Extension in the Central Metasedimentary Belt of the Ontario Grenville: Timing and tectonic significance

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ABSTRACT

A laterally extensive zone of southeast-dipping marble mylonites in the Central Metasedimentary Belt (CMB) of the southern Ontario Grenville (the "Bancroft shear zone") records southeast-directed extension and a displacement of about 10–12 km. Calcite-graphite carbon isotope thermometry indicates that the maximum temperature at which shearing occurred was ca. 450 °C. In contrast, carbon isotope fractionations ($\Delta^{13}C_{cc-gr}$) within the marble protolith consistently give temperatures of 650–700 °C. The Bancroft shear zone postdates 1060 Ma and older high-grade shear zones in the Central Gneiss Belt and the CMB that are associated with northwest-directed thrusting. Comparison of the temperature data from the retrograde marble mylonites with cooling curves for the CMB gives a late Grenvillian age range of 935–1010 Ma for the extensional event. The geometric relation between thrusting and normal faulting in the CMB is comparable to that in parts of the Himalayas and southern Tibet, and similarly we interpret late normal faulting in the CMB to be a result of gravitational collapse of a thrust-thickened crust. In contrast to the Himalaya-Tibet region, however, accretion in the Grenville becomes older in the direction of regional thrusting.

INTRODUCTION

The Grenville in southern Ontario, Canada, is subdivided into the Grenville front tectonic zone (GFTZ), the Central Gneiss Belt (CGB), and the Central Metasedimentary Belt (CMB) (Wynne-Edwards, 1972; Davidson, 1986). This general subdivision and the surrounding areas are shown in Figure 1. In recent years, the southwestern Ontario segment of the Grenville has attracted renewed interest following the recognition of major high-grade shear zones that separate a series of amphibolite to granulite grade thrust sheets (e.g., Davidson et al., 1982; Culshaw et al., 1983; Davidson, 1984, 1986; Mawer, 1987). Various lithotectonic domains and subdomains were recognized in the southern CGB, which in turn are overlain by the CMB (Hanmer and Cieselski, 1984; Davidson, 1986; Hanmer, 1988). The CMB is subdivided from west to east into the Central Metasedimentary Belt boundary zone (CMBBZ), and the Bancroft, Elzevir, and Frontenac (not shown) terranes.

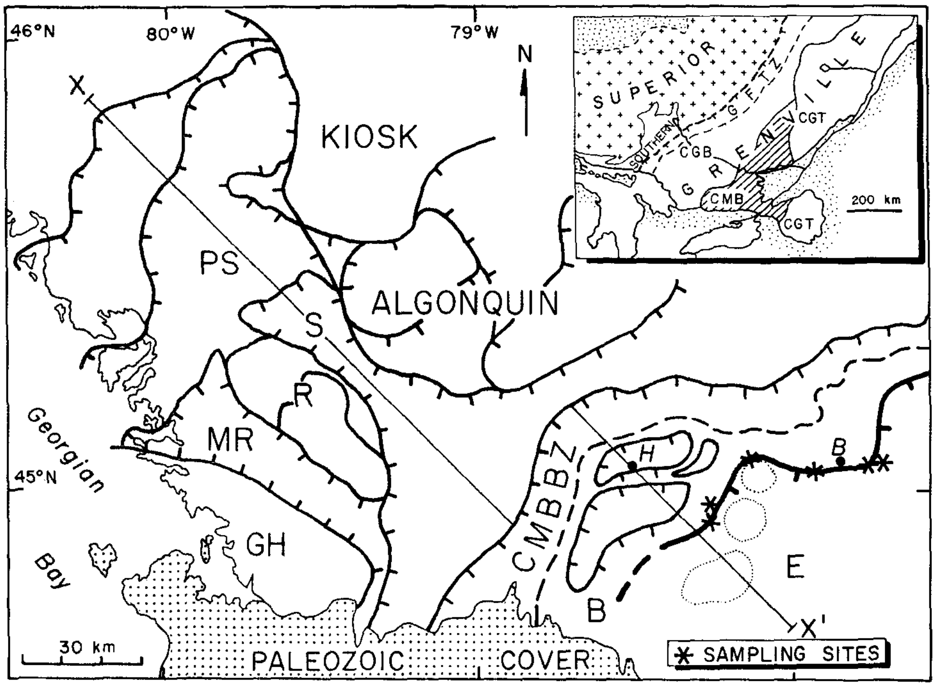

Figure 1. Regional setting (inset) and subdivision of Grenville in southern Ontario, Canada (after Wynne-Edwards, 1972; Davidson, 1986; Hanmer, 1988). Lines with ticks are ductile shear zones; heavy line in southeast is surface trace of extensional marble mylonites. CGB—Central Gneiss Belt, CGT—Central Granulite terrane, CMB—Central Metasedimentary Belt, CMBBZ—Central Metasedimentary Belt boundary zone, GFTZ—Grenville front tectonic zone. Domains and subdomains in CGB: GH—Go Home, MR—Moon River, PS—Parry Sound, S—Seguin, R—Rosseau. Terranes in CMB: B—Bancroft, E—Elzevir. *H* is location of Haliburton and *B* of Bancroft. Section along line X-X' is shown in Figure 4a.

The (sub)domains in the CGB were distinguished on the basis of rock assemblages, metamorphic grade, structure, and geophysical characteristics. Shear-sense indicators in the ductile shear zones, combined with the presence of gently southeast plunging lineations, indicate that the transport direction was toward the northwest (e.g., Davidson et al., 1982; Mawer, 1987). A northwestward transport direction was also determined in mylonitic gneisses of the CMBBZ (Hanmer et al., 1985).

In this paper we present carbon isotope data (calcite-graphite pairs) from mylonites and protoliths to estimate the temperature of an extensional shear zone in the CMB, and thereby constrain the timing of mylonitization. Furthermore, we discuss this late Grenvillian extensional event in view of a tectonic interpretation for the Ontario Grenville.

CHARACTERISTICS OF THE CENTRAL METASEDIMENTARY BELT

The dominant rock types in the western part of the CMB are greenschist to amphibolite facies marbles, paragneisses and orthogneisses (including tonalitic and nepheline-bearing gneisses), and gabbroic and granitic bodies (e.g., Anonymous, 1957; Wynne-Edwards, 1972). Isotopic age determinations indicate that volcanic activity and sedimentation took place from approximately 1280 to 1250 Ma (see Easton, 1986).

The boundary between the CGB and the CMB has been interpreted as a tectonic zone (the CMBBZ) by Davidson (1984) and Hanmer et al. (1985). A well-developed stretching lineation is common in the CMBBZ, and shear-sense indicators give a northwest-directed sense of motion for the emplacement of the CMB over the CGB. Synthrusting pegmatites, which were dated as 1060 Ma (U/Pb, zircons), suggest that this thrusting postdates the initiation of ductile shearing in the structurally underlying CGB by at least 60 m.y. (van Breemen and Hanmer, 1986; Hanmer 1988). Anovitz and Essene (1988) estimated pressures in the western CMB to be ca. 7 kbar. Across the CGB-CMB boundary they observed a 2 kbar *higher* pressure in the CGB (footwall), which would indicate *upward* movement of the CGB relative to the CMB of about 5–6 km.

High-grade marbles of the western CMB were described by Hanmer and Ciesielski (1984) as the highly ductile matrix of a major tectonic melange, containing kilometre- to centimetre-scale exotic blocks of paragneiss, granite, syenite, and mafic lithologies incorporated during large-scale northwest-directed ductile flow. These coarse (recrystallized?) marbles were subsequently reactivated during shear, and constitute the "protolith" in this study. Mylonites near Bancroft (Fig. 1) are southeast dipping; they contain rotated clasts and C-C′ and S-C fabrics that indicate a southeasterly transport direction (Carlson et al., in prep.). This mylonite zone can be traced over at least 70 km (Fig. 1) and has an average width of 10–15 m. We propose the name "Bancroft shear zone" for this laterally extensive ductile deformation zone. The combination of a southeast-dipping shear zone with a southeast-directed sense of movement dictates that these structures are normal faults and therefore record *extension* rather than thrusting. Fabrics formed during the extensional event locally crosscut the thrusting fabrics and have a slightly steeper dip. Regionally, however, both ductile fabrics are subparallel (Carlson et al., in prep.). Using 5–6 km vertical offset across the CGB-CMB boundary, based on barometry measurements and an average dip angle for the normal faults of 30°, we estimate the displacement on this shear zone to be 10–12 km.

The extensional marble mylonites are characterized by a variation in shear strain as reflected by variation in grain size and color. Dark, very fine grained marbles that contain mineral and lithic clasts grade into light-colored, coarser grained zones, which are interpreted to be the lower strain zones. Detailed field descriptions of the zone will be presented elsewhere (Carlson et al., in prep.).

CALCITE-GRAPHITE THERMOMETRY

Sample Description

Paired protolith-mylonite samples were collected from several sites along the shear zone (Fig. 1). At most sites the protolith sample was taken from approximately 1–2 m outside the shear zone adjacent to the mylonite sample. Sites WI-1 and WI-4 are exceptions; these protolith samples come from metre-scale lenses of coarse-grained marble preserved in the shear zone. One protolith sample several kilometres distant from the shear zone and a mylonite sample from an area where no protolith remains were added to the sample suite (GO-1B and BA-0, respectively).

The protolith is composed predominantly of calcite with grain sizes ranging from 1.5 to 5 mm. Though it represents the least deformed marbles, it contains several sutured calcite grain boundaries, growth of small new grains along grain boundaries, and extensive twinning. The most abundant silicates (5%–15% by volume) include phlogopite, diopside, tremolite, alkali feldspar, and plagioclase. Minor phases include dolomite, quartz, sphene, scapolite, apatite, zircon, magnetite, pyrite, and graphite. The graphite occurs as well-crystallized euhedral flakes with diameters of 0.5–1.5 mm. Most graphite is surrounded by calcite, but occasional flakes are armored by silicates.

The mylonites are mineralogically similar to the protoliths but are much finer grained. Graphite is extremely fine grained (<5 μm) and is variably distributed. In banded, light- and dark-colored samples (e.g., WI-1D), graphite is concentrated in subparallel planes separated by layers of calcite having grain sizes of 50–100 μm. Graphite in the darkest, finest-grained mylonites (calcite <15 μm) is finer grained than that in the banded samples and is more evenly distributed in the calcite matrix (BA-0). Occasionally, coarse graphite flakes occur within lithic clasts in the mylonite samples.

Analytical Methods

Crushed rock samples were dissolved in HCl to remove the carbonate. Large graphite flakes were then hand-picked from the protolith samples and examined under the microscope to ensure purity. No skeletal overgrowths as described by Weis (1980) were observed. Insoluble residues from the finer grained mylonites were sieved to remove any silicate clasts that could contain armored graphite flakes. The resulting residue was dissolved in HF to further concentrate the graphite and to eliminate any scapolite. Graphite separates were combusted to CO_2 in the presence of CuO at 1000 °C in evacuated quartz tubes.

Calcites were sampled from the same ca. 50 cm^3 volume of rock as the graphite and reacted with 100% H_3PO_4 at 55 °C. The C and O isotope ratios were then measured on the liberated CO_2 using a standard VG 602E ratio mass spectrometer. Isotopic compositions are given in per mil ($^0/_{00}$) relative to PDB; the C isotopic fractionation ($\Delta^{13}C_{cc\text{-}gr}$) is approximately equal to $\delta^{13}C_{cc}$–$\delta^{13}C_{gr}$. Reproducibility was better than $0.1^0/_{00}$ for calcite and $0.2^0/_{00}$ for graphite.

Results

The mean isotopic compositions of calcite (^{13}C and ^{18}O) and graphite (^{13}C) for marble protoliths and mylonites are given in Table 1. The $\delta^{13}C$ values of calcite are uniform on the scale of an individual thin section in the protolith marbles and vary by just over $0.2^0/_{00}$ within mylonite sections, whereas $\delta^{18}O$ values are slightly less uniform within a single thin section, possibly due to local exchange with silicates. Analysis of one scapolite-bearing sample made with and without HF treatment showed that C from scapolite changed the graphite value by less than $0.2^0/_{00}$.

TABLE 1. MEAN C AND O ISOTOPIC DATA FOR CALCITE (cc) AND GRAPHITE (gr)

Sample*	$\delta^{18}O_{cc}$	$\delta^{13}C_{cc}$	$\delta^{13}C_{gr}$	$\Delta^{13}C_{cc\text{-}gr}$
Mylonite				
BA-0(3)	18.6	-1.1	-10.6	9.5
BA-3D(3)	23.0	1.2	-7.1	8.3
BA-6B(2)	26.6	0.4	-7.5	7.9
GO-2A(2)	22.7	1.8	-5.6	7.4
WI-1D(2)	20.3	2.1	-3.4	5.5
WI-4B(2)	20.6	1.1	-3.6	4.7
Protolith				
BA-3B(2)	26.0	1.7	-2.0	3.7
BA-6E(2)	26.0	0.6	-3.6	4.2
GO-1B(2)	25.5	3.3	0.0	3.3
GO-2D(2)	26.2	3.3	-0.3	3.6
WI-1B(2)	20.9	2.0	-1.7	3.7
WI-4A(2)	19.7	1.2	-2.1	3.3

Note: ^{13}C data in parts per mil PDB (Peedee belemnite), ^{18}O in SMOW (standard mean ocean water); results from an extensive ^{13}C and ^{18}O isotopic study to be presented elsewhere.
* Number in parentheses is number of samples

Marble protoliths have relatively high $\delta^{13}C_{gr}$, between $-3.6^0/_{00}$ and $0.0^0/_{00}$; calcite values range from $0.6^0/_{00}$ to $3.3^0/_{00}$. The isotopic fractionation $\Delta^{13}C_{cc\text{-}gr}$ for the marble protoliths is remarkably consistent at $3.3^0/_{00}$ to $4.2^0/_{00}$ and is independent of the absolute $\delta^{13}C$ and $\delta^{18}O$ values (Table 1).

The $\delta^{13}C$ values of graphite from mylonite samples range from $-10.6^0/_{00}$ to $-3.4^0/_{00}$, and are lower and more variable than those of the protoliths. The $\delta^{13}C$ values of mylonite calcites are only slightly lower and more variable than their protolith counterparts, and range from $-1.1^0/_{00}$ to $2.1^0/_{00}$. Compared with the $\Delta^{13}C_{cc\text{-}gr}$ values of protoliths, ^{13}C fractionations in the mylonites are higher and more variable, and range from $4.7^0/_{00}$ to $9.5^0/_{00}$.

DISCUSSION AND CONCLUSIONS

Metamorphic Grade and Timing of Deformation

Figure 2 summarizes the distribution of $\Delta^{13}C_{cc\text{-}gr}$ values among protolith and mylonite samples. The protoliths have very similar fractionations; the average is $3.5^0/_{00}$. This uniformity over a 50 km distance within a complex metamorphic terrane suggests that isotopic equilibrium was attained. This conclusion is further supported by the fact that fractionations are independent of the absolute $\delta^{13}C$ and $\delta^{18}O$ values (Table 1). By using the empirically derived relation for the temperature dependence of $\Delta^{13}C_{cc\text{-}gr}$ (Fig. 3; Valley and O'Neil, 1981), a temperature of 650–700 °C is obtained for the protolith marbles, which is in good agreement with data determined from other thermometric systems (Anovitz and Essene, 1988).

Several explanations must be considered for

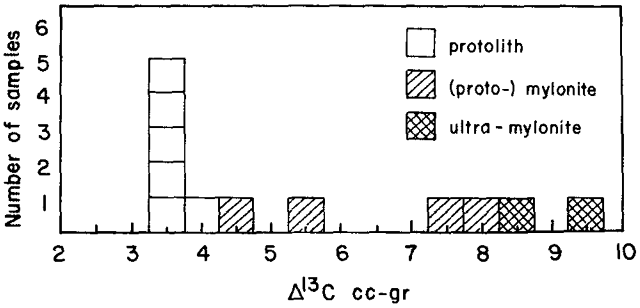

Figure 2. Histogram showing distribution of $\Delta^{13}C_{cc\text{-}gr}$ values of protoliths and mylonites. Protoliths group tightly at 3.5‰, but mylonites range between 4.5‰ and 9.5‰. Diagonal rules are values from gray, banded mylonites; double diagonal rules are values from darkest, finest grained mylonites.

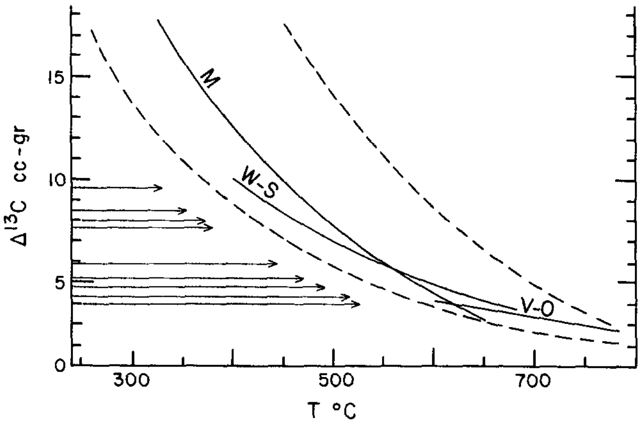

Figure 3. C isotope fractionations of calcite-graphite pairs vs. temperature (T; after Valley, 1986). Fractionation curves labeled V-O, W-S, and M are from Valley and O'Neil (1981), Wada and Suzuki (1983), and Morikiyo (1984), respectively. Dashed lines enclose area of naturally observed data. Horizontal lines show values for protolith and mylonite from this study.

the range of $\Delta^{13}C_{cc\text{-}gr}$ values observed among the mylonite samples. Fractionations range from 4.7‰ to 9.5‰, and might be the result of (1) an apparent change in fractionation caused by the failure of one mineral to exchange while the other undergoes exchange reactions with an external source of C; (2) equilibrium exchange at a variety of temperatures below 650 °C; and (3) partial exchange between calcite and graphite under retrograde conditions as a function of grain size.

The first explanation may be dismissed because of the dramatic $\delta^{13}C$ shifts in the rate-limiting graphite (e.g., Valley, 1986). Given that the Ontario Grenville cooled relatively slowly (2–4 °C/m.y.; Cosca et al., 1988) and that a 10–12 km displacement is likely to occur in only several million years, it is not likely that the mylonite zone was active over a wide range of temperatures. Fractionation in a zone of heterogeneous temperature is therefore also rejected as a viable explanation of the data.

Varying degrees of C isotope exchange between calcite and graphite are the best explanation for the mylonite data. At temperatures below 650 °C, the exchange of ^{13}C between calcite and graphite is slow, and disequilibrium conditions prevail (Valley and O'Neil, 1981). That low-temperature exchange of ^{13}C between calcite and graphite is observed in the mylonites indicates that the kinetic barriers to retrograde exchange have been minimized. Wada (1988) has shown that the C isotope composition of large grains of graphite (>1 mm) will not be significantly influenced by retrograde metamorphism. This seems confirmed by the paleotemperatures we determined for the protolith. We suggest that the overall grain-size reduction (and thus increase in surface/volume ratio) that is associated with progressive mylonitization of the marbles was responsible for the enhanced ^{13}C exchange between calcite and graphite. The highest fractionations are found in specimens with a grain size of 10 μm or less which correspond to samples with the highest degree of mylonitization. Because isotopic zonation (e.g., Wada, 1988) becomes more important as the grain size decreases (surface/volume ratio), equilibrium conditions will be approached only in the smaller grains. The highest fractionation (9.5‰) occurs in samples with graphite grain sizes well within the measured width of zonation (<15 μm) and thus approximates equilibrium values. Using the relations of Wada and Suzuki (1983) and Morikiyo (1984) shown in Figure 3, we determine a temperature of ca. 450 °C for the equilibration of ^{13}C between calcite and graphite in the mylonite zone. In addition to the surface/volume ratio, graphite in the banded, coarser mylonites is concentrated in discrete planes so that parts of it are shielded from contact with the calcite. In contrast, graphite in the darkest mylonites is much more evenly distributed throughout the calcite matrix, further facilitating isotopic exchange.

Cosca et al. (1988) have determined cooling curves for the CMB using $^{40}Ar/^{39}Ar$ stepwise degassing of hornblende, muscovite, biotite, and K-feldspar. Using their ca. 2–4 °C/m.y. cooling rates, the 200–250 °C temperature drop corresponds to 50–125 m.y. Because peak temperatures in protolith marbles of the CMB were probably synthrusting (1060 Ma), the timing of extensional shearing is in the range of 935 to 1010 Ma.

Tectonic Significance

In the closing chapter of *The Grenville Province* (Moore et al., 1986), Windley (1986) emphasized the analogous evolution of the Ontario Grenville and the Himalaya-Tibet region, following the earlier suggestion by Dewey and Burke (1973). On the basis of similarities in the igneous history, the deformation style (regional thrusting), and the relative timing and duration of events, Windley (1986) presented a tectonic scenario for the Grenville that closely resembles the continental collision model of India and Asia. The presence of a major zone of extensional faulting described in this paper further supports such an interpretation. In Figure 4, a schematic section across the southern Ontario

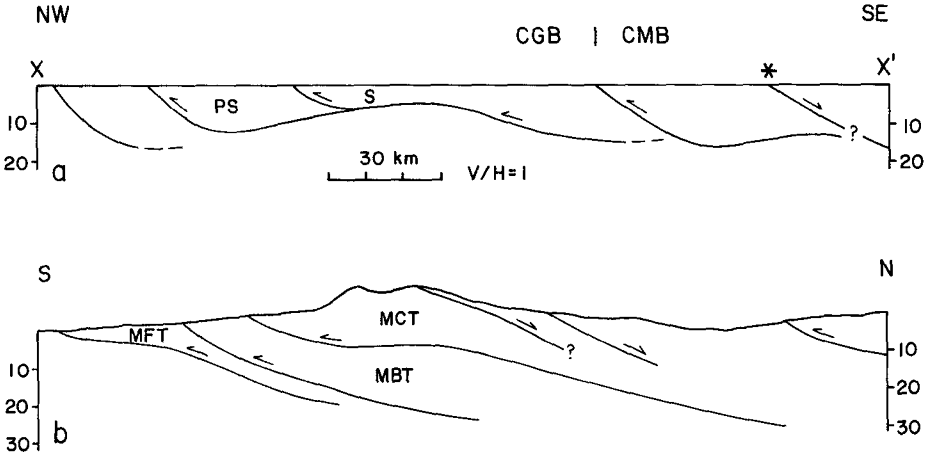

Figure 4. Schematic cross section of Ontario Grenville along line X-X' (Fig. 1), showing relation between northwest-directed thrusts (after Davidson, 1984) and extensional faulting (a). Star marks location of marble mylonites. b: Section through Himalayan system is shown for comparison (from Burchfiel and Royden, 1985). CGB—Central Gneiss Belt, CMB—Central Metasedimentary Belt, MBT—Main Boundary thrust, MCT—Main Central thrust, MFT—Main frontal thrust, PS—Parry Sound domain, S—Seguin domain. Horizontal and vertical scales in each section are equal.

Grenville (Fig. 4a) is compared with a representative section through the Himalayas (Fig. 4b) at the same horizontal and vertical scales. In addition to large-scale thrusting, Burg et al. (1984) documented extensional faulting in the Higher Himalayas and southern Tibet. Herren (1987) calculated the offset on these normal faults to be about 19 km. Burchfiel and Royden (1985) interpreted the formation of normal faults in the Himalayas to be a result of gravitational collapse associated with the change in topographic relief of a locally thickened crust. Figure 4 illustrates that the horizontal separation between the Main Central thrust and extensional faults in the Himalayas (Fig. 4b) is on the same order of magnitude as that between the CGB-CMB boundary and the Bancroft shear zone discussed in this paper (Fig. 4a). We therefore suggest that gravitational collapse following CMB thrusting may have been responsible for the retrograde extension.

In contrast to the Himalaya-Tibet orogenic belt, older foreland thrusting is present in the Grenville. A time interval of at least 60 m.y. separates deformation in the CGB from emplacement of the CMB, the older deformation being in the CGB. The time gap and backward (out-of-sequence) mode of thrusting suggest that CMB emplacement represents an event that is distinct from thrusting in the CGB. Thus, thickening and uplift associated with CMB thrusting produced the topographic relief that may have caused gravitational collapse and the formation of an extensional regime. This interpretation was used in the construction of Figure 4a, where the CMB front crosscuts structures in the CGB. Consequently, deformation in the southern Ontario Grenville does not represent a continuous crustal shortening event, but rather a history that comprises several distinct events (e.g., Davidson, 1984; Hanmer, 1988) that are possibly related to progressive terrane accretion. Note that in contrast to the Himalaya-Tibet system, accretion youngs in the direction opposite to the thrusting direction.

Grenville rocks that are on the surface at present were at crustal levels of at least 20 km and up to 35 km (Anovitz and Essene, 1988). If one accepts the analogy between the Grenville and the Himalaya-Tibet system (Windley, 1986), the CMB part of the Grenville section (Fig. 4a) corresponds to the unexposed root of the Himalayan section (Fig. 4b). Thus, through the study of ancient, deeply eroded orogenic systems such as the Grenville, we may be able to obtain an understanding of processes, such as deformation style and fluid and mass transfer, that occur at the deeper crustal levels of currently active orogenic belts.

REFERENCES CITED

Anonymous, 1957, Haliburton-Bancroft area (map sheet): *Province of Ontario Department of Mines* Map 1957b, scale 1:126,720.

Anovitz, L.M., and Essene, E.J., 1988, Pressure-temperature constraints on the metamorphism of the Grenville Province, Ontario: Journal of Petrology.

Burchfiel, B.C., and Royden, L.H., 1985, North-south extension within the convergent Himalayan region: Geology, v. 13, p. 679–682.

Burg, J.P., Brunel, M., Gapais, D., Chen, G.M., and Liu, G.H., 1984, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China): Journal of Structural Geology, v. 6, p. 535–542.

Cosca, M.A., Essene, E.J., and Sutter, J.F., 1988, Application of ^{40}Ar/^{39}Ar thermochronometry to the postmetamorphic cooling and denudation history of the Ontario Grenville terrane [abs.]: Gananoque, Grenville Workshop 1988, p. 8.

Culshaw, N.G., Davidson, A., and Nadeau, L., 1983, Structural subdivisions of the Grenville Province in the Parry Sound–Algonquin region, Ontario, *in* Current research, Part B: Geological Survey of Canada, v. 83-1B, p. 243–252.

Davidson, A., 1984, Identification of ductile shear zones in the southwestern Grenville Province of the Canadian Shield, *in* Kroner, A., and Greiling, R., eds., Precambrian tectonics illustrated: Amsterdam, Elsevier, p. 263–279.

——1986, New interpretations in 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. 61–74.

Davidson, A., Culshaw, N.G., and Nadeau, L., 1982, A tectono-metamorphic framework for part of the Grenville Province, Parry Sound region, Ontario, *in* Current research, Part A: Geological Survey of Canada, v. 82-1A, p. 175–190.

Dewey, J.F., and Burke, K.C.A., 1973, Tibetan, Variscan and Precambrian basement reactivation: Products of continental collision: Journal of Geology, v. 81, p. 683–692.

Easton, R.M., 1986, Geochronology 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. 127–189.

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

Hanmer, S.K., and Ciesielski, A., 1984, A structural reconnaissance of the northwest boundary of the Central Metasedimentary Belt, Grenville Province, Ontario and Quebec, *in* Current research, Part B: Geological Survey of Canada, v. 84-1B, p. 121–131.

Hanmer, S.K., Thivierge, R.H., and Henderson, J.R., 1985, Anatomy of a ductile thrust zone: Part of the northwest boundary of the Central Metasedimentary Belt, Grenville Province, Ontario (preliminary report), *in* Current research, Part B: Geological Survey of Canada, v. 85-1B, p. 1–5.

Herren, E., 1987, Zanskar shear zone: Northeast-southwest extension within the Higher Himalayas (Ladakh, India): Geology, v. 15, p. 409–413.

Mawer, C.K., 1987, Shear criteria in the Grenville Province, Ontario, Canada: Journal of Structural Geology, v. 9, p. 531–539.

Moore, J.M., Davidson, A., and Baer, A.J., editors, 1986, The Grenville Province: Geological Association of Canada Special Paper 31, 385 p.

Morikiyo, T., 1984, Carbon isotopic study on coexisting calcite and graphite in the Ryoke metamorphic rocks, northern Kiso district, central Japan: Contributions to Mineralogy and Petrology, v. 87, p. 251–259.

Valley, J.W., 1986, Stable isotope geochemistry of metamorphic rocks, *in* Valley, J.W., Taylor, H.P., Jr., and O'Neil, J.R., eds., Stable isotopes in high temperature geological processes: Mineralogical Society of America Reviews in Mineralogy 16, p. 445–490.

Valley, J.W., and O'Neil, J.R., 1981, ^{13}C/^{12}C exchange between calcite and graphite: A possible thermometer in Grenville marbles: Geochimica et Cosmochimica Acta, v. 45, p. 411–419.

van Breemen, O., and Hanmer, S., 1986, Zircon morphology and U-Pb geochronology in active shear zones: Studies on syntectonic intrusions along the northwest boundary of the Central Metasedimentary belt, Grenville Province, Ontario, *in* Current research, Part B: Geological Survey of Canada, v. 86-1B, p. 775–784.

Wada, H., 1988, Microscale isotopic zoning in calcite and graphite crystals in marble: Nature, v. 331, p. 61–63.

Wada, H., and Suzuki, K., 1983, Carbon isotopic thermometry calibrated by dolomite-calcite solvus temperatures: Geochimica et Cosmochimica Acta, v. 47, p. 697–706.

Weis, P.L., 1980, Graphite skeleton crystals—A newly recognized morphology of crystalline carbon in metasedimentary rocks: Geology, v. 8, p. 296–297.

Windley, B.F., 1986, Comparative tectonics of the western Grenville and the western Himalaya, *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., Variation in tectonic styles in Canada: Geological Association of Canada Special Paper 11, p. 263–334.

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