The Canadian Mineralogist
Vol. 35, pp. 1161-1171 (1997)

GARNET–KYANITE CLINOPYROXENITES AND GARNET–KYANITE RESTITES FROM THE MANICOUAGAN IMBRICATE ZONE: A CASE OF HIGH-P – HIGH-T METAMORPHISM IN THE GRENVILLE PROVINCE[§]

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Abstract

A high-pressure – high-temperature segment of crust, the Manicouagan Imbricate Zone (MIZ), was recently discovered in the Parautochthonous Belt of the eastern Grenville Province, in Quebec. The MIZ is composed of an imbricate thrust stack (Lelukuau Terrane) and an overlying extensional assembly of slices (Tshenukutish Domain). The Lelukuau Terrane consists of a high-Ca anorthosite – olivine gabbro complex locally intruded by granite. During the Grenvillian orogeny, the mesocratic components of the complex were transformed into plagioclase-free Grt–Ky clinopyroxenite with low-Na clinopyroxene. These rocks record minimum pressures of metamorphism as high as 1800–2000 MPa, and temperatures of 850–900°C. Despite the high pressures, these rocks cannot be classified as eclogites owing to their low bulk Na content. Conditions of high P and high T of metamorphism also are attested by the presence of Grt–Ky restite, in leucogranite. High-P conditions of metamorphism in the MIZ may result from the subduction of crust, followed by imbrication and exhumation by northwest-directed thrusting while extension was active at the upper part of the rising stack. In addition, high temperatures of metamorphism in the Lelukuau Terrane indicate possible involvement of asthenospheric heat. Therefore, subduction of this terrane down to asthenospheric depths, or local thinning of lithosphere (by breakoff of the slab?) should be considered.

Keywords: Grenville Province, high-P – high-T metamorphism, Grt–Ky clinopyroxenite, dehydration melting, subduction, Manicouagan Imbricate Zone, Quebec.

Sommaire

Un ensemble de roches métamorphiques à assemblages témoignant de pression et de température élevées, la zone imbriquée de Manicouagan, a récemment été découvert dans la ceinture parautochtone de la partie orientale de la province du Grenville, au Québec. Cette zone contient un empilement de nappes (le terrain de Lelukuau) et un assemblage d'écailles en extension (le domaine de Tshenukutish). Le terrain de Lelukuau est fait d'une association d'anorthosite à teneur élevée en Ca et de gabbro à olivine, que recoupent des venues granitiques. Au cours de l'orogenèse grenvillienne, les parties mésocrates de cette association ont été transformées en clinopyroxénite sans plagioclase, à grenat, kyanite, et clinopyroxène à faible teneur en Na. Ces roches témoignent d'une pression minimum de métamorphisme pouvant atteindre 1800–2000 MPa, et des températures de 850–900°C. Malgré cette pression élevée, ces roches ne seraient pas des éclogites à cause de leur faible teneur en Na. Les conditions de pression et de température de métamorphisme élevées expliquent aussi le développement de restite à grenat + kyanite dans les leucogranites. Le métamorphisme à pression élevée dans la zone imbriquée de Manicouagan pourrait résulter de la subduction de la croûte, suivie de l'imbrication et de l'exhumation suite au chevauchement vers le nord-ouest, avec de l'extension active dans la partie supérieure de l'empilement de nappes. De plus, la température élevée du métamorphisme dans le terrain de Lelukuau concorderait avec l'implication possible de chaleur provenant de l'asthénosphère. C'est donc dire qu'on devrait envisager la subduction de ces roches jusqu'à une profondeur asthénosphérique, ou bien un amincissement local de la plaque lithosphérique (peut-être par brisure de la plaque).

(Traduit par la Rédaction)

Mots-clés: province du Grenville, métamorphisme à pression et température élevées, clinopyroxénite à Grt–Ky, fusion avec déshydratation, subduction, zone imbriquée de Manicouagan, Québec.

Introduction

The Grenville Province of the Canadian Shield is interpreted as the result of continental collision about 1000 Ma ago. It display deeply eroded continental crust over large areas. Nevertheless, known occurrences of Grenvillian high-pressure rocks such as eclogites and high-pressure granulites are scarce. This situation is due to the enormous dimensions of the orogen, large portions of which are still poorly studied, and also to

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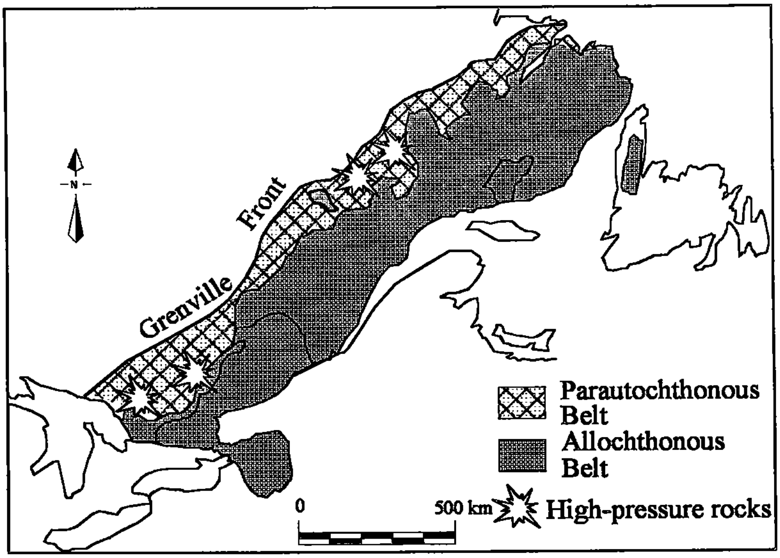

FIG. 1. Location of high-pressure rocks in the Grenville Province.

the high metamorphic temperatures, commonly in excess of 700°C. It is known that following crustal thickening, decompression under high-T regimes commonly leads to mineral re-equilibration under conditions of lower pressure, especially where thermal relaxation occurs (Thompson & England 1984).

Until recently, evidence of high-pressure metamorphism in the Grenville Province was limited to retrograde meta-eclogites and eclogitized metagabbros in its western part [Ontario: Davidson (1990); western Quebec: Indares & Dunning (1997); Fig. 1] and to coronitic metagabbros partially converted to eclogite in the Molson Lake Terrane [eastern Grenville Province: Indares (1993), Indares & Rivers (1995); Fig. 1]. Other occurrences of Grenvillian eclogite beyond the Grenville Province proper are found within the Llano Uplift, Texas (Wilkerson *et al.* 1988) and at Glenelg, Scotland (Sanders 1989).

This is a preliminary account of a new occurrence of well-preserved high-pressure rocks from the eastern Grenville Province. They are located in the approximately 1500 km^2 Lelukuau Terrane (LT), which is part of the Manicouagan Imbricate Zone (MIZ), formerly referred to as the Manicouagan Shear Belt (Eaton *et al.* 1995). The Manicouagan Imbricate Zone is a 2000-km^2 assemblage of high-pressure slices of crust recently discovered in a previously unmapped area near the Manicouagan Reservoir, in eastern Quebec (Fig. 2). In this paper, I present an overview of the MIZ with special reference to the Lelukuau Terrane, document the high-P metamorphism in that terrane, and discuss the geodynamic implications.

THE MANICOUAGAN IMBRICATE ZONE: GEOLOGICAL SETTING

The MIZ is situated at the southern margin of the Parautochthonous Belt of the eastern Grenville Province (Figs. 2, 3), at a similar structural level but some 100 km west of the partially eclogitized metagabbros of the Molson Lake Terrane (Indares 1993, Indares & Rivers 1995). To the north, the Manicouagan Imbricate Zone tectonically overlies the Gagnon Terrane along a ductile thrust contact, and can be clearly identified in aeromagnetic maps as a lobate structure that extends 25 km south of the Grenville front. The Gagnon Terrane consists of a Paleoproterozoic continental margin sequence of the Labrador Trough, and of its Archean basement, which are together disposed in a Grenvillian northwest-verging fold-thrust and nappe belt (Rivers *et al.* 1993). Metamorphic grade in the Gagnon Terrane increases from greenschist facies near the Grenville Front to high-pressure amphibolite facies farther south.

At its southeastern margin, the MIZ is truncated by an extensional detachment (Hart Jaune fault: Eaton *et al.* 1995), which separates it from overlying 1467-Ma-old granulites of the allochthonous Hart Jaune Terrane. The latter rocks are characterized by middle-amphibolite-facies Grenvillian metamorphism (Scott & Hynes 1994). West of the Hart Jaune Terrane, however, the southern extension of MIZ is obscured by the Triassic Manicouagan Impact crater (Fig. 3). The eastern edge of the MIZ is imaged on the seismic profile of the Manicouagan LITHOPROBE transect (Eaton *et al.*

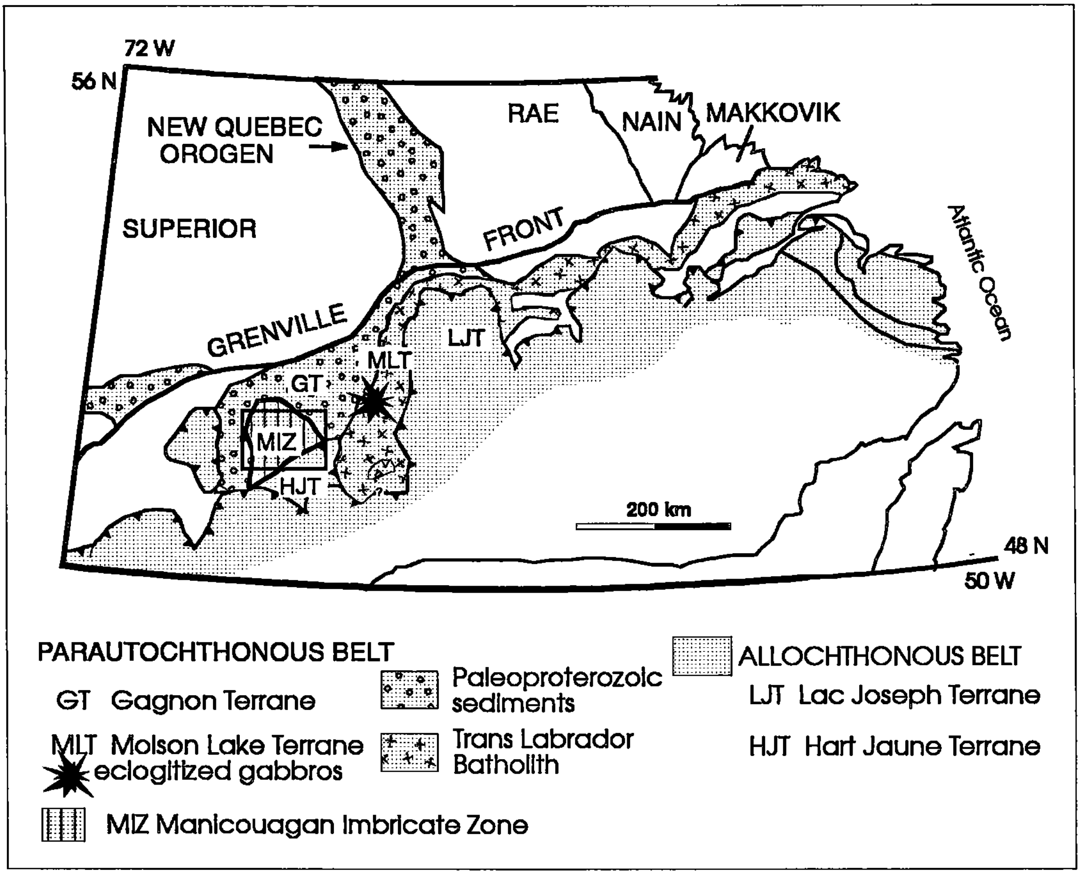

FIG. 2. Location of high-pressure terranes in the eastern Grenville Province (modified after Rivers & Chown 1986). Box shows location of Figure 3.

1995) as a gently southeast-dipping zone of high-amplitude reflections that may be traced in the subsurface farther south, between the allochthonous terranes and its footwall. Its root is located beyond the seismic profile, implying a transport of several tens of kilometers between the exposed part of MIZ and the root zone.

The MIZ consists of two contrasting, fault-bounded lithotectonic packages. The largest package, and structurally the lower, is the Lelukuau Terrane (LT in Fig. 3). It is a thrust stack of meta-igneous rocks (anorthosite, olivine gabbro, granitic rocks) that displays ubiquitous evidence of high-pressure metamorphism. The structurally overlying package, known as the Tshenukutish Domain (TD), is an assemblage of slices composed of meta-igneous rocks (diorite, gabbro sills, anorthosite, granite) bounded by southeast-dipping extensional shear-zones. Although high-pressure coronitic metagabbro is found in most of the TD, an amphibolite-grade overprint is widespread.

The Lelukuau Terrane is internally imbricated and has been divided into three principal south-dipping slices (Fig. 3). From bottom to top, these are composed of: an anorthosite – olivine gabbro complex intruded by granite (Slice LTI), olivine gabbro (Slice LTII), and an anorthosite – olivine gabbro complex intruded by leucogranite (Slice LTIII). In weakly deformed parts of slices LTI and LTIII, field relationships indicate that anorthositic rocks are intruded by the more mafic rocks. Typical samples of anorthosite and olivine gabbro from the three slices are relatively calcic and display low Na contents (Table 1; K. Williams, unpubl. data), which is characteristic of calcic anorthosite complexes (Ashwal 1993). U–Pb geochronology on igneous zircon from a leucogabbro from Slice LTIII has yielded upper intercept ages of igneous crystallization of 1648 +11/–10 Ma (Gale *et al.* 1994) and a lower intercept of 1035 ± 10 Ma; monazite from a leucogranite from the same slice yielded an age of 1033 ± 5 Ma, both estimates indicating a Grenvillian age for the metamorphism.

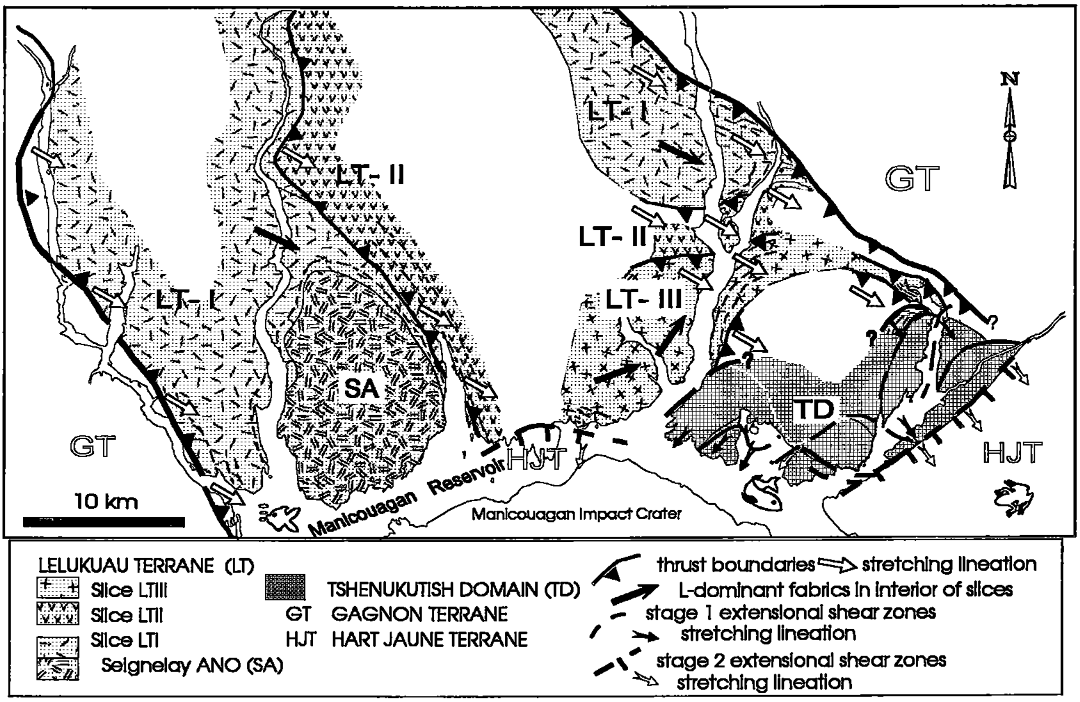

FIG. 3. Simplified lithotectonic framework of the Manicouagan Imbricate Zone.

The three slices of the LT are bounded by gently dipping shear-zones up to a few hundred meters wide, and display southeast-plunging stretching lineations. Winged σ clasts and the geometry of outcrop-scale thrusts indicate northwest-directed thrusting. The interior of each slice is characterized by tectonic lenses of weakly deformed igneous bodies, the largest of which is the Seignelay anorthosite (Fig. 3). These bodies are separated by an anastomosing network of shear zones. In addition, parts of slices LTI and LTIII are characterized by highly ductile *L*-dominant fabrics and by the absence of rotated elements (Fig. 3). Lineations are defined by the elongation of feldspar megacrysts and ferromagnesian aggregates, and are at a high angle to the stretching lineation of the bounding shear-zones in Slice LTIII. These fabrics are interpreted to have developed by extrusion of particularly ductile domains from between more rigid blocks during tectonic transport.

To the southeast, the LT is overlain by TD along amphibolite-facies shear zones that truncate earlier thrust-related structures (Fig. 3). These shear zones display stretching lineations and clasts that, together with the geometry of truncation of earlier *S*-fabrics, indicate top-to-the-south normal movement ("stage 1" extension, Fig. 3). Similar shear zones also bound the different slices within TD. Finally, at the southern boundary of the MIZ, all structures described above are truncated by the extensional Hart Jaune fault, which dips moderately to the south and is retrograded to greenschist-facies conditions ("stage 2" extension, Fig. 3).

TABLE I. TYPICAL BULK COMPOSITIONS

	sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	LOI
1	87b	47.26	0.11	25.97	2.75	0.05	5.18	16.52	1.47	0.23	0.27
2	20b	45.99	0.38	10.60	10.46	0.28	14.29	15.06	1.50	0.23	0.15
3	254	38.53	0.27	29.63	11.24	0.16	9.39	7.10	1.05	0.52	0.49

The proportion of oxides is expressed in wt.%. LOI: loss on ignition. Samples: 1 leucogabbro, 2 mesocratic olivine gabbro (Grt–Ky clinopyroxenite) from slice LTIII, 3 kyanite garnetite.

HIGH-PRESSURE CHARACTER OF THE LELUKUAU TERRANE

High-pressure metamorphic signatures are widespread in both the weakly and the highly deformed parts of the LT. Their distribution is mainly controlled by bulk chemistry. They include: (i) plagioclase-free Grt–Cpx–Ky assemblages [symbols of Kretz (1983) except where noted in the tables] developed at the expense of mesocratic olivine gabbro (Grt–Ky clinopyroxenites), (ii) Grt–Cpx–Ky–Pl assemblages in leucogabbro and anorthosite, and (iii) Grt–Ky–Kfs restite (kyanite

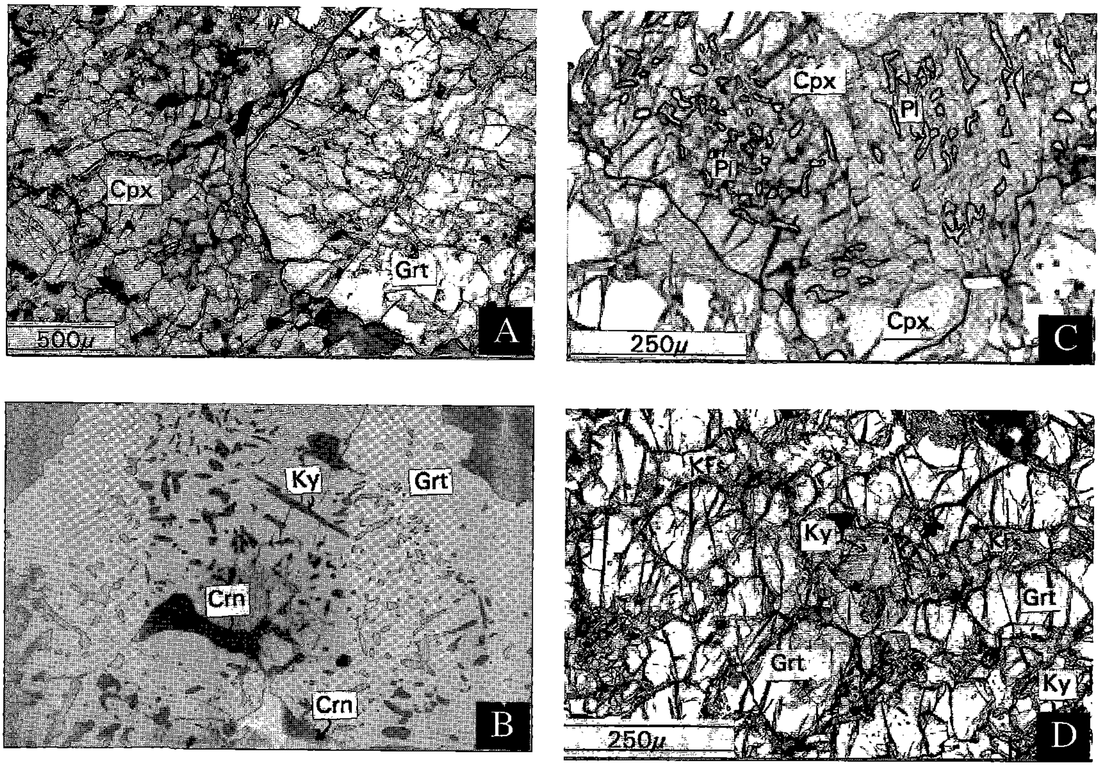

FIG. 4. (A) Photomicrograph of Grt–Ky clinopyroxenite, (B) back-scattered electron image of kyanite and corundum inclusions in garnet, (C) photomicrograph of clinopyroxene with plagioclase, (D) photomicrograph of kyanite garnetite.

garnetite), as aggregates in the leucogranite and as layers in shear zones, in Slice LTIII. The proportion of plagioclase-free rocks across the LT is variable, but averages roughly 20%.

TABLE 2. TYPICAL COMPOSITIONS OF GARNET (CORE) IN Grt–Ky CLINOPYROXENITE, MANICOUAGAN IMBRICATE ZONE

sample	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	total	Alm	Prp	Grs	Sps
20d-74	40.44	22.76	16.78	10.37	0.53	9.02	99.91	0.35	0.39	0.25	0.01
133c-83b	41.29	22.91	15.32	13.39	0.59	6.31	100.50	0.32	0.50	0.17	0.01
19-114	41.46	22.97	14.74	13.82	0.25	7.04	100.30	0.30	0.51	0.19	0.01

The proportion of oxides is expressed in wt.%.

Grt–Ky clinopyroxenites

Cpx–Grt–Ky rocks, derived from mesocratic olivine gabbro, consist of porphyroblastic garnet of irregular shape, that contains abundant inclusions of kyanite and minor corundum, mainly concentrated in the core of grains, in a granoblastic matrix that is dominated by clinopyroxene (Figs. 4A, B). Minor phases in the matrix are orthopyroxene, phlogopite, rutile, and patchy hornblende replacing clinopyroxene. Clinozoisite is locally observed as inclusions in the core of garnet. Locally, small granoblastic grains of plagioclase occur at the rim of garnet grains. They are interpreted to have developed during decompression.

The high concentration of kyanite and, in some cases, epidote inclusions in the center of garnet porphyroblasts and the presence of corundum suggest that garnet grew within former domains of calcic plagioclase, the grossular component being produced according to the reaction 3An +Crn = Grs +2Ky. Corundum is typically a transient phase that forms within plagioclase during early stages of reaction between olivine and plagioclase, as a result of limited diffusion of Al in the latter (Rivers & Mengel 1988). During production of grossular, extra Al and Si remain within plagioclase, where they form kyanite inclusions. On the other hand, if fluid is available, plagioclase breakdown will lead to epidote according to a reaction of the type: An + Crn + V = Zo + Ky (where V stands for the aqueous vapor phase).

The main metamorphic minerals were analyzed in typical samples from Slice LTIII (the conditions

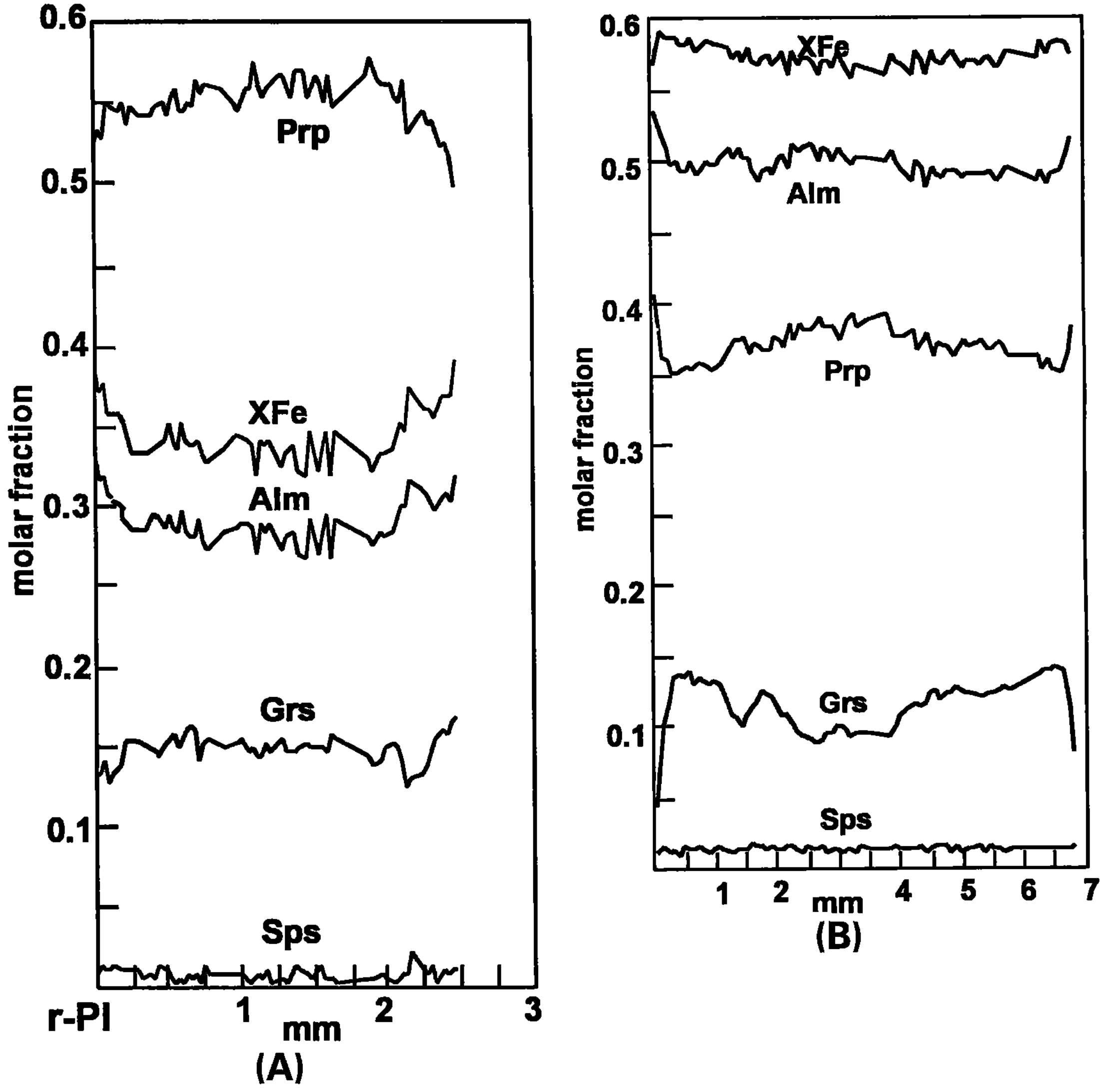

FIG. 5. Typical zoning profiles of garnet: (A) Grt–Ky clinopyroxenite, sample 133c (r–Pl: rim adjacent to plagioclase); (B) kyanite garnetite, sample 244.

of analysis are described in Appendix 1). *Garnet* porphyroblasts are pyrope-rich ($Prp_{40-60}Grs_{15-25}$ Alm_{25-45}; Table 2). They display a relatively homogeneous core, and a minor decrease of pyrope and slight increase of almandine contents at the rim (Fig. 5A). These trends are compatible with local Fe–Mg exchange between adjacent garnet and clinopyroxene during cooling. Where in contact with plagioclase, the rim of the garnet displays a minor decrease in grossular content, whereas plagioclase (An_{21-47}; Table 3) shows a systematic increase in An content toward the garnet. These features are interpreted to result from breakdown of grossular to anorthite during decompression, and indicate that plagioclase in these rocks postdates the peak pressure of metamorphism. The high pyrope content of garnet is typical of medium-temperature eclogites (Coleman *et al.* 1965, Carswell 1990).

Clinopyroxene is characterized by a ratio of the jadeite to Ca-Tschermaks components greater than 1.5, but jadeite contents are low (Jd_{8-12}, Table 4), which

TABLE 3. TYPICAL COMPOSITIONS OF PLAGIOCLASE IN Grt–Ky CLINOPYROXENITE, MANICOUAGAN IMBRICATE ZONE

sample		SiO_2	Al_2O_3	CaO	Na_2O	K_2O	total	X_{Ab}	X_{An}	X_{Or}
20d	22ri	60.61	25.48	6.53	8.10	0.19	101.20	0.685	0.305	0.010
	20rg	58.88	26.69	8.06	6.94	0.25	101.10	0.600	0.390	0.010
133c	6ri	58.00	25.78	7.60	7.30	0.29	99.45	0.624	0.360	0.020
	3rg	57.74	27.06	8.45	6.81	0.00	100.07	0.595	0.408	0.000
19	1ri	57.84	25.89	7.89	6.40	0.36	98.40	0.582	0.397	0.022
	8rg	56.47	27.74	9.80	5.92	0.20	100.42	0.516	0.472	0.011

The proportion of oxides is expressed in wt.%. rg: rim adjacent to garnet; ri: rim away from garnet.

is compatible with the low bulk-rock Na content (Table 1). This poses a problem in classification, because according to Carswell (1990) these rocks are not eclogites, the latter requiring the presence of omphacite. On the other hand, the alternative term of garnet clinopyroxenite, used for low-Na Cpx–Grt rocks of ultrabasic chemistry, stable under both granulite- and eclogite-facies conditions, is not appropriate either, because SiO_2 contents typically are higher than 45%, and kyanite is present. The name proposed here for these Cpx–Grt–Ky rocks is Grt–Ky clinopyroxenite. These rocks are chemically different from "common basalts" used for the classification of eclogites, mainly because of their higher Ca and lower Na contents. To the author's knowledge, this is the first report of plagioclase-free assemblages with pyrope-rich garnet, kyanite and Na-poor clinopyroxene.

TABLE 4. TYPICAL COMPOSITIONS OF CLINOPYROXENE IN Grt–Ky CLINOPYROXENITE, MANICOUAGAN IMBRICATE ZONE

sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	total	X_{Jd}	X_{Ae}	X_{CaTs}
20b-2	52.94	0.22	3.71	5.69	0.11	13.73	21.26	1.41	99.12	0.084	0.017	0.033
133c-17	52.42	0.14	5.63	4.35	0.18	13.41	21.21	1.73	99.06	0.109	0.009	0.058
19-5	52.98	0.22	3.92	3.77	0.10	14.48	22.27	1.07	98.81	0.077	0.000	0.041

The proportion of oxides is expressed in wt.%.
Symbols: Jd jadeite, Ae aegirine, CaTs Ca-Tschermaks component.

Leucogabbros and anorthosites

Leucogabbros and anorthosites are characterized by granoblastic Pl – Grt – Cpx – Ky ± Amp assemblages. Clinopyroxene occurs as large isolated grains or as fine-grained aggregates, both surrounded by garnet. The clinopyroxene contains abundant vermicular inclusions of plagioclase (Fig. 4C), interpreted as a product of the breakdown of jadeite during decompression (Boland & Roermund 1983). Kyanite forms large prisms in the matrix and inclusions in garnet. Given the local preservation of igneous relationships between anorthosites and the more mafic rocks that yielded the Grt–Ky clinopyroxenites, it is obvious that both were metamorphosed together under the same high-P conditions. The presence of plagioclase in the leucocratic rocks is compatible with high modal contents of plagioclase in the igneous protolith. It has been shown experimentally that anorthositic rocks retain plagioclase in equilibrium with garnet and clinopyroxene under P–T conditions where more mafic rocks are transformed to eclogite (Green & Ringwood 1967). In addition, the mineralogy of the anorthositic rocks from the LT seems to have been re-adjusted during decompression to a greater extent than of their mesocratic counterparts. This contrasts with the classic case of the Bergen Arcs in the Caledonides, where earlier granulite-facies assemblages in anorthosites have survived metastably a subsequent eclogite-facies metamorphism (Austrheim & Griffin 1985).

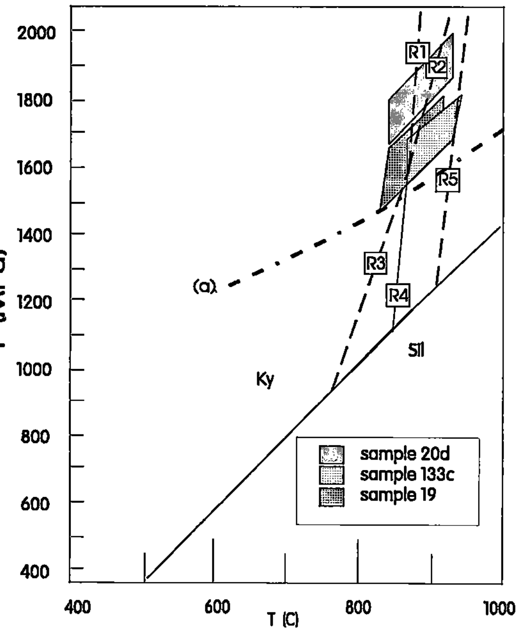

FIG. 6. Calculated P–T conditions and relevant melting reactions (after Vielzeuf & Holloway 1988, for Pl-free systems); R1: Bt + Phe + Qtz = L + Grt + Kfs; R2: Phe + Qtz = L + Kfs + Ky + Grt; R3: Phe + Qtz = Kfs + Ky + Bt + L; R4: Bt + Ky + Qtz = Grt + Kfs + L; R5: Bt + Qtz = Kfs + Opx + L; curve (a): lower-P limit of the eclogite facies, after Carswell (1990).

Kyanite garnetite

Kyanite garnetite occurs in Slice LTIII as decimeter-scale Grt – Ky – Kfs ± Pl ± Bt aggregates in the leucogranite, and as Grt – Ky – Kfs layers in shear zones. In the aggregates, garnet ($Alm_{48–55}Prp_{35–40}Grs_{5–15}Sps_1$) is up to several mm in diameter, and displays an outward increase in grossular content, from 10 to 15%, compensated by a slight decrease of both the almandine and pyrope contents. These trends are reversed in the outer few tens of micrometers, where grossular content drops sharply to 5% (Fig. 5B). The plagioclase is sodic ($An_{21–25}$) and homogeneous. Kyanite occurs as large porphyroblasts in the matrix and as inclusions in garnet. The layers of kyanite garnetite are composed of 70–80% garnet of homogeneous composition ($Prp_{45–50}Alm_{29–32}Grs_{15–25}$) and pods of kyanite and K-feldspar (Fig. 4D). They display a Si-poor and Al-rich bulk composition (Table 1).

Both types of kyanite garnetite are best interpreted as products of fluid-absent partial melting of mica-bearing protoliths according to reactions of the type: Bt + Phe ± Pl + Qtz = L + Grt + Kfs [R1], and Phe ± Pl + Qtz = L + Kfs + Ky + Grt [R2]. According to Vielzeuf & Holloway (1988), these reactions occur under high-P conditions (≥1600 MPa for bulk X_{Mg} ≥ 0.5), and, for plagioclase-free systems, at temperatures in excess of 850°C (Fig. 6). The alternative reactions Phe + Qtz ± Pl = Kfs + Ky + Bt + L [R3] and Bt + Ky + Qtz ± Pl = Grt + Kfs + L [R4] that occur at lower pressures (Fig. 6) do not seem appropriate, because they involve garnet development at the expense of kyanite, a feature that is inconsistent with textural evidence of equilibrium between these two minerals in the samples of kyanite garnetite. Finally, the local presence of biotite in the aggregates, along with the absence of orthopyroxene, indicate that metamorphic temperatures did not exceed those required for the reaction Bt ± Pl + Qtz = Kfs + Opx + L [R5] (Fig. 6), *i.e.*, approximately 950°C (at P ≥ 1600 MPa) for plagioclase-free systems (Vielzeuf & Holloway 1988). Note that addition of plagioclase displaces the reaction boundaries to lower temperatures by a few tens of degrees (Thompson & Tracy 1979) depending upon the albite content.

P–T Estimates in Slice LTIII

Melting reactions indicated by the kyanite garnetite constrain metamorphic temperatures in Slice LTIII between 800 and 900°C. This is 50°C lower than the range delimited by the reaction boundaries in Figure 6, in order to account for the presence of Ab-rich plagioclase in some aggregates. High-T conditions are also compatible with the highly ductile character of the *L*-dominant domain within this slice. The minimum pressure required for reactions R1 and R2 to occur is defined by the invariant point involving [R1], [R2], [R3] and [R4], and is directly related to the X_{Mg} of the rocks (Vielzeuf & Holloway 1988). Calculated values of X_{Mg} for both the aggregates and the layers of kyanite garnetite vary between 0.5 and 0.6; if the location of the invariant point for X_{Mg} = 0.5 calculated by Vielzeuf & Holloway (1988) is correct, then the pressure of melting was in excess of 1600 MPa.

TABLE 5. TEMPERATURES CALCULATED WITH KROGH'S (1988) Grt–Cpx CALIBRATION

sample	minimum temperature T °C	X_{Grs}	maximum temperature T °C	X_{Grs}
20d	773	0.165	901	0.232
133c	775	0.146	909	0.169
19	759	0.152	973	0.278

Despite abundant mineralogical evidence for high-P conditions throughout the LT, a quantitative estimation of the maximum pressure is problematic owing to the lack of plagioclase from the peak metamorphic assemblage in the Grt–Ky clinopyroxenites, and to the decompressional readjustments of the granoblastic plagioclase-bearing assemblages in the leucocratic rocks. However, a lower-P limit may be placed by calculating the P–T conditions of formation of retrograde plagioclase in the Grt–Ky clinopyroxenites. The Grt–Pl–Ky–Crn barometer, equivalent to the garnet – aluminosilicate – quartz – plagioclase ("GASP") barometer for quartz-free, corundum-bearing assemblages (Indares & Rivers 1995) was applied to the retrograde plagioclase and adjacent garnet (rim zone) containing kyanite and corundum in three samples (19, 20d and 133c) that best display the appropriate microtextures. In order to pinpoint the P–T conditions of formation of the very first plagioclase, garnet compositions of the rim area with maximum grossular contents (at the beginning of the X_{Grs} plateau that extends to the core, Fig. 5A) were used together with the most sodic composition of adjacent plagioclase, away from the Grt–Pl contact (10 estimates per sample; see Tables 2 and 3 for typical composition). Since this barometer is also temperature-dependent, corresponding temperatures of metamorphism were calculated with the Grt–Cpx Fe–Mg exchange reaction by using the same garnet composition, that also falls at the beginning of the X_{Fe} plateau, and adjacent clinopyroxene core (Table 4). As a result, calculated temperatures are close to the maximum recorded by these rocks.

P–T calculations were performed with the TWQ software program (Berman 1991), and made use of internally consistent thermodynamic data for end members and solid solutions (TWQ version 2.02; March 1996). These data account for nonideal mixing of Fe–Mg–Al in clinopyroxene and of Fe–Mg–Ca in garnet, and are based on the compositional data presented in Berman *et al.* (1995) for Grt–Cpx and in Berman & Aranovich (1996) for other Fe–Mg phases.

For the sake of comparison, temperatures were also calculated with Krogh's (1988) calibration of the Grt–Cpx thermometer, which has been widely used in high-pressure rocks. Note that in all samples, calculated Fe^{3+} in clinopyroxene (Appendix 1) is negligible (Table 4), therefore minimizing the possible overestimation of temperature with either method.

P–T results obtained with TWQ are shown in Figure 6. They fall in the range 850–920°C – 1750–2000 MPa (sample 20d), 850–900°C – 1600–1800 MPa (sample 133) and 830–900°C – 1550–1800 MPa (sample 19). These results are within the range indicated by the kyanite garnetite. For each sample, temperatures calculated with Krogh's (1988) calibration show a large variation, with the highest values being in the same range as those obtained with TWQ (Table 5). There seems to be a correlation between values obtained by Krogh's calibration and the Ca content of garnet, implying an overcorrection for the grossular effect in garnet solid-solution (see also Indares & Rivers 1995). Therefore, these temperatures will not be considered further.

P–T conditions recorded by decompressional textures in the Grt–Ky clinopyroxenites, as calculated with TWQ, lie close to the upper-T limit of the medium-temperature eclogite field, as defined by Carswell (1990) (Fig. 6). Since calculated pressures are minimum estimates, burial to depths in excess of 55 km is suggested for Slice LTIII.

Geodynamic Implications

On the basis of information on the high-P Molson Lake Terrane (Fig. 3), the southern part of the Parautochthonous Belt of the eastern Grenville Province is viewed as a deeply buried section of the lower plate in an overthickened crust, that was imbricated and uplifted along a crust-scale ramp over the Gagnon Terrane (Rivers *et al.* 1993). The data presented in this contribution provide important additional constraints on the tectonothermal evolution of the MIZ.

The earliest fabrics in the MIZ are associated with high-P metamorphism and are best preserved in the Lelukuau Terrane. They attest to imbrication by generally northwest-directed thrusting initiated under high-P – high-T conditions (P > 1800–2000 MPa, 800 < T < 900°C), whereas the top of the pile, to the south, is characterized by extensional shear-zones. These features can be explained by partial subduction of the MIZ followed by detachment, imbrication and exhumation of its constituent slices. Exhumation is interpreted to have occurred by northwest-directed thrusting that led to the emplacement of the Lelukuau Terrane over the Gagnon Terrane. Extensional shear-zones at the top of the LT and within TD developed while thrusting was still active at the sole of the LT, with thrusts propagating and younging toward the foreland. This interpretation is based on the model of subduction of continental lithosphere proposed by Chemenda *et al.* (1995). This model provides a likely mechanism for syncollisional exhumation of partially subducted buoyant segments of crust by thrusting, with normal faulting developing on the top of the rising sheet. An additional key element to be taken into account is the high temperature of metamorphism recorded in Slice LTIII, which is indicative of an external source of heat. Subduction of the LT to asthenospheric depths or local thinning of lithosphere, as for instance by slab breakoff (Davies & Blankenburg 1995, Andersen *et al.* 1991), are considered most likely.

Compared to other high-P terranes described in the literature, metamorphic conditions in the Lelukuan Terrane resemble those reported in high-P granulites that are widespread in the Variscan belt of Europe (Carswell & O'Brien 1993, Kryza *et al.* 1996). Although the significance of high-P – high-T metamorphism has been traditionally underestimated, I suggest that metamorphism under a high-T regime may locally be an important feature in deep levels of zones of collision between continental plates.

Acknowledgements

This investigation was funded by NSERC and Lithoprobe. Special thanks to C. Hurich, J. Martignole and T. Rivers for stimulating discussions, and to Maggy Piranian for support on the CAMECA SX50 electron microprobe at Memorial University of Newfoundland.

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Received January 21, 1997, revised paper accepted June 9, 1997.

Appendix 1. Analytical Techniques

Mineral analyses were performed on a CAMECA SX50 electron microprobe in energy-dispersion mode at Memorial University of Newfoundland with a specimen current of 20 nA, an accelerating potential of 15 kV, and a counting time of 75 s. Data were reduced with a ZAF correction program. Two to three rim-to-rim traverses across grains of garnet were performed, with a spacing of spot analyses ranging from 50 to 100 μm. In plagioclase-bearing samples, up to 10 grains per sample were analyzed, at several points, in order to check for zoning with increasing distance from garnet. In Grt–Ky clinopyroxenites, 10 to 15 grains of clinopyroxene (cores and rims) were analyzed per sample. Structural formulas of minerals were calculated using the THEBA6 software (Martignole *et al.*, Université de Montréal, unpublished). The proportion of Fe^{3+} in clinopyroxene was determined by the charge-balance scheme of Droop (1987). The end members were calculated according to the method of Cawthorn & Collerson (1974).