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New interpretations of industry seismic lines, southern Quebec Appalachians foreland[1]

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Séjourné, S., Dietrich, J.R., and Malo, M., 2002: New interpretations of industry seismic lines, southern Quebec Appalachians foreland; Geological Survey of Canada, Current Research 2002-D1, 10 p.

Abstract: Reprocessing and reinterpretation of sixteen industry seismic lines (Shell-Société Québecoise d'Initiatives Pétrolières, BHP, and Bow Valley) located south of Drummondville provide new information on the tectonic history and the stratigraphy of southern Quebec Appalachians structural front. Preliminary results show that the typical structural style of the parautochthonous domain is one of long décollements involving the platform strata from (?)Potsdam to Trenton groups. Some synsedimentary, basement-involved normal faults were active during the deposition of the Utica Shale. Those normal faults often control the location of the Taconian décollement ramps. A limestone unit at the base of the Potsdam Group is also clearly recognized on most of the lines.

Résumé : Un nouveau traitement et la réinterprétation de seize profils sismiques provenant de l'industrie (Shell-Société québécoise d'initiatives pétrolières, BHP, Bow Valley) et localisés au sud de Drummondville apportent de nouvelles informations sur l'évolution tectonique et la stratigraphie du front structural des Appalaches du sud du Québec. Les résultats préliminaires indiquent que le style structural caractéristique du domaine parautochtone consiste en de longs décollements impliquant les roches de la plate-forme, depuis le Groupe de Potsdam(?) jusqu'au Groupe de Trenton. Certaines failles normales synsédimentaires, enracinées dans le socle grenvillien, étaient actives pendant le dépôt du Shale d'Utica. Ces failles normales exercent souvent un contrôle sur l'emplacement des rampes des décollements taconiens. Une unité de calcaire à la base du Groupe de Potsdam est également clairement visible dans la plupart des profils.

[1] Contribution to Appalachian Foreland and Platform NATMAP

INTRODUCTION

Despite a good understanding of the general tectonic style in the southern Quebec Appalachians (St-Julien and Hubert, 1975; Colpron et al., 1992; Tremblay and Pinet, 1994; Chalaron and Malo, 1998; Castonguay, 2000), little is known about the tectonic expression of this orogen in its most external part, along the structural front. In particular, few studies are available to document the occurrence and structural styles of carbonate slices within this zone (Beaupré, 1975; Prichonnet and Raynal, 1977; Paradis and Faure, 1994; Séjourné, 2000; Séjourné and Malo, 2001). Such studies are mostly restricted to the surface geology of a single tectonic slice. A regional scale seismic interpretation is clearly needed to improve our understanding of the structural front in the southern Quebec Appalachians. In the scheme of the Appalachian Foreland and Platform NATMAP project, reprocessing and re-interpretation of industry and public seismic lines north of Drummondville (Fig. 1) have been recently undertaken by the Geological Survey of Canada (GSC) and the Ministère des Ressources Naturelles du Québec (MRNQ). Industry seismic lines south of Drummondville are also currently being analyzed by the GSC and the Institut National de la Recherche Scientifique (INRS-Eau Terre Environnement). Such interpretations help to document the geometry and the structural style of the southern Quebec Appalachians structural front, and also provide the link between studies north of Drummondville (Laroche, 1983; St-Julien et al., 1983; Dietrich et al., 2001; Castonguay et al., 2001) and south of the international border (e.g. Ando et al., 1984).

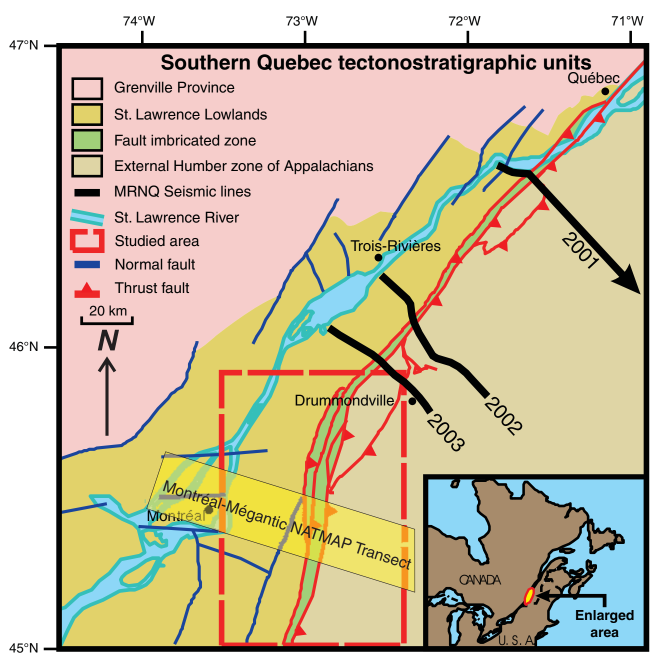

Figure 1. Map of main tectonostratigraphic units of southern Quebec, with location of the study area and Ministère des Ressources Naturelles du Québec seismic lines. Figure adapted from Héroux and Bertrand (1991).

REGIONAL GEOLOGICAL SETTING

The area under study (Fig. 1, 2) stretches from Drummondville to the Vermont, U.S.A. border and covers three distinct tectonistratigraphic domains separated by two north-trending major fault zones. From west to east, they are the autochthonous, the parautochthonous, and the allochthonous domains. The autochthonous domain consists of Upper Cambrian to Upper Ordovician St. Lawrence Platform strata (Potsdam to Trenton groups, Fig. 3) disconformably overlying Grenvillian basement rocks, and foreland basin strata (Utica Shale, Sainte-Rosalie and Queenston groups, Fig. 3). This domain has been affected by normal faults and by an open regional fold, the Chambly–Fortierville syncline, and is separated from the parautochthonous domain by the Aston and Saint-Barnabé faults (Fig. 2). The parautochthonous domain is composed of fault-imbricated carbonate rocks of the platform and of Upper Ordovician siliciclastic rocks of

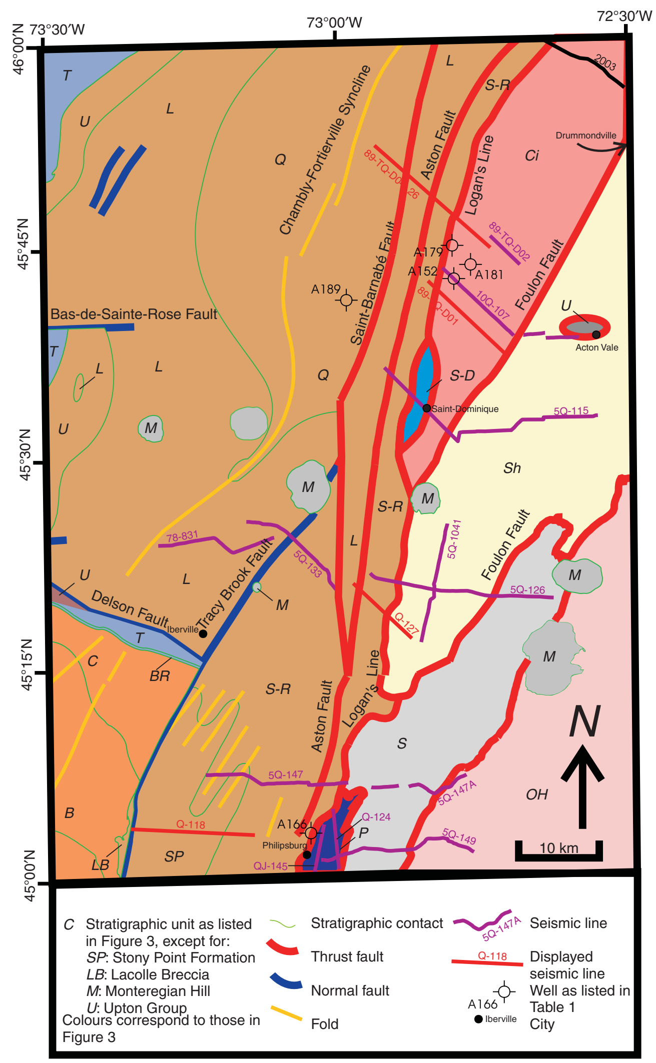

Figure 2. Simplified geological map of the study area with location of seismic lines and wells. See *Table 1 for legend of lines and wells. Figure adapted from Globensky (1987).*

the foreland basin (the Sainte-Rosalie and the Lorraine groups, Fig. 3). The allochthonous domain consists essentially of Lower Cambrian to Upper Ordovician basinal rocks and of minor Upper Cambrian to Middle Ordovician platform strata. It structurally overlies the parautochthonous domain along Logan's Line (Fig. 3), which defines an important stratigraphic and tectonic contrast.

Normal faults affecting the Grenvillian basement and the autochthonous domain are considered to be related to the Late Neoproterozoic to Early Cambrian Iapetus rift system

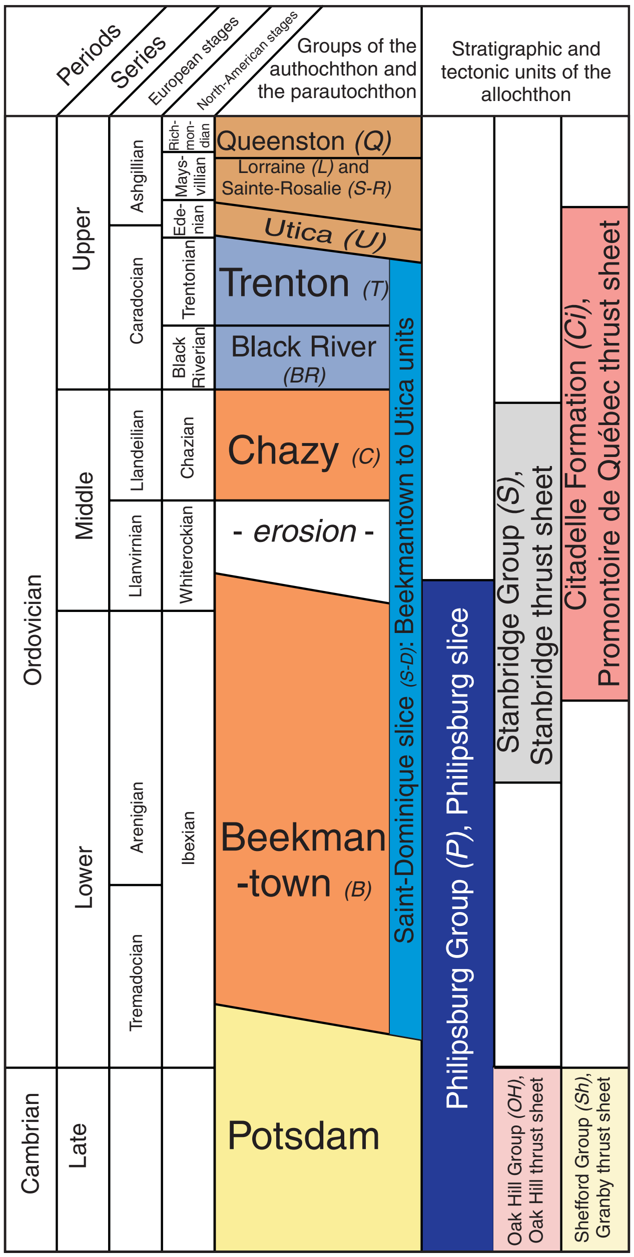

Figure 3. *Schematic stratigraphic column of the St. Lawrence Platform strata and allochthonous units of the study area. The bracketed letters refer to Figure 2. Figure adapted from Lavoie (1994).*

(St.-Julien and Hubert, 1975) and have probably been reactivated as synsedimentary normal faults during the deposition of St. Lawrence Platform strata (Lavoie, 1994) and/or during the lithospheric flexure due to loading of Appalachian thrust sheets (Chalaron and Malo 1998). Based on initial interpretations of regional seismic reflection (Laroche, 1983; St-Julien et al., 1983), Bradley and Kusky (1986) recognized an increase in the offset of the normal faults towards the hinterland. They interpreted this increase as a progressive reactivation of the normal faults during emplacement of the Taconian thrust sheets (i.e. the allochthons), during the Middle to Late Ordovician Taconic Orogeny (St-Julien and Hubert, 1975; Tremblay and Pinet, 1994). The superimposition of Taconian compressive features onto the long-lived basement-involved normal faults created the complex and unique geometry of the southern Quebec Appalachians structural front. This geometry has not been investigated in the past due to poor exposure. Reprocessed industry seismic lines are used to give new insight into the geometry of this part of the orogen.

PREVIOUS SEISMIC STUDIES

The first public seismic reflection surveys to be carried out in southern Quebec were three long seismic lines (a total of 270 km) recorded for the Ministère des Ressources Naturelles du Québec in 1978: lines 2001, 2002, and 2003 (Fig. 1). Laroche (1983) and St-Julien et al. (1983) have initially interpreted the first line, but the interpretation of the other two lines has never been published. Recently, the GSC reprocessed these three lines, and reinterpretation of line 2001 has already been published (Dietrich et al., 2001; Castonguay et al., 2001). Preliminary results of this ongoing study have showed that folds and thrusts are present in the autochthonous domain, and that the tectonic style of the parautochthonous domain is characterized by thrust duplexes, tectonic wedges, and décollements.

Following the initial publication of line 2001, two subsurface structure maps (top of Grenvillian basement and top of the autochthonous Trenton Group) were published for the autochthonous domain (Société Québecoise d'Initiatives Pétrolières, 1982, 1984); however, a more detailed analysis of the tectonic style of the covered area is precluded by three major limitations: 1) the subsurface structural maps are displayed in two-way traveltime and no velocity information is provided; 2) maps only show the basement and autochthonous strata geometry, there is no data in the parautochthonous nor in the allochthonous domains; 3) maps are based on old (1960s and 1970s vintage) data and concepts.

Several industry companies (Bow Valley, Vibra, BHP) have completed more recent seismic surveys in the 1980s and 1990s. Although the BHP lines are now in the public domain, the other data sets remain confidential and none of those lines have been published yet. The present study is the first attempt to reinterpret and publish some of the BHP and Bow Valley lines. Part of the Vibra data set is discussed in Morin (2000a).

CURRENT WORK AND SEISMIC REPROCESSING

The sixteen seismic lines acquired for this study are from three surveys of various quality and age (Table 1): Shell-Société Québecoise d'Initiatives Pétrolières, BHP, and Bow-Valley data sets. The reprocessing (Table 1) and reinterpretation were conducted with Promax^{TM} and Geoframe software. A few wells are available to support the study, but only one well (well A152, Table 1) provides a directly tie to a seismic line (line 10Q-107).

The post-stack reprocessing of the Shell-Société Québecoise d'Initiatives Pétrolières and BHP lines has included testing and application of FX deconvolution and signal enhancement (dipscan) filters, followed by (Kirchoff) time migrations using available stacking velocity information. The filtering and migration have significantly improved seismic image quality in all lines.

This paper summarizes preliminary results and is essentially focused on the interpretation of seismic events. The integration of the results with synthetic seismograms constructed with GMA Plus software and the interpretation of SOQUIP maps (Société Québecoise d'Initiatives Pétrolières 1982, 1984) will be discussed elsewhere.

SEISMIC EXPRESSION OF MAIN STRATIGRAPHIC UNITS

Autochthonous domain

Despite the lack of sufficient tied well data, it is possible to recognize the general stratigraphic framework of the autochthonous domain on the studied lines by along-strike correlation with other seismic data sets.

Near-surface autochthonous strata present on the studied lines are the siliciclastic assemblages of the Queenston and Lorraine groups and the more shaly units of the Utica Shale, Sainte-Rosalie Group, and Stony Point Formation. Rocks of these units are essentially argillaceous and show little, if any, resistivity contrasts. They appear as a weakly reflective, homogeneous area (area a, Fig. 4a), making the main sedimentological units and the dominant structural style difficult to recognize in the absence of well data. Immediately below this area, the contact between the Utica Shale and the highly reflective shaly limestone of the Trenton Group is underlain by a series of three high-amplitude reflections (area b, Fig. 4a). Below this interval the reflections diminish in amplitude and neither the formations of the Trenton Group nor the transition with the Black River Group are seismically visible (area c, Fig. 4a). A second package of three high-amplitude reflections underlying this zone of low-amplitude events (area d, Fig. 4a) corresponds to the highly reflective Chazy Group and to the top of the Beekmantown Group. The sequence of low- and high-amplitude reflections is a distinctive seismic characteristic of the autochthonous domain. The lowest units, the base of the Beekmantown Group and the Potsdam Group generally show little resistivity contrasts (area e, Fig. 4a) and are difficult to recognize from the discontinuous and variable amplitude reflections of the Grenvillian basement (area g, Fig. 4a). On the studied lines, however, a third series of high-amplitude reflectors appears at the base of the autochthonous sedimentary units, disconformably overlapping the Grenvillian basement reflections (area f, Fig. 4a). The only well drilled down to the Potsdam Group in the study area, 'Shell Saint-Armand ouest No 1' (A166, Fig. 2) cuts across limestone strata at the base of the Potsdam Group. Similar calcareous units have been recognized at the base of the Potsdam Group on geophysical logs from thirteen wells (Morin, 2000b) and have been described recently on core sections within the Potsdam Group (Salad Hersi and Lavoie, 2000).

Table 1. Studied seismic lines with data and reprocessing information. The listed lines and wells are located on Figure 2.

Lines data							Processing and reprocessing				
Name	Owner	Date	Source	Quality	Length in km	Wells with geophysics on the same fault bloc (*)	Final Stack	DipScan	FX-Deconvolution	KT Migration	Reprocessing laboratory
5Q-149	Shell-Soquip	n. d.	Vibroseis	Bad	21.6		YES	YES	YES	YES	GSC-Calgary
5Q-147		1970		Medium	19.5	A166	YES	YES	YES	YES	GSC-Calgary
5Q-147A		1970		Medium	12.5	A166	YES	YES	YES	YES	GSC-Calgary
78-831		n. d.		Fair	16.4		YES	YES	YES	YES	GSC-Calgary
5Q-133		n. d.		Fair	16.5		YES	YES	YES	YES	GSC-Calgary
5Q-126		1969		Bad	24.7		YES	YES	YES	YES	GSC-Calgary
5Q-1041		n. d.		Medium	16.2		YES				
5Q-115		1969		Bad	34.0	A152 - A179	YES	YES	YES	YES	GSC-Calgary
10Q-107		1968		Medium	20.2	A152 - A179 - A181	YES	YES	YES	YES	GSC-Calgary
89-TQ-D04_D26	Bow Valley	n. d.		Excellent	20.4	A181 - A189				YES	
89-TQ-D01		n. d.		Excellent	14.0	A152 - A179 - A181				YES	
89-TQ-D02		n. d.		Excellent	5.5	A181				YES	
Q-127	BHP	1990		Excellent	10.6		YES			YES	GSC-Calgary
Q-118		1990		Excellent	16.9		YES			YES	GSC-Calgary
Q-124		1990		Excellent	8.0	A166	YES			YES	
QJ-145		1990		Excellent	6.8	A166	YES				

(*) Legend of the wells: A152: Shell, Saint-Simon No 1; A166: Shell, Saint-Armand ouest No 1; A179: SOQUIP et al., Saint-Hugues No 1; A181: SOQUIP et al., Sainte-Hélène No 1; A189: SOQUIP, Saint-Thomas-d'Aquin No 1

The highly reflective strata at the base of the Potsdam Group on line Q-118 (area f, Fig. 4a) are interpreted as the expression of the limestone unit described in the nearby ‘Shell Saint-Armand ouest No 1’ well. The same basal reflections are also recognized in most of the other BHP and Bow Valley lines south of Drummondville. It is therefore suggested that the limestone strata at the base of the Potsdam Group form a widespread unit that can be recognized and followed in most of the area south of Drummondville.

It should be emphasized that the interval velocities vary considerably in the autochthonous domain, especially when comparing the velocities in the shallower shaly units with those in the deeper and more competent sandstone, limestone, and dolostone strata. No attempt has been made yet to generate depth profiles from the seismic time sections. As a general rule, however, the shallower shaly units will tend to appear thicker than they actually are, while the deeper and more competent units will tend to appear thinner.

Parautochthonous and allochthonous domains

In the absence of tied well data, establishing with accuracy the stratigraphy of the parautochthonous and allochthonous domains from seismic data is difficult; however, the high-amplitude reflections of the Beekmantown and Trenton groups as well as the limestone unit at the base of the Potsdam Group can easily be distinguished from the flysch units (the Utica Shale and the Sainte-Sabine, Iberville, and Stony Point formations). To a certain extent, it is possible to recognize individual tectonic slices within the parautochthonous domain, provided they involve reflective strata (lines Q-127, 89-TQ-D01, and 89-TQ-D04_26). The base and roof of the thrust sheets, however, cannot be drawn with precision since the shaly flysch units and most of the Potsdam Group rocks, as well as décollement planes between high-amplitude reflection zones are not clear on the seismic sections.

Generally, the allochthonous domain does not display conspicuous reflector events when compared with the neighbouring parautochthonous domain (e.g. lines 89-TQ-D01, 89-TQ-D04_26). This may be due to the low acoustic impedance contrasts between the allocthons and parautochthonous strata in the footwall of Logan’s Line.

STRUCTURAL STYLE

Extensional structures

The seismic data clearly show that the main tectonic features in the autochthonous domain are the normal faults that root from the Grenvillian basement and cut across all the strata up to the Trenton Group. Some faults also propagate into the Utica Shale and into the laterally equivalent flysch of the

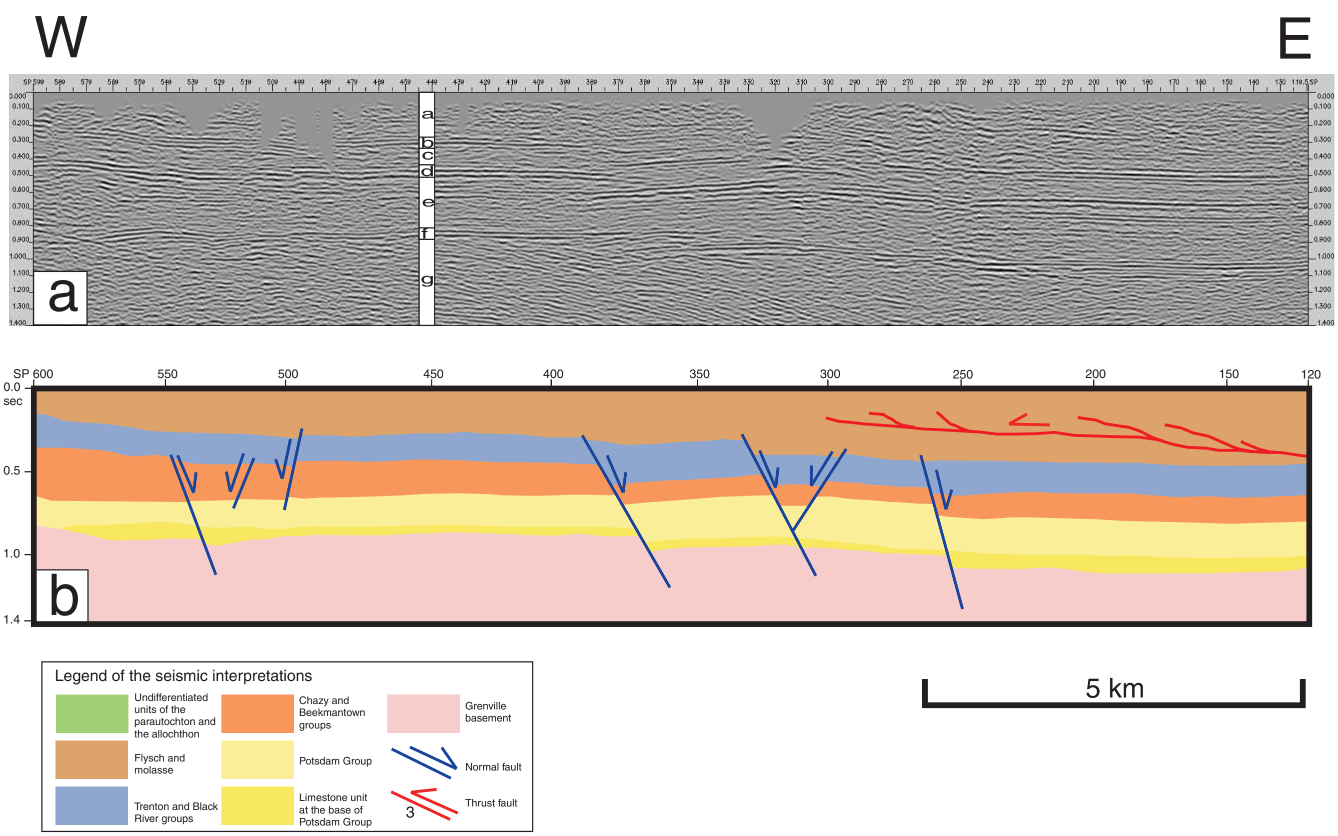

***Figure 4. a)** Seismic line Q-118 and **b)** proposed structural interpretation. Areas a to g are discussed in the text.*

Sainte-Sabine Formation (line Q-118), clearly demonstrating that the foreland basin strata deposited in front of the thrust sheets were affected by synsedimentary normal faults during the Late Ordovician Taconic Orogeny.

The increase in the offset of the normal faults towards the hinterland, recognized on line 2001 by Bradley and Kusky (1986), is also visible in many of the lines of the present study. Most of the normal faults dip towards the east or the southeast, which is consistent with the SOQUIP maps (Société Québecoise d'Initiatives Pétrolières, 1982, 1984) and initial interpretations of line 2001 (Laroche, 1983, St-Julien et al., 1983); however, many normal faults dipping towards the west or the northwest are also recognized on the Bow Valley and BHP lines (Fig. 4, 5, 6, 7). These faults are generally located in the hanging wall of east- or southeast-dipping normal faults to form graben structures. Clearly, there are more west- and northwest-dipping normal faults affecting the Grenvillian basement and the autochthonous strata than described from the initial interpretations of line 2001. The simple and commonly illustrated half-graben geometry should therefore be revised to a structural setting of large-scale half-grabens and smaller-scale horst-and-graben features.

Basement-involved compressional structures

At a first glance, apparent reverse faults involving the basement and directed either towards the structural front or the hinterland are visible on almost all the stack seismic sections and many migrated sections (Fig. 5a). These features, have never been described either on the SOQUIP maps (Société Québecoise d'Initiatives Pétrolières, 1982, 1984), or on initial interpretation of line 2001 before its reprocessing. Most of these overlap reflection features seem to involve the Grenvillian basement and the autochthonous strata up to the Trenton Group (Fig. 5a).

Such features are often interpreted as seismic diffractions or imaging artefacts, often corrected with proper migration parameters (the irregularities along a normal fault plane being generally the inferred cause of the aberrations). These apparent 'basement involved' compressive features are widespread across the study area and throughout surveys of various age, quality, and reprocessing parameters, and are also recognized in the reprocessed line 2001 (Dietrich et al., 2001). Consequently, the assumption of an artefact is difficult to sustain without further analysis.

The migrated version of line Q-127 has been chosen to illustrate the back-thrust features (Fig. 5). The strong overlap of some reflectors of this line might be due to major, basement-involved, hinterland-directed thrusts as expressed on Figure 5a; however, this compressive model raises major geometrical and mechanical problems. An alternative normal faulting model might be seen as the most simple and realistic (Fig. 5b) provided that the overlap features are interpreted as artefacts of reflection smearing around the faults. Such a smearing is more prone to develop when the fault plane is irregular or close to another major fault plane.

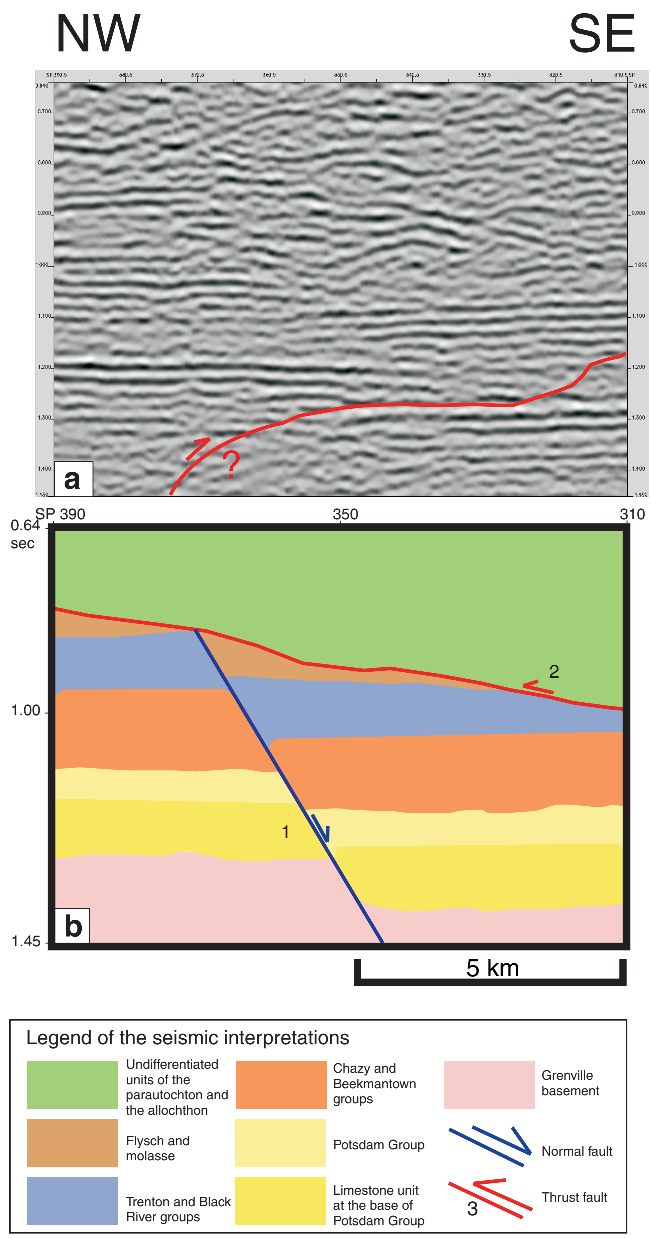

***Figure 5. a)** Part of seismic line Q-127, showing unusual overlap of near-horizontal reflectors at fault zones and possible thrust fault interpretation of the reflection patterns. **b)** Possible interpretation involving extensional faulting.*

The most realistic current interpretation for the thrust and back-thrust features involving the Grenvillian basement rocks is to consider them as artefacts associated with reflection smearing across fault planes. Further analysis of the SOQUIP structure maps (Société Québecoise d'Initiatives Pétrolières, 1982, 1984), new migration reprocessing of select seismic lines, and seismic modelling (all in progress) may add new insights into the evaluation of the thrust and back-thrust features.

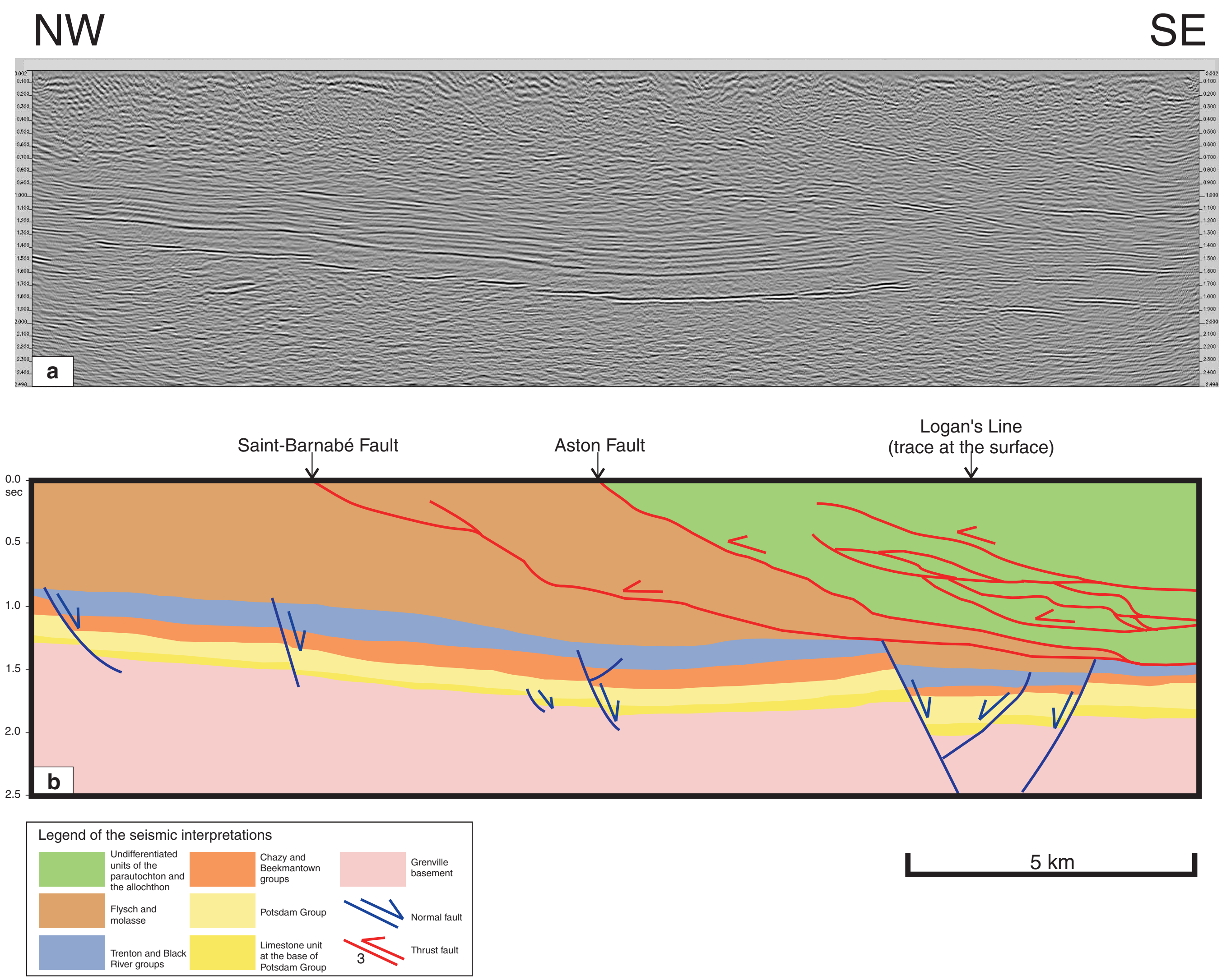

***Figure 6. a)** Seismic line 89-TQ-D04_D26 and **b)** proposed structural interpretation.*

Compressional structures

The main tectonic feature visible at the surface in the autochthonous domain, the Chambly-Fortierville regional syncline, is not recognized in the subsurface. The most western part of line 89-TQ-D04_D26 (Fig. 2), west of the Saint-Barnabé Fault, is located in the eastern limb of this syncline. At depth, however, the reflectors of the autochthonous Potsdam and Beekmantown groups are clearly tilted towards the hinterland (Fig. 6b). Since no contrasting reflector can be recognized and followed in the shallower flysch and molasse units, the apparent absence of the syncline on line 89-TQ-D04_D26 can have two alternative explanations. 1) The migration section may not properly image the low-angle dip of the eastern limb, located at the edge of the seismic section. A comparison with migrated seismic lines centred on the hinge line of the syncline might help to answer this postulate. 2) The Chambly–Fortierville syncline, despite its regional character, might be limited to the shallowest units of the autochthonous domain. This alternative explanation would imply the existence of a tectonic wedge at the base of the eastern limb of the syncline. Such a structure would be very similar to the triangle zone that marks the transition between the foothills of the Canadian Rocky Mountains (parautochthonous domain) and the autochthonous domain of the southern Rocky Mountains, but that has never been documented yet in the southern Quebec Appalachians structural front and is not visible on line 89-TQ-D04_D26.

Line 89-TQ-D04_26 (Fig. 6) shows the Aston and Saint-Barnabé faults (Fig. 1, 2) rooting into bedding-parallel décollements. On this line, the Saint-Barnabé Fault marks the western limit of the parautochthonous domain, which is in a good agreement with the surface geology data (Globensky, 1987). Farther to the south, the subsurface western limit of the parautochthonous domain appears to extend west of the Aston Fault, as shallow blind thrusts that propagate through the Sainte-Sabine and Iberville formations are visible on line

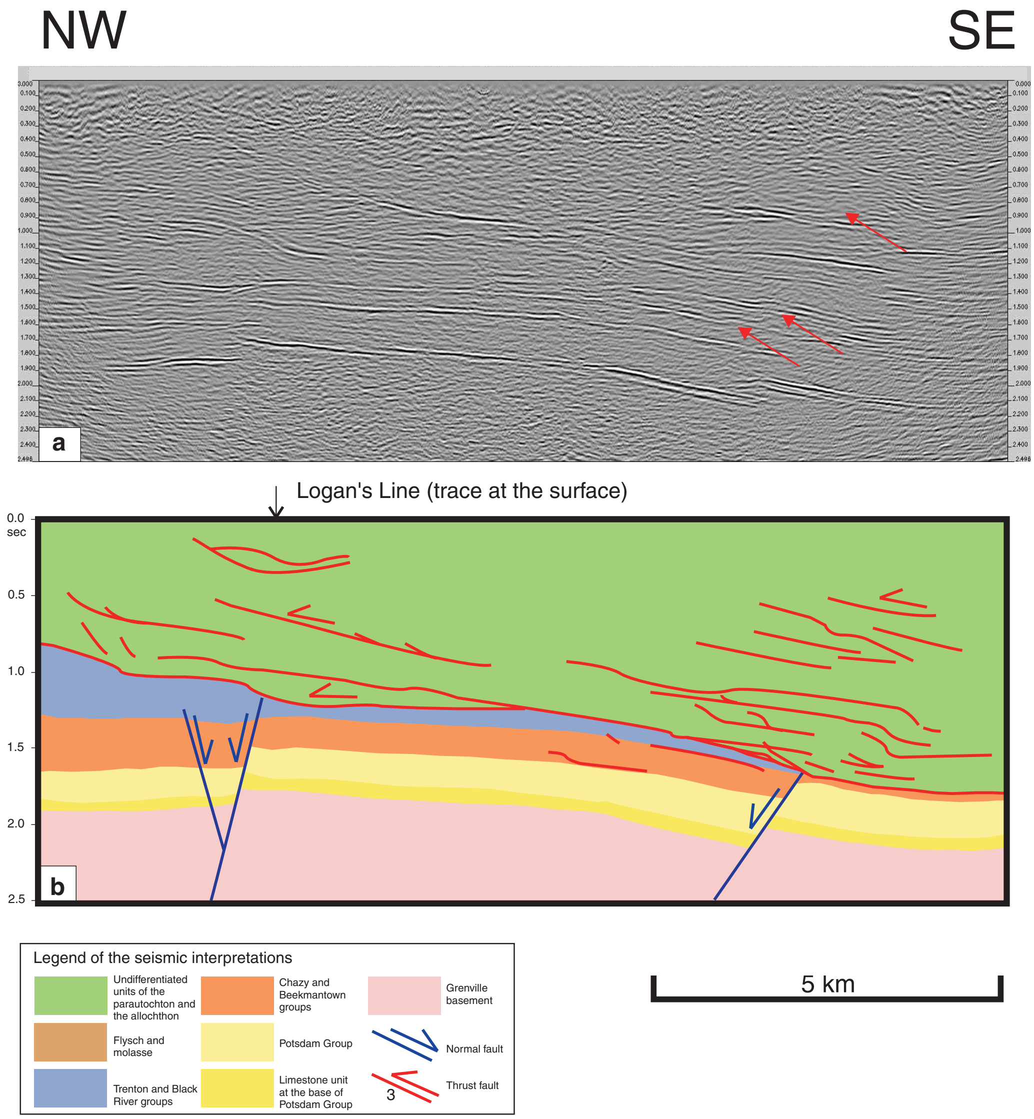

***Figure 7. a)** Seismic line 89-TQ-D01 and **b)** proposed structural interpretation. Arrows point towards fault-propagation folds.*

Q-118 (Fig. 4). These thrusts are expressed at the surface by north-northeast-trending folds (Fig. 1, 2). It is therefore stated that the actual southwestern extent of the parautochthonous domain is located at depth west of the Aston Fault.

The dominant structural style of the parautochthonous domain is the presence of long décollement planes (Fig. 4, 6, 7). Where the tip line of the décollement is recognizable, it is generally expressed as a fault-propagation fold (arrows, Fig. 7a). A few short tectonic slices are also stacked in duplexes dipping toward the hinterland. Where a crosscutting relationship is visible, the thrusts always postdate and cut across the normal faults described above (Fig. 7).

The major normal faults exerted a strong control on the thrust ramp locations, especially where the shallower shaly units of the hanging wall are in contact with the deeper and more competent dolostone and limestone units of the footwall. In such a case, the footwall had a buttressing effect on the shale units of the hanging wall as Taconian thrusts developed. As décollements tip lines approached the normal fault planes, ramps developed in order to bypass the competent footwall rocks (Fig. 5).

CONCLUSIONS

Despite the limited well data, which precludes any precise recognition of the regional stratigraphy of the parautochthonous and allochthonous domains, the studied seismic lines have provided many valuable insights into the tectonic style of the southern Quebec Appalachians structural front.

Some key observations are listed below.

A limestone unit at the base of the Potsdam Group is clearly expressed by high-amplitude reflections in the seismic lines south of Drummondville.

Many normal faults are recognized in the autochthonous domain. Most of them dip towards the hinterland, although some conjugate normal faults dipping to the west or the northwest are present, initiating a horst-and-graben pattern that contrasts with the half-graben pattern conventionally described.

The major normal faults dipping toward the hinterland always involve the Grenvillian basement, and often propagate through all the platform strata up to the Trenton Group.

Some basement-involved normal faults also propagate into the flysch units, which means they have been activated or reactivated as normal faults during or immediately after the deposition of those rocks. Therefore, synsedimentary normal faults may have propagated through the foreland basin strata while thrust faults were developing at the Taconian structural front.

Basement-involved thrusts and back-thrust features that are visible on many seismic lines are interpreted as reflection artefacts developed along normal fault planes. Ongoing studies may provide further information on these features.

The typical structural style of the parautochthonous domain as seen at depth is one of long décollements involving the platform strata from (?)Potsdam to Trenton groups, with few imaged ramp structures. The tip line of those décollements often ends in a fault-propagation fold. Less often, the tectonic slices are short and stacked in a duplex dipping toward the hinterland.

The location of the major normal faults in the autochthonous domain strongly controlled the location of the Taconian décollement ramps. As the faults placed the shallower and weaker shaly units of the hanging wall in contact with the more competent units of the footwall, the competent footwall block acted as a buttress when thrusts propagated through the shale.

The superimposition of two different structural styles, the long-lived normal faults and the Taconian thrusts, created a complex and unique geometry that is characteristic of the structural front of the southern Quebec Appalachians.

Further work is needed on the structural interpretation of the studied lines, especially in the parautochthonous domain, and more lines will be integrated into this study. Of particular interest is the identification of the stratigraphy, an aim that could be partly achieved through the construction of synthetic seismograms. The results of this study will be compared with the ongoing reinterpretation of seismic lines 2001, 2002 and 2003 currently done by the GSC. The comparison with detailed surface geology studies in the parautochthonous domain (in progress) will also add to the subsurface interpretations.

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