The Canadian Mineralogist
Vol. 35, pp.1237-1247 (1997)

A COMPILATION OF THERMOBAROMETRIC DATA FROM THE METASEDIMENTARY BELT OF THE GRENVILLE PROVINCE, ONTARIO AND NEW YORK STATE

MARGARET M. STREEPEY[1], ERIC J. ESSENE AND BEN A. VAN DER PLUIJM

Department of Geological Sciences, 2534 C.C. Little Building, University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

ABSTRACT

A new compilation of regional metamorphic temperature–pressure data in the Metasedimentary Belt (MB) of the Grenville Orogen, as exposed in Ontario and New York, shows the effect of major zones of ductile shear on metamorphic gradients. In addition to other thermometers, available data from garnet–biotite and two-feldspar thermometers were recalculated with a single calibration to permit comparisons among different field areas. Temperatures in the MB range from <500°C near Madoc, Ontario, in the Elzevir domain, and are in excess of 700°C in the western Gneiss Belt (GB) and the eastern Frontenac domain. Offsets in temperatures are observed across the Metasedimentary Belt Boundary Zone (MBBZ), the Sharbot Lake Shear Zone (SLSZ), and perhaps the Carthage–Colton Shear Zone (CCSZ). Pressures range from <6 kbar (<600 MPa) in the Elzevir domain near Madoc, Ontario to 8 kbar (800 MPa) in the westernmost part of the Frontenac domain. There is a 1–2 kbar (100–200 MPa) discontinuity in pressure across the Metasedimentary Belt Boundary Zone (MBBZ) and at the Robertson Lake (RLSZ) and Sharbot Lake (SLSZ) shear zones. However, some shear zones in the MB predate the peak of metamorphism, and do not seem to offset metamorphic gradients in the field (*e.g.*, the Mooroton shear zone). Comparing temperatures and pressures across these boundaries requires knowledge of the timing of peak metamorphism. Geochronological studies indicate that some boundaries juxtapose domains that do not have the same metamorphic histories. In the Grenville Orogen, such integrated data suggest that zones of ductile shear variably represent tectonically active terrane boundaries and intra-terrane zones of displacement.

Keywords: Grenville Orogen, Metasedimentary Belt, thermobarometry, shear zones, Ontario, New York.

SOMMAIRE

Une nouvelle compilation de données de pression et de température du métamorphisme régional dans la ceinture métasédimentaire de la province orogénique du Grenville, telle qu'exposée en Ontario et dans l'état de New York, montre les effets des zones majeures de cisaillement ductile sur la distribution des gradients métamorphiques. En plus des autres thermomètres, les données disponibles à propos de l'équilibre grenat – biotite et du géothermomètre fondé sur la coexistence de deux feldspaths ont été recalculées avec un seul calibrage afin de permettre des comparaisons d'une région à l'autre. Les températures dans la ceinture métasédimentaire vont de moins de 500°C, près de Madoc, en Ontario, dans le domaine d'Elzevir, à au delà de 700°C dans la ceinture gneissique dans le secteur ouest et dans le domaine de Frontenac, à l'est. Des déplacements dans la température sont évidents en traversant la zone limitrophe de la ceinture métasédimentaire, la zone de cisaillement du lac Sharbot, et possiblement la zone de cisaillement de Carthage – Colton. Les valeurs de pression varient entre moins de 6 kbar (<600 MPa) dans le domaine d'Elzevir, près de Madoc, jusqu'à 8 kbar (800 MPa) dans la partie la plus occidentale du domaine de Frontenac. Il y a une discontinuité de 1 à 2 kbar (100–200 MPa) en traversant la zone limitrophe de la ceinture métasédimentaire et la zone de cisaillement du lac Sharbot. Toutefois, certaines des zones de cisaillement (la zone de Mooroton, par exemple) précèdent le paroxysme métamorphique, et ne semblent donc pas déplacer les gradients métamorphiques sur le terrain. Une comparaison des températures et des pressions de part et d'autre de ces discontinuités nécessite une connaissance de l'âge du métamorphisme. Les études géochronologiques montrent que le long de certaines zones limitrophes, il y a eu juxtaposition de domaines qui ne partagent pas la même évolution métamorphique. Dans la province du Grenville, de telles données intégrées font penser que les zones de cisaillement ductile représentent soit des bordures de socles tectoniquement actifs, soit des zones de déplacement inter-socle.

(Traduit par la Rédaction)

Mots-clés: province du Grenville, ceinture métasédimentaire, thermobarométrie, zones de cisaillement, Ontario, New York.

INTRODUCTION

The Grenville Orogen of New York, Ontario, and western Quebec comprises three separate northeast-trending belts: the Gneiss Belt (GB), structurally overlain by the Metasedimentary Belt (MB) and the Granulite Terrane (GT) (Wynne-Edwards 1972, Davidson 1984a, 1986; Fig. 1). These belts are distinct lithotectonic packages (Wynne-Edwards 1972) separated by major shear zones (Davidson 1984a,

---

[1] *E-mail address*: mstreepe@umich.edu

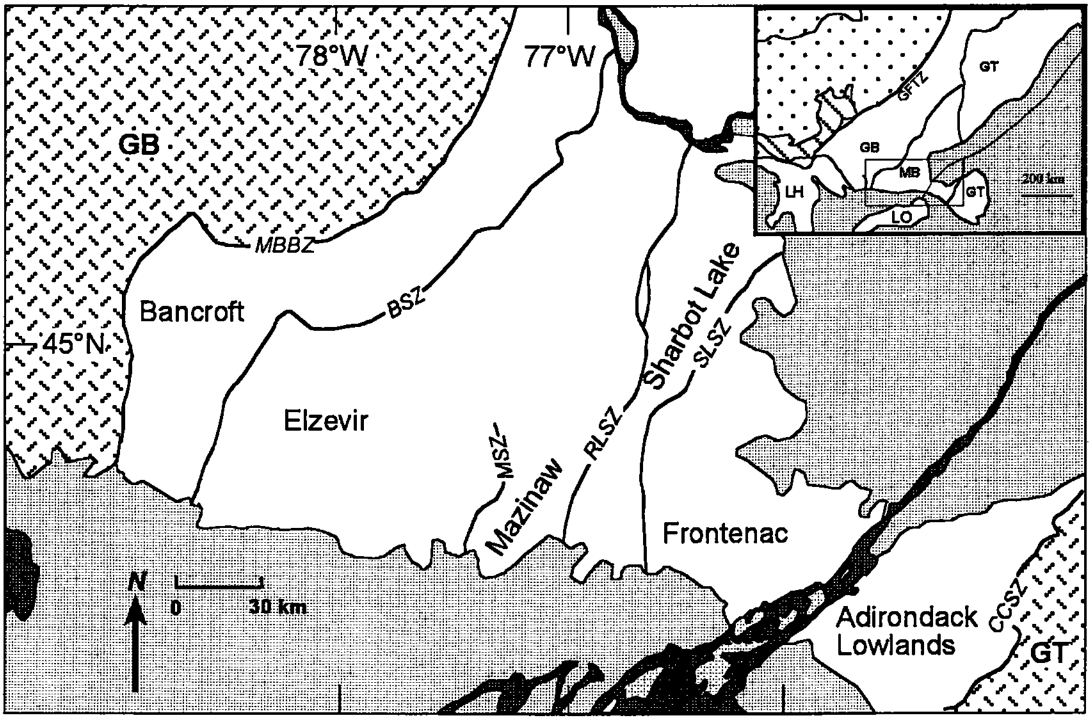

FIG. 1. Regional subdivision of domains and shear zones in the central portion of the Grenville Orogen of southern Ontario and northern New York. MB: Metasedimentary Belt, GB: Gneiss Belt, GT: Granulite Terrane, MBBZ: Metasedimentary Belt Boundary Zone, BSZ: Bancroft Shear Zone, MSZ: Mooroton Shear Zone, RLSZ: Robertson Lake Shear Zone, SLSZ: Sharbot Lake Shear Zone, CCSZ: Carthage–Colton Shear Zone. Light gray areas show approximate location of Paleozoic cover. Shear zones are not continued into the Quebec portion of the Grenville. Inset shows generalized subdivision of the Grenville Province, with study area outlined.

1995). The Metasedimentary Belt includes several domains, identified on the basis of their individual lithological and geophysical characteristics, whose boundaries also are the loci of ductile shear zones (Culshaw *et al.* 1983, Davidson 1984b, 1986, 1995, Hanmer 1988, Easton 1989, 1992a, b; Fig. 1). In addition to contractional tectonics, several recent studies have shown that late extension characterizes some of the major shear zones separating domains of the MB. These include the Bancroft shear zone (BSZ) between the Bancroft and Elzevir domains, the Robertson Lake shear zone (RLSZ) between the Mazinaw and Sharbot Lake domains, and possibly the Carthage–Colton shear zone (CCSZ), between the Adirondack Lowlands and the Adirondack Highlands of the GT (Hanmer 1988, van der Pluijm & Carlson 1989, Mezger *et al.* 1991b, 1992, Davidson 1995, Busch & van der Pluijm 1996).

The Metasedimentary Belt is characterized by marble, metasedimentary, and metavolcanic rocks in which metamorphic grade ranges from the upper greenschist to the granulite facies (*e.g.*, Carmichael *et al.* 1978, Davidson 1984b, Anovitz & Essene 1990). Various thermobarometers have been applied to rocks throughout the region in attempts to constrain the temperature – pressure conditions of metamorphism. The Grenville Province is ideally suited for thermobarometric studies as a result of the many types of metasedimentary and meta-igneous rocks that are present. However, metamorphic P–T gradients have previously been drawn across the region before constraints on the timing of metamorphism were developed (*e.g.*, Bohlen *et al.* 1985, Anovitz & Essene 1990). Since these shear zones commonly separate rocks with different metamorphic and cooling ages (Mezger *et al.* 1991a, b, van der Pluijm *et al.* 1994), pressures and temperatures calculated for individual domains are not necessarily representative of a single metamorphic event and may not correlate across the region. The purpose of this paper is to recompile recent thermobarometric data and generate new metamorphic maps, taking into account possible offsets across shear zones in the MB. In addition, results of this study point out discrepancies and weaknesses in quantitative pressure and temperature data, and thus point to possibilities for future thermobarometric work in the MB.

STRUCTURAL SETTING

The Grenvillian orogenic cycle (Moore & Thompson 1980) comprises several distinct phases of deformation in the area of the Metasedimentary Belt and the Gneiss Belt. Recent U–Pb studies of zircon and titanite constrain the timing of two deformational events for the MBBZ in Ontario: one thrusting event at *ca.* 1190 Ma, and a second episode of thrusting as young as 1060 Ma (van Breemen & Hanmer 1986, Mezger *et al.* 1991b, McEachern & van Breemen 1993). The early phase of deformation has been interpreted as the closure of a marginal basin, wherein the Elzevir terrane was juxtaposed against the southeastern margin of Laurentia (the present-day GB; Davidson *et al.* 1982, Culshaw *et al.* 1983, Hanmer & McEachern 1992, McEachern & van Breemen 1993). The tectonic framework of the younger episode of deformation is less well constrained, but is generally considered to have been produced by a collision between the Grenville Province (including the Adirondack Highlands) and an unspecified continent to the southeast (Windley 1986, Hanmer & McEachern 1992, McEachern & van Breemen 1993). Direction of displacement along these early thrusts is predominantly to the northwest, as defined by shear-sense indicators and widespread, gently plunging southeast lineations (*e.g.*, Davidson 1984b, Hanmer 1988).

Structural and geochronological studies have defined a later extensional component to some of the shear zones in the MB. Rocks in the southeast-dipping BSZ contain shear-sense indicators implying a normal sense of movement (Carlson *et al.* 1990). Although ages of peak metamorphism on both sides of the BSZ are similar, ^{40}Ar–^{39}Ar analyses of hornblende yield ages of 1021–1026 Ma immediately to the east of the BSZ and 959–989 Ma immediately to the west of the shear zone (Cosca *et al.* 1995), indicating a juxtaposition of the structurally higher Elzevir domain against the Bancroft domain (Mezger *et al.* 1991b). Structural studies in the southeast-dipping RLSZ yield mylonitic granites with S–C structures and mica fish, as well as brittle structures, that all indicate a normal (top down to the east) sense of displacement (Easton 1989, Busch & van der Pluijm 1996).

The U–Pb ages related to peak metamorphism are at least 100 m.y. older in the Sharbot Lake domain than in the adjacent Mazinaw domain; ^{40}Ar–^{39}Ar cooling ages of hornblende and biotite also reflect this offset (Cosca *et al.* 1992, 1995, Corfu & Easton 1995, Busch *et al.* 1996a). A U–Pb study of rocks along the CCSZ shows that the Adirondack Lowlands cooled through the closure temperature of titanite (600–650°C: Mezger *et al.* 1991a) between 1156 and 1103 Ma, whereas titanite in the adjoining Adirondack Highlands (GT) yields ages of 1050–982 Ma. This indicates a large difference in the age of peak regional metamorphism on either side of the CCSZ (Mezger *et al.* 1991b, 1992).

COMPILATION OF DATA

There have been numerous thermobarometric studies across the Metasedimentary Belt. Data from recent studies at the University of Michigan (Rathmell 1993, Busch *et al.* 1996b, Cureton 1997), complemented by data from the literature (Ewert 1977, Lonker 1980, Bohlen *et al.* 1980, Edwards & Essene 1988, Anovitz & Essene 1990), were compiled to generate a regional view of temperature–pressure conditions for metamorphism in the MB. Figure 2 shows sample locations, and Table 1 lists the corresponding thermometric and barometric results used in this compilation. Mineral analyses used for these calculations are available from the first author. Two-feldspar temperature data were checked for consistency among different studies using the computer program SOLVCALC (Wen & Nekvasil 1994), with the activity model of Fuhrman & Lindsey (1988). Because several calibrations have been used in the literature to obtain garnet–biotite temperatures for the MB, these temperatures were uniformly recalculated with the calibration of Patiño Douce *et al.* (1993) using an unpublished thermobarometry program (M.J. Kohn & F.S. Spear 1996, Version 2.0) to maintain internal consistency in the database. Recalculated temperatures were generally within ±50°C of the temperatures reported in the literature.

Pressures reported from the literature, mostly from recent studies at the University of Michigan, were directly compiled and averaged without further computation. Barometers used include garnet – amphibole – plagioclase – quartz, garnet – plagioclase – ferrosilite – quartz (GAFS: Bohlen *et al.* 1983b), garnet – plagioclase – diopside – quartz (GADS: Newton & Perkins 1982, Moecher *et al.* 1988), garnet – aluminosilicate – quartz – plagioclase (GASP: Koziol & Newton 1988), garnet – rutile – ilmenite – plagioclase – quartz (GRIPS: Bohlen & Liotta 1986), and garnet – rutile – ilmenite – aluminosilicate (GRAIL: Bohlen *et al.* 1983a).

Contours were drawn on the basis of an analysis of compiled data, combined with additional information from Anovitz & Essene (1990). Owing to widespread resetting, the calcite–dolomite thermometer in some cases yielded temperatures on the order of 300°C lower than other thermometers from the same area. The anomalously low calcite–dolomite temperatures reported by Ewert (1977) and Rathmell (1993) are considered to represent retrograde resetting after peak metamorphism and were generally disregarded when drawing contours. Two-feldspar, calcite–graphite, and garnet exchange thermometers (garnet–biotite, garnet–

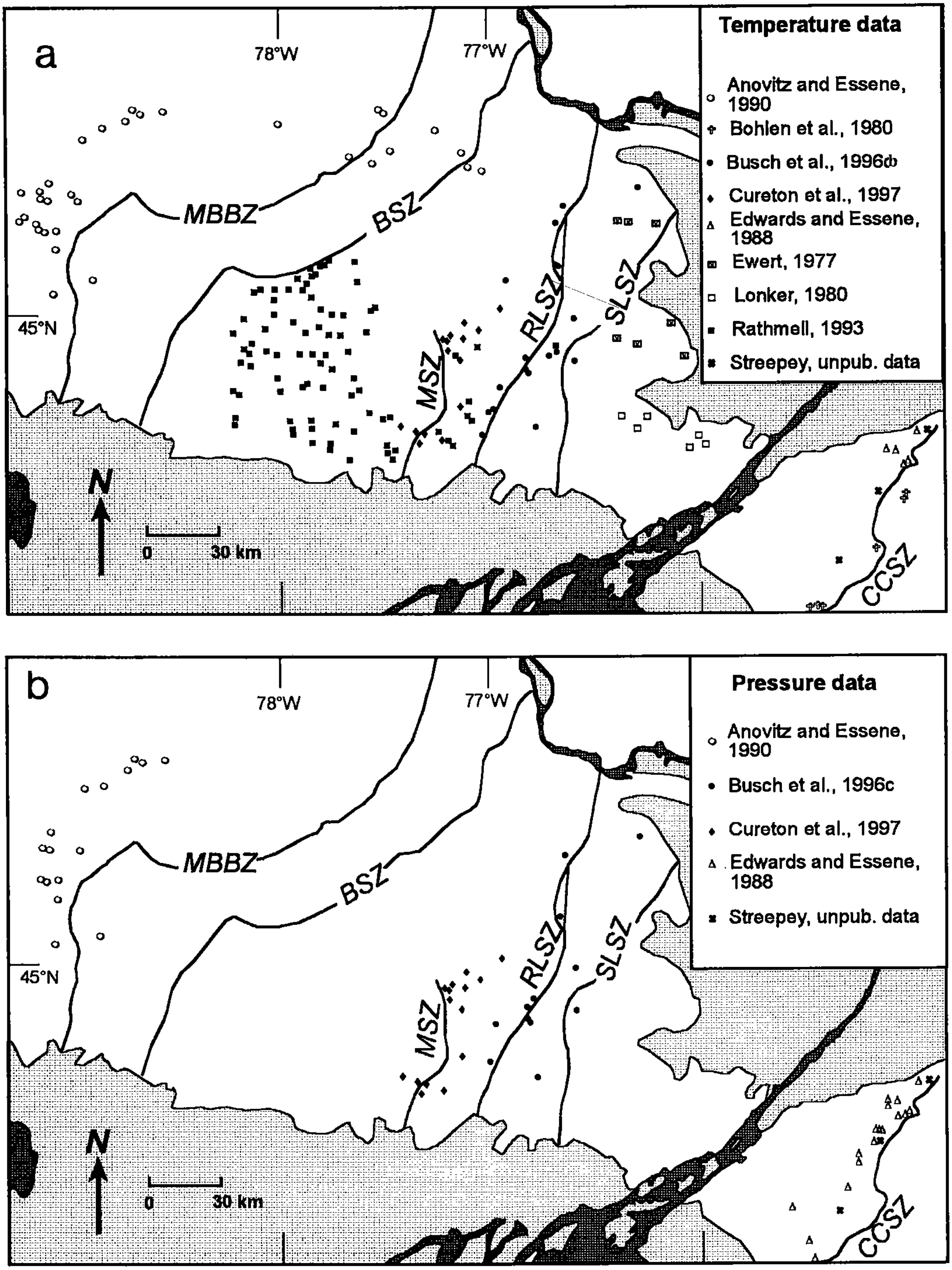

FIG. 2. Locations and sources of compiled temperature (a) and pressure (b) data. Thermometers used include garnet – biotite, garnet – hornblende, garnet – orthopyroxene, garnet – clinopyroxene, calcite – dolomite, calcite – graphite, and plagioclase – potassium feldspar. Barometers are based on the assemblages garnet – amphibole – plagioclase, garnet – plagioclase – diopside – quartz, garnet – plagioclase – ferrosilite – quartz, garnet – aluminosilicate – quartz – plagioclase, garnet – rutile – ilmenite – plagioclase – quartz, and garnet – rutile – ilmenite – aluminosilicate.

TABLE 1. THERMOBAROMETRIC DATA, METASEDIMENTARY BELT OF THE GRENVILLE PROVINCE, ONTARIO AND NEW YORK STATE

	UTM coordinates		Temperatures (°C) and Pressures (kbar)
Anovitz & Essene (1990)			
pem83c28	17T50495	3110	Grt–Cpx: 750 ± 20, Pl–Kfs: 590
pem83c36	17T50460	2752	Pl–Kfs: 630
ren83c13	17T50259	3450	Pl–Kfs: 700
ren83c15	17T50278	3419	Pl–Kfs: 780
ren83c17	17T50332	3399	Pl–Kfs: 650
ren83c28	17T50329	3018	Pl–Kfs: 650
ren83c30	17T50400	3314	Pl–Kfs: 700
ren83c50	17T50346	3150	Pl–Kfs: 730
hut85a5	17T50114	6600	Pl–Kfs: 720
hut85a12	17T50218	6555	Pl–Kfs: 740
dm8579a	17T50230	6720	Grt–Opx: 830 ± 40, Grt–Cpx: 800 ± 20
MIN 80 1	17T49826	6902	Pl–Kfs: 720
ALG83C 3	17T50484	7120	Pl–Kfs: 670
ALG83C 6-1*	17T50522	7090	Grt–Opx: 710, Grt–Cpx: 790, GAFS: <10.2
ALG83C 13	17T50508	6969	Grt–Opx: 79, Pl–Kfs: 650, GAFS: 9.1
ALG83C 14	17T50508	6969	Grt–Opx: 850, Grt–Cpx: 790, GAFS: 9
ALG83C 15	17T50502	6950	Grt–Cpx: 720
ALG 83C 20	17T50458	6825	Pl–Kfs: 670
ALG83C 26	17T50332	6700	Grt–Opx: 750, GAFS: 10.2
HAL 83 C 7	17T50298	6658	Pl–Kfs: 610
HAL 83 C 8	17T50226	6608	Grt–Cpx: 740, Pl–Kfs: 740, GRIPS: 10.5
HAL 83 C 24	17T50122	6692	Grt–Opx: 750, Grt–Cpx: 790, GAFS: 9.7
HAL 83 C 25	17T50125	6734	Grt–Opx: 790, Grt–Cpx: 730, GAFS: 9.1
HAL 83 C 38	17T49966	6892	GASP: 7.2
HAL83 C 75	17T49894	6698	Pl–Kfs: 590
HAL 84B49	17T50048	6502	Grt–Opx: 750, GAFS: 10.4
ALG85A2*	17T50522	7090	Grt–Opx: 850, Grt–Cpx: 710, GAFS: 8.8
ALG 85 A 6	17T50455	6810	GASP: 9, GRIPS: >6.3, GRAIL: >2.9
HUT 85 A 4	17T50235	6535	Grt–Opx: 680, Grt–Cpx: 710, GAFS: 10.3
HUT 85 A 5	17T50114	6600	Pl–Kfs: 720
H37A DPM	17T50140	6644	Grt–Opx: 670, GAFS: 10
DMM 80 188B	17T50926	6672	Grt–Opx: 830, Grt–Cpx: 810, GAFS: 11
DM 85 79A	17T50230	6720	Grt–Opx: 830, Grt–Cpx: 800, GAFS: 8.6
DMC 85 4002	17T50450	6780	Grt–Opx: 700, Grt–Cpx: 750, GAFS: 9.7
DMC 8551 03	17T50484	6910	Grt–Opx: 830, Grt–Cpx: 750, GAFS: 9
HAL 83 C 50	17T49922	7305	Pl–Kfs: 730
Bohlen *et al.* (1980)			
LB-1	18T48850	4710	Pl–Kfs: 690
LB-2	18T48815	4620	Pl–Kfs: 690
LB-4	18T48820	4630	Pl–Kfs: 690
LB-5	18T48825	4655	Pl–Kfs: 740
GVR-136	18T49065	4825	Pl–Kfs: 650
GVR-62	18T49245	4955	Pl–Kfs: 630
GVR-64	18T49220	4955	Pl–Kfs: 650
Busch *et al.* (1996b)			
203	18T4757460	372380	Grt–Opx: 750, Grt–Cpx: 780, Grt–Amp–Pl: 8.9, GAFS: 8.2, GADS: 7.8
237	18T4932900	356370	Grt–Cpx: 730, GADS: 8
265	18T4937950	339070	Grt–Cpx: 820, GADS: 9.8
240	18T4939150	341420	Grt–Hbl: 620
68	18T4947050	344320	Grt–Hbl: 630
173	18T4954610	354630	Grt–Bt: 830, Grt–Opx: 720, GAFS: 6
170	18T4955620	354610	Grt–Bt: 560, Grt–Hbl: 520, Grt–Amp–Pl: 5
84	18T4959455	357290	Grt–Hbl: 630, Grt–Amp–Pl: 8
179	18T4959180	363370	Grt–Bt: 650
60	18T4961475	358895	Grt–Amp–Pl: 7.7
206	18T4970875	372890	Grt–Hbl: 560, Grt–Amp–Pl: 7.1
164	18T5003920	370350	Grt–Hbl: 640
152	18T5010675	372390	Grt–Hbl: 570, Grt–Amp–Pl: 8.3
242	18T5015650	398910	Grt–Hbl: 750, Grt–Amp–Pl: 8.6
35	18T4032090	338550	Grt–Bt: 620
268	18T4984770	449910	Grt–Hbl: 590
270	18T4958900	364140	Grt–Hbl: 580
44	18T4989310	366860	Grt–Bt: 660
140	18T4989250	366210	Grt–Hbl: 580, Grt–Amp–Pl: 7.1
137	18T4955575	344760	Grt–Amp–Pl: 5.5
Cureton *et al.* (1997)			
AD16593	18T49770	3470	Grt–Bt: 640, Grt–Hbl: 510, GAFS: >5.8, GASP: <9.2, GRIPS: <8.2
MS3893	18T49715	3380	Grt–Bt: 460, GAFS: >4.5, GASP: <4.7, GRIPS: <5.5
QB8993	18T49385	3080	Grt–Bt: 470, GAFS: >2.5, GASP: <4.0, GRIPS: <5.1
92-7	18T49670	3320	Grt–Bt: 540
CL13393	18T49730	3325	Grt–Bt: 700, GAFS: >5.7, GASP: <13.9, GRIPS: <9.6
AT8793	18T49355	3145	Grt–Bt: 540, Grt–Hbl: 530, GAFS: >4.7, GASP: <9.1, GRIPS: <7.7
CL7393	18T49640	3270	Grt–Bt: 560, GAFS: >2.3, GASP: <4.0, GRIPS: <5.1
CL1493	18T49665	3265	Grt–Bt: 600, GAFS: >5.5, GASP: <8.2, GRIPS: <7.1
CL5793	18T49685	3280	Grt–Bt: 600, GAFS: >3.5, GASP: <5.1, GRIPS: <5.6
SK1593	18T49680	3250	Grt–Bt: 690, GAFS: >5, GASP: <5.2, GRIPS: <6.1
BC3293	18T49605	3300	Grt–Bt: 580, GAFS: >3.7, GASP: <4.7, GRIPS: <6.1
AT3693	18T49360	3155	Grt–Bt: 620, GAFS: >3, GASP: <5.8
KA7593	18T49445	3290	Grt–Bt: 540, Grt–Hbl: 590, GAFS: >5.5, GASP: <10.9, GRIPS: <9.3
SU17593	18T49340	3230	Grt–Crd: 570, GAFS: >6.5, GASP: <8.2, GRIPS: <7.1
Edwards & Essene (1988)			
PD-14	18T49370	5015	Pl–Kfs: 760, GASP: 8
CT-17	18T49310	4920	Pl–Kfs: 720, GASP: 6.8
RS-14	18T49295	4985	GASP: >5.7
RS-10	18T49290	4895	Pl–Kfs: 680
RS-12	18T49285	4895	GASP: 6.7
RSL-13	18T49295	4975	GASP: 7.5
RS-33	18T49270	4970	Pl–Kfs: 760, GASP: <10.4
RS-34	18T49270	4975	Pl–Kfs: 740
CT-10	18T49260	4940	GASP: 6.7
RS-73	18T49225	4845	GASP: >3.9
RS-18	18T49200	4815	GASP: >5.2
GVR-5	18T49050	4710	GASP: 7
RS-2	18T49215	4870	GASP: 6.6
GVR-46	18T49145	4780	GASP: 7.2
GVR-30	18T49115	4775	GASP: <9
GVR-12	18T49050	4720	GASP: 7
ANT-99	18T48985	4500	GASP: 5.4
ANT-88	18T48880	4614	GASP: <5.7
LB-145	18T48820	4645	Pl–Kfs: 690
Ewert (1977)			
920035	18T50030	3945	Cal–Dol: 470
895003	18T50035	3900	Cal–Dol: 390
857634	18T49640	3865	Cal–Dol: 320
0 61674	18T49685	4045	Cal–Dol: 290
0 28004-3	18T50025	4020	Cal–Dol: 480
0 95567	18T49575	4095	Cal–Dol: 310
948621	18T49615	3945	Cal–Dol: 260
Lonker (1980)			
GN-11-76-A	18T49250	4140	Pl–Kfs: 670
GN-18-76-C	18T49225	4065	Grt–Crd: 720, Pl–Kfs: 700
WP-62-76-A	18T49350	3850	Pl–Kfs: 690
WP-88-77-A	18T49305	3905	Pl–Kfs: 670
WP-112-77-C	18T49345	3955	Grt–Crd: 730, Pl–Kfs: 690
GN-165-77-A	18T49270	4120	Grt–Crd: 680, Pl–Kfs: 680

TABLE 1. THERMOBAROMETRIC DATA, METASEDIMENTARY BELT OF THE GRENVILLE PROVINCE, ONTARIO AND NEW YORK STATE (continued)

	UTM coordinates	Temperatures (°C) and Pressures (kbar)
	Rathmell (1993)	
BB91159	18T702421	Grt–Bt: 590
BB91149	18T709385	Cal–Dol: 480
BB91148	18T709384	Cal–Dol: >510, Cal–Gr: 560
BB91143	18T765345	Cal–Dol: >250, Cal–Gr: 460
BB9145	18T840339	Cal–Dol: <250
BB9144	18T838335	Cal–Dol: <250
CF9134	18T915285	Cal–Dol: 440, Cal–Gr: 380
BB9138	18T921384	Cal–Dol: 480
KA9206	18T26312	Grt–Bt: 540
KA9126	18T38275	Cal–Dol: >370, Cal–Gr: 520
KA9121	18T19415	Cal–Dol: 430, Cal–Gr: 460
KA9113A	18T44419	Cal–Dol: 290
CH91133	18T641673	Grt–Bt: 680
BB9142	18T859407	Cal–Dol: <250, Cal–Gr: 590
BB9207	18T774401	Grt–Bt: 440
BB9147	18T767422	Cal–Dol: 480
KI902B	18T983444	Cal–Dol: >410, Cal–Gr: 440
KI909	18T294649523	Cal–Dol: 470, Cal–Gr: 500
BB9148	18T918512	Cal–Dol: >470, Cal–Gr: 480
BB9223A	18T754540	Grt–Bt: 600
BB9224	18T753540	Cal–Dol: <250
BB91153	18T670526	Cal–Dol: <250
BB91154	18T669526	Cal–Dol: <250, Cal–Gr: 550
BB91155	18T669528	Grt–Bt: 670
BB91156	18T671582	Cal–Dol: 520, Cal–Gr: 640
CH908A	18T916657	Cal–Dol: 390, Cal–Gr: 480
CH9153	18T850651	Cal–Dol: >500, Cal–Gr: 470
CH9152	18T868603	Cal–Dol: >480, Cal–Gr: 410
CH9214	18T818615	Grt–Bt: 640
CH91130	18T676655	Cal–Dol: 530, Cal–Gr: 560
CH91116	18T634748	Cal–Dol: 550
CH91113	18T737769	Cal–Dol: >500
CH9186	18T677849	Cal–Dol: 340
CH9184	18T675797	Cal–Dol: >480, Cal–Gr: 630
BF9110	17T282525	Cal–Dol: >300, Cal–Gr: 300
GH91134	17T332662	Cal–Dol: >390
GH91123	17T289637	Cal–Dol: <250
GH91124	17T306672	Cal–Dol: <250
GH91126	17T333700	Cal–Dol: <250, Cal–Gr: 530
GH9181	17T339830	Cal–Dol: >460
KA901B	18T25324	Cal–Dol: <250, Cal–Gr: 490
KA914A	18T25324	Cal–Dol: <250
KA914C	18T25324	Cal–Dol: >370
KA9124	18T50305	Cal–Dol: <250
KA9117	18T144325	Cal–Dol: <250
KA91163	18T163361	Grt–Bt: 560
KA91135	18T212362	Cal–Dol: >340, Cal–Gr: 510
KA91116	18T233324	Cal–Dol: <250, Cal–Gr: 530
KA91118	18T278344	Cal–Dol: 600
KA91119	18T254306	Cal–Dol: <250, Cal–Gr: 230
KA91138	18T315395	Cal–Dol: 550, Cal–Gr: 580
KA91136	18T318456	Cal–Dol: <250
KA91142	18T315394	Grt–Bt: 640
KA91115	18T201298	Cal–Dol: 400
KI9221	18T336249664	Cal–Dol: <250
GH9201	17T345805	Grt–Bt: 800
GH9215C	17T271736	Grt–Bt: 800
GH9178	17T307779	Cal–Dol: 280, Cal–Gr: 190
BA9189	18T786870	Cal–Dol: 550, Cal–Gr: 410
BA903A	18T767915	Cal–Dol: >470
BA904A	18T795887	Cal–Dol: 340, Cal–Gr: 550
BA9191	18T806912	Cal–Dol: 330
BA9212	18T815915	Grt–Bt: 650
BA9211	18T815912	Grt–Bt: 650
BA916B	18T849939	Cal–Dol: 530
BA9195	18T908963	Cal–Gr: 630
BA9202	18T918971	Grt–Bt: 680, Cal–Dol: 470
BA9197	18T04964	Cal–Dol: >600, Cal–Gr: 360
BA9198	18T977896	Cal–Dol: <250
WF9219	18T337877	Grt–Bt: 770
CH91107	18T773718	Cal–Dol: 560, Cal–Gr: 540
CH9164	18T826733	Cal–Dol: >520
CH906	18T841799	Cal–Dol: >260
CH905	18T813851	Cal–Dol: 530, Cal–Gr: 600
CH9158	18T871794	Cal–Dol: 500
CH9159	18T916784	Cal–Dol: 510, Cal–Gr: 590
CH91100	18T896861	Cal–Dol: 530, Cal–Gr: 540
CH9204	18T860735	Grt–Bt: 620
CH9203	18T25802	Grt–Bt: 670
CH9170	18T989726	Cal–Dol: 480, Cal–Gr: 480
CH9171	18T12795	Cal–Dol: 540, Cal–Gr: 540
CH9166	18T900717	Cal–Dol: 540, Cal–Gr: 550
CH9217	18T751644	Grt–Bt: 690
BB91121	18T826542	Cal–Dol: >290, Cal–Gr: 190
BF918	17T274441	Cal–Dol: >270
BF917	17T278422	Cal–Dol: 520
BF9216	17T278535	Grt–Bt: 810
KI912	18T365449619	Cal–Dol: >460
BB915	17T932567	Cal–Dol: 460
BA9183	17T360874	Cal–Dol: 570, Cal–Gr 190
	M.M. Streepey, unpubl. data	
A132-1	18T49300 4975	Grt–Bt: 710, Pl–Kfs: 680, GASP: 7.5, GRIPS: 6, GRAIL: 6.9
A132-3	18T49300 4975	Grt–Bt: 850
A114-1	18T49205 4860	Grt–Bt: 880, Pl–Kfs: 520, GASP: 9, GRIPS: 6.3, GRAIL: 8
A121-1	18T48955 4710	Grt–Bt: 730, Pl–Kfs: 520, GASP: 7, GRIPS: 7.5, GRAIL: 7.3
A111-1	18T49210 4845	Grt–Bt: 760, GASP: 8.5, GRIPS: 6, GRAIL: 7.6
A111-2	18T49210 4845	Grt–Bt: 700, GASP: 8.5, GRIPS: 6, GRAIL: 7.5

Mineral symbols in this compilation follow the convention of Kretz (1983); in addition, Amp is used to represent amphibole. The table is arranged alphabetically according to name of authors cited. Limiting temperatures and pressures are noted by the signs ">" and "<". Acronyms: GAFS: garnet – plagioclase – ferrosilite – quartz; GRIPS: garnet – rutile – ilmenite – plagioclase – quartz; GASP: garnet – aluminosilicate – quartz – plagioclase; GRAIL: garnet – rutile – ilmenite – aluminosilicate; GADS: garnet – plagioclase – diopside – quartz.

cordierite, garnet–hornblende, garnet–orthopyroxene, and garnet–clinopyroxene), on the other hand, are considered more reliable, and temperatures calculated using these thermometers were used preferentially in contouring. Some assemblages required the use of limiting barometers (Edwards & Essene 1988, Anovitz & Essene 1990, Cureton *et al.* 1997), although absolute pressures were used instead of limiting pressures wherever possible.

RESULTS OF THE COMPILATION

Temperatures

Figure 3a shows the contour map resulting from the compilation of temperature data. In the Gneiss Belt, temperature ranged from greater than 750°C in the west to 650–700°C in the east (Anovitz & Essene 1990). There appears to be a discontinuity in temperature across the southern part of the MBBZ; temperatures of 700–750°C in the west decrease to 600–650°C in the east. Temperatures decrease south from the BSZ to less than 500°C at the Hastings Low near Madoc, Ontario (Anovitz & Essene 1990, Rathmell 1993). In the Mazinaw domain, temperature estimates between 600 and 650°C have been reported near the RLSZ (Busch *et al.* 1996b, Cureton *et al.* 1997). Across the RLSZ, temperatures remain between 600 and 650°C, increasing to 650–700°C at the SLSZ. Temperature estimates to the east of the SLSZ are on the order of 700–750°C in the Frontenac domain (Reinhardt 1968, Carmichael *et al.* 1978, Lonker 1980, Davidson 1986, Anovitz & Essene 1990, Busch *et al.* 1996b). Lonker (1980) argued that the pyroxene granulites in the Frontenac domain attained *ca.* 800°C and were variably reset after the peak of metamorphism. However, an evaluation of uncertainties in maximum temperatures of granulite-facies rocks are complex and beyond the scope of this paper. Temperature appears to have decreased locally to 650–700°C in the Adirondack Lowlands and then increased again across the CCSZ to 700–750°C in the Adirondack Highlands (Bohlen & Essene 1977, Brown *et al.* 1978, Bohlen *et al.* 1980, 1985, Powers & Bohlen 1985, Edwards & Essene 1988, Cartwright *et al.* 1993, Lamb 1993, Kitchen & Valley 1995). It is possible that peak temperatures in the Frontenac domain and the Adirondack Highlands were somewhat higher than those preserved by the systems that were applied (perhaps in the range of 750–800°C).

Pressures

Although available data on pressure are sparse in comparison to data on temperature, pressures are significantly less variable, and the data are easier to interpret than data on temperature. Figure 3b shows a contour map based on compiled data on pressure. In the GB, pressure estimates exceed 8 kbar (800 MPa) and decrease across the MBBZ (Anovitz & Essene 1990). We surmise that pressure decreased in a manner similar to temperature in the Elzevir domain, to less than 6 kbar (600 MPa) in the vicinity of the MSZ (Busch *et al.* 1996b, Cureton *et al.* 1997). Pressure estimates increase to the east to 7–8 kbar (700–800 MPa) at the RLSZ, and then drop sharply to 6–7 kbar (600–700 MPa) across the RLSZ. In the Sharbot Lake domain, higher values are recorded, up to ~8 kbar (800 MPa) at the SLSZ (Busch *et al.* 1996b). Pressures decrease across the SLSZ to approximately 6 kbar (600 MPa) in the Frontenac domain (Reinhardt 1968, Lonker 1980), and increase slightly to 7–8 kbar (700–800 MPa) in the vicinity of the CCSZ (Edwards & Essene 1988, Busch *et al.* 1996b).

DISCUSSION

Anovitz & Essene (1990) noted major changes in peak pressures and temperatures of metamorphism in the Grenville Province of Ontario, both on a regional scale and across known tectonic boundaries. However, age determinations on shear zones in the MB were not available at the time, and so contours were drawn across boundaries that join domains that we now know to have different metamorphic ages. Geochronological data, considered in conjunction with pressure–temperature data, help to elucidate the influence of major shear zones on thermobarometric gradients in the Metasedimentary Belt and the pattern of regional metamorphism in the Grenville Orogen (van der Pluijm *et al.* 1994, Cosca *et al.* 1995). For instance, there is no systematic offset in ages across the MSZ, and there are no apparent thermobarometric discontinuities (Cureton *et al.* 1997). Thus, the MSZ is interpreted to be a shear zone that predates the most recent peak metamorphic event. Ages are discontinuous across the RLSZ, and there are also marked changes in pressure–temperature conditions across this boundary. Thermobarometric conditions are slightly different across the SLSZ, which separates rocks that were metamorphosed at the same time but have different cooling histories (Busch *et al.* 1996a). Finally, rocks of the Adirondack Lowlands in the upper amphibolite to granulite facies have metamorphic ages that are distinctly older than rocks of the granulite-facies Adirondack Highlands across the CCSZ. Therefore, the CCSZ separates rocks with dissimilar metamorphic histories (Mezger *et al.* 1991a).

Incorporating the results of our pressure–temperature compilation with what is known about ductile shear zones in the MB shows that distinct thermobarometric discontinuities occur across zones that represent late to post-orogenic extension (BSZ, RLSZ, CCSZ). Although it is possible to generate common contours for the entire MB, it is important to recognize that the pattern does not represent a single metamorphic event. Rather, at least two major episodes

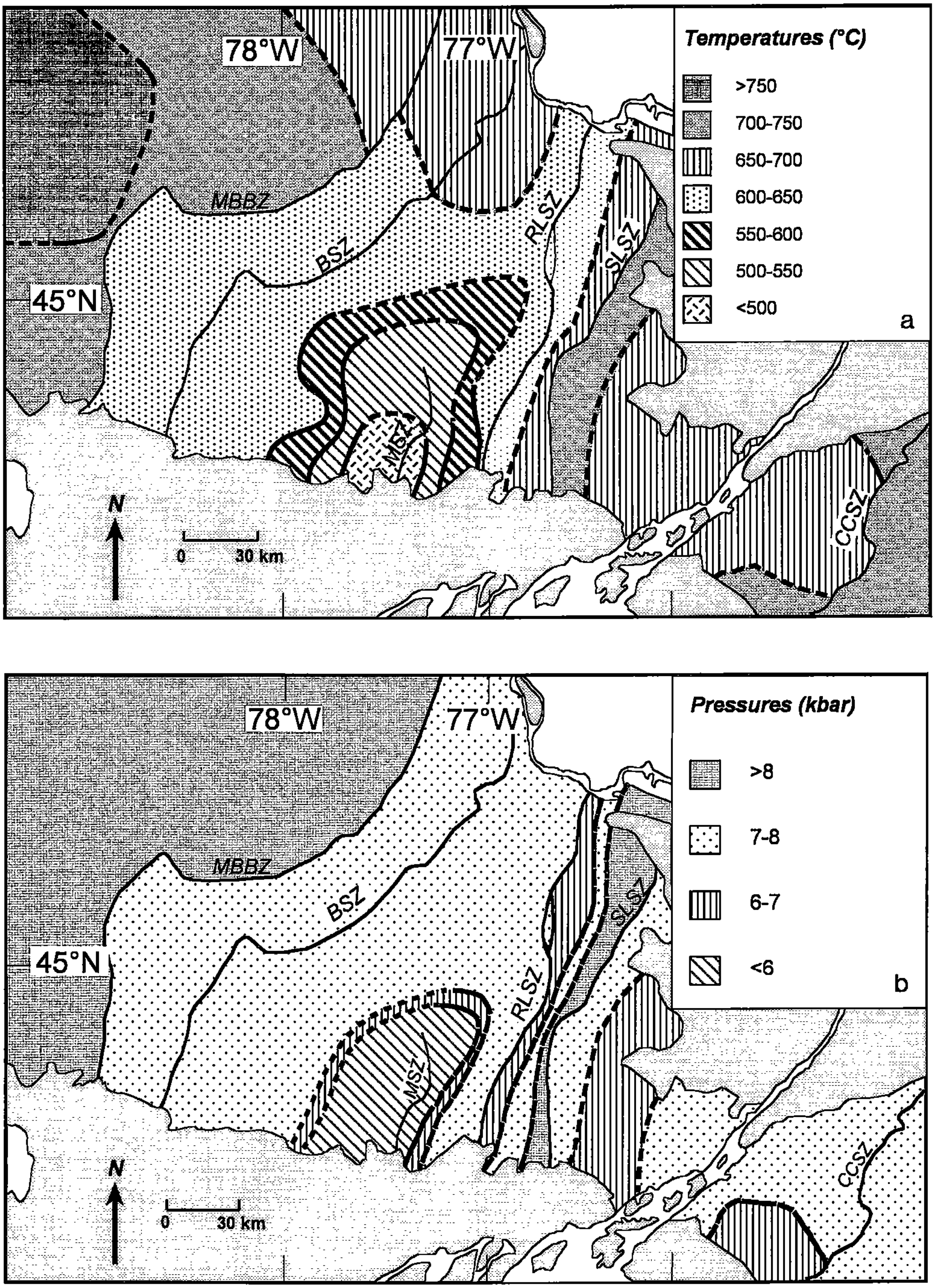

FIG. 3. Generalized contour maps of temperatures (a) and pressures (b) in the Metasedimentary Belt. Data points from Figure 2 have been removed for clarity. Also shown are the major zones of ductile shear (see Fig. 1). Dashed lines represent inferences, whereas solid lines are based on thermobarometric measurements. Titanite ages range from 1000 to 1070 Ma in the Bancroft domain, from 1040 to 1070 Ma in the Elzevir domain, approximately 1010 Ma in the Mazinaw domain, 1150 to 1555 Ma in the Sharbot Lake domain, 1150 to 1170 in the Frontenac and the Adirondack Lowlands, and 1030 to 1050 in the Adirondack Highlands (*e.g.*, van der Pluijm *et al.* 1994).

of deformation, at *ca.* 1150 Ma and *ca.* 1040 Ma, characterize the region (van Breemen & Hanmer 1986, Mezger *et al.* 1991b, 1993, McEachern & van Breemen 1993, Corfu & Easton 1995). It is crucial, therefore, to incorporate geochronological studies when evaluating temperature–pressure gradients in regions that expose complex structural and metamorphic histories of rocks of the middle to lower crust.

Future work

The purpose of this paper is not only to elucidate the significance of shear zones on thermobarometric gradients, but also to examine weaknesses in the database of temperatures and pressures. For instance, there is a marked lack of data in the Bancroft domain as well as a paucity of data on pressure of metamorphism in the Elzevir and Frontenac domains. Only tentative temperature–pressure contours can be drawn across these areas. In addition, the reliability of individual thermometers must be evaluated. Calcite–dolomite data from Rathmell (1993) and Ewert (1977) have been ignored when drawing contours because of the susceptibility of resetting of the calcite–dolomite thermometer. This is supported in the Elzevir and Mazinaw domains by additional data from garnet–biotite and calcite–graphite thermometers; however, few other constraints are available for temperatures in the Sharbot Lake domain. The portion of the Sharbot Lake domain near the Ottawa River may represent a second low-grade lobe of Grenville metamorphism in Ontario (Ewert 1977). As an alternative, the apparent low-grade character of these rocks may be produced by extensive retrograde metamorphism. Application of the calcite–graphite thermometer may prove useful in determining the extent of resetting of the calcite–dolomite thermometer in this area.

Quantitative thermobarometry can have serious limitations in that the rocks of interest may not have the full mineral assemblages needed, and thermobarometers can also be affected by retrograde metamorphism. In these cases, the most powerful determinations of peak conditions of metamorphism come from field characteristics and mapped isograds. In addition, thermometers cannot distinguish between temperatures reached by regional metamorphism and those influenced by contact metamorphism. In many instances, the influence of intrusions on peak temperatures is not straightforward, and these complexities are reflected in the data. Correlating patterns generated from quantitative data and field isograds will ultimately give the most coherent picture of peak conditions of metamorphism in the Metasedimentary Belt.

ACKNOWLEDGEMENTS

This study was most recently supported by NSF grants EAR 93–05736 and EAR 96–27911. F. Spear is thanked for help with thermobarometric calculations and generously sharing new software. M. Easton made insightful comments on early versions of the contour maps. K. Johnson is thanked for help with the compilation. P. Tropper and S. Keane provided helpful comments and discussion of the manuscript. A. Davidson and an anonymous reviewer provided insights and comments that improved the manuscript.

REFERENCES

ANOVITZ, L.M. & ESSENE, E.J. (1990): Thermobarometry and pressure – temperature paths in the Grenville Province of Ontario. *J. Petrol.* **31**, 197-241.

BOHLEN, S.R. & ESSENE, E.J. (1977): Feldspar and oxide thermometry of granulites in the Adirondack Highlands. *Contrib. Mineral. Petrol.* **62**, 153-169.

________ & LIOTTA, J.J. (1986): A barometer for garnet amphibolites and garnet granulites. *J. Petrol.* **27**, 1025-1034.

________, ________ & HOFFMAN, K.S. (1980): Feldspar and oxide thermometry in the Adirondacks Mountains: an update. *Geol. Soc. Am., Bull.* **91**, 110-113.

________, VALLEY, J.W. & ESSENE, E.J. (1985): Metamorphism in the Adirondacks. I. Petrology, pressure, and temperature. *J. Petrol.* **26**, 971-992.

________, WALL, V.J. & BOETTCHER, A.L. (1983a): Experimental investigations and geologic applications of equilibria in the system $FeO–TiO_2–Al_2O_3–SiO_2–H_2O$. *Am. Mineral.* **68**, 1049-1058.

________, ________ & ________ (1983b): Experimental investigations and application of garnet granulite equilibria. *Contrib. Mineral. Petrol.* **83**, 52-61.

BROWN, P.E., ESSENE, E.J. & KELLY, W.C. (1978): Sphalerite geobarometry in the Balmat–Edwards district, New York. *Am. Mineral.* **63**, 250-257.

BUSCH, J.P., ESSENE, E.J. & VAN DER PLUIJM, B.A. (1996b): Evolution of deep-crustal normal faults: constraints from thermobarometry in the Grenville orogen, Ontario, Canada. *Tectonophys.* **265**, 83-100.

________ & 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 Res.* **77**, 41-57.

________, ________, HALL, C.M. & ESSENE, E.J. (1996a): Listric normal faulting during postorogenic extension revealed by $^{40}Ar/^{39}Ar$ thermochronology near the Robertson Lake shear zone, Grenville orogen, Canada. *Tectonics* **15**, 387-402.

CARLSON, K.A., VAN DER PLUIJM, B.A. & HANMER, S. (1990): Marble mylonites of the Bancroft shear zone: evidence for extension in the Canadian Grenville. *Geol. Soc. Am., Bull.* **102**, 174-181.

CARMICHAEL, D.M., MOORE, J.M. & SKIPPEN, G.B. (1978): Isograds around the Hastings metamorphic low. *In* Toronto '78 (A.L. Currie & W.O. Mackasey, eds.). *Geol. Assoc. Can., Field Trips Guidebook*, 325-346.

CARTWRIGHT, I., VALLEY, J.W. & HAZELWOOD, A.-M. (1993): Resetting of oxybarometers and oxygen isotope ratios in granulite facies orthogneisses during cooling and shearing, Adirondack Mountains, New York. *Contrib. Mineral. Petrol.* **113**, 208-225.

CORFU, F. & EASTON, R.M. (1995): U–Pb geochronology of the Mazinaw terrane, an imbricate segment of the Central Metasedimentary Belt, Grenville Province, Ontario. *Can. J. Earth Sci.* **32**, 959-976.

COSCA, M.A., ESSENE, E.J., KUNK, M.J. & SUTTER, J.F. (1992): Differential unroofing within the Central Metasedimentary Belt of the Grenville Orogen: constraints from ^{40}Ar/ ^{39}Ar thermochronology. *Contrib. Mineral. Petrol.* **110**, 211-225.

__________, ________, MEZGER, K. & VAN DER PLUIJM, B.A. (1995): Constraints on the duration of tectonic processes: protracted extension and deep-crustal rotation in the Grenville Orogen. *Geology* **23**, 361-364.

CULSHAW, N.G., DAVIDSON, A. & NADEAU, L. (1983): Structural subdivisions of the Grenville Province in the Parry Sound – Algonquin region, Ontario. *Geol. Surv. Can., Pap.* **83-1B**, 243-252.

CURETON, J.S., VAN DER PLUIJM, B.A. & ESSENE, E.J. (1997): Nature of the Elzevir – Mazinaw domain boundary, Grenville Orogen, Ontario. *Can. J. Earth Sci.* **34**, 976-991.

DAVIDSON, A. (1984a): Identification of ductile shear zones in the southwestern Grenville Province of the Canadian Shield. *In* Precambrian Tectonics Illustrated (A. Kröner & R. Greiling, eds.). E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany (263-279).

________ (1984b): Tectonic boundaries within the Grenville Province of the Canadian Shield. *Geodynamics* **1**, 433-444.

________ (1986): New interpretations in the southwestern Grenville Province. *In* The Grenville Province (J.M. Moore, A. Davidson & A.J. Baer, eds.). *Geol. Assoc. Can., Spec. Pap.* **31**, 61-74.

________ (1995): A review of the Grenville orogen in its North American type area. *J. Aust. Geol. Geophys.* **16**, 3-24.

________, CULSHAW, N.G. & NADEAU, L. (1982): A tectonometamorphic framework for part of the Grenville Province, Parry Sound region, Ontario. *Geol. Surv. Can., Pap.* **82-1A**, 175-190.

EASTON, R.M. (1989): Regional mapping and stratigraphic studies, Grenville Province. *Ont. Geol. Surv., Misc. Pap.* **146**, 153-157.

________ (1992a): Revised terrane subdivision and observations on the tectonic assembly of the Central Metasedimentary Belt, Ontario. *Geol. Soc. Am., Abstr. Programs* **24**, 94.

________ (1992b): The Grenville Province and Proterozoic history of central and southern Ontario. *In* Geology of Ontario (P.C. Thurston, H.R. Williams, R.H. Sutcliffe & G.M. Stott, eds.). *Ont. Geol. Surv., Spec. Vol.* **4**, 714-904.

EDWARDS, R.L. & ESSENE, E.J. (1988): Pressure, temperature, and C–O–H fluid fugacities across the amphibolite – granulite transition, northwest Adirondack Mountains, New York. *J. Petrol.* **29**, 39-72.

EWERT, W.D. (1977): *Metamorphism of Siliceous Carbonate Rocks in the Grenville Province of Southeastern Ontario.* Ph.D. thesis, Carleton Univ., Ottawa, Ontario.

FUHRMAN, M.L. & LINDSLEY, D.H. (1988): Ternary-feldspar modeling and thermometry. *Am. Mineral.* **73**, 201-215.

HANMER, S. (1988): Ductile thrusting at mid-crustal level, southwestern Grenville Province. *Can. J. Earth Sci.* **25**, 1049-1059.

________ & MCEACHERN, S. (1992): Kinematical and rheological evolution of a crustal scale ductile thrust zone, Central Metasedimentary Belt, Grenville orogen, Ontario. *Can. J. Earth. Sci.* **29**, 1779-1790.

KITCHEN, N.E. & VALLEY, J.W. (1995): Carbon isotope thermometry in marbles of the Adirondack Mountains, New York. *J. Metamorphic Geol.* **13**, 577-594.

KOZIOL, A.M. & NEWTON, R.C. (1988): Redetermination of the anorthite breakdown reaction and improvement of the plagioclase – garnet – Al_2SiO_5 – quartz geobarometer. *Am. Mineral.* **73**, 216-223.

KRETZ, R. (1983): Symbols for rock-forming minerals. *Am. Mineral.* **68**, 277-279.

LAMB, W.M. (1993): Retrograde deformation within the Carthage – Colton Zone as recorded by fluid inclusions and feldspar compositions: tectonic implications for the southern Grenville Province. *Contrib. Mineral. Petrol.* **114**, 379-394.

LONKER, S. (1980): Conditions of metamorphism in high-grade pelitic gneisses from the Frontenac Axis, Ontario, Canada. *Can. J. Earth Sci.* **17**, 1666-1684.

MCEACHERN, S.J. & 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. *Can. J. Earth Sci.* **30**, 1155-1165.

MEZGER, K., ESSENE, E.J., VAN DER PLUIJM, B.A. & HALLIDAY, A.N. (1993): U–Pb geochronology of the Grenville Orogen of Ontario and New York: constraints on ancient crustal tectonics. *Contrib. Mineral. Petrol.* **114**, 13-26.

________, RAWNSLEY, C.M., BOHLEN, S.R. & HANSON, G.N. (1991a): U–Pb garnet, sphene, monazite, and rutile ages: implications for the duration of high-grade metamorphic and cooling histories, Adirondack Mt., New York. *J. Geol.* **99**, 415-428.

________, VAN DER PLUIJM, B.A., ESSENE, E.J. & HALLIDAY, A.N. (1991b): Synorogenic collapse: a perspective from the middle crust, the Proterozoic Grenville orogen. *Science* **254**, 695-698.

________, ________, ________ & ________ (1992): The Carthage – Colton mylonite zone (Adirondack Mountains, New York): the site of a cryptic suture in the Grenville Orogen? *J. Geol.* **100**, 630-638.

MOECHER, D.P., ESSENE, E.J. & ANOVITZ, L.M. (1988): Calculation and application of clinopyroxene – garnet – plagioclase – quartz geobarometers. *Contrib. Mineral. Petrol.* **100**, 92-106.

MOORE, J.M., JR. & THOMPSON, P.H. (1980): The Flinton Group: a late Precambrian metasedimentary succession in the Grenville Province of eastern Ontario. *Can. J. Earth Sci.* **17**, 1685-1707.

NEWTON, R.C. & PERKINS, D., III (1982): Thermodynamic calibration of geobarometers based on the assemblages garnet – plagioclase – orthopyroxene (clinopyroxene) – quartz. *Am. Mineral.* **67**, 203-222.

PATIÑO DOUCE, A.E., JOHNSTON, A.D. & RICE, J.M. (1993): Octahedral excess mixing properties in biotite: a working model with applications to geobarometry and geothermometry. *Am. Mineral.* **78**, 113-131.

POWERS, R.E. & BOHLEN, S.R. (1985): The role of synmetamorphic igneous rocks in the metamorphism and partial melting of metasediments, northwest Adirondacks. *Contrib. Mineral. Petrol.* **90**, 401-409.

RATHMELL, M.A. (1993): *Comparison of Garnet–Biotite, Calcite–Graphite, and Calcite–Dolomite Thermometry in the Grenville Orogen, Canada.* M.Sc. thesis, Univ. Michigan, Ann Arbor, Michigan.

REINHARDT, E.W. (1968): Phase relations in cordierite-bearing gneisses from the Gananoque area, Ontario. *Can. J. Earth Sci.* **5**, 455-482.

VAN BREEMEN, O. & 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. *Geol. Surv. Can., Pap.* **86-1B**, 775-784.

VAN DER PLUIJM, B.A. & CARLSON, K.A. (1989): Extension in the Central Metasedimentary Belt of the Ontario Grenville: timing and tectonic significance. *Geology* **17**, 161-164.

________, MEZGER, K., COSCA, M.A. & ESSENE, E.J. (1994): Determining the significance of high-grade shear zones by using temperature–time paths, with examples from the Grenville orogen. *Geology* **22**, 743-746.

WEN, S. & NEKVASIL, H. (1994): SOLVCALC: an interactive graphics program package for calculating the ternary feldspar solvus and for two-feldspar geothermometry. *Comput. Geosci.* **20**, 1025-1040.

WINDLEY, B.F. (1986): Comparative tectonics of the western Grenville and western Himalaya. *In* The Grenville Province (J.M. Moore, A. Davidson & A.J. Baer, eds.). *Geol. Assoc. Can., Spec. Pap.* **31**, 341-348.

WYNNE-EDWARDS, H.R. (1972): The Grenville Province. *In* Variations in Tectonic Styles in Canada (R.A. Price & R.J.W. Douglas, eds.). *Geol. Assoc. Can., Spec. Pap.* **11**, 263-334.

Received January 8, 1997, revised manuscript accepted July 24, 1997.