The Canadian Mineralogist
Vol. 35, pp. 1173-1189 (1997)

METAMORPHIC SIGNATURES OF FAULTING IN THE MANICOUAGAN RESERVOIR REGION, GRENVILLE PROVINCE, EASTERN QUEBEC§

ANDREW HYNES[1]

Department of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, Quebec H3A 2A7

ALGER ST-JEAN

Falconbridge Ltd., 1977 McKenzie Road, RR#2, Chelmsford, Ontario P0M 1L0

Abstract

In the Grenville Province of eastern Quebec, slices of granulite- and amphibolite-facies rocks overlie high-P metamorphosed rocks of the Manicouagan Imbricate Zone in normal-faulted contact. The lowest slice comprises the Hart Jaune terrane (HJT), which is tectonically overlain by rocks of the Gabriel domain (GaD). The uppermost HJT is cut by normal-sense shear zones. HJT rocks preserve evidence of an early, low-P granulite-facies event overprinted by a later, higher-P one, correlated to *ca.* 1470 and *ca.* 990 Ma U–Pb dates, respectively. Near the GaD, and especially in the normal shear zones, HJT rocks carry amphibolite-facies mineral assemblages. Rocks of the GaD are amphibolite facies exhibit no evidence for polymetamorphism, and have yielded only *ca.* 1010 Ma U–Pb ages. Grains of garnet in pelites of the GaD show marked decline in Mg, some decline in Ca, and marked increase in Mn toward rims, indicating re-equilibration with decreasing P and T, and consistent with cooling and unroofing following tectonic burial. Grains of garnet in pelites from the uppermost HJT, in contrast, show marked increases in Ca with minor decline in Mg toward rims, indicating re-equilibration with increasing P and mildly decreasing T. The later stages of re-equilibration in the HJT occurred under the same conditions as those for the GaD. The metamorphic data indicate that rocks of the GaD were thrust onto those of the HJT, which implies that the normal shear zones do not reflect the large-scale kinematics. Many of the HJT metapelites studied, however, come from these shear zones, and they carry sillimanite-defined lineations, confirming that metamorphism was synchronous with normal slip. We interpret the normal faults as splays from the roof fault to the Manicouagan Imbricate Zone. In this interpretation, normal slip on this roof fault was coeval with overthrusting in the overlying slices.

Keywords: Grenville Province, garnet, Manicouagan, normal faulting, exhumation, Quebec.

Sommaire

Dans la province du Grenville au Québec, des écailles de roches recristallisées dans le faciès granulite et amphibolite recouvrent, le long d'un faille normale, un socle métamorphisé à pression élevée de la zone imbriquée de Manicouagan. L'écaille la plus profonde constitue le bloc de Hart Jaune (BHJ), que recouvre en contact tectonique les roches du domaine de Gabriel (DGa). La partie supérieure du BHJ est recoupée par des zones de cisaillement de sens normal. Les roches de ce bloc témoignent d'un événement métamorphique précoce au faciès granulite à faible pression; les assemblages ont partiellement été oblitérés par un événement à pression plus élevée. Ces événements seraient responsables des âges U–Pb obtenus, environ 1470 et 990 Ma, respectivement. En s'approchant du DGa, et plus particulièrement des zones de cisaillement normal, les roches du BHJ possèdent des assemblages de minéraux typiques du faciès amphibolite. Les roches du DGa sont équilibrées dans le faciès amphibolite, ne montrent aucune évidence d'une évolution polymétamorphique, et n'ont donné que des âges U–Pb proches de 1010 Ma. Les grains de grenat des pélites de DGa font preuve d'une diminution en Mg et jusqu'à un certain point en Ca, et d'une augmentation marquée en Mn vers leur bordure, indications d'un ré-équilibrage dû à la diminution de P et T, en concordance avec un refroidissement et un soulèvement suite à un enfouissement tectonique. Les grains de grenat des pélites de la partie supérieure du BHJ, en revanche, montrent une augmentation frappante en Ca et une diminution en proportion de Mg vers la bordure, indications d'un ré-équilibrage dû à une augmentation de la pression et à une légère diminution de la température. Aux stades tardifs du ré-équilibrage, les conditions dans le BHJ ont convergé avec celles du DGa. Les données métamorphiques montrent que les roches du DGa ont chevauché celles du BHJ, ce qui implique que les zones de cisaillement ne témoignent pas de la cinématique à grande échelle. Dans la plupart des cas étudiés, toutefois, les échantillons de pélite du BHJ proviennent de ces zones de cisaillement, et contiennent une foliation imposée par la sillimanite, confirmant ainsi que le métamorphisme était

§ LITHOPROBE contribution number 895.

[1] *E-mail address*: andrew@stoner.eps.mcgill.ca

synchrone avec l'affaissement normal. Nous considérons les failles normales comme failles secondaires liées à la faille sommitale délimitant la zone imbriquée de Manicouagan. Selon cette interprétation, l'affaissement normal le long de cette faille sommitale était contemporaine du chevauchement des écailles supérieures.

(Traduit par la Rédaction)

Mots-clés: province du Grenville, grenat, Manicouagan, failles normales, exhumation, Québec.

Introduction

The Mesoproterozoic Grenville Province of Canada, like many younger orogenic belts, has a complex tectonic evolution. Although the Grenville orogeny is commonly considered a geon 10 (1100 to 1000 Ma; *cf.* Gower & Tucker 1994) event, there is widespread geon 16 ("Labradorian") tectonism in the eastern Grenville (Gower *et al.* 1992), and geon 14 tectonism is reported along the entire length of the Grenville (Gower & Tucker 1994). Faults separating tectonic units may, therefore, have moved repeatedly. This possibility, combined with the complex kinematic schemes that may develop in general shear zones (Simpson & de Paor 1993) and the rheological heterogeneity of the lithological units involved, makes the characterization of fault movements along large-scale tectonic boundaries difficult, even in regions where such boundaries are well exposed. In this paper, we use the metamorphic characteristics of the blocks on either side of a fault zone, and within the fault zone itself, to characterize the fault motion. We show that the characterization is at variance with some of the more obvious kinematic features of the fault zone, and discuss reasons why this may be true.

Regional Setting

The area of our study is the Manicouagan Reservoir region in the Grenville of eastern Quebec. The reservoir straddles the boundary between Early Proterozoic rocks of the Knob Lake Group, which were deposited unconformably on Archean basement of the Superior Province and are clearly parautochthonous (Rivers *et al.* 1993), in the northwest, and terranes of more uncertain affinity to the southeast (Fig. 1). Rocks of the Knob Lake Group are tectonically overlain to the southeast by the Manicouagan Imbricate Zone (MIZ), consisting largely of granitic and anorthositic intrusive bodies with abundant geon 16 ages and well-developed eclogitic metamorphic signatures that appear to have developed in geon ten (Indares *et al.* 1996). The MIZ is bounded to the southeast by a complex fault zone. In the northeastern part of the reservoir, the contact is a late, high-angle fault, the Hart Jaune fault, but along the southeastern and southern shores, the contact is a moderately southeast-dipping fault, the Triple Notch fault (Fig. 1). Motion on the Triple Notch fault occurred under amphibolite-facies conditions, and is probably responsible for the strong contrast between the eclogite-facies metamorphism preserved in the MIZ and adjacent rocks of the Gagnon Group, and much lower-pressure metamorphism preserved in the tectonically overlying rocks to the southeast. In the northeastern part of the reservoir, the overlying rocks belong to the predominantly mafic, granulite-facies Hart Jaune terrane (HJT). On the eastern shore of the reservoir, rocks of the HJT are tectonically overlain, at the Gabriel fault, by a deformed succession of feldspathic metasediments with abundant mafic intrusive bodies, the Gabriel domain (GaD), and the HJT is pinched out between the Gabriel and Triple Notch faults (Fig. 1). It is the nature of motion on the Gabriel fault that is the primary focus of this paper.

Regional mapping by the Ministère de l'Énergie et des Ressources, Québec (Kish 1968, Gobeil 1996a, b) and the distinctive magnetic signature of the HJT have clearly established the regional trajectory of the Gabriel fault. In the far east, near the Rivière Petite Manicouagan (40 km E of Fig. 1), the fault appears to dip steeply north, with normal-slip kinematics (A. Gobeil, pers. commun., 1995). Between there and the Manicouagan Reservoir, its attitude is obscured by vegetation. On Highway 389, just east of the reservoir, it dips steeply to the southwest, and on islands in the reservoir, where the contact is best exposed, it dips steeply south. Lithoprobe Line 55, however, which was shot along Highway 389, provides clear evidence that rocks of the HJT underlie those of the GaD for at least 20 km, and constrains the dip to be moderate and to the southeast going south (Fig. 2). The Gabriel fault, therefore, has a strongly curved surface in the neighborhood of the reservoir.

The Hart Jaune Terrane

In the Hart Jaune terrane, the majority of rocks are massive metagabbros. Along the reservoir itself, however, layered two-pyroxene – plagioclase mafic granulites predominate, and are in places interlayered on the scale of decimeters to meters with quartzofeldspathic gneisses. Minor pelitic and calc-silicate rocks are present, and are particularly common in the southern part of the terrane, near the Gabriel fault. The scale and continuity of the layering and the presence of metasediments indicate that the granulites may represent a largely supracrustal mafic volcanic assemblage, although more massive intrusive bodies occur in places along the shore of the reservoir and predominate in the highlands to the east (Kish 1968; A. Gobeil, pers. commun., 1995).

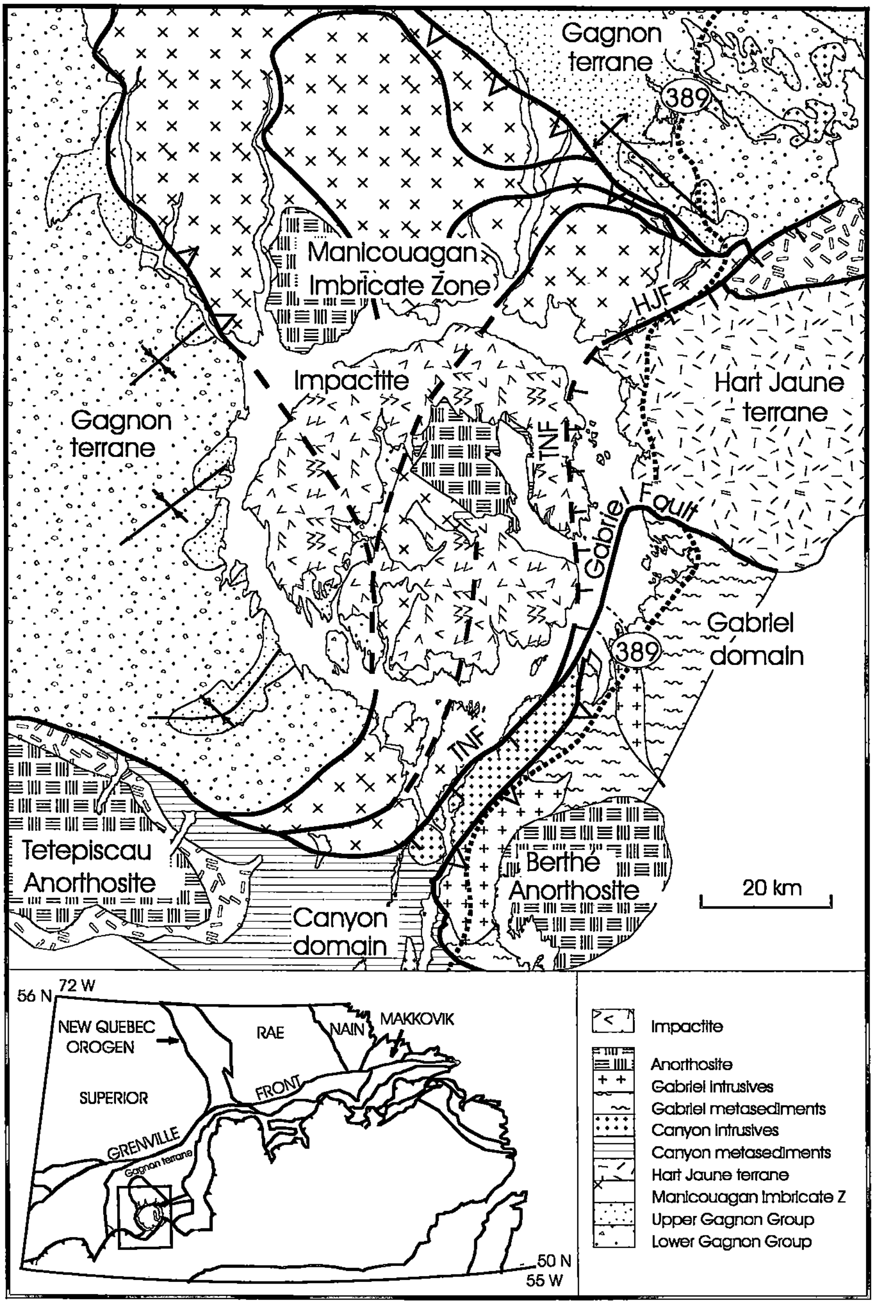

FIG. 1. Major geological units in the Manicouagan Reservoir region. Heavy lines represent major tectonic boundaries. The Gagnon terrane, consisting of Early Proterozoic rocks of the Knob Lake Group and Archean basement, is tectonically overlain by several tectonic slices comprising the Manicouagan Imbricate Zone, and by a stack of thrust slices comprising the Hart Jaune terrane, Canyon domain, Gabriel domain and anorthositic fold-nappes. Relationships among Precambrian units on the central island are obscured by impactite cover from the Triassic meteorite impact (Murtaugh 1976). HJF: Hart Jaune fault; TNF: Triple Notch fault. Geological boundaries are based on Avramtchev (1983), Clarke (1977), Franconi *et al.* (1975), Kish (1968), Murtaugh (1976), A. Indares (pers. commun., 1995), A. Gobeil (1996a, b), and the mapping of the authors.

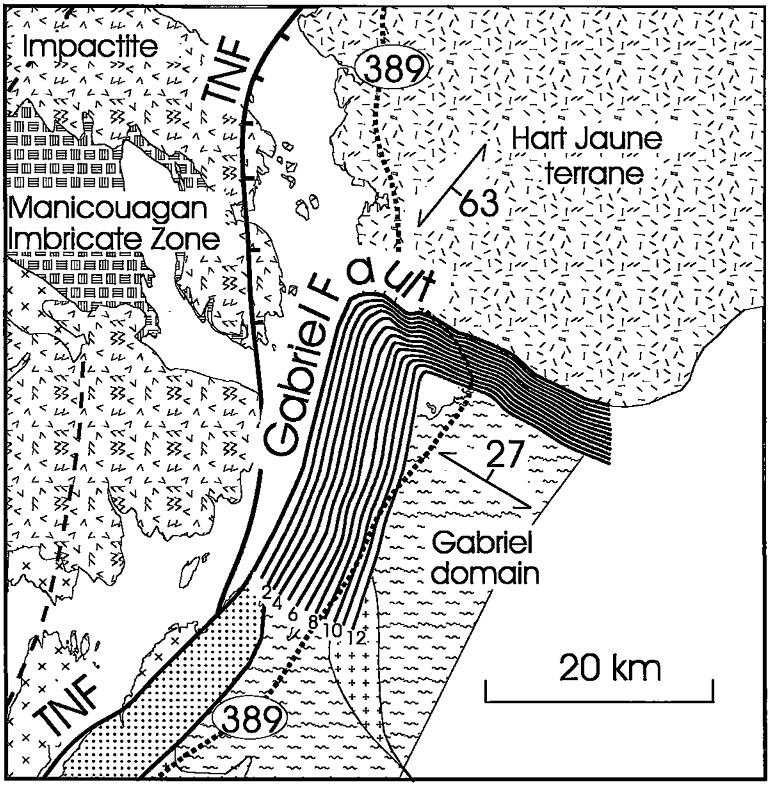

FIG. 2. Structure contours on the Gabriel fault, based on interpretation of Lithoprobe Line 55 (Eaton *et al.* 1995), which was shot along Highway 389. Contours are marked every 1 km to a depth of 12 km. They were constructed to comply with observed reflection-boundaries along the line in both depth (two-way travel time) and apparent dip, assuming constant dips with depth (Hynes *et al.*, in prep.).

Along the shores of the reservoir, compositional layering in the HJT has a uniform, steeply southeast-dipping attitude (039/63; Figs. 2, 3). Regional studies (André Gobeil, pers. commun., 1995; Gobeil 1996a, b) indicate that this attitude is the result of high strain during the latest of several episodes of deformation and is not representative of the entire region of HJT exposure. The attitude is parallel to that of very well-developed north-directed thrust planes that are exposed at the northernmost exposure of the HJT, where it abuts the late, normal Hart Jaune fault. We interpret this attitude as due to transposition or rotation (or both) of the layering during thrusting; to the southeast, in the Manicouagan Haut Plateau region, north-striking foliations predating this transposition or rotation dominate the map pattern (Kish 1968, Gobeil 1996a, b). Strong, south-plunging mineral lineations observed in the HJT (Fig. 3) probably reflect the transport direction of this thrusting.

Metamorphic assemblages in the HJT are granulite-facies, except in the southern region of the terrane, near the GaD, where they have commonly re-equilibrated locally under amphibolite-facies conditions. Mafic granulites are composed of clinopyroxene (20–65%), plagioclase (15–35%), orthopyroxene (5–30%), potassium feldspar (5–20%), Fe–Ti oxides (up to 10%; usually ilmenite) and minor quartz (<10%). Garnet occurs in less magnesian mafic assemblages as a reaction rim around Fe–Ti oxides (and, more rarely, orthopyroxene), and may comprise up to 10% of the rock. Pyroxene aggregates define the mineral lineation. Quartzofeldspathic gneisses are composed of quartz (15–45%), plagioclase (15–35%), potassium feldspar (10–20%), garnet (15–50%), and Fe–Ti oxides and titanite (<5%). Garnet commonly occurs in these rocks as porphyroblasts a few centimeters in diameter, and gives them a mottled red-and-white appearance.

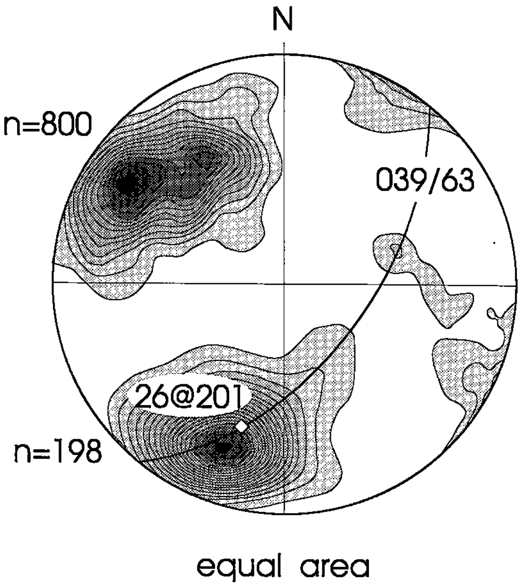

FIG. 3. Dominant structural fabric in rocks of the Hart Jaune terrane along the reservoir shoreline. The figure shows contours of poles to gneissic layering (800 data) and mineral lineations (198 data) in equal-area projection. Diamond: maximum eigenvector for the lineation distribution (26@201). Great circle: plane corresponding to maximum eigenvector for the gneissic layering (039/63). Contouring using Spheristat (Pearce & Stesky 1990). The lowest level (lightest shading) is the expected value for randomly distributed data; successively higher (shaded darker) levels step up by 2σ, where σ is the statistical dispersion of the data (Robin & Jowett 1986).

In the mafic granulites, it is commonly possible to distinguish an early, garnet-free mineral assemblage from a later, garnet-bearing one on textural grounds, with the garnet appearing only as a product of reaction between pre-existing granoblastic phases. The pyroxenes, plagioclase, opaque phases and potassium feldspar are granoblastic and appear to have equilibrated as a coarse-grained assemblage during high-T metamorphism outside the stability field of garnet. This coarse-grained assemblage is intimately associated with the appearance of an anatectic melt. Garnet appears to have grown by reaction between Fe–Ti oxides and plagioclase of this assemblage, and occurs as a rim between them. The rims vary greatly in width from sample to sample, being very thin or nonexistent in Fe-poor, orthopyroxene-rich rocks, and up to several times the diameter of their opaque oxide cores in orthopyroxene-poor rocks. Generally, only the most mafic and magnesian rocks show no evidence of this reaction. Garnet growth clearly postdates crystallization of the anatectic melt. Pyroxenes in the mafic rocks commonly contain exsolution lamellae in their cores. Thin rims are generally free of lamellae.

Granulite-facies metamorphism in the HJT thus appears to have occurred in two stages. The first stage was accompanied by partial melting at high temperatures and relatively low pressures outside the stability field of garnet, and the second occurred at higher pressures within the stability field of garnet for the same rocks. The lamellae-free rims of the pyroxene grains may have grown during the second stage. Zircon from a nebulitic melt in the granulites has yielded an age of 1467 +5/–4 Ma (Scott & Hynes 1994), which we interpret as the age of the earlier stage. The later stage is probably a Grenvillian metamorphic overprint, since monazite grains from the HJT have yielded ages of 989 ± 3 Ma (Scott & Hynes 1994). Development of the pyroxene mineral-lineation, and therefore, by inference, the north-directed thrusting, were associated with the earlier stage.

In the southern regions of the HJT, approaching the GaD, there is widespread evidence of hydration of the Hart Jaune rocks. Most commonly, this takes the form of an amphibole rim on pyroxene. In places, it also results in the development of biotite and granoblastic garnet. Pelitic rocks near the GaD exhibit only amphibolite-facies mineral assemblages. They are composed of quartz (30–45%), garnet (10–30%), biotite (5–20%), plagioclase (5–20%), sillimanite (up to 10%), potassium feldspar (<10%), and Fe–Ti oxides and titanite (<10%).

THE GABRIEL DOMAIN

Rocks of the Gabriel domain are predominantly feldspathic metasediments with subordinate pelitic rocks. In the north, there are widespread, conformable, mafic bodies, and there is also a 5-km-thick granitic sill. Layering in the GaD is predominantly NNE-dipping (301/27), with a well-developed, subhorizontal, ESE-trending lineation, parallel to the axes of major folds (Fig. 4). It is thus in very marked contrast to the southeast-dipping foliation and south-plunging lineation in the adjacent HJT, reflecting a major structural contrast across the Gabriel fault.

Geochronological studies in the GaD have yielded no evidence for metamorphism earlier than 1011 Ma (Scott & Hynes 1994). This finding, combined with the relatively well-preserved nature of the GaD and the simple structure, lead us to believe it has experienced only one important tectonic and metamorphic event. Individual crystals of monazite from two conformable granitic veins in the Gabriel domain have yielded ages of 1011 ± 3 and 992 ± 2 Ma, and titanite in a migmatitic vein in layered mafic rocks has been dated at 992 ± 3 Ma (Scott & Hynes 1994). Collectively, these data provide the best evidence for the timing of metamorphism in the Gabriel domain.

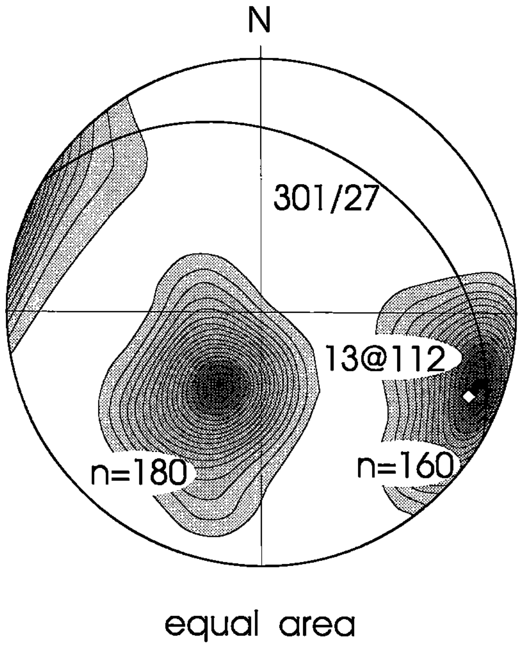

FIG. 4. Dominant structural fabric in rocks of the Gabriel domain along the reservoir shoreline. The figure shows contours of poles to bedding/gneissic layering (180 data) and mineral lineations (160 data) in equal-area projection. Diamond: maximum eigenvector for the lineation distribution (13@112). Great circle: plane corresponding to maximum eigenvector for the gneissic layering (301/27). Contouring as for Fig. 3.

Metamorphic assemblages in the supracrustal rocks of the GaD are in the amphibolite facies. The pelitic rocks consist of quartz – biotite – garnet – plagioclase – potassium feldspar ± sillimanite, and associated mafic rocks comprise plagioclase and hornblende with, in a few cases, clinopyroxene. The lithological, structural and geochronological contrast is therefore accompanied by a profound contrast in metamorphic assemblages.

The Boundary Between HJT and GaD

The Gabriel fault is marked by a broad zone consisting primarily of sheared and recrystallized amphibolites. It is exposed on Highway 389 northwest of Relais Gabriel, and on the northern shoreline of a small island in the reservoir. Neither location has yielded reliable kinematic indicators for the nature of the fault because of the degree of recrystallization. Rocks of the HJT north of the fault are highly sheared. There are local top-to-the-north (thrust) kinematic indicators, but the most prominent shear zones in the region contain steeply southward-dipping panels of pelitic metasediments with clear top-to-the-south (normal) kinematics (Fig. 5). Structural kinematic indicators are therefore equivocal. Contrasts between the metamorphic history of the Gabriel domain and the retrograde region of the Hart Jaune provide the most compelling evidence for the character of their juxtaposition.

In the Hart Jaune terrane, amphibolite-facies metamorphism is restricted to the regions near the Gabriel fault. Furthermore, the pelitic rocks in the southern Hart Jaune have abundant south-plunging sheath folds and well-developed south-plunging lineations defined by sillimanite, attesting to the synchroneity of faulting and the amphibolite-facies metamorphism. Studies of the amphibolite-facies metamorphism in the retrograde Hart Jaune terrane should, therefore, provide clear indications of the conditions in the Hart Jaune at the time of faulting. Whereas we cannot demonstrate conclusively that this metamorphism was Grenvillian, the monazite age of 989 Ma recorded in the HJT is consistent with such a model and is, furthermore, very similar to the ages recorded for metamorphism in the GaD. We argue, therefore, that the amphibolite-facies metamorphism in the HJT was coeval with that in the GaD, and we have conducted electron-microprobe studies to ascertain the character of the metamorphism in both regions.

Analytical Methods and Thermobarometry

Electron-microprobe analyses for this study were conducted on the JEOL 8900L instrument at McGill University. Quantitative analyses were conducted with an accelerating voltage of 15 kV and a specimen current of 20 nA, using a wavelength-dispersion system and a variety of pure standards. The mineral compositions presented in this paper are the averages of several point-analyses. Garnet maps were collected with an accelerating voltage of 15 kV and a specimen current of 40 nA. Raw counts-per-second data were smoothed by convolution with a Gaussian kernel after discarding points outside the range for garnet (Hynes's program) and contoured using Generic Mapping Tools (Wessel & Smith 1995).

Calculations of the equilibrium P–T conditions for metamorphic assemblages were conducted with the 1996 version (TWQ 2.02) of the TWQ software (Berman 1991) using the garnet mixing-model of Berman *et al.* (1995), the plagioclase mixing-model of Fuhrman & Lindsley (1988), and a mixing model for biotite developed by L.Y. Aranovich and R.G. Berman (unpublished). In calculations of stoichiometry, all iron was treated as Fe^{2+}.

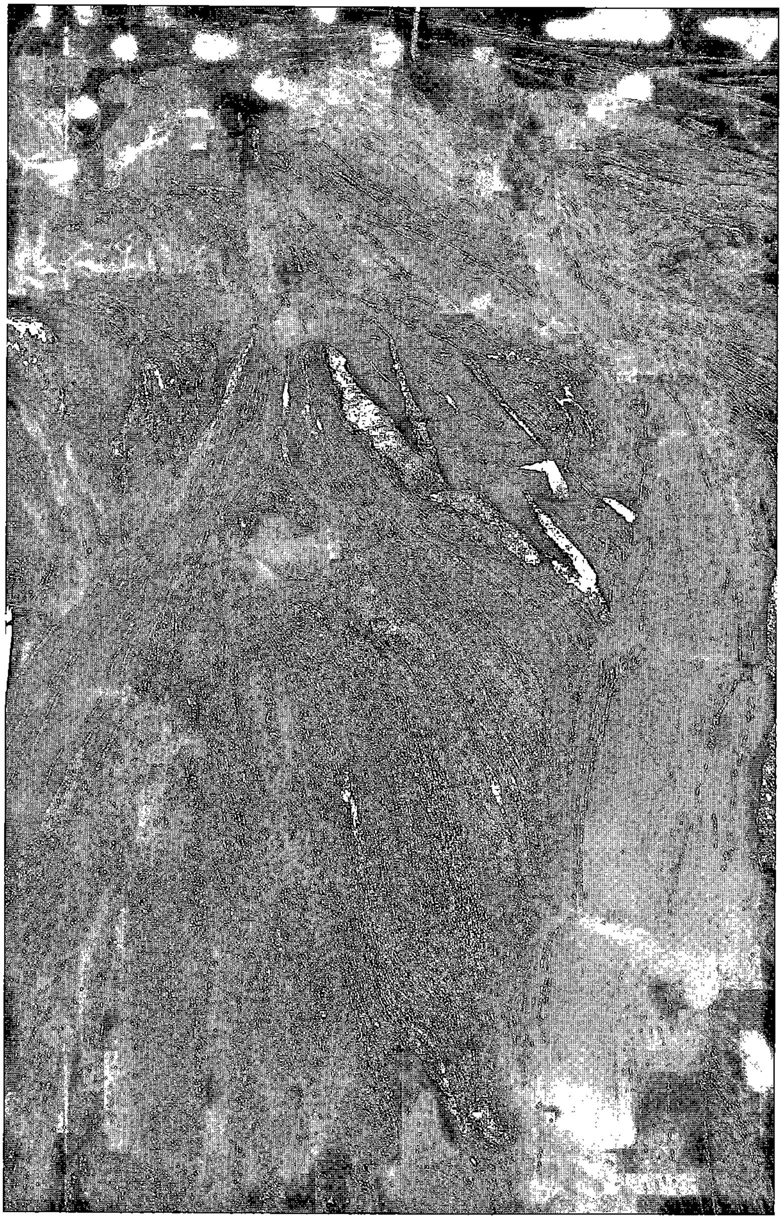

FIG. 5. Mylonitic shear zones developed in rocks of the HJT adjacent to the Gabriel fault. These shear zones are exposed on an island in the reservoir, where the Gabriel fault strikes east. The shear zones themselves strike east and dip steeply (80°) south. The view is eastward, on a steeply westwardly inclined surface. South-side-down drag is evident at shear-zone margins. The pelitic rocks involved in these shear zones have well-developed steeply south-plunging sillimanite lineations at the shear-zone margins. The field of view is approximately 5 m wide.

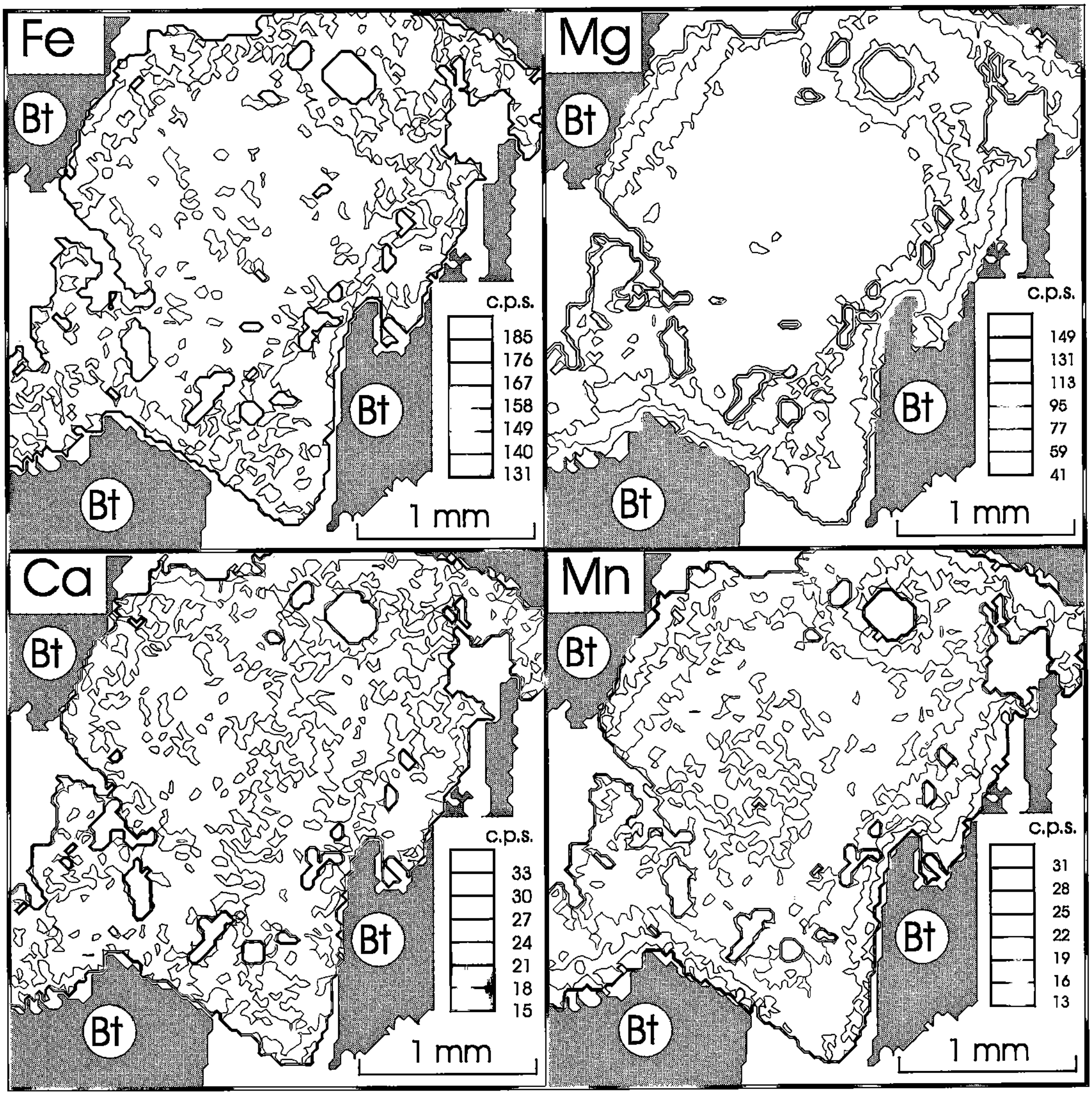

FIG. 6. Zoning in Fe, Mg, Ca and Mn in a single grain of garnet from a pelite in the Gabriel domain (spec. ah9280). This and all other maps are contoured in counts-per-second. For this map, counting was conducted on a 550 × 550 grid for 90 ms at each position.

PHYSICAL CONDITIONS OF METAMORPHISM IN THE GABRIEL DOMAIN

In assessing the physical conditions of metamorphism, we have restricted ourselves to the study of metapelites with the mineral assemblage quartz – plagioclase – biotite – garnet – sillimanite ± potassium feldspar, in which sillimanite is abundant and there is proportionately more biotite and plagioclase than garnet. Use of the same mineral assemblage on either side of the fault permits direct comparison of the conditions experienced by the rocks. The restriction to rocks that contain proportionately more biotite and plagioclase than garnet permits estimation of the conditions of equilibration for the core zone of garnet grains, where their compositions differ from those of the rim, since the biotite and plagioclase may then be considered to have been "infinite reservoirs" whose compositions should not have changed markedly as the garnet composition changed (*cf.* Spear 1993). In principle, the Fe–Mg exchange between garnet and biotite (Ferry & Spear

TABLE 1. AVERAGE COMPOSITION OF BIOTITE, GABRIEL DOMAIN AND HART JAUNE TERRANE

Rock	ah9280	ah9287	ss9309	ss9362	ss9367	ah9453	ah9456	asjb62	ss9370	ss9377
SiO_2	34.93	35.61	37.21	34.67	34.68	35.03	35.37	36.20	35.69	35.48
Al_2O_3	18.56	17.98	17.52	17.82	18.32	17.44	17.95	16.69	16.54	16.34
TiO_2	4.77	4.23	4.23	3.85	3.17	4.29	4.31	4.56	4.37	4.44
FeO	15.97	17.98	12.43	19.73	19.06	16.72	18.30	13.74	16.94	17.74
MnO	0.03	0.02	0.05	0.07	0.06	0.02	0.02	0.02	0.02	0.02
MgO	11.39	10.76	14.72	9.97	9.03	11.25	9.66	14.02	10.99	10.39
CaO	0.02	0.00	0.05	0.03	0.01	0.01	0.03	0.03	0.01	0.01
Na_2O	0.10	0.10	0.12	0.08	0.12	0.12	0.12	0.06	0.10	0.03
K_2O	9.91	10.47	10.11	10.40	10.20	10.29	10.02	10.52	9.82	10.26
Total	95.69	97.14	96.45	96.60	94.66	95.18	95.78	95.83	94.47	94.71
FeX	2.004	2.247	1.516	2.507	2.459	2.125	2.318	1.708	2.162	2.275
MgX	2.548	2.396	3.202	2.257	2.076	2.548	2.182	3.107	2.501	2.376
MnX	0.004	0.003	0.006	0.009	0.008	0.003	0.003	0.002	0.003	0.002
TiY	0.538	0.475	0.464	0.440	0.368	0.490	0.491	0.509	0.502	0.513
K	1.897	1.996	1.882	2.015	2.006	1.994	1.936	1.995	1.912	2.007
NaA	0.030	0.004	0.035	0.000	0.000	0.005	0.036	0.001	0.029	0.000
CaA	0.003	0.000	0.008	0.005	0.002	0.001	0.005	0.005	0.001	0.001
AlZ	2.760	2.679	2.570	2.732	2.650	2.678	2.642	2.617	2.552	2.559
AlY	0.522	0.487	0.444	0.460	0.682	0.445	0.563	0.308	0.424	0.395
Si	5.240	5.321	5.430	5.268	5.350	5.322	5.358	5.383	5.448	5.441
# anal	4	6	8	6	5	8	5	6	5	5

1978) provides a good thermometer in such rocks, and it may be combined with the garnet – aluminosilicate – plagioclase ("GASP": Newton & Haselton 1981) barometer to provide both pressures and temperatures. In practice, however, the assessment of the physical conditions of metamorphism is seriously hampered at the metamorphic grades of the Manicouagan region by diffusion at and following the peak of metamorphism (*cf.* Spear 1991), so that an assessment of the nature and causes of zoning in minerals is required before interpretation of the physical conditions of metamorphism.

Electron-microprobe studies of pelites from the Gabriel domain reveal little variation in the compositions of either biotite or plagioclase within individual rocks, but substantial chemical zoning within grains of garnet. These generally exhibit decreasing Mg and, to a lesser degree, Ca, and increasing Mn and Fe from core to rim (*e.g.*, Fig. 6). Given the generally high metamorphic grade of these rocks, it is unlikely that any of this zonation preserves evidence of changing conditions during growth of the garnet (*cf.* Spear 1993); it is all interpreted as due to adjustments to the garnet composition after homogenization at the metamorphic peak. The increase in concentration of Mn toward the rim of the garnet, in particular, is difficult to explain by processes other than consumption of garnet, since only garnet is a significant repository of Mn in pelitic rocks (Spear 1993). The much better-developed Mn enrichment adjacent to biotite than adjacent to other minerals (*e.g.*, Fig. 6) indicates that garnet consumption was associated with biotite growth. The concomitant decreases in Mg and Ca provide strong indications of re-equilibration under conditions of declining temperature and pressure, given the weak pressure-dependence of the Mg content of garnet in pelitic rocks (Spear *et al.* 1991). The decrease in concentration of Ca requires a pressure drop if temperature was declining. The preservation of zoning indicates that diffusion was too slow for re-equilibration of the garnet with declining P and T to have been complete, and the presence of cores that are essentially homogeneous (*e.g.*, Fig. 6) suggests that the composition of the cores themselves was largely unaffected by diffusion. The cores of the garnet may, therefore, preserve compositions appropriate to the peak of metamorphism. Provided there was sufficient biotite and plagioclase in the rocks to buffer the composition of these phases, their compositions may

TABLE 2. AVERAGE COMPOSITION OF PLAGIOCLASE, GABRIEL DOMAIN AND HART JAUNE TERRANE

Rock	ah9280	ah9287	ss9309	ss9362	ss9367	ah9453	ah9456	asjb62	ss9370	ss9377
SiO_2	60.68	61.02	61.67	59.99	62.37	60.91	61.52	60.18	59.91	60.74
Al_2O_3	24.57	23.93	23.76	24.91	23.07	24.27	24.02	25.15	25.51	22.96
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	0.12	0.06	0.02	0.05	0.02	0.07	0.03	0.14	0.07	0.03
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	6.26	5.99	5.48	6.97	4.81	6.13	5.84	6.89	7.12	5.33
Na_2O	8.01	8.07	8.25	7.22	9.05	8.05	8.19	7.57	7.05	8.42
K_2O	0.24	0.26	0.25	0.35	0.21	0.35	0.15	0.36	0.21	0.35
Total	99.88	99.33	99.44	99.49	99.54	99.78	99.74	100.28	99.88	97.84
Si	10.809	10.929	11.025	10.779	11.083	10.858	10.968	10.704	10.736	11.011
Al	5.158	5.051	5.007	5.275	4.831	5.100	5.047	5.272	5.388	4.905
Ca	1.195	1.150	1.049	1.341	0.916	1.170	1.115	1.313	1.367	1.036
Na	2.766	2.802	2.859	2.516	3.118	2.782	2.831	2.610	2.450	2.960
K	0.055	0.059	0.057	0.080	0.048	0.079	0.034	0.081	0.047	0.082
Ab	0.691	0.701	0.720	0.638	0.780	0.690	0.711	0.652	0.634	0.726
An	0.295	0.285	0.262	0.242	0.208	0.290	0.280	0.328	0.354	0.254
Or	0.014	0.015	0.014	0.020	0.012	0.020	0.009	0.020	0.012	0.020
# anal	9	7	5	6	8	5	5	2	6	10

TABLE 3. AVERAGE COMPOSITION OF GARNET, GABRIEL DOMAIN

Rock	ah9280		ah9287		ss9309		ss9362		ss9367	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO_2	37.58	37.11	37.46	37.24	38.24	38.35	37.11	37.11	37.62	37.63
Al_2O_3	21.68	21.40	21.83	21.72	21.71	21.76	21.35	21.47	21.20	21.24
TiO_2	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00
FeO	29.96	32.51	30.30	31.60	28.34	28.44	30.60	31.17	32.74	32.66
MnO	1.42	2.12	1.40	1.48	3.87	3.89	2.69	2.76	3.11	3.29
MgO	7.34	5.37	6.73	6.09	7.53	7.40	5.98	5.69	4.14	4.14
CaO	1.59	1.40	1.93	1.40	1.14	1.10	1.96	1.77	1.32	1.29
Total	99.58	99.91	99.66	99.55	100.84	100.95	99.69	99.98	100.14	100.24
Fe^{2+}	3.946	4.335	3.997	4.196	3.687	3.696	4.071	4.144	4.371	4.357
Mg	1.722	1.275	1.581	1.442	1.745	1.715	1.418	1.347	0.986	0.983
Mn	0.190	0.286	0.187	0.199	0.509	0.512	0.362	0.372	0.421	0.444
Ca	0.268	0.239	0.327	0.239	0.190	0.183	0.333	0.302	0.226	0.221
Ti	0.001	0.000	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.000
AlZ	0.082	0.084	0.091	0.087	0.052	0.041	0.096	0.101	0.000	0.000
AlY	3.942	3.937	3.966	3.977	3.928	3.943	3.907	3.923	3.989	3.993
SiZ	5.918	5.916	5.909	5.913	5.948	5.959	5.904	5.899	6.000	6.000
SiY	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.002
XFe	0.644	0.707	0.656	0.691	0.601	0.605	0.658	0.672	0.728	0.726
XMg	0.281	0.208	0.260	0.237	0.285	0.281	0.229	0.219	0.164	0.164
XCa	0.044	0.039	0.054	0.039	0.031	0.030	0.054	0.049	0.038	0.037
XMn	0.031	0.047	0.031	0.033	0.083	0.084	0.059	0.060	0.070	0.074
# anal	30	4	18	30	41	5	21	5	6	3

be used with those of the cores to estimate the peak conditions. Garnet rims in contact with biotite may well have remained open to the exchange of Fe and Mg to temperatures considerably below those at which the garnet-consumption reactions ceased to operate. We have, therefore, used garnet-rim compositions located away from biotite, together with groundmass biotite and plagioclase compositions, to estimate the physical conditions at the latest stages of garnet consumption.

The mean composition of groundmass biotite (Table 1), groundmass plagioclase (Table 2), garnet core and garnet rim far from biotite (Table 3) were used

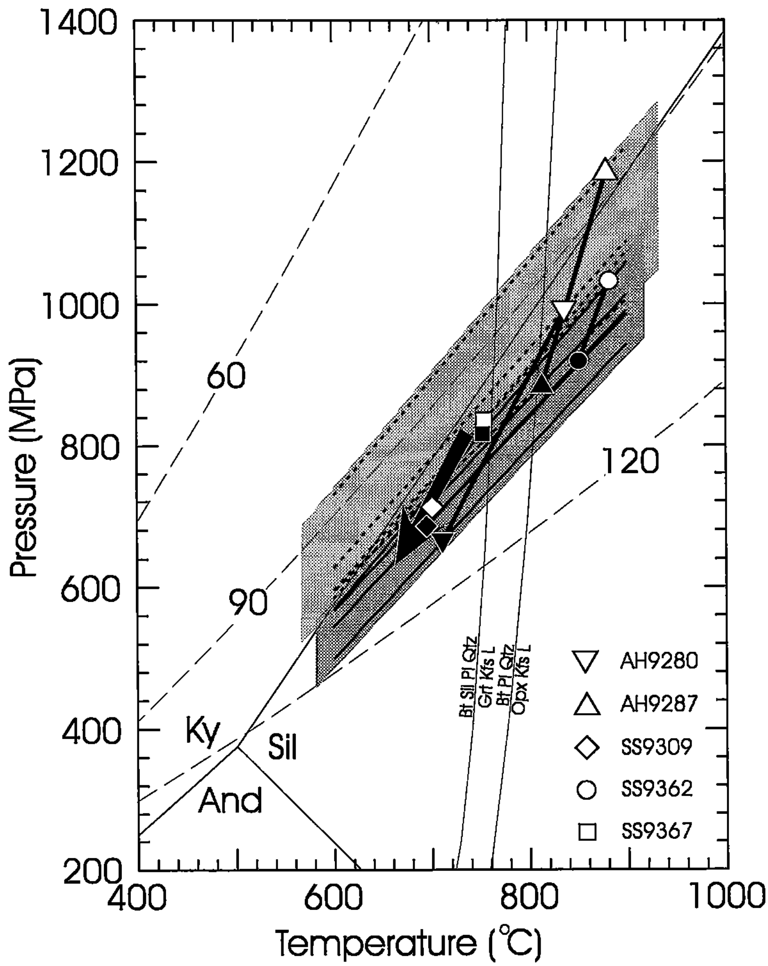

FIG. 7. Metamorphic P–T estimates for five samples of sillimanite-bearing pelite from the Gabriel domain. The heavy solid lines within the dark-shaded region are GASP (garnet – aluminosilicate – plagioclase) isopleths using rim compositions of garnet. Black symbols with white outlines are the positions of intersections of rim garnet – biotite equilibria with the GASP equilibria for each of the rocks. The heavy dashed lines within the paler-shaded region, and the white symbols with black outlines, are the equivalents for the garnet cores. The heavy lines join core-to-rim results from the same rock. The light solid lines are estimated positions of the andalusite – kyanite – sillimanite transitions, after Holdaway (1971), and of the anhydrous melting of the assemblages biotite + aluminosilicate + plagioclase + quartz and biotite + plagioclase + quartz, after Spear (1993, Fig. 10–16). The dashed lines are generalized continental geotherms for surface heat-flows of 60, 90 and 120 mW m^{-2}, after Pollack & Chapman (1977). The heavy black arrow marks the interpreted general trend of P and T from metamorphic peak to rim equilibration.

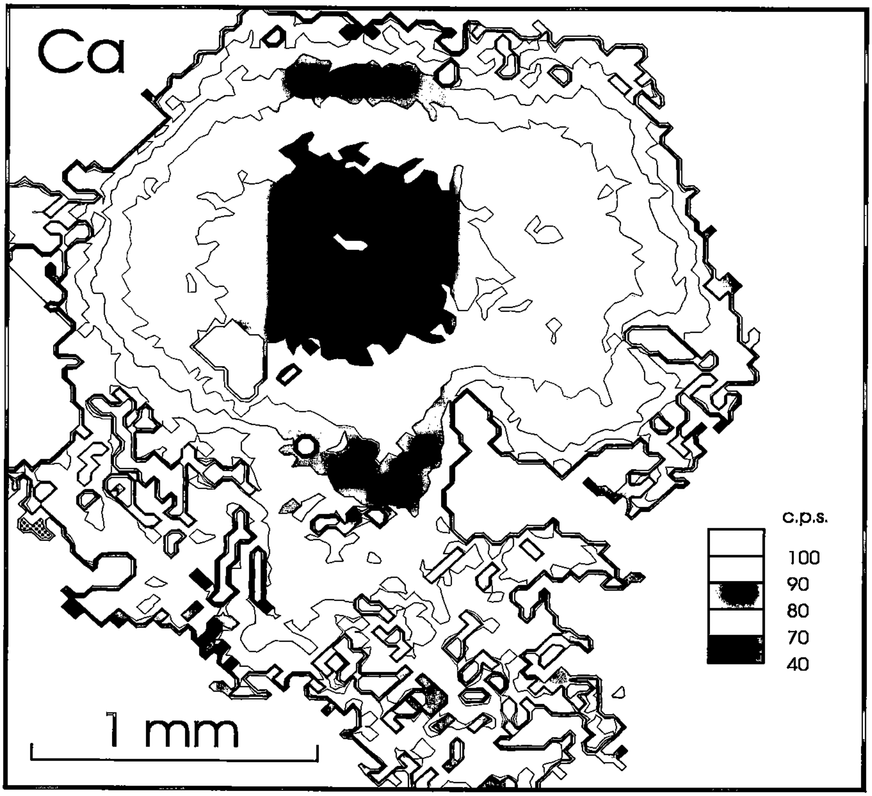

FIG. 8. Zoning in Ca in a single grain of garnet from a quartzofeldspathic gneiss in the Hart Jaune terrane (spec. asj9319). For this map, counting was conducted on a 600 × 600 grid for 90 ms at each position. The range in mole fraction of grossular is approximately 0.10 to 0.18.

to constrain the pressures and temperatures at the time of equilibration of the cores and rims of the garnet grains, from assessment of the garnet–biotite exchange reaction and the GASP net-transfer reaction (Fig. 7). The GASP reaction-constant isopleths (hereafter "isopleths") for garnet rims fall in a 100-MPa-wide zone within the stability field of sillimanite. GASP isopleths calculated from the cores are displaced consistently to higher pressure than those of the rims. Garnet–biotite isopleths vary over a range of more than 200°C, and their intersections with the GASP isopleths (marked by the symbols on Fig. 7), even for the garnet rims, are in some cases above the curve for the anhydrous melting of biotite + aluminosilicate + plagioclase + quartz (Fig. 7). Since this mineral assemblage is widely developed in all the rocks examined, and shows no signs of reaction relationships in thin section, the temperatures yielded by garnet–biotite thermometry are clearly too high. The likely cause for this is our treatment of all the Fe as Fe^{2+}, which is consistent with Berman's & Aranovich's (in prep.) extraction of thermodynamic data for biotite. The ratio $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ in non-graphitic pelites like those of the Manicouagan region is typically greater than 0.1, may be greater than 0.2 (Williams & Grambling 1990), and certainly is greater than the $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ of experimental biotite analyzed by Berman & Aranovich (in prep.). The assignment of 20% of the Fe in biotite to Fe^{3+} would drop the calculated temperatures, typically by approximately 100°C, thereby making them consistent with the stability field of the mineral assemblage. In light of this, and the fact that we have no reliable control on the Fe^{3+} contents of the biotite in the Manicouagan region, we cannot use the garnet–biotite equilibria to provide firm constraints on the equilibration temperatures. For the rims at least, it is clear that they must have been below the Bt–ALS–Pl–Qtz (ALS: aluminosilicate) reaction line and, given the general abundance of these phases in the rocks studied, this was also probably true for the cores. An approximate trajectory can be drawn for the passage of the GaD pelites from their peak condition to their retrograde condition by requiring that it remain at temperatures below the Bt–ALS–Pl–Qtz reaction line and within the stability field of sillimanite, that it begin on the core GASP isopleths and end on the rim GASP isopleths, and that it be parallel to the calculated trajectories for the individual rocks, given that these trajectories provide a first-order estimate of the character of changes in P and T during re-equilibration. We have shown such an approximate trajectory as the solid black arrow on Figure 7. Only the GASP isopleth for the core of AH9280 falls far above this trajectory, and this may reflect inadequate buffering of Al_2SiO_5 at the peak of metamorphism, since there is now only roughly 5% sillimanite in this rock, much of which may have developed during retrograde consumption of garnet.

The overall scheme of re-equilibration of garnet with decreasing pressure and temperature evident on Figure 7 is consistent with metamorphism associated with the slow exhumation of rocks following an episode of tectonic burial (*cf.* England & Richardson 1977, England & Thompson 1984). We interpret the metamorphism of the GaD to result from tectonic burial of the GaD by thrust- and fold-stacking during the Grenville orogeny *sensu stricto*. Patterns of distribution of lineations within the Gabriel domain, and of southerly plunging ones within the Canyon domain that structurally underlies it farther to the south (Fig. 1), indicate that tectonic vergences for this event were probably toward the west-northwest and north.

Physical Conditions of Metamorphism in the Hart Jaune Terrane

We cannot reliably estimate the physical conditions of metamorphism during the early granulite-facies metamorphism in the HJT because of widespread post-peak unmixing of the pyroxenes, but the absence of garnet from the assemblage indicates that pressures were relatively low. The growth of garnet in some rocks in the second stage of granulite-facies metamorphism shows that pressures were higher, but again no reliable quantitative estimates of temperatures and pressures can be made because of the inhomogeneity of the pyroxenes. Grains of garnet in the granulites, however, show consistent and dramatic increases in Ca content from core to rim (*e.g.*, Fig. 8) indicative of response of the garnet to increasing pressure. The same characteristics are shared by grains of garnet in the amphibolite-facies pelites near the GaD, and such grains also exhibit a marked decrease in Mg near their rim (*e.g.*, Fig. 9). The zoning of Ca is opposite to that observed in the Gabriel domain.

As was the case in the Gabriel domain, we consider the zonal distribution of Mg in the Hart Jaune terrane to reflect retrograde diffusion following the peak of metamorphism. In this case, our interpretation is based primarily on the high metamorphic grade of the rocks, which renders preservation of growth zoning unlikely. There is evidence for minor increase in Mn at some contacts with biotite (*e.g.*, Fig. 9) that provides limited direct evidence for this interpretation, but is not as widespread or as well developed as was the case in the Gabriel domain. In a pelitic system, decline in Mg in garnet requires a decline in temperature (Spear *et al.* 1991). An associated increase in Ca requires that there be little or no decompression associated with the cooling. An alternative possibility is that the Ca zoning, unlike that in Mg, was inherited from the growth phase and is preserved owing to the slower rates of diffusion of Ca than of other cations (*cf.* Spear & Florence 1992). We consider this possibility unlikely in the Hart Jaune terrane, because there is evidence in some grains of garnet from the Hart Jaune pelites that enrichment in Ca is localized at fractures in the garnet (*e.g.*, Fig. 10), requiring that it postdates growth. We therefore interpret all the zoning in the Hart Jaune pelites, like that in the Gabriel domain, as reflecting retrograde diffusion following the peak of metamorphism. As in our treatment of the GaD rocks, we have used garnet rims far from biotite and garnet cores, combined with groundmass biotite and plagioclase compositions, to provide estimates of the peak conditions of metamorphism and conditions of re-equilibration of the HJT metapelites, using the garnet–biotite thermometer and the GASP equilibrium (Tables 1, 2, 4, Fig. 11).

The garnet–biotite thermometer again yields temperatures that are too high for the observed mineral assemblages, which we ascribe to greater $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ in the natural biotite compared with the synthetic biotite used in the derivation of thermodynamic data (Berman & Aranovich, in prep.). Notwithstanding this problem, our results illustrate clearly that the degree of increase in Ca in grains of garnet toward their rim is such that it requires not just constant pressure during the cooling reflected in the decreasing Mg, but a substantial increase in pressure. The GASP isopleths we calculate using garnet-rim data are essentially indistinguishable from those for the Gabriel domain, consistent with retrograde equilibration of the Hart Jaune pelites after they were juxtaposed to those of the GaD. Core compositions of garnet, on the other hand, yield pressures consistently (150 MPa) lower than the rim compositions. Figure 11 includes an arrow indicating our best estimate of the path followed by Hart Jaune pelites from the peak of metamorphism to the retrograde conditions, constrained using the same principles as in the case of the Gabriel domain.

Discussion

Amphibolite-facies metamorphism in the HJT probably resulted from motion on the Gabriel fault. Our mineralogical data indicate that the metamorphism took place under conditions of increasing pressure, which is consistent with burial of the HJT by the GaD and overlying tectonic units due to thrust motion on the

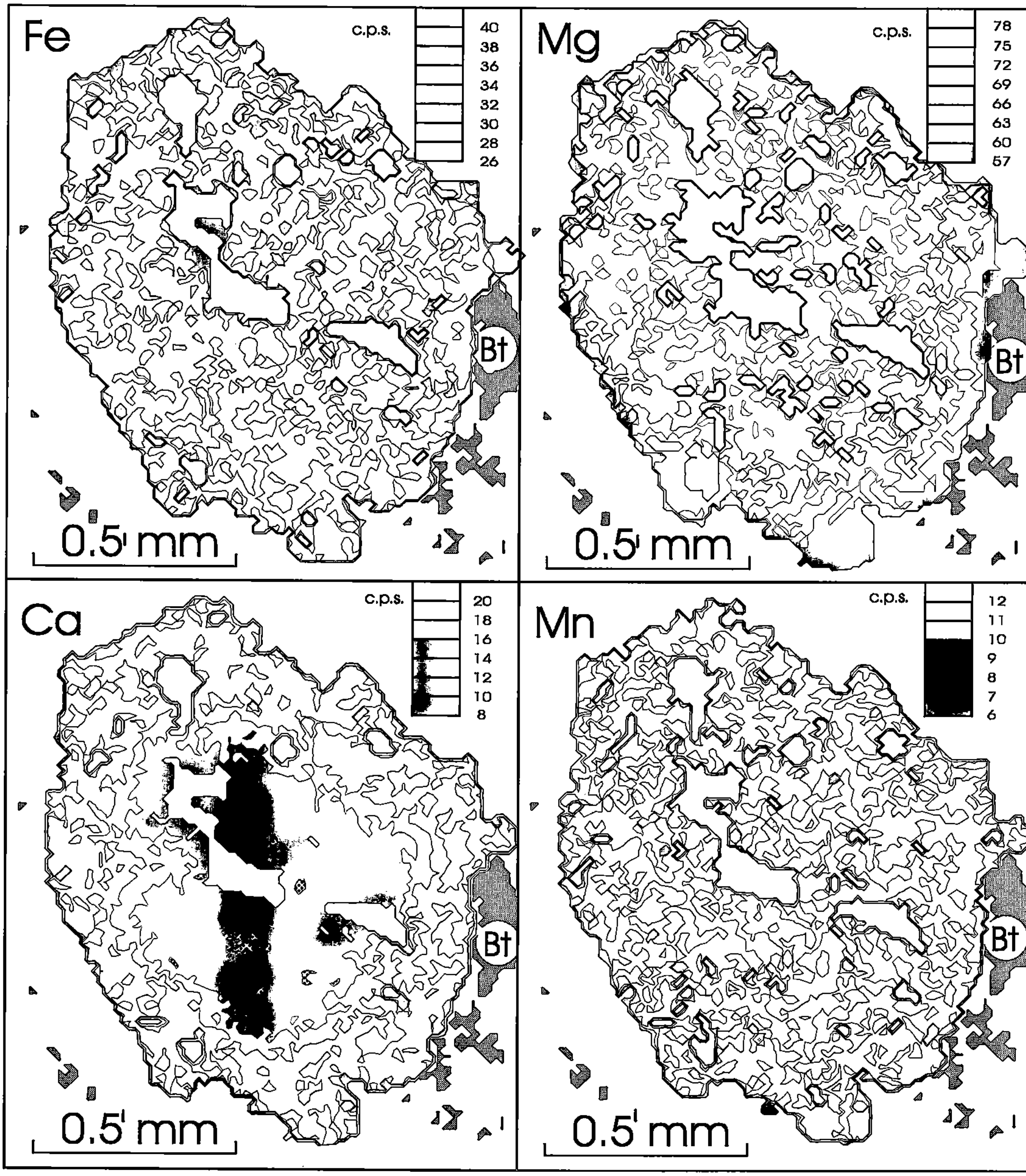

FIG. 9. Zoning in Fe, Mg, Ca and Mn in a single grain of garnet from a pelite in the southern Hart Jaune terrane (spec. ss9377a). For this map, counting was conducted on a 420 × 510 grid for 50 ms at each position. Bt: biotite grains.

Gabriel fault. The coincidence of the GASP isopleths calculated for the later stages of equilibration in the HJT pelites with those for the late-stage equilibration of the GaD pelites is also consistent with this interpretation. Furthermore, the widely observed increases in Ca from core to rim in garnet in the HJT mafic granulites and quartzofeldspathic rocks indicate that they responded similarly to the increasing-P conditions exhibited by the pelites.

Some kinematic indicators in sheared HJT rocks on the shores of the reservoir are consistent with a thrusting scenario for the Gabriel fault, as are the

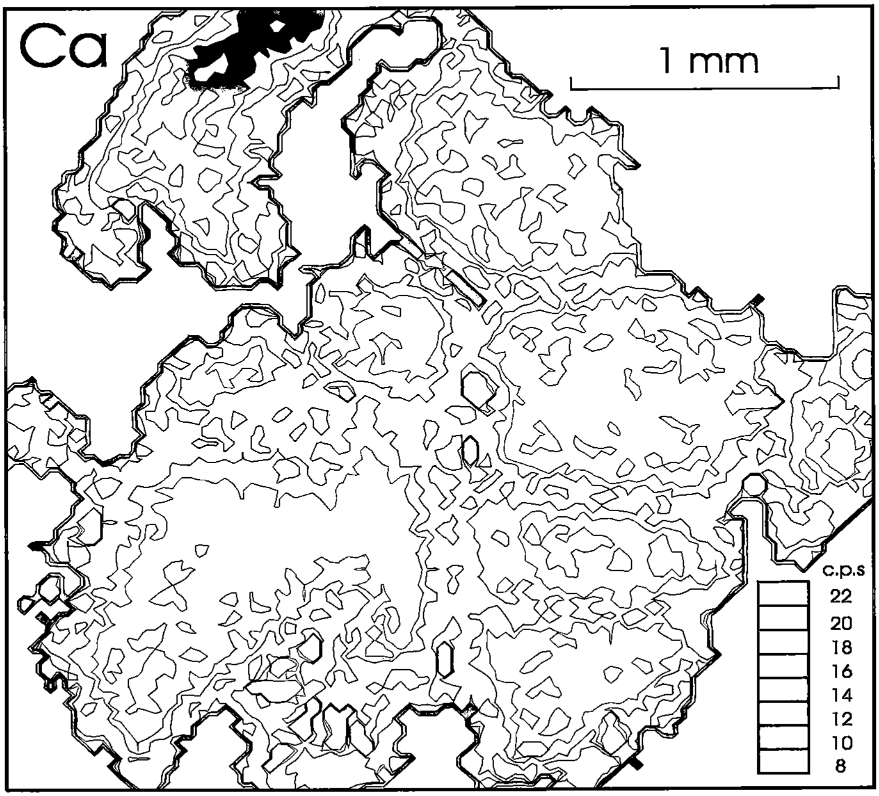

FIG. 10. Zoning in Ca in a single grain of garnet from a pelitic rock in the Hart Jaune terrane (spec. ss9377). For this map, counting was conducted on a 500 × 500 grid for 90 ms at each position. The figure shows a clear relationship between increasing Ca and the locations of fractures in the garnet.

normal-fault kinematic indicators on the fault where it has become north-dipping on the Little Manicouagan River, but the most prominent kinematic indicators, normal-sense shears in the HJT just north of the Gabriel fault (Fig. 5), are anomalous. This is disturbing, especially since most of the HJT pelites we have studied are from these shear zones, and well-developed lineations of sillimanite leave little doubt that the mineral assemblages developed in association with the observed top-to-the-south (normal) displacement within the uppermost HJT. The garnet profiles indicate that this normal faulting was associated with a pronounced increase in pressure, which effectively precludes an association with orogenic collapse (*cf.* Dewey 1988). Since the Gabriel fault has a markedly curved surface (Fig. 2), antithetic faults might have developed to accommodate space problems as the GaD rode up the surface, but they would generally be expected in the hanging wall, not the footwall as observed here. The simplest interpretation we can devise to explain these normal faults is that they are minor splays from the Triple Notch fault, which underlies both the GaD and the HJT at depth (Fig. 1). This fault is the roof fault to the Manicouagan Imbricate Zone, and exhibits top-to-the-southeast, normal-fault kinematics where it is exposed on the reservoir shore farther south. If this interpretation is correct, the spatial association of these shears with the Gabriel fault is fortuitous, and normal motion on the Triple Notch fault was synchronous with thrust motion on the Gabriel fault.

The P–T path traced by the HJT pelites forms part of an "anticlockwise" P–T path and requires heating before tectonic loading (*cf.* Bohlen 1987) or a period of unloading without cooling (*cf.* Wickham & Oxburgh 1985) before the loading evidenced in the path of metamorphism. This is clearly illustrated by the position of the path in P–T space; the GASP isopleths calculated for the HJT pelites using garnet-core data all lie close to the geotherm of Pollack & Chapman (1977) for a continental region with a surface heat-flow of 120 mW m^{-2} (Fig. 11), thus indicating that before loading by the GaD the HJT was in a region of very high geothermal gradient. Rocks of the HJT were

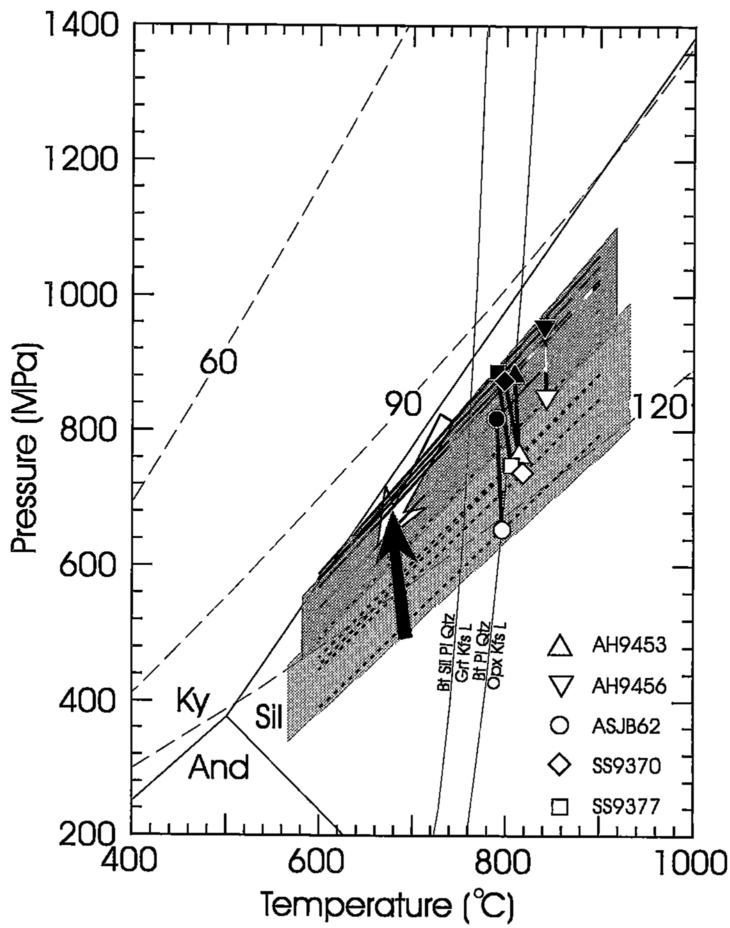

FIG. 11. Metamorphic P–T estimates for five samples of sillimanite-bearing pelite from shear zones in the southern part of the Hart Jaune terrane, near the Gabriel fault. Black symbols with white outlines are the positions of intersections of rim garnet – biotite equilibria with the GASP isopleths for each of the rocks. The heavy dashed lines within the paler-shaded region, and the white symbols with black outlines, are the equivalents for the garnet cores. The heavy lines join core-to-rim results from the same rock. Other features are as for Figure 7. Note that the region that is shaded heavily, approximately encompassing the rim GASP isopleths, is identical to that in Figure 7. The thick black arrow marks the interpreted trend of P and T from the metamorphic peak to re-equilibration recorded in the rim of the garnet. The thick hollow arrow marks the same trend for the Gabriel domain (from Fig. 7).

apparently in this high-gradient condition just before tectonic juxtaposition to the GaD (in geon 10).

CONCLUSIONS

Our study provides metamorphic evidence for a thrust relationship between rocks of the Gabriel domain and those of the Hart Jaune terrane that is considerably more convincing than the structural data we have been able to detect and, indeed, contradicts those we had originally considered the most compelling. The metamorphic signature of the juxtaposition is unusual in the degree to which it preserves the apparently pre-thrusting metamorphic signature in the footwall block. In the scenario that is typical for overthrusting, the hanging wall is warmer than the footwall, and heating of the footwall following fault motion largely resets the metamorphic assemblages (Crowley 1988). In this case, however, the footwall block had temperatures comparable with those in the hanging wall, so

TABLE 4. AVERAGE COMPOSITION OF GARNET, HART JAUNE TERRANE

Rock	ah9453		ah9456		asjb62		ss9370		ss9377	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO_2	37.49	37.40	37.48	37.27	37.89	37.87	37.43	37.43	37.35	37.42
Al_2O_3	22.54	21.41	21.22	22.96	21.85	21.78	21.52	21.30	21.10	21.08
TiO_2	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00
FeO	29.47	30.69	32.05	30.62	28.64	28.75	31.16	31.49	32.25	32.47
MnO	1.78	1.75	1.23	1.21	0.92	0.92	1.17	1.19	1.14	1.18
MgO	6.68	6.49	6.10	5.64	9.16	8.61	6.76	6.14	6.20	5.72
CaO	1.11	1.51	1.21	1.44	1.26	1.77	1.32	1.86	1.01	1.39
Total	99.08	99.25	99.30	99.15	99.71	99.70	99.38	99.43	99.06	99.26
Fe^{2+}	3.888	4.076	4.269	4.050	3.730	3.751	4.129	4.184	4.307	4.337
Mg	1.571	1.536	1.448	1.329	2.125	2.003	1.598	1.454	1.477	1.362
Mn	0.238	0.235	0.166	0.162	0.121	0.121	0.157	0.161	0.154	0.160
Ca	0.187	0.257	0.206	0.244	0.210	0.296	0.225	0.317	0.172	0.238
Ti	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.001	0.000
AlZ	0.086	0.059	0.031	0.104	0.101	0.091	0.070	0.052	0.035	0.024
AlY	4.105	3.949	3.951	4.176	3.909	3.915	3.949	3.937	3.937	3.943
SiZ	5.914	5.941	5.969	5.896	5.899	5.909	5.930	5.948	5.965	5.976
SiY	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
XFe	0.661	0.668	0.701	0.700	0.603	0.608	0.676	0.684	0.705	0.711
XMg	0.267	0.252	0.238	0.230	0.344	0.325	0.262	0.238	0.242	0.223
XCa	0.032	0.042	0.034	0.042	0.034	0.048	0.037	0.052	0.028	0.039
XMn	0.040	0.038	0.027	0.028	0.020	0.020	0.026	0.026	0.025	0.026
# anal	19	10	6	36	27	9	4	27	7	4

that thermal relaxation of the footwall was negligible. This presumably reflects the high ambient geothermal gradient in the footwall at the time of juxtaposition.

The high geothermal gradients evidenced in the Hart Jaune terrane before emplacement of the GaD require some kind of rift or subduction-related arc in the region of the HJT before about 1.0 Ga. If it was an arc, the arc developed in older continental crust, given that the Hart Jaune terrane exhibits a long pre-Grenville history. We cannot exclude the possibility that the HJT was affiliated to North America before 1.0 Ga but, if it was, the intervening high-pressure metamorphosed rocks of the Manicouagan Imbricate Zone make it clear that it had separated from North America before its subsequent collision at *ca.* 1.0 Ga.

We interpret the normal faults that cut the uppermost part of the HJT as splays from the underlying Triple Notch fault, which is the roof fault to Manicouagan Imbricate Zone. Our metamorphic data show that the normal faults in the HJT were active at a time when the HJT was undergoing burial. If they are splays from the Triple Notch fault, the high-pressure metamorphosed rocks of the Manicouagan Imbricate Zone were riding up beneath the HJT as it was being overthrust by the GaD. Emplacement of the high-pressure rocks at a high structural level was, then, intimately linked to the compressional stages of the orogenic process (*cf.* Hsü 1991, Hynes *et al.* 1996).

Acknowledgements

We acknowledge financial support from the Natural Sciences and Engineering Research Council in the form of operating grants to Hynes through the regular grants program and the Lithoprobe project and a Postgraduate Award to St-Jean. We are also grateful for field support from the Department of Indian and Northern Affairs through a grant to the McGill Centre for Northern Studies. We thank Steve St-Cyr for providing some of the structural data and specimens from the Gabriel domain, and Aphrodite Indares, Tom Clark, André Gobeil and Toby Rivers for discussions about the evolution of the region. This paper has benefitted from constructive reviews by L. Corriveau and A. Indares, and was handled by guest associate editor Michael Easton.

References

AVRAMTCHEV, L. (1983): Carte des gîtes mineraux du Québec, région de la Baie James. *Ministère de l'Énergie et des Ressources, Québec DPV* **940**.

BERMAN, R.G. (1991): Thermobarometry using multi-equilibrium calculations: a new technique, with petrological implications. *Can. Mineral.* **29**, 833-855.

________, ARANOVICH, L.Y. & PATTISON, D.R.M. (1995): Reassessment of the garnet–clinopyroxene Fe–Mg exchange thermometer. II. Thermodynamic analysis. *Contrib. Mineral. Petrol.* **119**, 30-42.

BOHLEN, S. (1987): Pressure–temperature–time paths and a tectonic model for the evolution of granulites. *J. Geol.* **95**, 617-632.

CLARKE, P.J. (1977): Région de Gagnon. *Ministère des Richesses naturelles, Québec, Rapp. Géol.* **178**, 1-79.

CROWLEY, P.D. (1988): Metamorphic break across postmetamorphic thrust faults: an unreliable indicator of structural throw. *Geology* **16**, 46-49.

DEWEY, J.F. (1988): Extensional collapse of orogens. *Tectonics* **7**, 1123-1139.

EATON, D.W., HYNES, A., INDARES, A. & RIVERS, T. (1995): Seismic images of eclogites, crustal-scale extension, and Moho relief in the eastern Grenville province, Quebec. *Geology* **23**, 855-858.

ENGLAND, P.C. & RICHARDSON, S.W. (1977): The influence of erosion upon the mineral facies of rocks from different metamorphic environments. *J. Geol. Soc. London* **134**, 201-213.

________ & THOMPSON, A.B. (1984): Pressure–temperature–time paths of regional metamorphism 1. Heat transfer during the evolution of thickened crust. *J. Petrol.* **25**, 894-928.

FERRY, J.M. & SPEAR, F.S. (1978): Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contrib. Mineral. Petrol.* **66**, 113-117.

FRANCONI, A., SHARMA, K.N.M. & LAURIN, A.F. (1975): Région des rivières Betsiamites et Moisie. *Ministère des Richesses naturelles, Québec, Rapp. Géol.* **162**, 1-149.

FUHRMAN, M.L. & LINDSLEY, D.H. (1988): Ternary-feldspar modelling and thermometry. *Am. Mineral.* **73**, 201-216.

GOBEIL, A. (1996a): Géologie de la région du lac Lacoursière (22N/08). *Ministère des Richesses naturelles, Québec, RG* **96-03** (in press).

________ (1996b): Géologie de la région du lac Grandmesnil (22O/05). *Ministère des Richesses naturelles, Québec, RG* **96-04** (in press).

GOWER, C.F., SCHÄRER, U. & HEAMAN, L.M. (1992): The Labradorian orogeny in the Grenville Province, eastern Labrador, Canada. *Can. J. Earth Sci.* **29**, 1944-1957.

________ & TUCKER, R.D. (1994): Distribution of pre-1400 Ma crust in the Grenville province: implications for rifting in Laurentia–Baltica during geon 14. *Geology* **22**, 827-830.

HOLDAWAY, M.J. (1971): Stability of andalusite and the aluminum silicate phase diagram. *Am. J. Sci.* **271**, 97-131.

HSÜ, K.J. (1991): Exhumation of high-pressure metamorphic rocks. *Geology* **19**, 107-110.

HYNES, A., ARKANI-HAMED, J. & GREILING, R. (1996): Subduction of continental margins and the uplift of high-pressure metamorphic rocks. *Earth Planet. Sci. Lett.* **140**, 13-25.

INDARES, A., DUNNING, G. & COX, R. (1996): Manicouagan Imbricate Zone: an exposed deep crustal segment in the eastern Grenville Province. *Abitibi–Grenville Lithoprobe Workshop (Quebec City), Abstr.*, 18.

KISH, L. (1968): Hart-Jaune River area. *Quebec Department of Natural Resources, Geol. Rep.* **132**.

MURTAUGH, J.G. (1976): Manicouagan impact structure. *Quebec Dep. Natural Resources, DPV* **432**.

NEWTON, R.C. & HASELTON, H.T. (1981): Thermodynamics of the garnet - plagioclase - Al_2SiO_5 - quartz geobarometer. *In* Thermodynamics of Minerals and Melts (Newton, R.C., Navrotsky, A. & Wood, B.J., eds.). Springer-Verlag, New York, N.Y. (129-145).

PEARCE, G.W. & STESKY, R.M. (1990): *Spheristat: Orientation Analysis and Plotting for MS-DOS Computers*. Frontenac Wordsmiths, Brockville, Ontario.

POLLACK, H.N. & CHAPMAN, D.S. (1977): On the regional variation of heat flow, geotherms, and lithospheric thickness. *Tectonophys.* **38**, 279-296.

RIVERS, T., VAN GOOL, J.A.M. & CONNELLY, J.N. (1993): Contrasting tectonic styles in the northern Grenville province: implications for the dynamics of orogenic fronts. *Geology* **21**, 1127-1130.

ROBIN, P.-Y.F. & JOWETT, C. (1986): Computerized density contouring and statistical evaluation of orientation data using counting circles and continuous weighting functions. *Tectonophys.* **121**, 207-223.

SCOTT, D.J. & HYNES, A. (1994): U–Pb geochronology along the Manicouagan Corridor, preliminary results: evidence for ca. 1.47 Ga metamorphism. *Lithoprobe Report (Abitibi–Grenville Transect)* **41**, 109-111.

SIMPSON, C.A. & DE PAOR, D. (1993): Strain and kinematic analysis in general shear zones. *J. Struct. Geol.* **15**, 1-20.

SPEAR, F.S. (1991): On the interpretation of peak metamorphic temperatures in light of garnet diffusion during cooling. *J. Metamorphic Geol.* **9**, 379-388.

________ (1993): *Metamorphic Phase Equilibria and Pressure – Temperature – Time Paths.* Mineralogical Society of America, Monogr. **1**.

________ & FLORENCE, F.P. (1992): Thermobarometry in granulites: pitfalls and new approaches. *Precambrian Res.* **55**, 209-241.

________, KOHN, M.J., FLORENCE, F.P. & MENARD, T. (1991): A model for garnet and plagioclase growth in pelitic schists: implications for thermobarometry and P–T path determinations. *J. Metamorphic Geol.* **8**, 683-696.

WESSEL, P. & SMITH, W.H.F. (1995): New version of the Generic Mapping Tools released. *Eos, Trans. Am. Geophys. Union* **76**, 329.

WICKHAM, S.M. & OXBURGH, E.R. (1985): Continental rifts as a setting for regional metamorphism. *Nature* **318**, 330-333.

WILLIAMS, M.L. & GRAMBLING, J.A. (1990): Manganese, ferric iron, and the equilibrium between garnet and biotite. *Am. Mineral.* **75**, 886-908.

Received December 31, 1996, revised manuscript accepted June 11, 1997.