, M.J., ed., The Grenville event in the Appalachians and related topics: Review and synthesis: Geological Society of America Special Paper 194, p. 1–55.

Williams, H., and Hiscott, R.N., 1987, Definition of the Iapetus rift-drift transition in western Newfoundland: Geology, v. 15, p. 1044–1047.

Windley, B.F., 1986, Comparative tectonics of the western Grenville and western Himalayas, *in* Moore, J.M., Davidson, A., and Baer, A.J., eds., The Grenville province: Geological Association of Canada Special Paper 31, p. 341–348.

Wynne-Edwards, H.R., 1972, The Grenville province, *in* Price, R.A., and Douglas, R.J.W., eds., Variations in tectonic styles in Canada: Geological Association of Canada Special Paper 11, p. 263–334.

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