Suturing and extensional reactivation in the Grenville orogen, Canada

Jay P. Busch*
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109
Klaus Mezger
Max-Planck Institut für Chemie, D-55020, Mainz, Germany
Ben A. van der Pluijm
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109

ABSTRACT

Sutures are zones of weakness within orogenic belts that have the potential to become reactivated during orogenic evolution. The Robertson Lake shear zone marks a major tectonic boundary in the southeastern Grenville orogen of Canada that has been intermittently active for at least 130 m.y. The shear zone played a major role in the compressional stage of the orogenic cycle as well as during postorogenic collapse. The zone separates the Elzevir terrane to the west and the Frontenac terrane to the east. Sphene ages (U-Pb) indicate that these two terranes have distinct tectonothermal histories and that the shear zone represents a "cryptic suture." In its current state, the shear zone is a low angle (30°ESE dip) plastic to brittle extensional shear zone that separates the Mazinaw (footwall) and Sharbot Lake (hanging wall) domains. Integration of structural, metamorphic, and chronologic data leads to a model that describes the complete evolution of this fundamental tectonic boundary that evolved from an early compressional zone (ca. 1030 Ma) to a late extensional zone (until at least 900 Ma).

INTRODUCTION

During the contractional stages of orogenesis, strain tends to be focused along shear zones that are characterized by gently dipping thrust faults and/or steeply dipping strike-slip faults. Shear zones are regions of material weakness and it is likely that they are preferentially (re)activated during later stages. Such multiply active shear zones are known from shallow-crustal rocks in modern orogenic belts, but similar behavior in the deeper part of an orogen requires study of deeply eroded, ancient mountain belts, which will also provide complementary insights into the dynamics of orogenic evolution.

In this paper we provide information on the evolution of a shear zone in a deeply eroded part of the Grenville orogen of Ontario, Canada. This well exposed and completely evolved mountain belt allows direct access to rocks deformed and metamorphosed at middle to lower crustal levels during orogenesis. Therefore, the Grenville orogen provides the opportunity to gain insight into deep crustal tectonic processes with the ultimate goal of defining the complete history of a major orogenic cycle. The potential also exists to use the Grenville orogen as an analogue for deep crustal tectonic processes in modern orogenic belts, and this has been explored successfully in some cases (e.g., Windley, 1986; Hanmer, 1988; Mezger et al., 1993; van der Pluijm et al., 1994). The Grenville orogen is traditionally interpreted as a product of ductile thrusting and crustal imbrication during convergence (e.g., Davidson, 1984; Hanmer, 1988; Hildebrand and Easton, 1995) and has clear similarities to modern orogenic belts, such as the Alpine-Himalayan chain. It is now also established that synorogenic and postorogenic extension is a significant process in the tectonic evolution of the Grenville orogen (van der Pluijm and Carlson, 1989; Mezger et al., 1991; Cosca et al.,

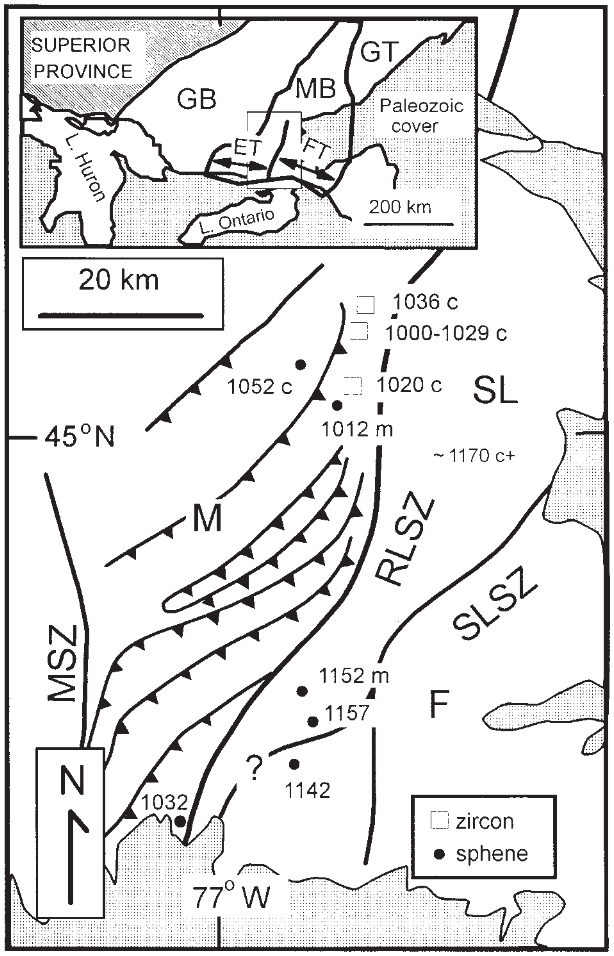

Figure 1. Map showing U-Pb cooling and metamorphic ages, regional structures, and tectonic boundaries in southeast Ontario, Grenville orogen. Ages are from: c, Corfu and Easton (1995); m, Mezger et al. (1993); and c+, Corfu et al. (1995). Abbreviations: M, Mazinaw domain; SL, Sharbot Lake domain; F, Frontenac domain; MSZ, Mooroton shear zone; RLSZ, Robertson Lake shear zone; SLSZ, Sharbot Lake shear zone. Stippled pattern indicates Paleozoic sedimentary rocks. Boundary with question mark is proposed boundary of Easton (1992). Curvature of structures in Mazinaw domain is interpreted to be product of emplacement of Sharbot Lake domain via sinistral transpression. Inset shows Elzevir terrane (ET) and Frontenac terrane (FT) on either side of Robertson Lake shear zone and study area relative to Gneiss belt (GB), Metasedimentary belt (MB), and Granulite terrane (GT).

---

*Present address: Exxon Production Research Company, Houston, Texas 77252.

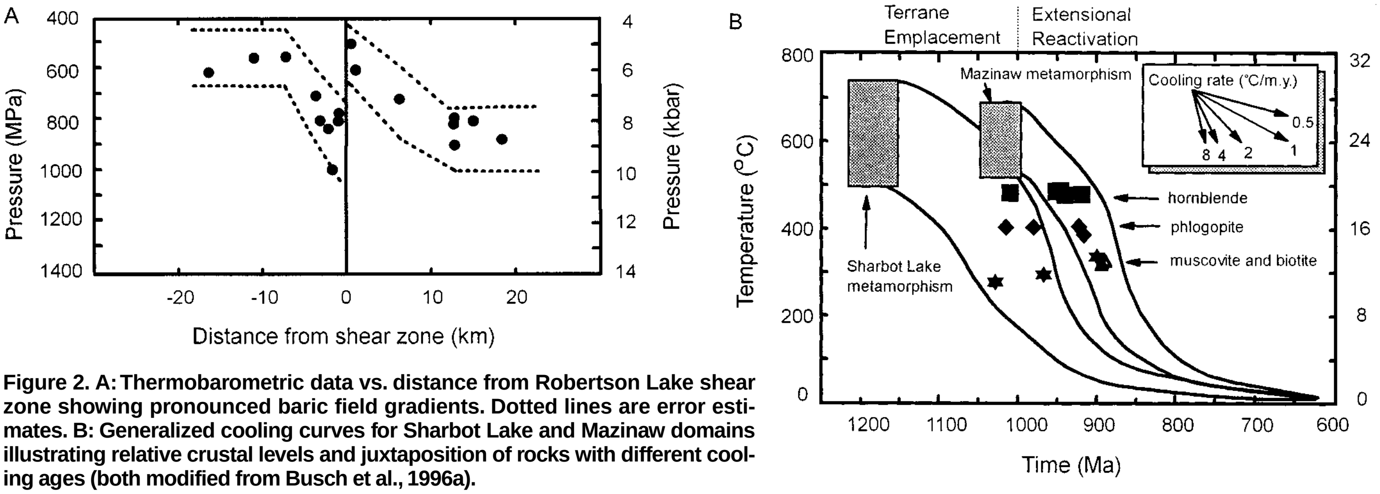

Figure 2. A: Thermobarometric data vs. distance from Robertson Lake shear zone showing pronounced baric field gradients. Dotted lines are error estimates. B: Generalized cooling curves for Sharbot Lake and Mazinaw domains illustrating relative crustal levels and juxtaposition of rocks with different cooling ages (both modified from Busch et al., 1996a).

1992, 1995; Culshaw et al., 1994; Busch and van der Pluijm, 1996) and of orogenic belts in general (e.g., Dewey, 1988).

The present configuration of portions of the Grenville orogen is a product of extensional processes, so that relating the shallowly dipping tectonite fabrics to synorogenic thrusting may not always be warranted (e.g., White et al., 1994). Moreover, the significance of shear zones is often obscured due to the high-grade metamorphism and polyphase deformation typically associated with deeply eroded orogenic belts, and overprinting extensional deformation commonly leaves little evidence for the earlier history of the shear zones. Thus, a multidisciplinary approach is required to unravel the complete orogenic history of high grade metamorphic terranes (see also van der Pluijm et al., 1994).

Whereas most of the Grenville orogen of Ontario has been mapped in detail and numerous petrologic and geochemical studies have been completed, the nature of amalgamation and complete orogenic history are still poorly defined. In fact, in many regions the significance of shear zones and the identification of terrane boundaries are still under debate. Tectonic models developed using the chronologic and petrologic approach generally lack a kinematic-geometric framework for evaluating the mode of terrane amalgamation along individual terrane boundaries. This study focuses on the eastern region of the Grenville orogen near the Robertson Lake shear zone, which separates two domains in southeastern Ontario (Fig. 1). This region has received considerable attention in recent years and abundant structural, petrologic, and chronologic data now exist (Easton, 1988; Cosca et al., 1992; Mezger et al., 1993; Corfu and Easton, 1995; Corfu et al., 1995; Busch and van der Pluijm, 1996; Busch et al., 1996a, 1996b), which provides a unique opportunity to develop a complete tectonic-structural model of crustal shear zone evolution and insights into the dynamic processes acting in the deep sections of orogenic belts.

REGIONAL GEOLOGY

The Robertson Lake shear zone lies within the Metasedimentary Belt of the Grenville orogen and separates the Sharbot Lake and Mazinaw domains (Fig. 1). The Metasedimentary Belt has been divided into several lithotectonic domains on the basis of lithologic, chronologic, and geophysical data (e.g., Easton, 1992). Throughout this paper the term domain is used to imply a relatively homogeneous volume of rock bounded by a structural discontinuity, and the term terrane is used when it can be demonstrated that the volume of rock is tectonically distinct from neighboring rocks. Easton (1988) first recognized the regional extent of the Robertson Lake shear zone and the contrast in metamorphic facies and rock types on either side of the zone. The zone has been defined as an east-southeast-dipping, crystal-plastic mylonite zone with locally intense cataclastic deformation (Easton, 1988; Busch and van der Pluijm, 1996). Normal shear-sense indicators within the zone have been reported for both brittle and crystal plastic structures (Busch and van der Pluijm, 1996 and references therein). Quantitative thermobarometric data indicate that displacement along the Robertson Lake shear zone has produced discontinuities in metamorphic field gradients (Busch et al., 1996a), and ^{40}Ar-^{39}Ar cooling ages are diachronous across the zone, which has been interpreted to be a result of late extensional displacement that lasted until at least 900 Ma (Busch et al., 1996b) (Fig. 2).

The Mazinaw domain is the easternmost domain in the Elzevir terrane and is dominated by deformed plutonic rocks, clastic metasedimentary rocks (quartzo-feldspathic schist, gneiss and mica schist), and metavolcanic rocks (amphibole schist) that probably represent a Middle Proterozoic continental margin (Moore and Thompson, 1980). As many as three metamorphic events have affected the Mazinaw domain, resulting in a complex tectono-metamorphic history (Easton, 1992; Mezger et al., 1993; Corfu and Easton, 1995). The youngest metamorphism in the Mazinaw domain has been associated with internal imbrication of the domain during compression from 1000 to 1050 Ma (Corfu and Easton, 1995). Abundant fold closures and the regional trend of axial surfaces and thrust faults are curved near the shear zone (Fig. 1).

The Sharbot Lake domain is the westernmost domain of the Frontenac terrane and is dominated by mafic and intermediate metaigneous rock and marble. The age of metamorphism in the Sharbot Lake domain has been constrained by U-Pb dates from sphenes and zircons as from 1140 to 1170 Ma (Mezger et al., 1993; Corfu et al., 1995; this study). Hildebrand and Easton (1995) proposed that marbles of the Sharbot Lake domain represent platform carbonates that have been overridden by a northwest-directed thrust sheet that may extend across the Grenville orogen of Ontario into the Gneiss Belt (Fig. 1). In this interpretation metamorphism is associated with magmatism in the hanging wall and emplacement of a hot thrust sheet (magmatic arc) over platform carbonates at 1161 Ma. Many rocks retain U-Pb and ^{40}Ar-^{39}Ar crystallization ages of 1170 to 1224 Ma (Corfu et al., 1995; Busch et al., 1996b; A. Davidson, 1995 personal communication), indicating that metamorphism did not reset portions of the Sharbot Lake domain and the Sharbot Lake domain did not undergo the 1030 Ma metamorphic event documented in the Mazinaw domain. On the basis of lithologic and geochemical data, Easton (1992) suggested that the southeastern Sharbot Lake domain is genetically related to the Mazinaw domain (Fig. 1).

ROBERTSON LAKE SUTURE ZONE

The Mazinaw domain is generally characterized by amphibolite facies metamorphism and the Sharbot Lake domain is characterized by upper amphibolite to granulite facies metamorphism (e.g., Carmichael et al., 1978). New U-Pb ages of sphene extracted from marble in the Sharbot Lake domain were obtained to constrain the age of metamorphism (ca. 1140–1160 Ma, Table 1; see

TABLE 1. U-Pb ISOTOPIC DATA AND AGES FROM SPHENE

Sample	U (ppm)	Pb (ppm)	^{206}Pb/^{204}Pb*	^{207}Pb/^{206}Pb†	^{208}Pb/^{206}Pb†	^{207}Pb/^{235}U (Age, Ma)	^{206}Pb/^{238}U (Age, Ma)	^{207}Pb/^{206}Pb (Age, Ma)	Error (2σ)
94-27	215.2	76.02	280.1	0.07840	0.7275	1159	1161	1157	4
94-30/2	32.84	11.51	759.8	0.07780	0.9255	1141	1141	1142	2
6593	76.97	14.21	578.0	0.07366	0.03518	1035	1034	1032	3

*Measured ratio.
†Ratio for mass fractionation, blank and common Pb.

Mezger et al., 1993, for analytical techniques). Metamorphic temperatures in the region are relatively high (650–750 °C; Busch et al., 1996a) and thus are equal to or slightly higher than the closure temperature for Pb in sphene (650–700 °C, Mezger et al., 1993; Scott and St-Onge, 1995), so that these ages reflect cooling immediately after peak metamorphism. Regardless of the precise closure temperature for Pb in sphene, the ages document that the Mazinaw domain has a metamorphic history that is temporally different from the Sharbot Lake domain. When combined with the contrast in rock types between domains, the Robertson Lake shear zone is interpreted as a cryptic suture, as originally hypothesized by Mezger et al. (1993) on the basis of only one U-Pb sphene age (1152 Ma) from the Sharbot Lake domain. Sphene ages from both sides of a proposed boundary in the southern Sharbot Lake domain (Easton, 1992) indicate that this boundary does not separate rocks with temporally distinct metamorphic histories (Fig. 1). Thus, despite the lithologic and geochemical similarity between the Mazinaw domain and the southwestern Sharbot Lake domain, there is no evidence for a common tectono-metamorphic history. These new ages are similar to metamorphic ages from the Frontenac domain and Adirondack Lowlands domains to the southeast (Mezger et al., 1993), and therefore, the Sharbot Lake, Frontenac, and Adirondack lowlands domains are considered to represent a coherent tectonic element (called the Frontenac terrane) at least since 1160 Ma.

EXTENSIONAL REACTIVATION

Peak metamorphic pressures increase in the Mazinaw domain (footwall) toward the Robertson Lake shear zone from 550 MPa to 770–890 MPa, whereas metamorphic pressures decrease across the zone to 500 MPa in the hanging wall and increase away from the zone to 900 MPa (Fig. 2). Uniform metamorphic ages but varied metamorphic pressures within each domain indicate that rocks now exposed at the surface were originally at varied depths. These observations are resolved by a model of isostatically induced flexural rotations that accompanied extension and produced gradients in metamorphic pressure adjacent to the shear zone. The magnitude of rotation inferred from barometric data constrains the pre-extension dip angle of the terrane boundary ("suture") to values of 65° to 90° (Busch et al., 1996a).

Hornblende cooling ages across the Mazinaw domain (footwall) show little variation, indicating uniform unroofing of the footwall since 940 Ma (Cosca et al., 1991, 1992; Busch et al., 1996b). Phlogopite, muscovite, and biotite cooling ages are 924 to 890 Ma (Busch et al., 1996b). Cooling curves constructed for the Mazinaw domain show a period of relatively rapid cooling (~5 °C/m.y.) from 940 to 890 Ma (Fig. 2). The cooling history of Sharbot Lake domain is characterized by a similar cooling rate (~5 °C/m.y.), but from 1010 to 970 Ma. Hornblende and biotite cooling ages in the Sharbot Lake domain are 70 to 130 m.y. older than in the Mazinaw domain, indicating that the Sharbot Lake domain was at shallow crustal levels as early as 1029 Ma. Juxtaposition of rocks with different biotite cooling ages (ca. 900 Ma vs. ca. 1030 Ma) indicates that normal faulting along the Robertson Lake shear zone must have been active until at least 900 Ma. Moreover, because hornblende cooling ages are uniform in the Mazinaw domain, thermochronologic data indicate that rotation of the footwall during extension must have ceased by ca. 940 Ma.

MODEL OF TERRANE EMPLACEMENT

On the basis of metamorphic, chronologic, and structural data, it is possible to construct a model for the evolution of the Robertson Lake shear zone and adjacent terranes. The Mazinaw domain was undergoing high-grade metamorphism at 1000 to 1050 Ma, whereas the western Sharbot Lake domain was at shallow crustal levels (300 °C) as early as 1029 Ma (cooling age of biotite), and the eastern Sharbot Lake domain reached 500 °C at 1010 Ma. Thus, the Sharbot Lake domain was cooling at shallow crustal levels while the Mazinaw domain was still undergoing metamorphism.

The Sharbot Lake domain was juxtaposed with the Mazinaw domain during the 1030 Ma metamorphic event in the Mazinaw domain (Fig. 3A). Rocks now exposed in the Sharbot Lake domain were at shallow crustal levels and thus did not undergo this metamorphic event. The pre-extension, high-dip angle of the Robertson Lake shear zone associated with terrane accretion suggests that pure dip-slip thrusting was not operative, because such movement typically occurs on faults with a shallow dip. Rather, imbrication and metamorphism in the Mazinaw domain (ca. 1030 Ma) resulted from transpressional convergence, which offers an explanation for both the metamorphic history and the curvature of regional structures near the shear zone. During transpression, imbrication of the Mazinaw domain was accompanied by sinistral displacement along the Robertson Lake suture zone, which produced the curved map pattern of regional structures in the Mazinaw domain (Fig. 1). The period of rapid cooling of the Sharbot Lake domain (1010–970 Ma) is consistent with enhanced unroofing of the hanging wall in the waning stages of transpression. The transition to extensional tectonics in the region took place during the interval between peak metamorphism (at 1030 Ma) and 940 Ma, which reactivated the Robertson Lake suture zone. Isostatically induced flexural rotations were complete by 940 Ma and were followed by a period of rapid cooling of the footwall (940–890 Ma) that coincided with final phases of normal faulting and the transition from crystal-plastic to brittle deformation along the Robertson Lake shear zone (Fig. 3B).

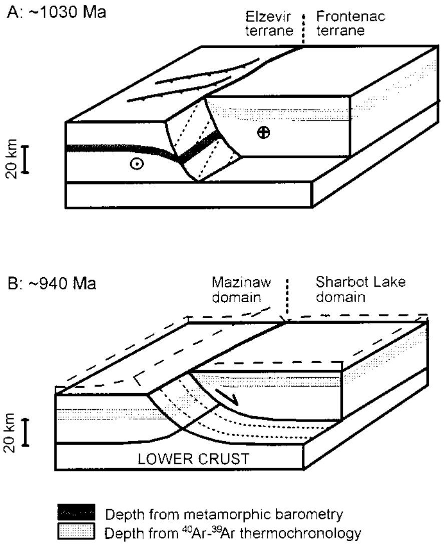

Figure 3. Model for terrane emplacement and subsequent extensional reactivation along Robertson Lake zone. A: Transpressional emplacement (sinistral) of Sharbot Lake domain. Mazinaw domain is undergoing metamorphism and internal imbrication, and Sharbot Lake domain is at shallow crustal levels. Shaded regions are rocks currently exposed in Mazinaw and Sharbot Lake domains. B: By 940 Ma, Mazinaw domain had reached 500 °C and was being uniformly unroofed. Displacement continued until at least 900 Ma, on the basis of offset biotite cooling ages. Depths are calculated from thermochronologic data using ~25 °C/km and from barometric data using crustal density of 2700 kg/m^3 and errors from metamorphic barometry. Dotted lines are displacement directions along the Robertson Lake zone and dashed lines show degree of unroofing.

DISCUSSION

The early significance of the Robertson Lake shear zone for the history of the Grenville orogen can be appreciated only after removal of the effects of extension. The timing and conditions of metamorphism in each domain are important parameters for assessing whether a tectonic boundary is a terrane or subdomain boundary, but definition of the geometric evolution of the boundary is required to evaluate the nature of terrane emplacement. The proposed model resolves the diachronous metamorphism of domains in the region and accounts for the geometry of footwall structures and geometry prior to extension along the zone. From our chronologic data and analysis of pre-extensional geometry, it follows that the Robertson Lake shear zone is a fundamental tectonic boundary (a deeply eroded plate boundary or "cryptic suture") in the Grenville orogen, which separates the Elzevir terrane (Bancoft, Elzevir, and Mazinaw domains) from the Frontenac terrane (Sharbot Lake and Frontenac domains, and Adirondack Lowlands).

The new chronologic data and structural model provide insights into the significance of crustal-scale shear zones, fault reactivation, and tectonic boundaries in the Grenville orogen. The proposed thrust contact above marbles of the Sharbot Lake domain (Hildebrand and Easton, 1995) does not account for the lack of metamorphism at 1030 Ma in the Sharbot Lake domain (see also discussion by Davidson and Carmichael, 1997). If this boundary exists and can be correlated across the Robertson Lake shear zone as suggested by Hildebrand and Easton (1995), then the Mazinaw and Sharbot Lake domains were in contact by 1161 Ma, and both domains should have undergone the younger metamorphism. Rather, the model proposed here accounts for varied metamorphic history via transpressional emplacement and the extensional history of the zone, which is lacking in other models. Following transpressional terrane emplacement along the zone, this major crustal discontinuity was reactivated by extension resulting in movement along this fault that lasted at least 130 m.y.

Active faults in modern orogenic belt are often characterized by rapid movement, reaching several centimeters per year. This implies that the duration of the movement cannot be very long and thus presents an apparent contrast to the observations made for the Robertson Lake shear zone. This comparison with modern analogs indicates that the duration of movement along the fault may have lasted for at least 130 m.y., but that movement was likely episodic. The long interval therefore represents a time span over which this fault was active episodically.

Extension along the Robertson Lake shear zone occurred at least until 100 m.y. after contraction in the region ceased, which is a considerable time span when compared to modern settings of orogenic extension. Is this extension related to gravitational instability and orogenic collapse (e.g., Dewey, 1988), or is the extension related to plate tectonic reorganization and continental breakup (i.e., postorogenic)? On the basis of the lag time between contraction and cessation of extension it is likely that the latest stages of extension are a product of the latter. Plate tectonic reconstructions for this time period (900 Ma) are not well defined and the temporally nearest rifting phase along the Laurentian margin is 740 Ma (Su et al., 1994). Perhaps the late, postorogenic extension evident along the Robertson Lake shear zone is a yet unrecognized phase of (aborted?) continental breakup. To test this hypothesis one should look for contemporaneous normal faulting in cratons that were juxtaposed with Laurentia at that time.

ACKNOWLEDGMENTS

Supported by grants from the National Science Foundation (EAR 93-05736 and EAR 96-27911), the Scott Turner Fund (University of Michigan), and the Geological Society of America (4875-92 and 5122-93). We thank R. M. Easton for introducing us to the Robertson Lake shear zone, his insights into the regional geology, and generous field assistance. Comments by journal reviewers J. McLelland and L. Ratschbacher helped focus the manuscript.

REFERENCES CITED

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-orogenic extension in the Grenville Orogen, Canada: Precambrian Research, v. 77, p. 41–57.

Busch, J. P., Essene, E. J., and van der Pluijm, B. A., 1996a, Evolution of deep crustal normal faults: Constraints from thermobarometry in the Grenville Orogen, Ontario, Canada: Tectonophysics, v. 265, p. 83–100.

Busch, J. P., van der Pluijm, B. A., Hall, C. M., and Essene, E. J., 1996b, 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.

Carmichael, D. M., Moore, J. M., and Skippen, G. B., 1978, Isograds around the Hastings metamorphic 'low' (field trip guidebook): Geological Society of America–Geological Association of Canada–Mineralogical Association of Canada, p. 325–346.

Corfu, F., and Easton, R. M., 1995, U/Pb geochronology of the Mazinaw terrane, an imbricate segment of the Central Metasedimentary Belt, Grenville Province: Canadian Journal of Earth Sciences, v. 32, p. 959–976.

Corfu, F., Easton, R. M., and Hildebrand, R. S., 1995, Late Mesoproterozoic history of Sharbot Lake, Frontenac and Adirondack Lowland terranes, Grenville Province: Geological Society of America Program with Abstracts, v. 27, no. 6, p. A160.

Cosca, M. A., Sutter, J. F., and Essene, E. J., 1991, Cooling and inferred uplift/erosion history of the Grenville Orogen: 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.

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

Davidson, A., and Carmichael, D. M., 1997, An 1161 Ma suture in the Frontenac terrane, Ontario segment of the Grenville orogen: Comment, v. 25, p. 88–89.

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

Easton, R. M., 1988, The Robertson Lake mylonite zone—A major tectonic boundary in the Central Metasedimentary Belt, eastern Ontario. Geological Association of Canada–Mineralogical Association of Canada–Canadian Society of Petroleum Geologists joint meeting Program with Abstracts, v. 13, p. A34.

Easton, R. M., 1992, Part 2, The Grenville Province and the Proterozoic history of central and southern Ontario, *in* Thurston, P. C., et al., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, p. 714–904.

Hanmer, S., 1988, Ductile thrusting at mid-crustal levels, southwestern Grenville Province: Canadian Journal of Earth Sciences, v. 25, p. 1049–1059.

Hildebrand, R. S., and Easton, R. M., 1995, An 1161 Ma suture in the Frontenac terrane, Ontario segment of the Grenville orogen: Geology, v. 23, p. 917–920.

Mezger, K., van der Pluijm, B. A., Essene, E. J. and Halliday, A. N., 1991, Synorogenic collapse: A perspective from the middle crust, the Proterozoic Grenville Orogen: Science, v. 254, p. 695–698.

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.

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.

Scott, D. J., and St-Onge, M. R., 1995, Constraints on Pb closure temperature in titanite based on rocks from the Ungava orogen, Canada: Implications for U-Pb geochronology and *P-T-t* path determinations: Geology, v. 23, p. 1123–1126.

Su, Q., Goldberg, S. A., and Fullagar, P. D., 1994, Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia: Precambrian Research, v. 68, p. 81–95.

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.

White, D. J., Easton, R. M., Culshaw, N. G., Milkereit, B., Forsyth, D. A., Carr, S., Green, A. G., and Davidson, A., 1994, Seismic images of the Grenville Orogen in Ontario: Canadian Journal of Earth Sciences, v. 31, p. 293–307.

Windley, B. F., 1986, Comparative tectonics of the western Grenville and western Himalaya, *in* Moore, J. M., et al., eds., The Grenville Province: Geological Association of Canada Special Paper 31, p. 341–348.

Manuscript received November 26, 1996
Revised manuscript received February 28, 1997
Manuscript accepted March 4, 1997