Crustal structure and kinematic framework of the northwestern Pontiac Subprovince, Quebec: an integrated structural and geophysical study[1]

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Structural mapping, gravity and magnetic modelling, and interpretation of a deep-seismic profile in the northwestern Pontiac Subprovince outline the crustal structure and early structural development of the region. Penetrative D_1 fabrics in the Pontiac Group and in the underlying Opasatica Gneiss may record south-vergent thrusting of a high-grade nappe. D_2 and D_3 structures record southeast-vergent folding and thrusting within the Pontiac Group. Steeply dipping northeast-trending ductile shear zones may represent oblique ramps initiated during D_1. Gravity and magnetic model profiles are consistent with north-dipping structures in the shallow crust, and indicate that the Pontiac Group is a wedge underlain by north-dipping slabs of different densities and magnetic susceptibilities. Interpretation of a seismic reflection profile shows mid-crustal duplex structures overlying a deeper thrust between 16 and 24 km. From the surface to the deep crust, the structure of the northwestern Pontiac Subprovince records south- to southeast-directed thrusting and important crustal thickening during a collisional event. In light of field observations, available isotopic ages suggest that D_1 deformation began no earlier than 2694 Ma, and that deformation continued until at least 2668 Ma.

La cartographie structurale, les modélisations gravimétrique et magnétique, et l'interprétation du profil de sismique profonde dans la partie nord-ouest de la sous-province de Pontiac définissent la structure de la croûte et renseignent sur le développement structural précoce dans la région. La fabrique pénétrative D_1 dans le Groupe de Pontiac et dans le Gneiss d'Opasatica reflètent possiblement un charriage à vergence sud de la nappe de degré métamorphique élevé. Les structures D_2 et D_3 représentent le plissement à vergence sud-est et le charriage au sein du Groupe de Pontiac. Les zones de cisaillement ductile de direction nord-est à forte pente correspondent possiblement à des rampes obliques créées durant D_1. Les profils gravimétrique et magnétique modélisés sont en accord avec les structures à pendage nord dans la croûte peu profonde, et ils montrent que le Groupe de Pontiac est un prisme qui repose sur des dalles à pendage nord caractérisées par des densités et susceptibilités magnétiques différentes. L'interprétation du profil de sismique réflexion révèle l'existence dans la croûte médiane de structures de type duplex sus-jacentes à un charriage plus profond, entre environ 16 et 24 km. De la surface jusqu'à la croûte profonde, la structure de la région nord-ouest de la sous-province de Pontiac révèle un charriage de direction sud à sud-est et un épaississement crustal majeur causés par un évènement de collision. À la lumière des observations faites sur le terrain, les âges isotopiques disponibles suggèrent que la déformation D_1 n'a pas débuté avant 2694 Ma, et que cette déformation a continué à être active jusqu'à il y a au moins 2668 Ma.

[Traduit par la rédaction]

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Introduction

The Pontiac Subprovince is a late Archean metasedimentary granitoid-gneiss terrane situated along the southeastern margin of the Superior Province in Quebec. It is limited to the south by the Grenville Province, which contains some granulite-grade Archean gneisses (Gariépy et al. 1990) uplifted during the Proterozoic Grenvillian orogeny, to the west by Huronian sedimentary rocks of the Proterozoic Cobalt embayment, and to the north by the Cadillac – Larder Lake fault zone, which separates the Pontiac Subprovince from the Southern Volcanic Zone (Ludden et al. 1986) of the Abitibi Subprovince (Fig. 1). The geology and structure of the Abitibi greenstones have been extensively studied in both Quebec (Dimroth et al. 1982, 1983*a*, 1983*b*; Hubert et al. 1984; Ludden et al. 1986; Chown et al. 1992) and Ontario (review in Jackson and Fyon 1991). Structural and kinematic analysis has also been extended to the high-grade Opatica granite-gneiss belt, which is now viewed as the metamorphic–plutonic hinterland to the thrust belt represented by the Northern Volcanic Zone of the Abitibi Subprovince (Benn et al. 1992; Sawyer and Benn 1993). In contrast, a relatively small amount of work has been published concerning the structural geology of the Pontiac Subprovince.

Seismic reflection profiles and other geophysical studies carried out along the Abitibi–Grenville Lithoprobe transect (Clowes et al. 1992) have provided an opportunity to link surface geology with subsurface structure. In this paper, we present a synthesis of the principal structural elements of the northwestern Pontiac Subprovince, based on mapping, gravity and magnetic modelling, and our interpretation of Lithoprobe seismic reflection profile 16A. The aim is to establish a picture of the crustal structure and of the structural development in the area, which will contribute to a better understanding of the tec-

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[1] Lithoprobe Publication 487.

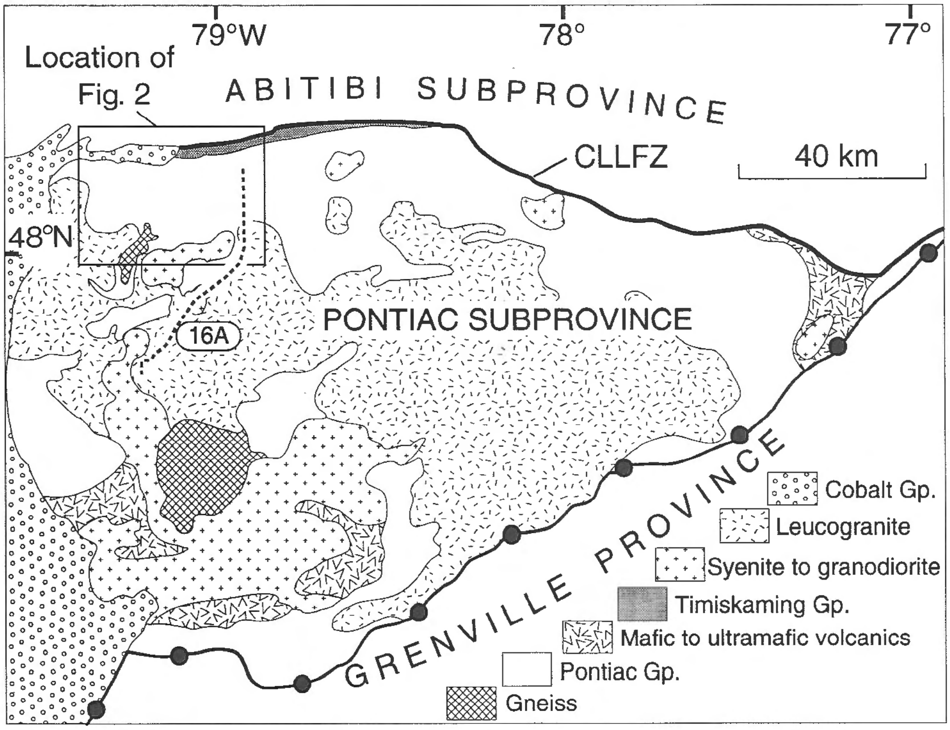

FIG. 1. Location map of the study area in the Pontiac Subprovince, modified from Hocq (1989). Lithoprobe seismic reflection profile 16A is indicated by the broken line. CLLFZ, Cadillac – Larder Lake fault zone.

tonic development of the southeastern Superior Province. The data and interpretations presented in this paper represent a review of our ongoing work in the Pontiac Subprovince.

The field area corresponds closely to that studied by van de Walle (1978) and Camiré and Burg (1993), who documented thin-skinned thrusting. However, the multidisciplinary approach of the present work allows us to extend the study to the deep crust, and to propose a new structural model for the northwestern Pontiac Subprovince.

Tectonic setting

Two plate tectonic models have been put forward to explain the structural and magmatic evolution of the Southern Volcanic Zone and the Pontiac Subprovince. Based on geological and structural mapping, Dimroth et al. (1983*a*) proposed that the Pontiac Subprovince would represent the fore-arc accretionary prism of an ensimatic magmatic arc (Southern Volcanic Zone), intruded by syntectonic plutons during collision with a crustal block farther to the south. Kerrich and Feng (1992) proposed an alternative model in which the Pontiac Subprovince would be an exotic crustal block (microcontinent), having collided with and underthrust the Southern Volcanic Zone. These models suggest that the Cadillac – Larder Lake fault zone would represent a north-dipping thrust, but differ in their placement of the suture zone to the north or to the south of the Pontiac Subprovince. Interpretation of Abitibi–Grenville Lithoprobe seismic reflection profile 14 suggests that the Cadillac – Larder Lake fault zone dips steeply northwards at depths greater than a few kilometres (Clowes et al. 1992). Dextral and sinistral strike-slip movements on the Cadillac – Larder Lake fault zone have also been documented (Hubert et al. 1984; Robert 1989).

Geology

The principal units in the study area are indicated in the simplified geological map presented in Fig. 2. The most widespread supracrustal assemblage is represented by the Pontiac Group, which is composed of metasediments and locally abundant mafic to ultramafic rocks. Conglomeratic rocks of the Timiskaming Group are concentrated in the north, and the Opasatica Gneiss is located in the western part of the study area. The principal granitoid suites include the monzonites and syenites of the Lac Frechette complex, and the Décelles suite of granites and pegmatites.

Supracrustal rocks

The Pontiac Group is dominated by turbiditic metasediments, classified petrographically as greywackes and argillites by Dimroth et al. (1982), and as quartz-rich sandstones and pelites by Lajoie and Ludden (1984). Dimroth et al. (1982) proposed that the Pontiac Group was deposited on a basement of ultramafic lavas, and estimated a total stratigraphic thickness of ≥1000 m. Sedimentary structures, including cross-bedding, graded-bedding, and trough structures, are preserved in many places. An increase in metamorphic grade from greenschist facies in the north to amphibolite grade towards the south was documented by Jolly (1978). Our observations, based on detailed mapping, confirm a gradual increase in metamorphic grade from north to south, but we place isograds (Fig. 2) farther north than previous workers (Jolly 1978; Camiré and Burg 1993). Geochemical and petrographic study of the Pontiac Group turbidites has shown their source to have been composed of tonalites, mafic and ultramafic rocks, and some older sedimentary rocks as evidenced by the presence of standstone lithics (Dimroth et al. 1982; Lajoie and Ludden 1984; Camiré et al. 1993). The source region is poorly con-

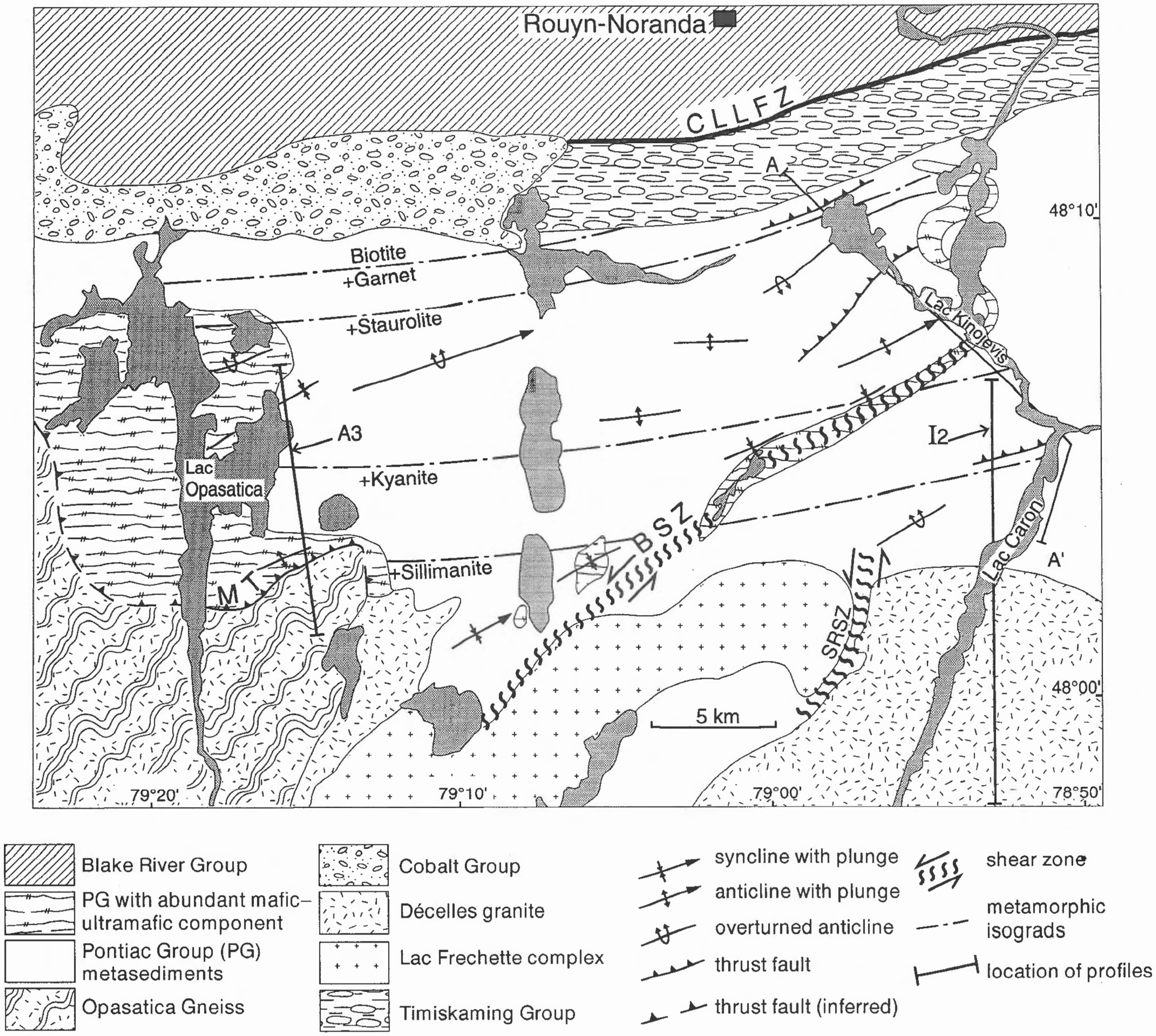

FIG. 2. Simplified map of the study area. The locations of modelled gravity and magnetic profiles A3 and I2, and of the structural profile A–A′ (Fig. 3) are indicated. MT, Montbeillard thrust; BSZ, Bellecombe shear zone, SRSZ, Saint-Roch shear zone; CLLFZ, Cadillac – Larder Lake fault zone.

strained, and may have been to the north within the Abitibi Subprovince, or to the south and east within the reworked Archean rocks of the Grenville Province (Dimroth et al. 1982; Camiré et al. 1993). Disagreement exists as to whether the conglomeratic rocks of the Timiskaming Group represent a proximal facies of the Pontiac Group (Dimroth et al. 1982) or a sequence derived from an entirely different source region (Lajoie and Ludden 1984).

U–Pb ages for detrital zircons from the Pontiac Group (Gariépy et al. 1984; D.W. Davis 1991, 1992; Mortensen and Card 1993) vary from 2980 to 2683 Ma. Possible source rocks of an age comparable to that of older detrital zircons (2980–2760 Ma) have not been found anywhere within the southern Abitibi Subprovince or the Pontiac Subprovince, though recent dates from the Opatica Belt document the presence of tonalitic plutonic rocks with ages of about 2830 Ma (W.J. Davis et al. 1993).

Opasatica Gneiss

The amphibolite-grade Opasatica Gneiss consists of interlayered leucocratic and melanocratic components. The rocks are strongly foliated and lineated. The melanocratic component is a locally migmatized paragneiss derived from sediments and interlayered mafic and ultramafic rocks, which we interpret as the stratigraphically lower parts of the Pontiac Group. The leucocratic component may have been derived from early syntectonic intrusive sheets (Dimroth et al. 1983*b*), or may represent quartz- and feldspar-rich sediments. An age of 2660 ± 6 Ma for the Opasatica Gneiss has been interpreted as a minimum age for the last metamorphic event that affected

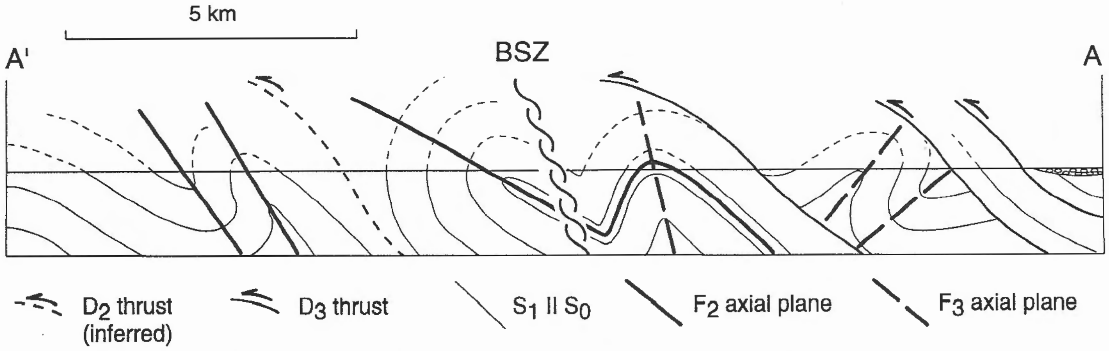

FIG. 3. Structural profile within the study area. Location of profile given in Fig. 2.

the rocks (Machado et al. 1991, U–Pb titanite).

Granitoids

Rive et al. (1990) grouped the granitoids of the Abitibi and Pontiac subprovinces into eight principal and three minor petrological suites. Two of the principal suites occur in the study area, and are represented by clinopyroxene–hornblende monzonites and monzodiorites and associated syenites of the Lac Frechette complex, and by the two-mica garnet- and sillimanite-bearing granites and pegmatites of the Décelles suite (Fig. 2). Absolute timing of emplacement of these plutonic bodies can be inferred from published isotopic ages (Machado et al. 1991, U–Pb zircon and monazite; Feng and Kerrich 1991, Pb–Pb zircon; Mortensen and Card 1993, U–Pb zircon and monazite). The Lac Frechette complex would have been emplaced at about 2685–2670 Ma, while the Décelles suite crystallized at about 2655–2630 Ma.

Structural geology

Structural mapping was concentrated within the Pontiac Group and the Opasatica Gneiss. In the following discussion, we will refer to different periods in the regional structural evolution as D_1, D_2, and D_3, and the structures developed during each period will be presented in relative chronological order. The relative ages of D_1–D_3 structures were determined by field and microstructural observations (e.g., folding of earlier fabrics), which are supported by map-scale structural relationships. All three periods of deformation appear to be related to south- to southeast-vergent thrusting, and may have occurred during one tectonic event, that is, a collisional event accompanied by crustal shortening. Structures related to D_1, D_2, and D_3 are also preserved within steeply dipping shear zones, which will be discussed separately. Figure 2 is a simplified structural map, and a structural cross section based on the map is presented in Fig. 3.

D_1 structures

D_1 structures are found in the Pontiac Group and in the Opasatica Gneiss. D_1 fabrics are best preserved in the western part of the area where they are very penetrative, recording pervasive D_1 shearing throughout a metamorphic pile at least several kilometres thick. In the Opasatica Gneiss, an L_1 stretchng lineation is defined by streaky biotite aggregates and quartzo-feldspathic rods that are parallel to the axes of intrafolial F_1 folds. The average trend of L_1 is east-northeast – west-southwest (Fig. 4), the direction of plunge varying due to later folding.

In the Pontiac Zone, an L_1^0 intersection lineation is best preserved in the hinge zones of isoclinal F_1 folds, and an L_1 hornblende mineral lineation is also locally observed. Both L_1^0 and L_1 trend on average east-northeast – west-southwest, which is coaxial with the D_1 stretching trajectory indicated by L_1 in the underlying gneisses. Locally within the Pontiac Group, where D_2 overprinting of D_1 fabrics is not very intense, mesoscopic D_1 shear-sense indicators (asymmetrical boudins of quartz veins) associated with north-dipping S_1 have been observed that indicate top-to-the-south shearing, highly oblique to the L_1 stretching lineation. This suggests that the non-coaxial component of D_1 shearing may record early south-vergent thrusting, while the L_1 stretching lineations in Fig. 4 indicate a maximum finite stretch parallel to F_1 fold axes.

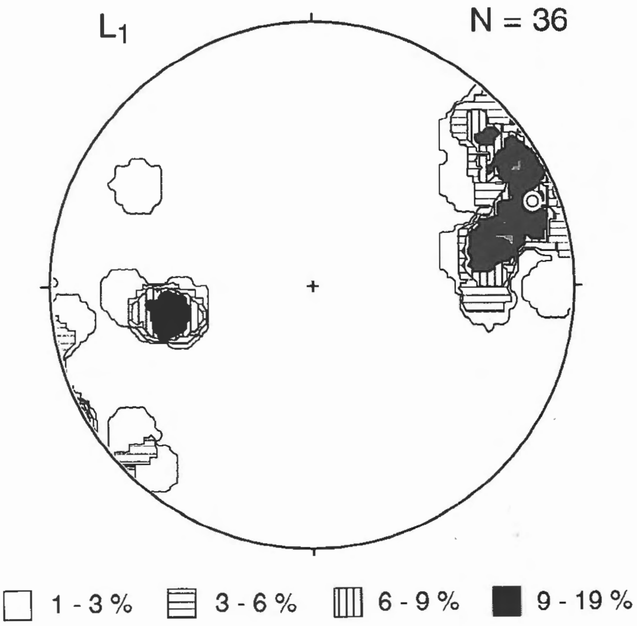

FIG. 4. Contoured lower-hemisphere equal-area projection of L_1 stretching lineations. *N*, number of measurements.

D_2 structures

D_2 deformation resulted in discrete thrusts and associated F_2 folding mapped within the Pontiac Group (Figs. 2, 3). F_2 folds are most often inclined or overturned to the south and have an asymmetry indicating southeast vergence (Fig. 5). S_2 is an axial-planar crenulation cleavage (differentiated layering of Williams (1990)) defined by biotite-rich cleavage bands and

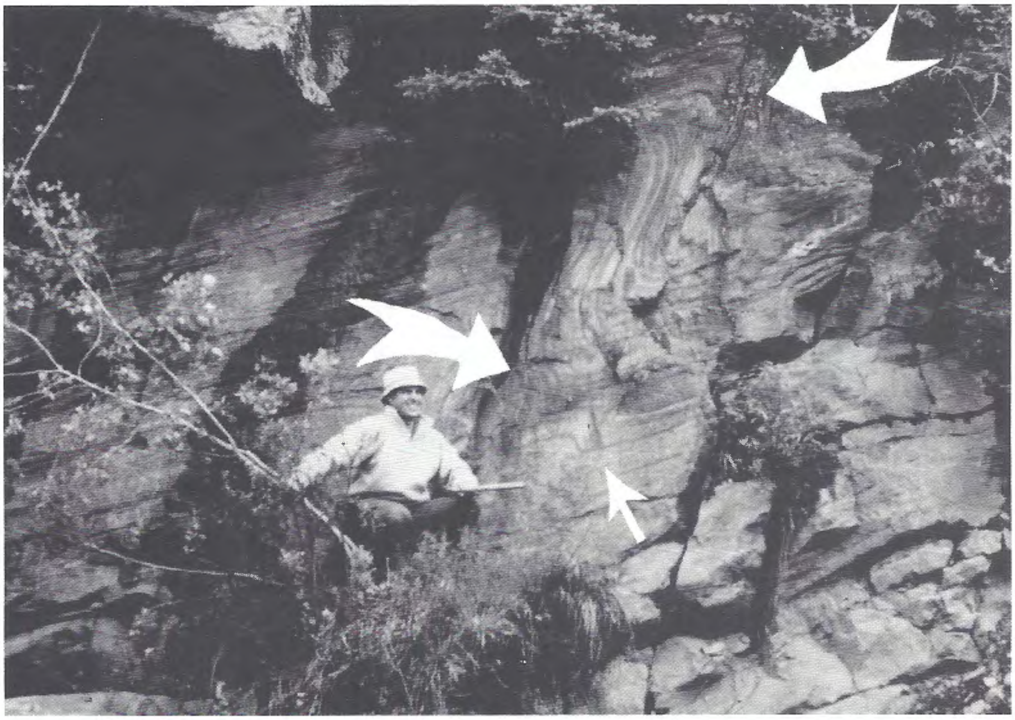

FIG. 5. Southeast-vergent overturned F$_2$ folds of S$_0$ in the Pontiac Group in the hanging wall of the Montbeillard thrust. South is to the right of the photo. Large arrows indicate hinges of an overturned F$_2$ synform–antiform pair. Small arrow indicates a top-to-the-southeast D$_2$ kink of S$_0$.

quartzo-feldspathic microlithons, within which folded S$_1$ foliation is preserved. S$_1$ is also preserved as trails of quartz inclusions within rotated staurolite and kyanite porphyroblasts. Sigmoidal inclusion trails, consistent with D$_2$ crenulation of S$_1$, found within kyanite porphyroblasts (Fig. 6), indicate that peak metamorphism may have occurred during D$_2$.

S$_2$ strikes on average east-northeast and dips to the north (Fig. 7*a*). The asymmetrical south-vergent geometry of F$_2$ folding is demonstrated at the regional scale by the monoclinic symmetry of the distribution of poles to S$_1$ and S$_0$, seen in Figs. 7*b* and 7*c*, where maxima correspond to steep overturned short limbs and shallowly north-dipping long limbs of F$_2$ folds. F$_2$ fold hinges and L_2^1 intersection lineations trend dominantly northeast–southwest to east-northeast – west-southwest (Fig. 8). The bulk transport direction associated with D$_2$ is interpreted to be southeast, highly oblique to the average trends of F$_2$ hinges and of L_2^1.

Camiré and Burg (1993) mapped several shallowly north-dipping thrusts along the shores of Lake Opasatica. These are interpreted as D$_2$ thrusts, and most appear to be minor structures formed by slip along layers of talc- and serpentine-rich metamorphosed ultramafic rock. One thrust, herein named the Montbeillard thrust, occurs at the contact between the overlying Pontiac Group and the underlying Opasatica Gneiss (Fig. 2). Within the Montbeillard thrust, rotated boudins of ultramafic material within metasedimentary rock (Fig. 9) confirm southeastward transport of the Pontiac Group over the Opasatica Gneiss.

D$_3$ structures

D$_3$ deformation is recognized where S$_2$ cleavage is folded both at the microscale (crenulations) and at the map scale (Fig. 3), though development of a differentiated cleavage

FIG. 6. Photomicrograph of D$_2$ crenulations of S$_1$ (sigmoidal inclusion trails of quartz highlighted by broken white line) within a kyanite porphyroblast.

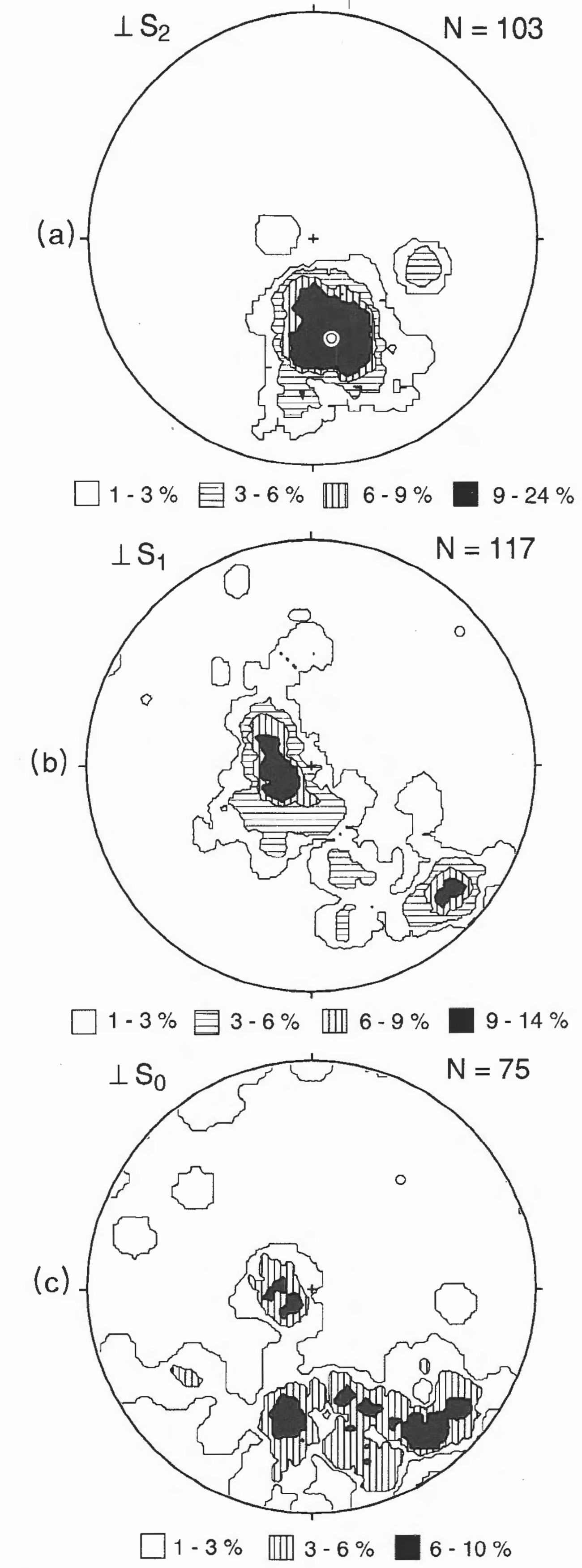

FIG. 7. Contoured lower-hemisphere equal-area projections of poles to planar fabric elements within the Pontiac Group. N, number of measurements.

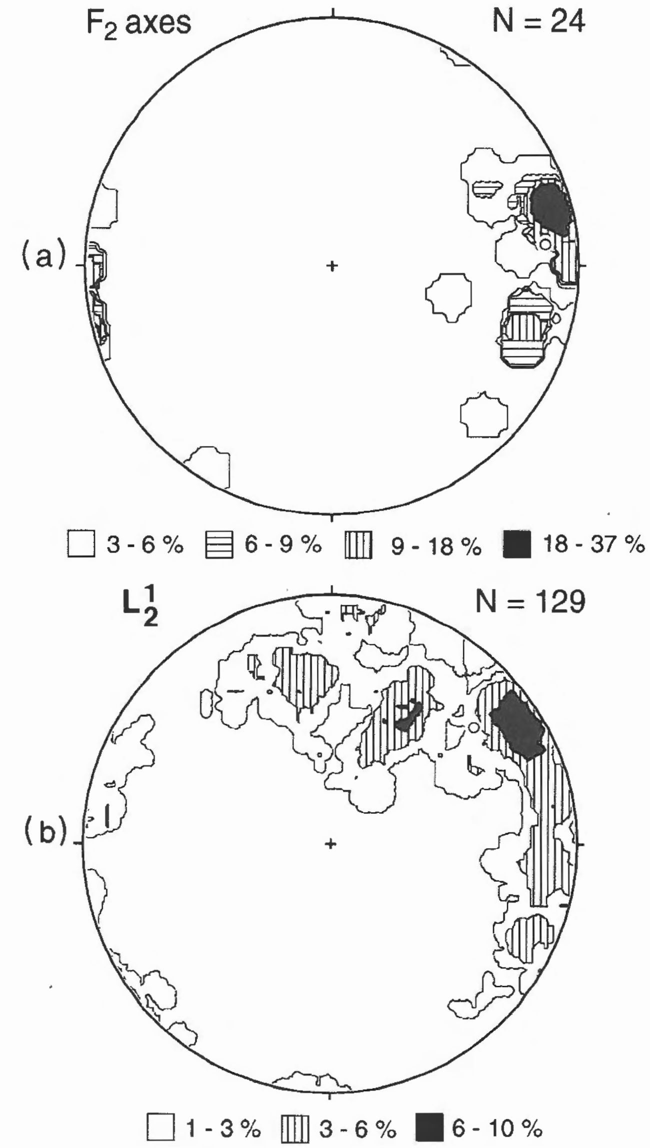

FIG. 8. Contoured lower-hemisphere equal-area projections of F_2 fold axes and L_2^1 intersection lineations within the Pontiac Group. N, number of measurements.

associated with F_3 folding has not been observed. Some mapped thrusts, with associated F_3 folding (Fig. 3), are also considered to be D_3 structures. The sense of vergence of F_3 folding is consistent with southeast-vergent thrusting and with sinistral strike-slip movements across the shear zones described below.

Shear zones

Two steeply dipping shear zones have been identified in the study area (Fig. 2), and are herein named the Bellecombe and the Saint-Roch shear zones. Both shear zones dip steeply to the northwest. Isoclinal folds that record the first phase of deformation within the shear zones appear to represent F_1 (folding of S_0, no evidence of folding of an earlier cleavage); the shear zones may therefore have been initiated during D_1. Shear-sense indicators associated with D_2 and D_3 structures within the shear zones are dominantly sinistral. Dykes corresponding to the Lac Frechette complex and to the Décelles suite were emplaced syntectonically within the shear zones, as

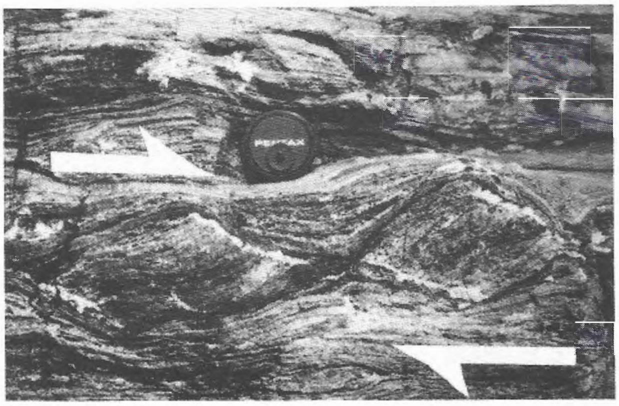

FIG. 9. Rotated boudins of ultramafic rock within the Montbeillard thrust, along the northern margin of the Opasatica Gneiss. South is to the right of the photo. Half-arrows indicate shear sense. Feldspathic leucosome can be seen in pressure shadows at ends of boudins.

evidenced by highly sheared and tightly folded dykes that are crosscut by later, less-deformed dykes. Deformation within the shear zones therefore continued during emplacement of monzonitic and granite plutonic rocks.

Magnetic and gravity studies

Magnetic and gravity modelling of the upper few kilometres of the subsurface are complementary to our study of the surface structure, and to the seismic reflection profile that images the deep crust. Magnetic profiles were modelled using aeromagnetic data from the Geological Survey of Canada's National Aeromagnetic Data Base with flight line spacing of 800 m. The aeromagnetic data were digitized from contour maps, and have a precision equal to the contour interval (10 nT). The gravity data used was a compilation of available data from the Geological Survey of Canada and the Ministère de l'Énergie et des Ressources du Québec and the authors' data gathered from 60 stations. Rock densities and magnetic susceptibilities were measured from 120 samples and outcrops. These data are not sufficient to fully constrain the geophysical models, but allow us to place limits on the possible geological interpretations. Gravity data coverage north of 48°N is along accessible roads and the lakeshore, at intervals of 500 m to 1 km. South of 48°N, coverage is sparse. The accuracy of the gravity data is ±0.5 mGal (1 mGal = 10^{-3} cm/s^2) (Keating 1992).

Two magnetic and one gravity profile were modelled along two lines (A3 and I2; Fig. 2), using the modelling package MAGRAV2 (Broome 1989). The modelling method involves comparing an observed magnetic or gravity profile with calculated profiles of model cross sections, the models being constrained by known geological contacts and measured magnetic susceptibilities or densities. MAGRAV2 allows definition of model bodies along the profile and symmetrically perpendicular to that profile (2.5-dimensional modelling). The use of 2.5-dimensional models therefore limits the location of profiles to geological contacts where the strike extent to either side of the profile is roughly equal. The location of gravity profiles is also restricted by the availability of data. The small data set for rock densities and magnetic susceptibilities places loose constraints on the physical properties of the rock units modelled. These factors mean that modelling results may be used to define general bulk trends, and to identify targets for further investigation.

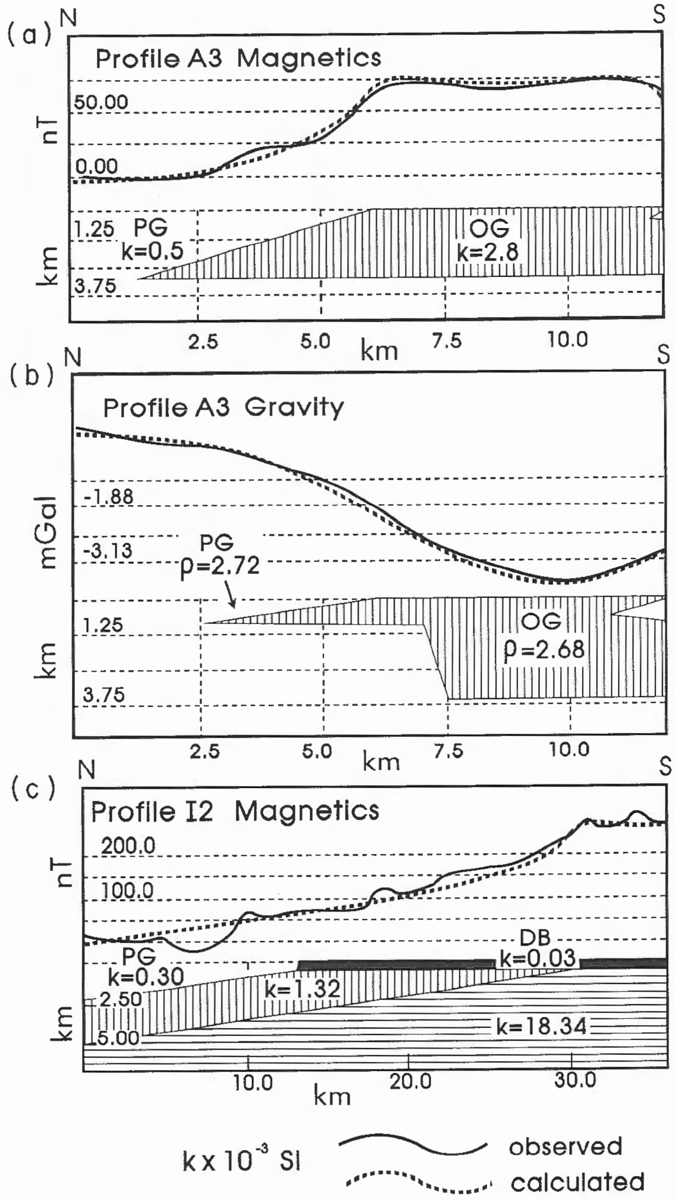

FIG. 10. Gravity and magnetic profiles A3 and I2. Locations of profiles are indicated in Fig. 2. PG, Pontiac Group; OG, Opasatica Gneiss; DB, Décelles Batholith; ρ, density; k, magnetic susceptibility. 1 mGal = 10^{-3} cm/s^2.

The results of magnetic and gravity models perpendicular to the north-dipping Montbeillard thrust (profile A3) are shown in Figs. 10*a* and 10*b* respectively. The densities and magnetic susceptibilities for the Opasatica Gneiss are derived from only four samples, whereas those of the Pontiac Group are well constrained by a large sampling suite. These samples indicate higher magnetic susceptibility and lower density for the Opasatica Gneiss in relation to the Pontiac Group. The lack of constraint on the physical properties of the gneiss makes the thickness of the model and the amplitude of its calculated anomaly profile somewhat unreliable. The shape of the calculated magnetic profile is affected most by near-surface changes in model body shape and very little by changes at or below 3 km depth. The nature of gravitational forces dictates that

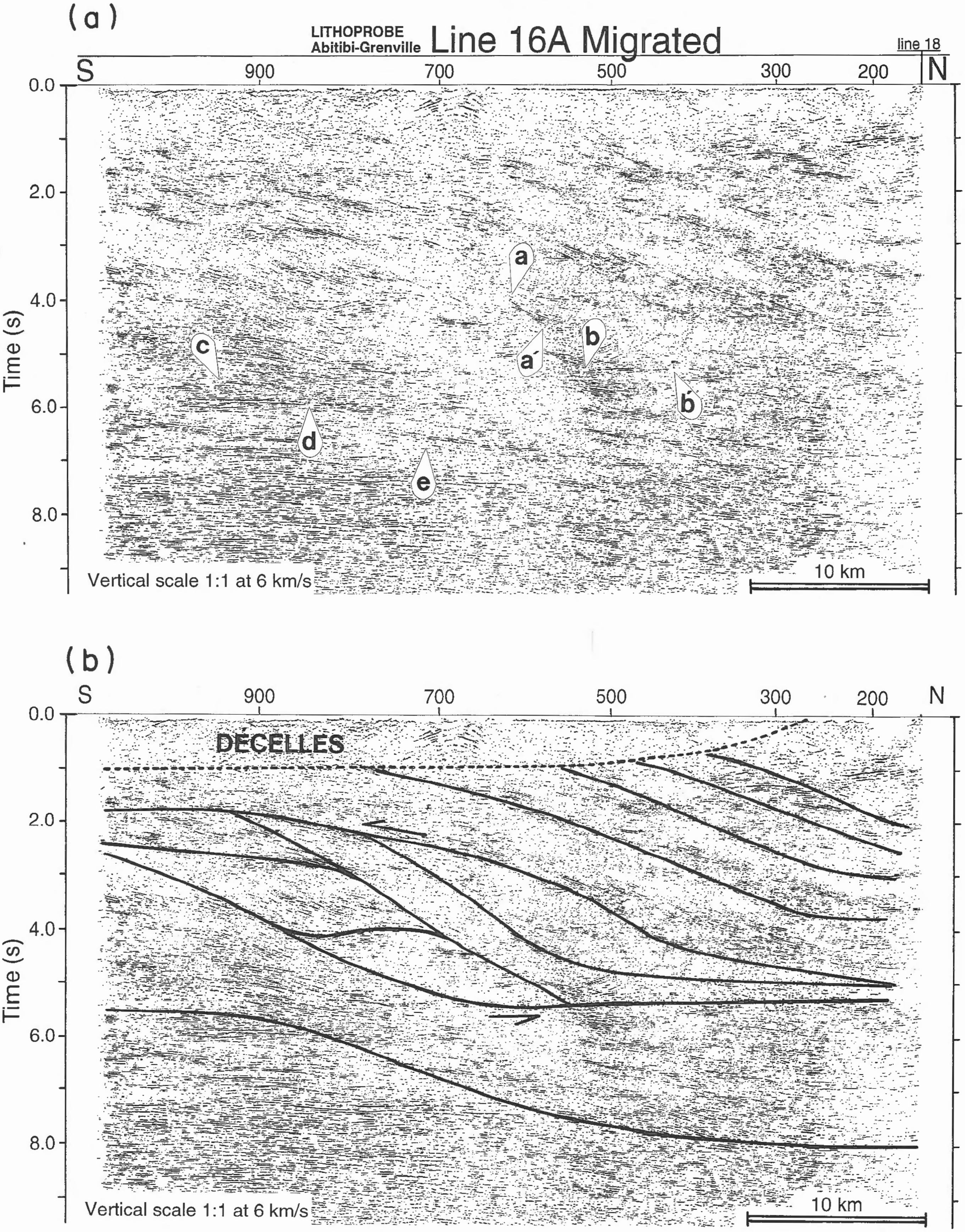

FIG. 11. Migrated seismic reflection profile 16A. Location indicated in Fig. 1. Interpretation in (*b*) is overlain on uninterpreted profile in (*a*). See text for discussion.

changes to body shape at 3 km depth can have profound effects on the calculated gravity profile. However, the general shape of the profile clearly indicates that the tectonic contact between the gneiss and the Pontiac Group dips gently to the north to between 1 and 3 km depth. Three other magnetic profiles (not presented here) across the thrust fault provided results similar to those of profile A3.

Profile I2 (Fig. 10*c*) was modelled in order to investigate the thickness of the Pontiac Group, and the orientation of the contact with underlying rocks to the east of the Lac Frechette complex. Only magnetics were modelled, as gravity data were not available in the area most suitable for 2.5-dimensional models. Although only six samples from the northern margin of the Décelles suite were available, the low magnetic susceptibilities of the samples are typical of collisional granites such as the Décelles suite (ilmenite series granitoids of Ishihara (1981)). Magnetic susceptibilities of the Pontiac Group are an order of magnitude higher than those of the Décelles rocks. However, the magnetic intensity over the outcrop of the Décelles suite is higher than that over the Pontiac Group (Fig. 10*c*). This suggests that higher susceptibility material underlies a relatively thin, low-susceptibility tabular body of granites and pegmatites. The modelled profile indicates two slabs of higher magnetic susceptibility material dipping gently to the north, underlying the Pontiac Group. These results are similar to those obtained for profile A3. The nature of the material underlying the Décelles suite is unknown, as it has not been identified in outcrop.

Seismic reflection

The migrated seismic reflection profile 16A is presented in Fig. 11. In Fig. 11*b*, our interpretations of the profile are overlain as a line drawing on the uninterpreted profile given in Fig. 11*a*. The major structures indicated in Fig. 11*b* are deep within the crust, and do not project to the surface along the profile. However, the good quality of the migrated profile allows a structural interpretation that is consistent with surface structure and with our geophysical modelling of the shallower crust. Profile 16A is typified by generally horizontal to shallowly north-dipping reflectors and packages of reflectors. These are taken to represent the regional layering and cleavage, and possibly some sill-like igneous intrusions. More strongly reflective packages may correspond to rocks of higher density or more pronounced fabric anisotropies or both. By visual inspection of the migrated profile, we have defined domains containing reflectors whose orientations are clearly discordant with those of surrounding domains. These domains are interpreted as being separated by ductile shear zones, which are in some cases imaged as discontinuous in arrow zones of very strong reflectivity (a−a′ and b−b′ in Fig. 11*a*). The higher reflectivity of shear zones could be due to higher seismic anisotropies resulting from a strong degree of lattice-preferred orientation in mylonitic rocks (Siegesmund et al. 1991; Barruol et al. 1992).

Below 8 s in the north and 5.5 s in the south, the crust is strongly reflective and reflectors are horizontal. Above this deeper domain, and separated from it by an apparent structural discontinuity, reflectors generally dip shallowly northward. Discordance between reflectors in these two domains is clearly imaged along the trace of the structural discontinuity at points c, d, and e in Fig. 11*a*, which is interpreted as a smooth-trajectory thrust, with a gently north-dipping ramp linking flats in the north (8 s) and the south (5.5 s). Within the middle crust, there is a complex assemblage of lozenge-shaped domains, resembling the seismic duplexes or ramp-and-flat structure of Sadowiak et al. (1991*a*, 1991*b*). This reflection pattern is interpreted as a smooth-trajectory hinterland-sloping structural duplex, with a roof thrust at 2 s and a floor thrust at 5.5 s. The geometry of the duplex is suggestive of out-of-sequence thrusting, that is, assuming south-directed thrusting consistent with both surface structure and with north-dipping ramps, thrusts that are structurally higher and towards the hinterland are progressively younger. Above the mid-crustal duplex, four shear zones dip gently to the north. These shear zones may represent part of a duplex structure, and appear to be truncated by a flat-lying tabular zone of low reflectivity, which in outcrop corresponds to the monzogranites and pegmatites of the Décelles suite. This may indicate that the emplacement of the large batholith of granites and pegmatites was spatially controlled by the roof thrust of this duplex.

In magnetotelluric modelling of the crust in the Pontiac Subprovince, Kellett et al. (1992) found that the electrical characteristics of the crust defined a broad layering, with a conductive mid-crustal layer between about 12 and 25 km, underlain by a more resistive and anisotropic lower crust. The mid-crustal duplex interpreted in Fig. 11*b* has a roof thrust at about 6 km depth and a floor thrust at about 16 km. It may be that the low-resistivity mid-crustal layer modelled by Kellett et al. (1992) corresponds to a complex structural layer of mid-crustal thrusting.

Synthesis and discussion

Crustal structure and kinematics

From the surface to deep-crustal levels, the northwestern Pontiac Subprovince is typified by north-dipping structures related to thick-skinned and thin-skinned thrusting. Our interpretation of seismic reflection profile 16A includes a mid-crustal duplex at 6−16 km depth, underlain by a deeper thrust at 16−24 km depth, and overlain by thrusts that may be part of another duplex. Profile 16A (Fig. 11) represents a profile through the northern part the Pontiac Subprovince. Further processing, presently being carried out, of profile 16B (the southern extension of 16A), will reveal the crustal structure across the entire subprovince, and allow comparison with other orogenic belts.

Gravity and magnetic model profiles concur, and indicate northward-dipping slabs of different densities and magnetic susceptibilities within the upper few kilometres of the crust, underlying a wedge of Pontiac Group rocks. The modelled thickness of the Pontiac Group is consistent with results of gravity modelling just south of the Cadillac Larder Lake fault zone (Keating 1992).

Surface mapping confirms the southeast-vergent fold-and-thrust structural style documented by van de Walle (1978) and Camiré and Burg (1993). The latter authors defined two distinct nappes, characterized by different structural fabrics (presence of only one cleavage (S_1) in their lower nappe) and by different metamorphic grades (staurolite-in isograd within their lower nappe). However, this interpretation is inconsistent with our observations, which indicate (1) a gradual increase in metamorphic grade from north to south, with the staurolite-in isograd situated farther north than previously

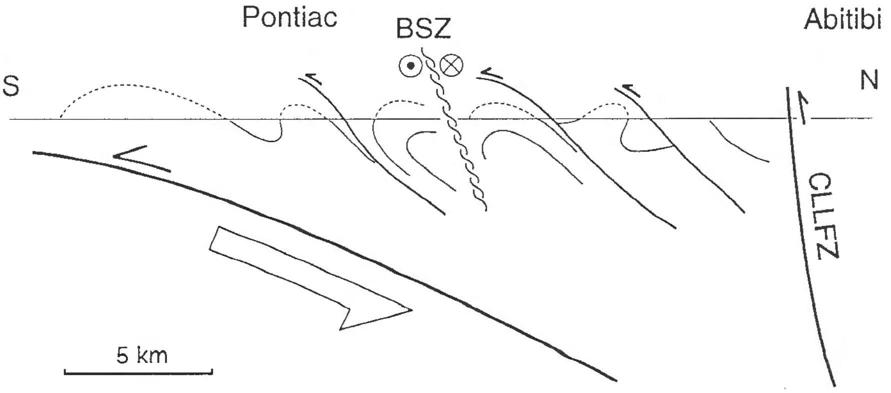

FIG. 12. Schematic structural model of the northwestern Pontiac Subprovince. CLLFZ, Cadillac – Larder Lake fault zone; BSZ, Bellecombe shear zone.

recognized, within the upper nappe defined by Camiré and Burg (1993) and (2) that D_1, D_2, and D_3 structures are all present in the southern part of the mapped area, within their lower nappe. Note that the D_1 and D_2 fabrics in Fig. 6 are found in a sample taken near the southern end of profile A–A′ (Figs. 2, 3).

D_2 and D_3 structures clearly record southeast-vergent thrusting, as deduced from orientations of asymmetric F_2 folds, and from kinematic indicators within thrusts. The very penetrative nature of D_1 fabrics in the Opasatica Gneiss and the Pontiac Group is typical of high-grade F-type nappes present in the internal zones of orogenic belts (Hatcher and Hooper 1992). Based on observations of mesoscale kinematic indicators, we interpret D_1 as recording early, southward nappe transport related to collision, though this interpretation needs to be verified by further study. L_1 stretching lineations would in this case not record the trajectory of nappe transport, but rather flow parallel to hinges of F_1 folds. The steeply dipping Bellecombe and Saint-Roch shear zones may represent oblique ramps, initiated during formation of D_1 nappes.

Any structural model of the northwestern Pontiac Subprovince must reconcile the abundant evidence for thrust tectonics with the lack of evidence for inverted metamorphic gradients (i.e., higher grade rocks emplaced over lower grade rocks). A schematic model is presented in Fig. 12. Underthrusting of the Pontiac Subprovince beneath the Abitibi Subprovince would have resulted in southeastward transport of a large nappe (Pontiac Group and Opasatica Gneiss) on a D_1 thrust (or thrusts) underlying the study area. Throw on D_2 and D_3 thrusts mapped within the study area would be minor and would therefore not result in an obvious inversion of the metamorphic gradient.

Timing of deformation

Timing of D_1-D_3 deformations can be tentatively inferred from published ages of rock units, assuming that the isotopic systems of dated zircons from the Pontiac Group have not been disturbed by metamorphism, and that zircons dated from plutonic rocks record timing of pluton emplacement (i.e., the zircons are not inherited). The youngest published age for detrital zircons samples from the Pontiac Group *within the present study area* is 2694 Ma (D.W. Davis 1992). This may be interpreted as a maximum age for the onset of D_1 in the northwestern part of the Pontiac Subprovince. Younger ages for detrital zircons from the Pontiac Group (2686 Ma, D.W. Davis 1991; 2683 Ma, Mortensen and Card 1993), sampled more than 50 km outside the present study area, overlap with the apparent crystallization age of the Lac Frechette complex (2685 Ma; Mortensen and Card 1993), which was clearly emplaced following the onset of D_1. This may indicate that sedimentation, deformation, metamorphism, and plutonism were diachronous across the Pontiac Subprovince.

Dykes of similar composition to both the Lac Frechette complex and the Décelles suite were deformed in the Bellecombe and the Saint-Roch shear zones. Therefore, deformation in the study area appears to have continued at least until 2668 Ma, corresponding to the oldest published zircon age for pegmatites of the Décelles suite (Mortensen and Card 1993).

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Barruol, G., Mainprice, D., Kern, H., de Saint Blanquat, M., and Compte, P. 1992. 3D seismic study of a ductile shear zone from laboratory and petrofabric data (Saint Bartélémy massif, Northern Pryénées, France). Terra Nova, **4**: 63–76.

Benn, K., Sawyer, E.W., and Bouchez, J.-L. 1992. Orogen parallel and transverse shearing in the Opatica belt, Quebec: implications for the structure of the Abitibi Subprovince. Canadian Journal of Earth Sciences, **29**: 2429–2444.

Broome, J. 1989. MAGRAV2: an interactive magnetics and gravity modelling program for microcomputers version 1.5. Geological Survey of Canada, Open File 1581.

Camiré, G.E., and Burg, J.-P. 1993. Late Archean thrusting in the northwestern Pontiac Subprovince, Canadian Shield. Precambrian Research, **61**: 51–66.

Camiré, G.E., Laflèche, M.R., and Ludden, J.N. 1993. Archean metasedimentary rocks from the northwestern Pontiac Subprovince of the Canadian Shield: chemical characterization, weathering and modelling of the source areas. Precambrian Research, **62**: 285–305.

Chown, E.H., Daigneault, R., Mueller, W., and Mortensen, J.K. 1992. Tectonic evolution of the Northern Volcanic Zone, Abitibi belt, Quebec. Canadian Journal of Earth Sciences, **29**: 2211–2225.

Clowes, R.M., Cook, F.A., Green, A.G., et al. 1992. Lithoprobe: new perspectives on crustal evolution. Canadian Journal of Earth Sciences, **29**: 1813 – 1864.

Davis, D.W. 1991. Age constraints on deposition and provenance of Archean sediments in the southern Abitibi and Pontiac Subprovinces from U – Pb analyses of detrital zircons. Abstracts, Geological Association of Canada Annual Meeting, Toronto, p. A-29.

Davis, D.W. 1992. Age constraints on deposition and provenance of Archean sediments in the southern Abitibi and Pontiac Subprovinces from U – Pb analyses of detrital zircons. Lithoprobe Abitibi – Grenville Transect, Report 25, pp. 147 – 150.

Davis, W.J., Machado, N., Gariépy, C., Sawyer, E., and Benn, K. 1993. U – Pb geochronology of the Opatica Belt metaplutonic-gneiss belt, Québec and its relationship to the northern Abitibi. Abstracts, Geological Association of Canada Annual Meeting, Edmonton, p. A-22.

Dimroth, E., Imreh, L., Rocheleau, M., and Goulet, N. 1982. Evolution of the south-central part of the Archean Abitibi Belt, Quebec. Part I: Stratigraphy and paleogeographic model. Canadian Journal of Earth Sciences, **19**: 1729 – 1758.

Dimroth, E., Imreh, L., Goulet, N., and Rocheleau, M. 1983*a*. Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part II. Tectonic evolution and geomechanical model. Canadian Journal of Earth Sciences, **20**: 1355 – 1373.

Dimroth, E., Imreh, L., Goulet, N., and Rocheleau, M. 1983*b*. Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part III: Plutonic and metamorphic evolution and geotectonic model. Canadian Journal of Earth Sciences, **20**: 1374 – 1388.

Feng, R., and Kerrich, R. 1991. Single zircon age constraints on the tectonic juxtaposition of the Archean Abitibi greenstone belt and Pontiac subprovince, Quebec, Canada. Geochimica et Cosmochimica Acta, **55**: 3437 – 3441.

Gariépy, C., Allègre, C.J., and Lajoie, J. 1984. U – Pb systematics in single zircons from the Pontiac sediments, Abitibi greenstone belt. Canadian Journal of Earth Sciences, **21**: 1296 – 1304.

Gariépy, C., Verner, D., and Doig, R. 1990. Dating Archean metamorphic minerals southeast of the Grenville front, western Quebec, using Pb isotopes. Geology, **18**: 1078 – 1081.

Hatcher, R.D., and Hooper, R.J. 1992. Evolution of crystalline thrust sheets in the internal parts of mountain chains. *In* Thrust tectonics. *Edited by* K.R. McClay. Chapman and Hall, London, pp. 217 – 233.

Hocq, M. 1989. Carte lithotectonique des sous-provinces de l'Abitibi et du Pontiac. Ministère de l'Énergie et des Ressources du Québec, DV 89-04.

Hubert, C., Trudel, P., and Gélinas, L. 1984. Archean wrench fault tectonics and structural evolution of the Blake River Group, Abitibi Belt, Quebec. Canadian Journal of Earth Sciences, **21**: 1024 – 1032.

Ishihara, S. 1981. The granitoid series and mineralization. Economic Geology, **75**: 458 – 484.

Jackson, S.L., and Fyon, J.A. 1991. The western Abitibi Subprovince in Ontario. *In* Geology of Ontario. *Edited by* P.C. Thurston, H.R. Williams, R.H. Sutcliffe, and G.M. Stott. Ontario Geological Survey, Special Volume 4, Part 1, pp. 405 – 482.

Jolly, W.T. 1978. Metamorphic history of the Archean Abitibi Belt. *In* Metamorphism in the Canadian Shield. *Edited by* J.A. Fraser and W.W. Heywood. Geological Survey of Canada, Paper 78-10, pp. 63 – 78.

Keating, P. 1992. Interpretation of the gravity anomaly field in the Noranda – Val d'Or region, Abitibi Greenstone Belt, Canadian Shield. Canadian Journal of Earth Sciences, **29**: 962 – 971.

Kellett, R.L., Mareschal, M., and Kurtz, R.D. 1992. A model of lower crustal electrical anisotropy for the Pontiac Subprovince of the Canadian Shield. Geophysical Journal International, **111**: 141 – 150.

Kerrich, R., and Feng, R. 1992. Archean geodynamics and the Abitibi – Pontiac collision: implications for advection of fluids at transpressive collisional boundaries and the origin of giant quartz vein systems. Earth-Science Reviews, **32**: 33 – 60.

Lajoie, J., and Ludden, J. 1984. Petrology of the Archean Pontiac and Kewagama sediments and implications for the stratigraphy of the southern Abitibi belt. Canadian Journal of Earth Sciences, **21**: 1305 – 1314.

Ludden, J., Hubert, C., and Gariépy, C. 1986. The tectonic evolution of the Abitibi greenstone belt of Canada. Geological Magazine, **123**: 153 – 166.

Machado, N., Gariépy, C., Philippe, S., and David, J. 1991. Géochronologie U – Pb du territoire québecois: fosses du Labrador et de l'Ungava et sous-province du Pontiac. Ministère de l'Énergie et des Ressources du Quebec, Rapport interimaire MB 91-07.

Mortensen, J.K., and Card, K.D. 1993. U – Pb age constraints for the magmatic and tectonic evolution of the Pontiac Subprovince, Quebec. Canadian Journal of Earth Science, **30**: 1970 – 1980.

Rive, M., Pintson, H., and Ludden, J.N. 1990. Characteristics of late Archean plutonic rocks from the Abitibi and Pontiac Subprovinces, Superior Province, Canada. *In* The northwestern Quebec polymetallic belt: a summary of 60 years of mining exploration. *Edited by* M. Rive, P. Verpaelst, Y. Gagnon, et al. Canadian Institute of Mining, Special Volume 43, pp. 65 – 91.

Robert, F. 1989. Internal structure of the Canadian tectonic zone southeast of Val d'Or, Abitibi greenstone belt, Quebec, Canadian Journal of Earth Sciences, **26**: 2661 – 2675.

Sadowiak, P., Wever, T., and Meissner, R. 1991*a*. Deep seismic reflectivity patterns in specific tectonic units of Western and Central Europe. Geophysical Journal International, **105**: 45 – 54.

Sadowiak, P., Meissner, R., and Brown, L. 1991*b*. Seismic reflectivity patterns: comparative investigations of Europe and North America. *In* Continental lithosphere: deep seismic reflections. *Edited by* R. Meissner, L. Brown, H.-J. Dürbaum, W. Franke, K. Fuchs, and F. Seifert. American Geophysical Union, Geodynamics Series, Vol. 22, pp. 363 – 369.

Sawyer, E.W., and Benn, K. 1993. Structure of the high-grade Opatica belt and the adjacent low-grade Abitibi Subprovince: An Archean mountain front. Journal of Structural Geology, **15**: 1443 – 1458.

Siegesmund, S., Fritzsche, M., and Braun, G. 1991. Reflectivity caused by texture-induced anisotropy in mylonites. *In* Continental lithosphere: deep seismic reflections. *Edited by* R. Miessner et al. American Geophysical Union, Geodynamics Series, Vol. 22, pp. 291 – 298.

van de Walle, M. 1978. Canton de Montbeillard. Ministère de l'Énergie et des Ressources du Quebec, Rapport géologique 188.

Williams, P.F. 1990. Differentiated layering in metamorphic rocks. Earth-Science Reviews, **29**: 267 – 281.