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Crustal-scale reflection seismic investigations in the Bathurst Mining Camp, New Brunswick, Canada

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ABSTRACT

The Bathurst Mining Camp, northern New Brunswick, Canada contains the super giant Brunswick No. 12 massive sulphide deposit and the smaller, now abandoned, Brunswick No. 6 deposit. Discoveries of additional base metal deposits in the camp require a better understanding of geological structures at depth. To this end, reflection seismic data in the Brunswick No. 6 area were acquired along three 2D profiles in 1999, with a total length of about 30 km. We have recovered, processed and interpreted these seismic data in conjunction with petrophysical and geological data from the study area. The seismic data and the borehole geophysical data allow a better understanding of both the shallow and deep structures (to 9 km depth) in the area. The seismic data show steeply dipping structures of the Brunswick No. 6 area, many of which reach the surface and allow for correlation with the surface and borehole geological information. Finite-difference modeling of major geological formations constrained with borehole petrophysical measurements indicates good correlation between the observed seismic and the synthetic data. A sequence of seismically reflective and transparent zones indicates a thrust stack in the Brunswick No. 6 area. The contact between the reflective and transparent zones is a series of faults bringing the two units over each other. A reflective package is observed in all three profiles and correlates well with the Brunswick horizon, the key mineralized zone in the study area. The Brunswick horizon extends down to depth greater than 3 km, increasing the hope for discovery of deeper base metal deposits. Two other sets of reflections are also observed in all three profiles in the depth range of about 5–8 km. We interpret them as two sets of thrusted sheets, which could be an indication that the Brunswick belt extends down to a maximum depth of 8 km.

1. Introduction

It is widely accepted that the future in mining and mineral exploration in established mining camps lies at deeper levels (>1000 m) and those who search for deep-seated deposits and extract them will prosper (Eaton et al., 2003). This in turn is feasible in major mining camps where infrastructures and mining facilities are already in place. Understanding and imaging subsurface structures that control and/or are associated with mineralization in major mining areas are important prerequisites for planning and improving deep exploration strategies and optimizing drilling and exploitation expenses. Reflection seismic methods can be very helpful in understanding and imaging both shallow and deep structures (e.g., Dehghannejad et al., 2010; Juhlin et al., 2010; Malehmir et al., 2006, 2007, 2009b; Tryggvason et al., 2006) and in combination with other geological and geophysical data can provide a framework along which 3D geologic models can be created (e.g., Malehmir et al., 2009a). Successful 2D and 3D seismic reflection studies in major mining areas worldwide suggest that volcanic-hosted massive sulphide (VHMS) deposits and associated structures are suitable targets for investigation by seismic methods (e.g., Adam et al., 2003; Malehmir and Bellefleur, 2009; Milkereit et al., 1996; Milkereit et al., 2000; Pretorius et al., 1989; Pretorius et al., 2003; Stevenson et al., 2003).

The poly-deformed Bathurst Mining Camp (BMC) in northeast New Brunswick, Canada, contains several mineral deposits including the super-giant Brunswick No. 12 and the No. 6 VHMS deposits (Fig. 1 and 2; Wills et al., 2006). The area near the Brunswick No. 6 deposit is the focus of this study. The Brunswick No. 6 produced a total of about 13 million tons of base-metal during its 20 years of production before closure in 1983 (Luff, 1995). The Brunswick No. 6 deposit amongst others in the BMC, are related to an Algoma-type iron formation, generally referred to as the Brunswick horizon (Gross and Mcleod, 1980). Several detailed geological studies indicate a direct relationship between this iron formation and VHMS deposits in the BMC (e.g., Peter, 2003; Peter and Goodfellow, 1996; Saif, 1983; Troop, 1984). Because of available infrastructure and global interest in base-metal exploration, the Brunswick No. 6 and adjacent areas are of great interest for targeting deep-seated mineral deposits. However, successful exploration requires a better understanding of upper crustal

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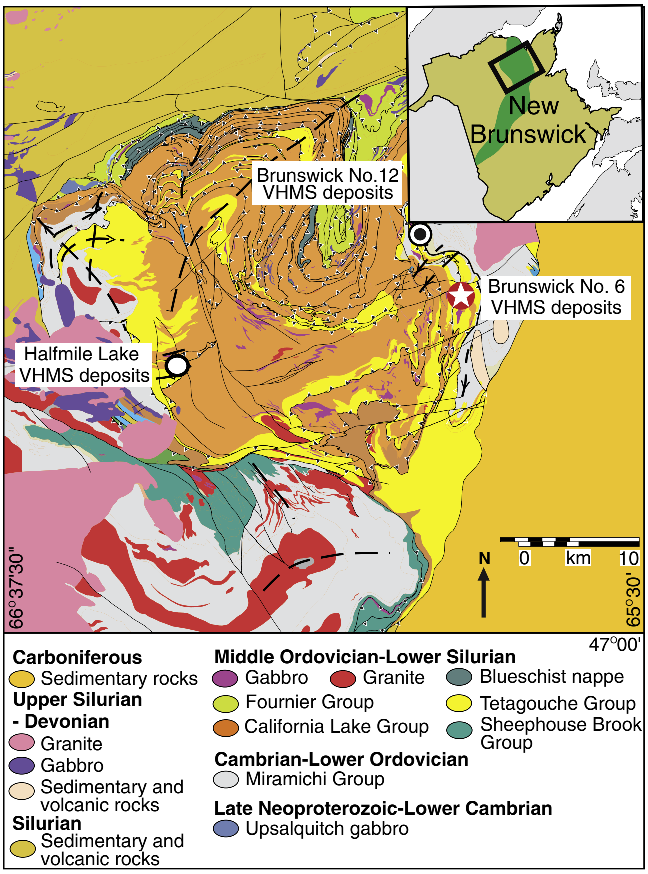

Fig. 1. Geological map of the Bathurst Mining Camp (modified from Goodfellow, 2007), New Brunswick, showing location of the Brunswick No. 6 VHMS deposit in this area and other major deposits.

structures and the 3D geometry of key mineralized horizons (e.g., the Brunswick horizon) at depth. Surface geological studies indicate that the Brunswick horizon is a strongly folded formation that may continue to greater depth (Wills et al., 2006). However, there is no direct geological and geophysical support available to provide information on the deep mineral potential at the Brunswick No. 6 deposit.

In 1999, Noranda Inc. (now Xstrata) acquired three high-resolution reflection seismic profiles over the Brunswick No. 6 area with the aim of assessing the general reflectivity of the various lithological units and providing a structural framework at depth (Fig. 2). Two of the three seismic profiles were never released publically. Malehmir and Bellefleur (2010) recently published results from one of the seismic profiles down to only 1.5 s. In this paper, we present results from the re-processing and analysis of the three Brunswick No. 6 seismic reflection profiles. The processing sequence was designed to improve imaging of steeply dipping reflections at shallower depths where geological information is available. The main objectives of this study are (1) to correlate seismic data with available surface and borehole geological and geophysical observations, (2) to provide a better understanding of the deep framework of key stratigraphic horizons and thrust faults, (3) to assess the mineralization potential based on the continuity of reflections associated with key stratigraphic horizons at depth, and (4) to provide insights on large scale structures in the Brunswick No. 6 area. We show how the seismic data image the steeply dipping structures of the Brunswick No. 6 area associated with mineralization and two sets of high-amplitude reflections at depth possibly associated with thrusted nappes of the Brunswick belt not exposed at surface. Moreover, in order to provide better insights into the processing work and the interpretation of the observed reflections, finite-difference modeling results constrained with borehole geological and geophysical data are also presented and discussed.

2. Geological Setting

The Brunswick No. 6 area is located within the highly productive base-metal Bathurst Mining Camp, approximately 27 km southwest of the city of Bathurst, New Brunswick, Canada. The Bathurst Mining Camp is made of several tectonic blocks and slivers that were juxtaposed during the closure of the Tetagouche-Exploits back-arc basin (van Staal et al., 2003). A detailed tectonic history of the Brunswick complex and associated structures of the Bathurst Mining Camp is given by van Staal (1994) and van Staal et al. (2003). Fig. 3 shows a schematic cartoon of tectonic framework of the Brunswick complex in the late Ordovician–early Silurian (450–440 Ma, see van Staal, 1994). According to van Staal (1994), the Brunswick complex formed during a continent–continent collision in the late Ordovician and Early Silurian. Prior to the collision, a series of oceanic-continental obductions in the early Ordovician and before that trapped large blocks of oceanic rocks (mainly ophiolite) underneath the volcanic and sedimentary rocks of the Miramichi Group. The presence of oceanic rocks trapped at shallow depths was also suggested by Stockmal et al. (1990) based on the results of regional scale seismic transects acquired in the New Brunswick.

Ductile thrusting and upright folding systems observed in the camp suggest the numerous repetitions of lithological units and thickening of volcanic rocks (van Staal, 1987). Several allochthonous blocks and nappes have been identified, with the major blocks containing a similar basement consisting mainly of deep-water sandstones and shales of the Miramichi Group in the area of the seismic survey (van Staal, 1987). The structure of the various blocks and nappes is not well-understood at depth. It is also not clear if more thrusted blocks exist underneath the Carboniferous sedimentary rocks exposed at the surface east of the mining camp. The location of the three seismic profiles is well-suited to provide some information about the deep structural framework of the volcano-sedimentary rocks and their possible continuation to the east. The profiles may also provide evidence for the presence of oceanic crust assumed to underlie the Bathurst Mining Camp (van Staal, 1994).

The Brunswick belt hosts several VHMS deposits, for example, the Brunswick No. 12, No. 6 and Austin Brook deposits (Fig. 2). Massive sulphide mineralization in the Brunswick No. 6 area was first observed in 1907 during an investigation of the iron formations in the region (Belland, 1992). In 1952, the Brunswick No. 6 deposit was discovered following drilling of electromagnetic anomalies north of the Austin Brook iron deposit. Mining commenced in 1966 from an open pit, and later by underground methods. By 1982, Brunswick No. 6 had produced about 12.2 Mt of 5.43% Zn, 2.15% Pb, 0.40% Cu, and 67 g/t Ag (Luff, 1995).

The oldest rocks in the region belong to the Miramichi Group, a Cambro-Ordovician clastic metasedimentary sequence (van Staal et al., 2003). These rocks are overlain by the middle Ordovician bimodal volcanic and sedimentary rocks of the Tetagouche Group that formed within the Tetagouche-Exploits back-arc basin (Rogers and van Staal, 1997; van Staal, 1987, 1994; van Staal et al., 2003; Whalen et al., 1998), and host the VHMS and iron deposits, which constitute the Brunswick horizon. The lower part of the Tetagouche Group consists of dominantly felsic volcanic and volcanoclastic rocks of the Nepisiguit Falls Formation, which are overlain by the younger rhyolite flows and rhyolitic volcanic/hyaloclastic rocks of the Flat Landing Brook Formation (Rogers et al., 2003). The youngest part of the Tetagouche Group consists of alkali basalt flows and associated clastic and exhalative sedimentary rocks of the Little River Formation (Fig. 2).

In the Brunswick No. 6 area, the Nepisiguit Falls Formation exhibits varying thicknesses of altered quartz-feldspar-phyric crystal tuffs and felsic volcano-sedimentary rocks (Goodfellow and McCutcheon,

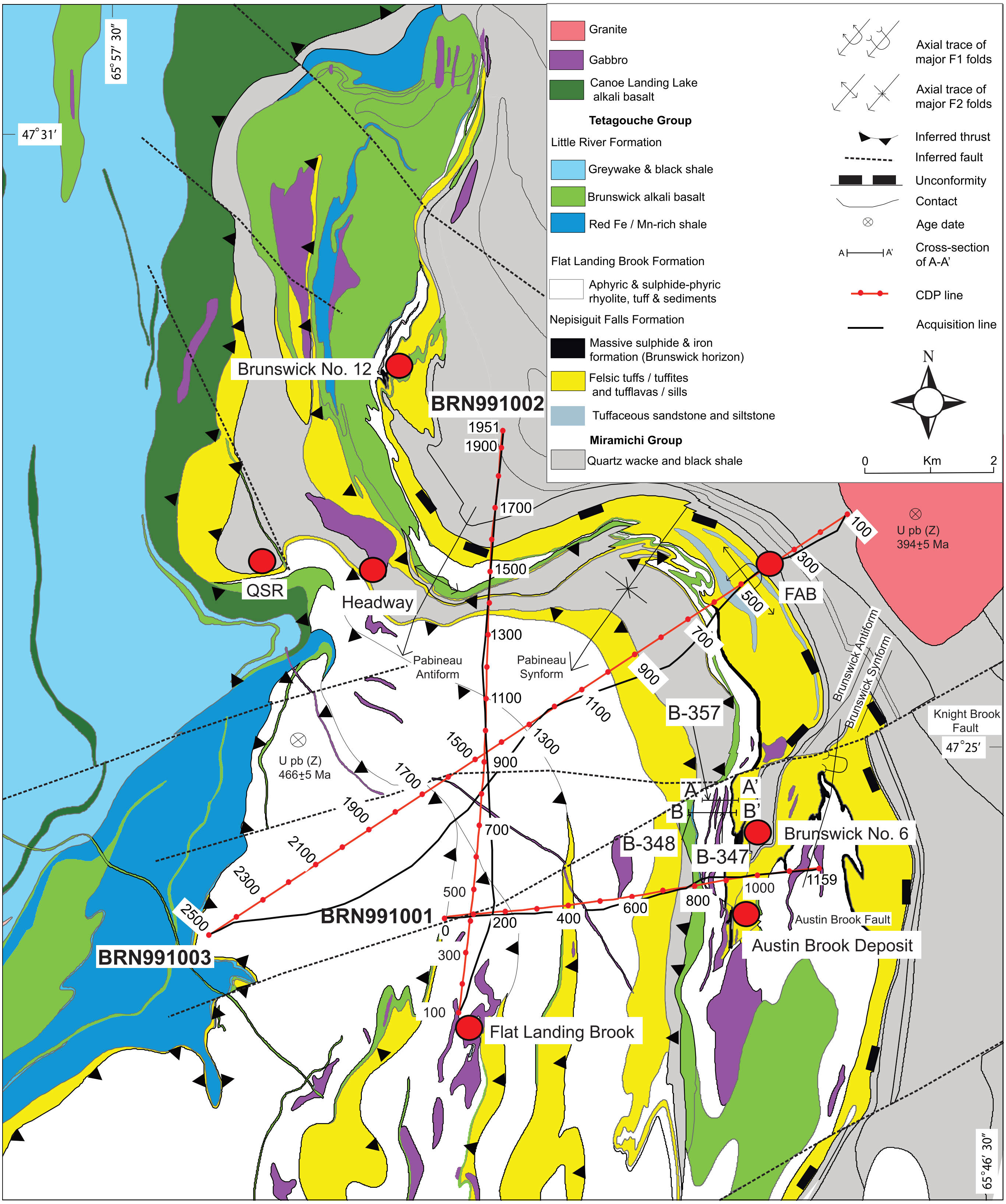

Fig. 2. Geological map of the Brunswick No. 6 area, Bathurst Camp, New Brunswick (modified from van Staal et al., 2003) showing location of major mineral deposits and seismic profiles BRN991001, BRN991002, and BRN991003. A–A′ and B–B′ are geological cross-sections shown later. The boreholes B-347, B-348 and B-357 are also shown in this map.

2003; van Staal et al., 1992). Fine-grained tuffs and sedimentary rocks become more prevalent towards the top of the formation. The massive sulphides and associated iron formation of the Brunswick horizon covers the upper part of the Nepisiguit Falls Formation. Iron formation in the Brunswick horizon is a mixture of sulphide, carbonate, oxide, and silicate facies. It is the most reliable key horizon for

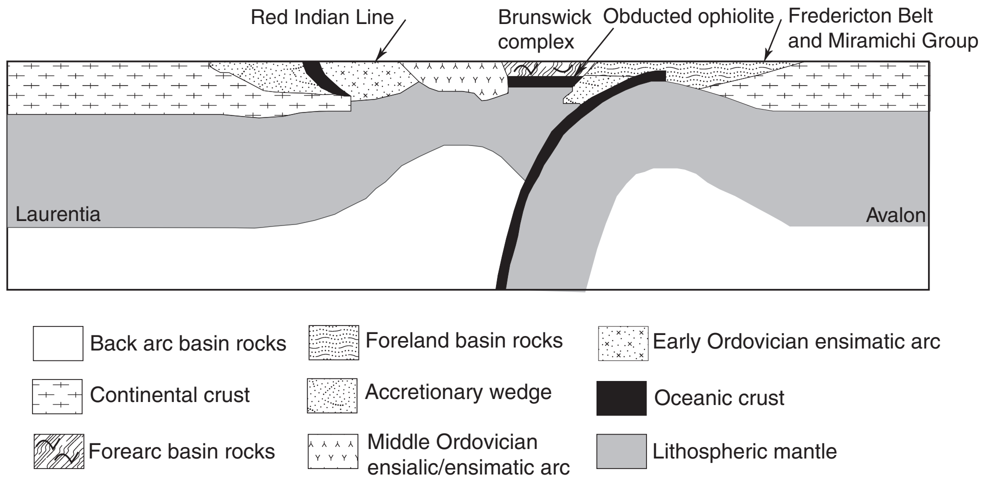

Fig. 3. Tectonic model of the Brunswick complex in the late Ordovician–early Silurian (450–440 Ma; modified from van Staal, 1994). The Brunswick horizon (massive sulphide and iron formation) is part of the Brunswick complex and is strongly folded and deformed. Note that large blocks of thrusted/obducted ophiolite rocks are expected to be trapped in the upper crust.

geophysical and geochemical exploration in the BMC (Gross and McLeod, 1980). The fine-grained ash tuffs (the upper part of the Nepisiguit Falls Formation) usually constitute the footwall for the Brunswick horizon (Goodfellow and McCutcheon, 2003; McCutcheon, 1992). The Flat Landing Brook Formation dominates the upper section of the Tetagouche Group and comprises massive, aphyric to sparsely quartz-feldspar-phyric rhyolite flows, domes, fragmental rhyolite, hyalotuffs, and reworked volcanoclastic debris. The Flat Landing Brook Formation is stratigraphically located in the hanging-wall of the Brunswick horizon (Cas, 1992; McCutcheon, 1992; Wills et al., 2006). The Little River Formation overlies the Flat Landing Brook Formation and comprises mafic volcanic and associated sedimentary rocks (Rogers et al., 2003). Based on borehole data, Wills et al. (2006) depict a short and shallow geologic cross-section of the Brunswick horizon as shown in Fig. 4a (see A–A′ in Fig. 2). Also, Lentz and McCutcheon (2006) produced another cross-section of the Brunswick horizon south of the A–A′ cross-section presented in Fig. 4b (see B–B′ in Fig. 2). Both cross-sections show the same trend for depth extension of the Brunswick horizon near the Brunswick No. 6 area. Tight and small folding structures were interpreted partly to control the geometry of the Brunswick horizon. The Brunswick horizon and these associated lithological and structural units were the main targets of the seismic data re-processing and posed a challenge in the interpretation of the data.

3. Petrological and Petrophysical Properties

Petrophysical properties are keys to understanding the nature and possible cause of the reflections observed on seismic profiles. In the Brunswick No. 6 area, most petrophysical data were collected in borehole B-357 (Fig. 2). The collar of this borehole is located approximately 1.5 km northwest of the Brunswick No. 6 deposit in the felsic volcanic and volcano-sedimentary rocks of the Tetagouche Group. Approximately 57 core samples were collected to study petrological and geochemical characteristics of the rocks (Wills et al., 2006). The geological log of borehole B-357 is shown in Fig. 5. Based on the geochemical analysis, Wills et al. (2006) suggested that the intersection of iron formations at different depths (i.e., at about 250 m, 400 m and 350 m below the sea level) represents a repetition of the same time-stratigraphic horizon along isoclinal folds (i.e., the Brunswick horizon; see also Fig. 4a).

In 2000, Noranda Inc. carried out well logging measurements in borehole B-357. The measurements included density and compressional wave velocity (Fig. 5). Analysis of the logs indicates an average density of 2700 kg/m³ with the Brunswick horizon and mafic rocks showing higher densities of about 3400 kg/m³ and 3000 kg/m³, respectively. The sonic measurements show an average velocity of 5500 m/s for the entire rock column except for the Brunswick horizon and gabbro units, which have velocities of about 6000 m/s and 6500 m/s, respectively.

Calculated reflection coefficients are strongest when felsic volcanic rocks of the Tetagouche Group are in contact with the Brunswick horizon and gabbro/basalt units (about 0.25 and 0.2, respectively). Weaker reflection coefficients are expected (0.03–0.05) between felsic volcanic rocks of the Flat Landing Brook Formation and the Nepisiguit Falls Formation. Reflection coefficients in a volcano-sedimentary environment should be more than 0.06 to produce an observable reflection (Salisbury et al., 1996). Thus, on the basis of the borehole logging data analysis, it is expected that the strongest reflections on the three seismic profiles would indicate contacts between felsic volcanic rocks and the Brunswick horizon and/or gabbro units. Malehmir and Bellefleur (2010) made similar observations using logging data from a borehole located south of the Brunswick No. 6. Synthetic seismic traces generated from the logs using a 70 Hz Ricker wavelet further support results from the reflection coefficient study (see Fig. 5) and indicate that the Brunswick horizon and associated lithological units could be detectable on seismic data acquired under the proper parameters and with a sufficient signal-to-noise ratio (see also Salisbury et al., 1996).

Borehole B-357 does not intersect the sedimentary rocks of the Miramichi Group and consequently cannot provide information about the reflectivity of these rocks when they are in contact with the volcanic rocks of the Tetagouche Group. Petrophyscial measurements on rock samples from the Bathurst Mining Camp suggest, however, that sedimentary rocks should produce detectable reflections when juxtaposed against mafic rocks (Salisbury et al., 2000). This suggests that any contacts, if occur, between the sedimentary rocks of the Miramichi Group and the mafic rocks of the Tetagouche Group are likely to be detected by the seismic surveys whereas contacts between the Miramichi Group and the felsic volcanic rocks of the Tetagouche Group are unlikely to be detected. We later present finite-difference modeling results over the geological section shown in Fig. 4b constrained by these petrophysical measurements.

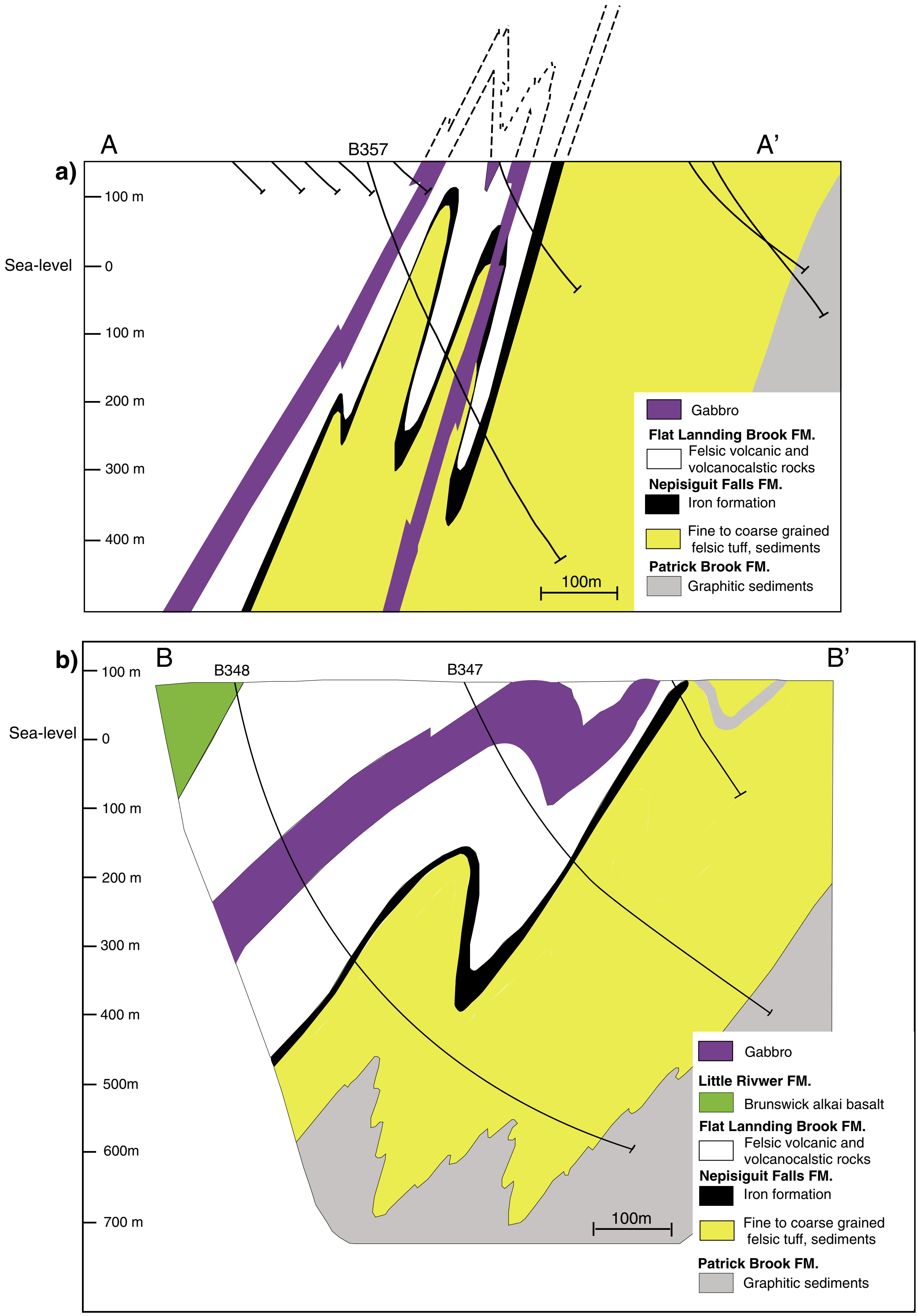

Fig. 4. (a) Geological cross-section along the profile A–A′ shown in Fig. 2 obtained from a series of shallow and deep boreholes including B-357, showing complex structures of the Brunswick No.6 and associated Brunswick horizon (modified from Wills et al., 2006). Petrophysical measurements of borehole B-357 are shown in Fig. 5. (b) Geological cross-section along the profile B–B′ (see Fig. 2) obtained from deep and shallow boreholes including B-347 and B-348 (modified from Lentz and McCutcheon, 2006).

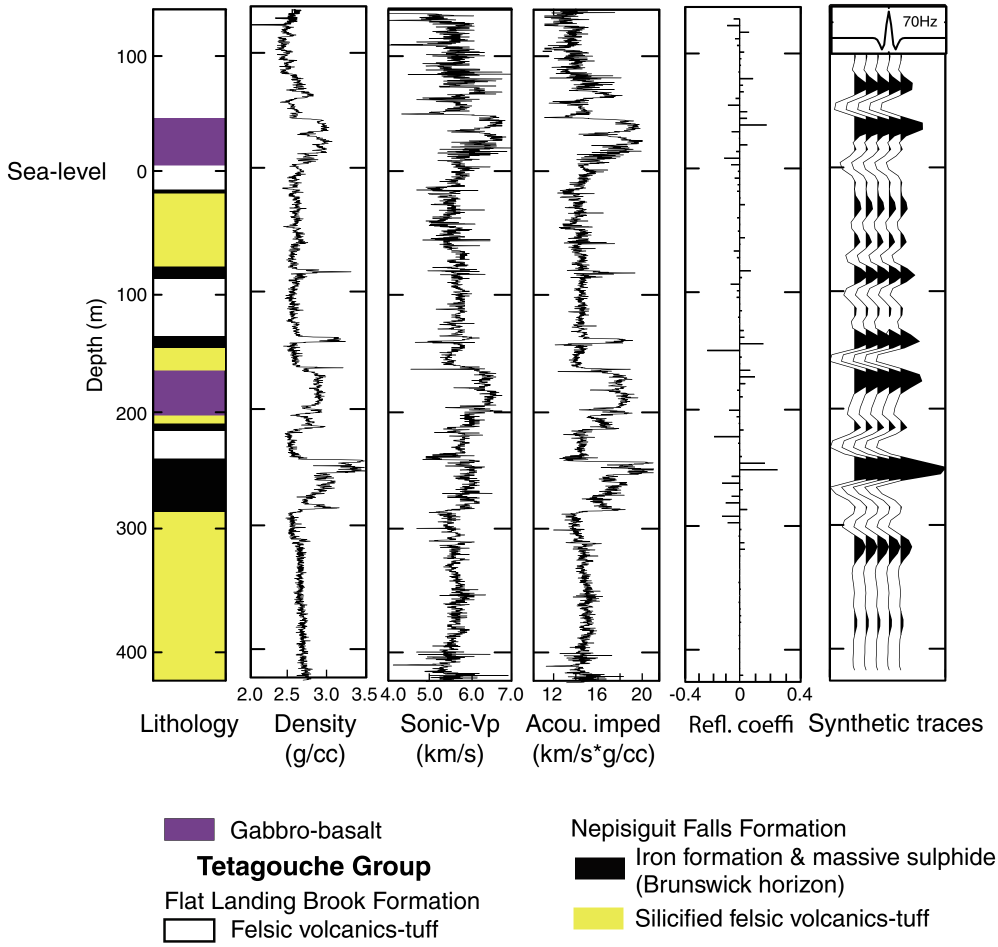

Fig. 5. Density, compressional-wave velocity, calculated acoustic impedance, reflection coefficient, and synthetic seismogram produced using a central frequency of 70 Hz obtained from borehole geophysical measurements in B-357.

4. Data Acquisition

To unravel geological structures and to aid mineral exploration at depth, Noranda Inc. conducted reflection seismic data acquisition along three profiles having a total length of about 30 km. The three profiles were also acquired to confirm the reflectivity of the key exploration horizon and to assess the overall quality of data in the area in preparation for a possible larger 3D survey. The profiles BRN991001, BRN991002, and BRN991003 have different orientations and were designed to crosscut almost orthogonally the Brunswick horizon in an area of the mining camp characterized by small local fold (see Fig. 2). The profiles also intersect each other in a few locations to provide critical ties and control on the 3D geometry of the main structures (Fig. 2). Profiles BRN991001 and BRN991002 intersect each other at about CDP (common depth point) 100 on BRN991001 (about CDP 400 on BRN991002). The intersection point for profiles BRN991002 and BRN991003 is at about CDP 900 and at CDP 1500, respectively (Fig. 2).

Prior to the data acquisition, Noranda Inc. made a few test records to define the optimum charge size and depth of shot holes. Results suggested that a 6 m deep hole with a 0.5 kg dynamite charge size would be cost effective and should produce sufficiently high signal-to-noise ratio data for high-resolution imaging of the main structures (for details see Malehmir and Bellefleur, 2010). For all three profiles, the nominal receiver and shot spacing were 10 m and 40 m, respectively. Each shot record comprised a total of 481 active channels. Table 1 lists the main acquisition parameters. Data quality in raw shot gathers are good and occasionally some reflections can be observed. However, source-generated noise, such as strong shear-wave and ground-roll, masks most of the reflections, especially at shallow travel times and required particular attention during data processing. A typical raw shot gather recorded along profile BRN991002 is shown in Fig. 6a.

5. Seismic Data Processing

We chose a prestack dip-moveout (DMO) and poststack migration processing sequence similar to that outlined by Schmelzbach et al. (2007). Careful focus on a few critical steps is important for processing seismic data acquired from crystalline rocks. The basic processing steps were similar for all three profiles and included (1) refraction static corrections, (2) coherent and random noise removal, (3) shear-wave attenuation, (4) velocity analysis and normal moveout (NMO) corrections, (5) residual statics, (6) DMO corrections and (7) stacking and migration of the data. Table 2 summarizes all the steps used for processing of the seismic data.

Seismic waves travel slowly through the overburden and are significantly faster in the crystalline bedrock. This contrasting velocity introduces large travel-time variations that depend on the thickness of overburden beneath each receiver. Refraction statics play a critical role to correct these time variations (e.g., Juhlin, 1995; Wu and Mereu, 1992) and is a crucial step for high-resolution imaging of deeper reflections. To obtain good refraction statics, we carefully picked the first arrivals using an automatic approach followed by a rigorous manual inspection and fine-tuning of the picks. Time delays were

Table 1
Main seismic acquisition parameters, 1999.

Survey parameters			
Recording system	SERCEL 388		
Profile	BRN991001	BRN991002	BRN991003
Spread geometry	Asymmetric split spread (60–80 station tailing)	Asymmetric split spread (60–80 station tailing)	Asymmetric split spread (60–80 station tailing)
No. active channels	481	481	481
Maximum offset	4800 m	4800 m	4800 m
Survey length	6.9 km	9.2 km	12.01 km
Source	Dynamite	Dynamite	Dynamite
Nominal CDP fold	60	60	60
Receiver spacing	10 m	10 m	10 m
Source interval	40 m	40 m	40 m
Recording length	3 s	3 s	3 s
Sampling rate	2 ms	2 ms	2 ms
Geophone frequency	10 Hz	10 Hz	10 Hz
No. geophone per set	6 over 8 m	6 over 8 m	6 over 8 m
Geophone separation	1.5 horizontal	1.5 horizontal	1.5 horizontal
Source pattern	Single hole	Single hole	Single hole
Shot depth	6 m	6 m	6 m
Nominal charge size	0.5 kg	0.5 kg	0.5 kg
No. shots	169	260	343

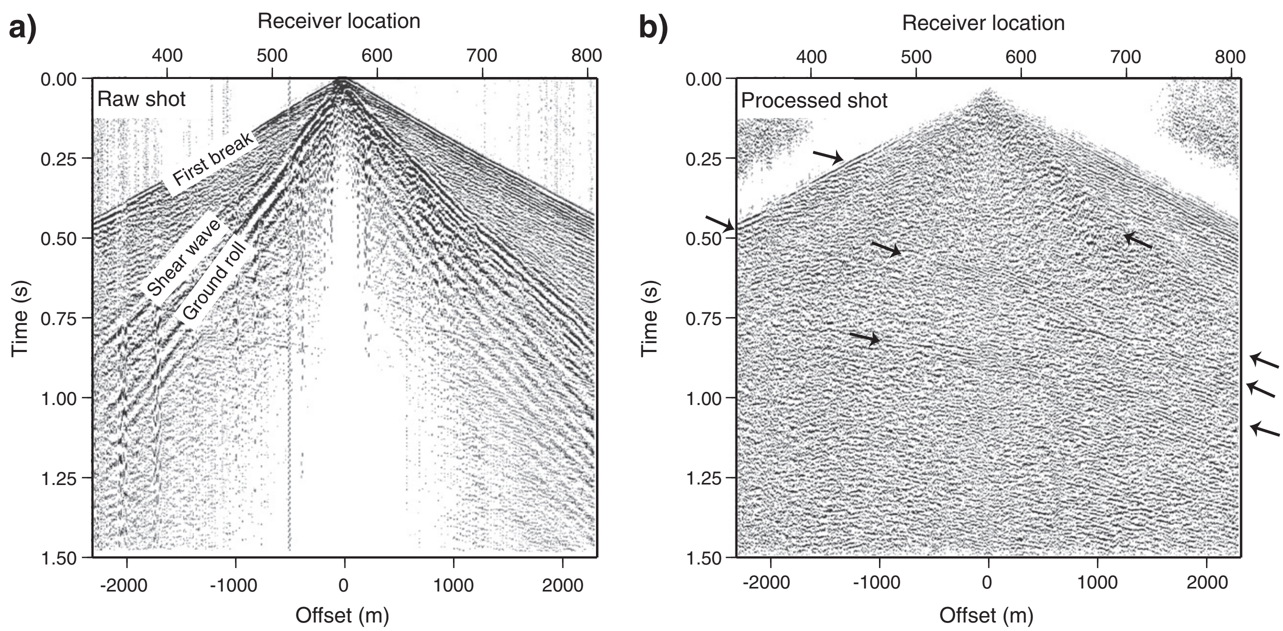

Fig. 6. (a) Raw and (b) processed shot record from profile BRN991002, showing strong coherent source-generated and random noise that were reduced during the processing and allowed to enhance reflections marked by black arrows.

Table 2
Processing sequence of the Brunswick No. 6 data, 2011.

Step	Parameters
1.	Read 3.0 s SEG-2 data
2.	Build geometry data
3.	Trace editing
4.	Pick first breaks: full offset range, automatic neural network algorithm but manually inspected and corrected
5.	Refraction static, replacement velocity 5200 m/s, V0 1000 m/s
6.	Geometric-spreading compensation: V^2t
7.	Band-pass filtering: 20–35–150–170 Hz
8.	Surface-consistent deconvolution: filter 100 m/s, gap 14 ms, white noise 0.1%
9.	Top mute: 20 ms after first break
10.	Direct shear-wave attenuation (near-offset)
11.	Air blast attenuation
12.	Trace balance using data window
13.	Velocity analysis (iterative)
14.	Residual static corrections (iterative)
15.	NMO corrections: 30% stretch mute
16.	DMO corrections (only for BRN991001)
17.	Stack
18.	Migration (Stolt)
19.	Time-to-depth conversion using constant 6000 m/s

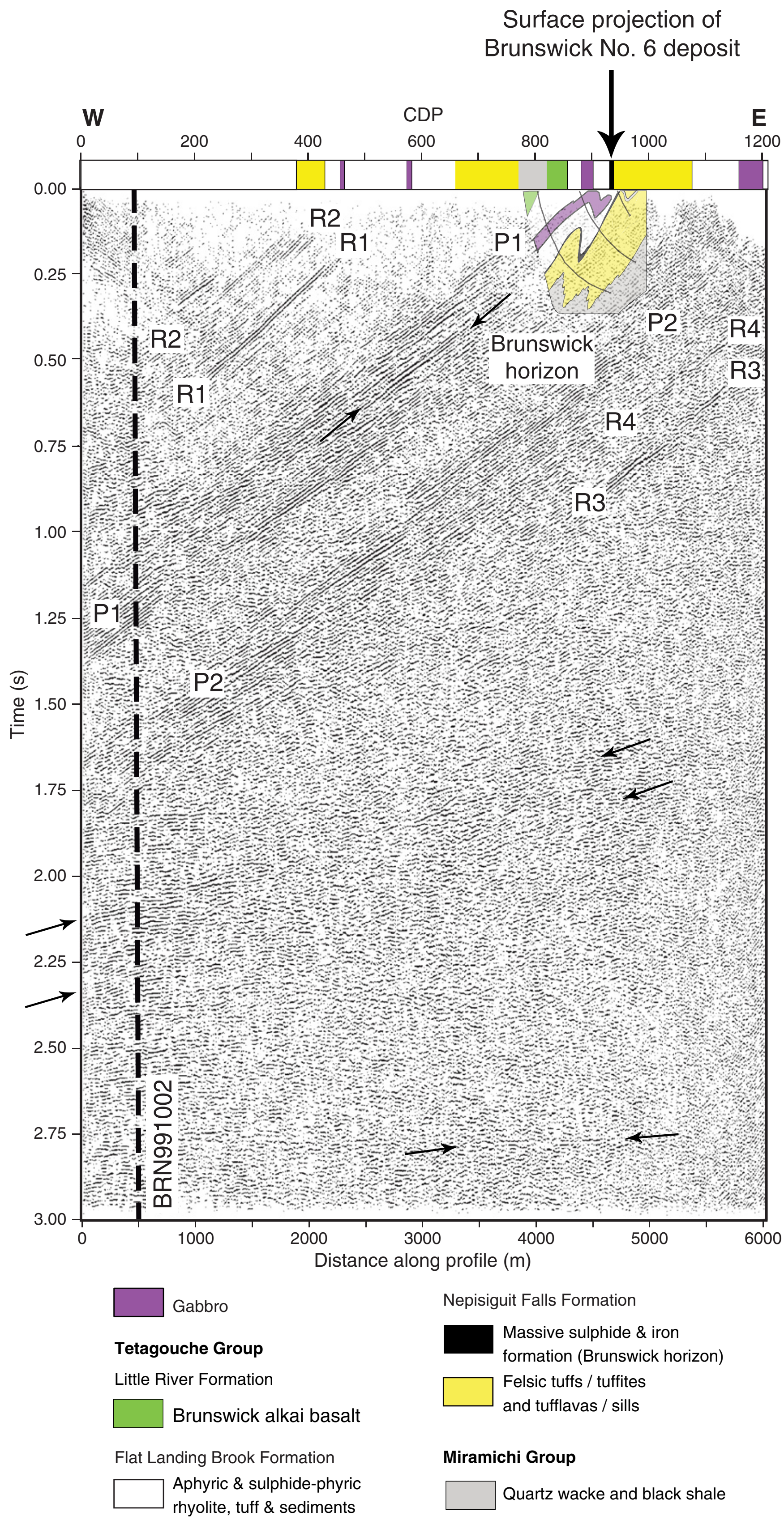

Fig. 7. Stacked section along BRN991001, showing a series of westward steeply dipping reflections imaged down to about 1.7 s. Reflectivity pattern indicates a sequence of reflective and transparent package repeating from the east to the west. The Brunswick horizon and associated structures appear within the reflective package P1. The dashed line shows intersection with BRN991002. See text for interpretation of P1, P2, R1, R2, R3 and R4. The cross-section B–B′ is projected onto the profile to support the interpretations given for this profile.

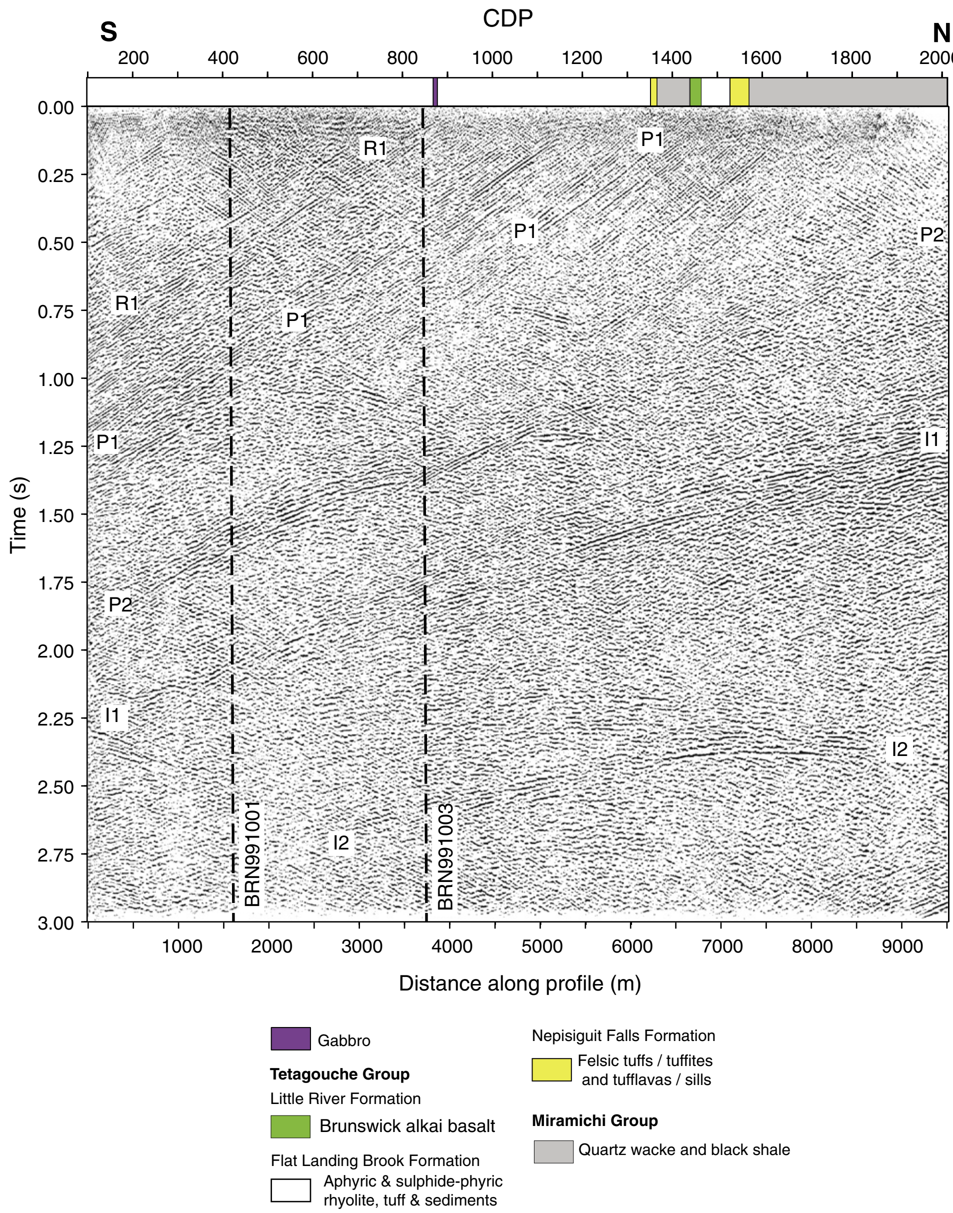

Fig. 8. Stacked section along BRN991002, showing a series of shallow and deep southward steeply dipping reflections. Dashed lines show intersections with BRN991002 and BRN991003. P1 and P2 reflections show good correspondence in BRN991001 and BRN991003. I1 and I2 can also be followed in BRN991003. See text for the interpretation of I1, I2, P1, P2 and R1.

calculated using a single layer model with a typical overburden velocity of 1000 m/s and a replacement velocity of 5200 m/s.

Seismic data acquired with explosives is often characterized by coherent events (non-reflection) including the air blast, ground-roll, and shear-wave energy (Fig. 6a). To reduce these events and the non-reflected part of the signal, we muted first-arrival and air-wave energy, attenuated the shear-wave using a median filter, and filtered out parts of the low-frequencies associated with ground-roll energy. Random noises were reduced using band-pass filters and the frequency content of the seismic signal was increased using surface-consistent deconvolution. Fig. 6b shows the results after the application of these processing steps on the corresponding raw shot gather. A series of steeply dipping reflections are identifiable on the processed gather.

Surface geological observations in the Brunswick No. 6 area indicate a complex geological setting with varying dipping structures (Wills et al., 2006). In such an environment, NMO corrections are challenging as structures with different dips may appear at the same time but with different velocities. A series of constant velocity stacks was run to define the optimum stacking velocities. We considered velocities from 5500 m/s to 10000 m/s as dipping reflections require higher stacking velocity to be coherently stacked. The analysis of constant velocity stacks helped to assign a proper stacking velocity for each individual reflection, but imaging challenges remained where reflections with varying dips are present. Theoretically, the DMO process should take care of imaging conflicting dips, but this only worked partially for the data along BRN991001 (see also Malehmir and Bellefleur, 2010) and did not improve the quality for BRN991002 and BRN991003. Therefore, the seismic data for these two profiles were not DMO corrected. The reason for the DMO failure may be due to an irregular offset distribution in the data caused by gaps in the shot

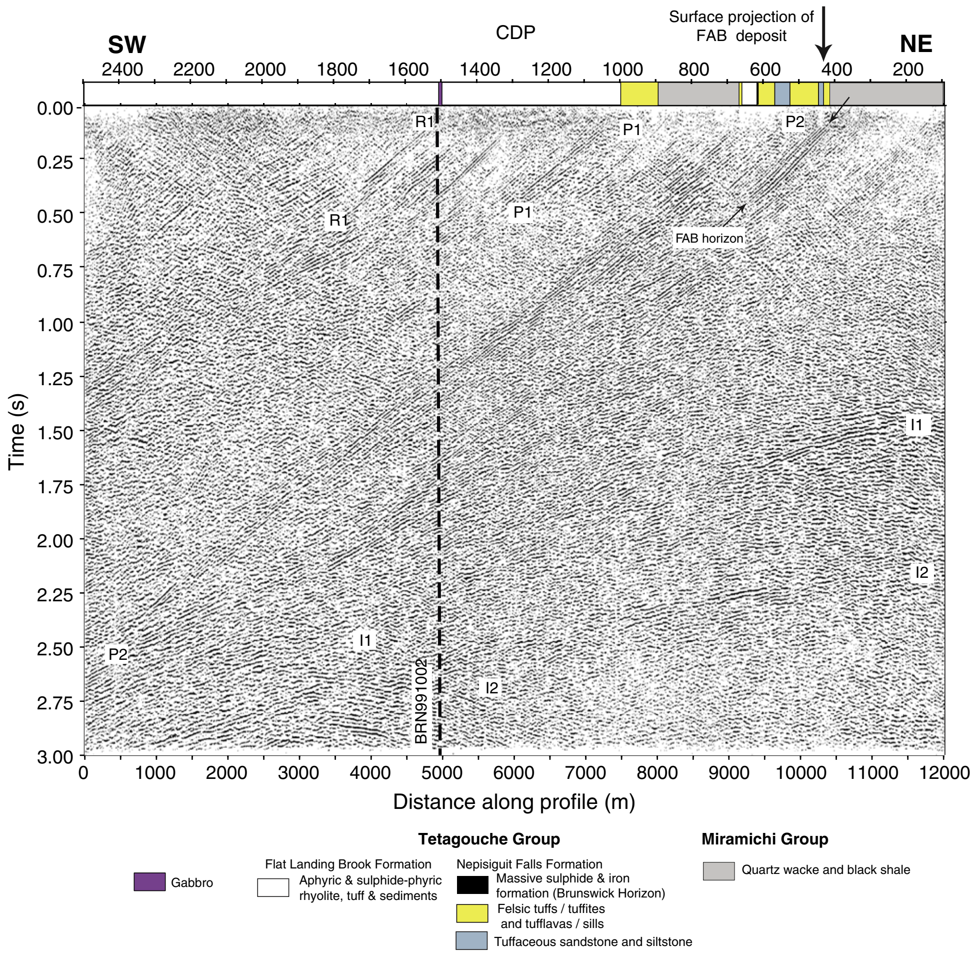

Fig. 9. Stacked section along BRN991003, showing a series of shallow and deep steeply dipping southwestward reflections. The surface location of FAB VHMS deposit is shown and may be associated with the strongest part of the P2. Dashed line shows intersection with BRN991003. See text for detailed interpretation of events marked on the section.

point distribution. Stacked sections for BRN991001, BRN991002 and BRN991003 are shown in Figs. 7, 8 and 9, respectively.

6. Migration Test and Finite-difference Modeling

For the migration, we ran a series of tests using different migration algorithms such as Kirchhoff, phase-shift (Gazdag, 1978), Stolt (Stolt, 1978) and finite-difference methods. The best results were obtained using the Stolt algorithm, which is able to properly migrate reflections up to 75º dip. Reflector modeling work conducted by Malehmir and Bellefleur (2010) suggests that the maximum dip of the observed reflectors along profile BRN991001 is about 72°, further supporting that the Stolt method is appropriate for the migration of the data.

To further evaluate the cause of reflectivity and our processing approach including the migration approach, we modeled the geologic cross-section shown in Fig. 4b using a finite-difference modeling algorithm (see Brenders and Pratt, 2007). We simulated 100 shots and receivers placed at every 10 m along the ~1.2 km long model. The sampling rate was set to 1 ms and the synthetic seismograms were generated using a minimum-phase wavelet with a center frequency of 60 Hz. The synthetic data were processed using similar processing approach presented in Table 2. The resulting stacked and migrated sections of the model are shown in Fig. 10. A careful comparison between the real and the synthetic stacked data (see Fig.10a and b) suggests consistent reflection geometry for the major lithological units. However, the real stacked data do not show any of the weak diffractions observed on the synthetic data. The migrated synthetic data (Fig. 10c) clearly includes main structures of the model except for the tight folds and the steep (>80º) flank of the Brunswick horizon.

A general conclusion of the modeling work is that the tight folds within or at the contact between the volcanic and the metasedimentary rocks manifest themselves as very weak diffractions that are either not recognized in the data or not preserved during data processing. The tight folds, at the end, are transparent zones in the seismic data (c.f., Fig. 10b and c). Another conclusion drawn here is that the Stolt migration is able to handle the steeply-dipping reflections observed in these data (see also Malehmir and Bellefleur, 2010).

Migrated sections of these profiles are shown in Figs. 11, 12, and 13. According to our experience with data acquired in crystalline rocks, the Brunswick seismic data show excellent quality with numerous steeply and moderately dipping reflections, many reaching to the surface and allowing for correlation with surface geology.

7. Results and Interpretations

In the Brunswick No. 6 area, complex geological structures generate reflections with various dips and length. Some of the reflections extend to the surface (see Figs. 9 and 11) and others do not (e.g., Figs. 8 and 12). In order to better tie the reflections observed in all the three profiles, the stacked sections of intersection points are presented in

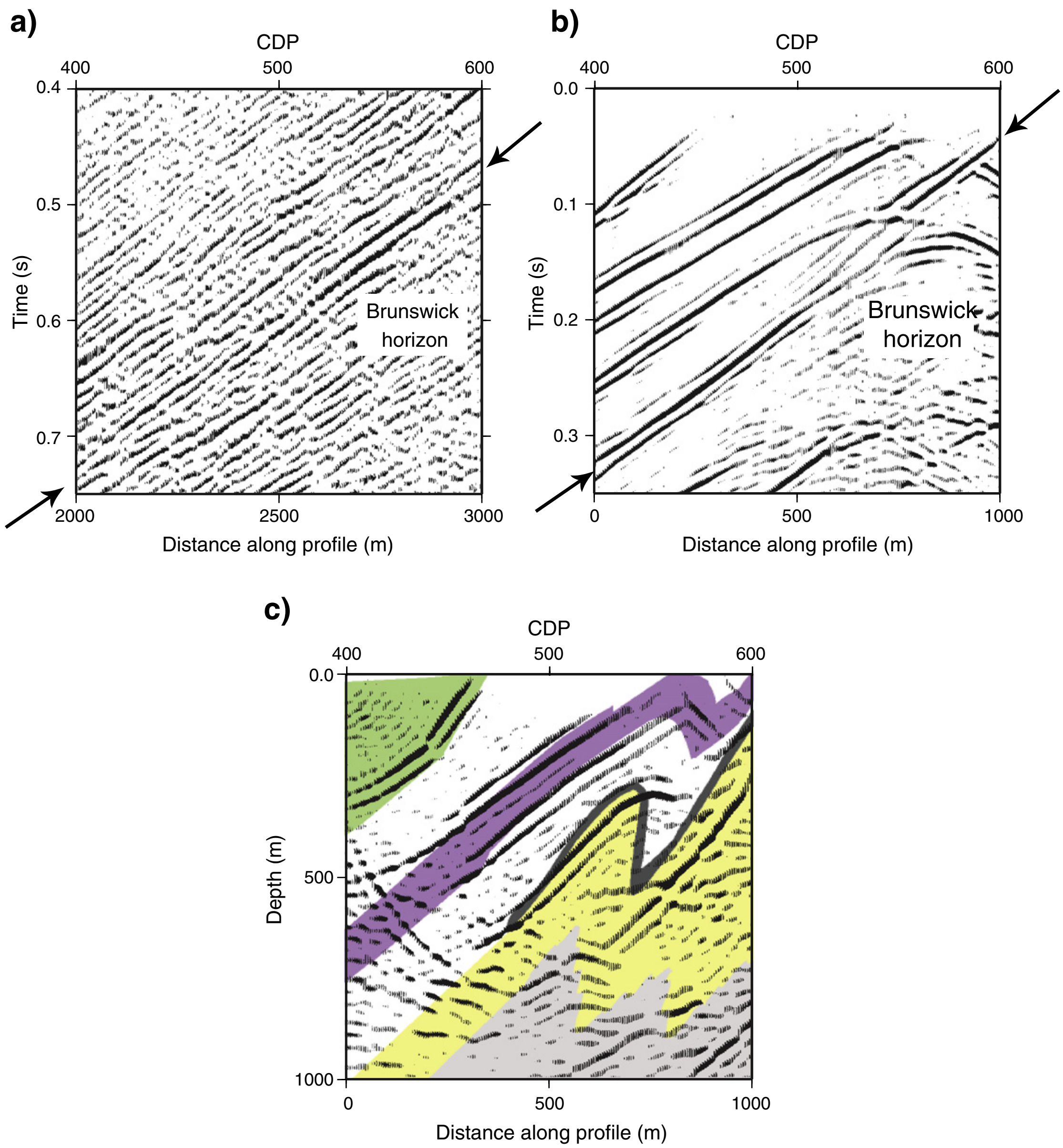

Fig. 10. (a) Observed and (b) synthetic stacked sections along a portion of profile BRN991001. (c) Migrated synthetic data superimposed on the model used to generate the data. See text for detailed description of the results.

Figs. 14 and 15. Our interpretation is based on the stacked sections as reflections show a better tie with each other.

7.1. Profile BRN991001

This profile passes over the Austin Brook fault slightly south of the Brunswick No. 6 deposit. Reflectivity patterns on the stacked section shown in Fig. 7 (see Fig. 11 for migrated section) can be divided into highly reflective or transparent groups. Reflections all dip to the west in alternation with noticeable transparent sequences. Recent modeling work in the upper 1.5 s of profile BRN991001 indicates that reflections dip between 55º and 70º within the plane of the seismic profile (Malehmir and Bellefleur, 2010). A comparison between surface geological observations and shallow reflections suggests that reflective zones (e.g., P1 and P2 in Figs. 7 and 11) are generated from gabbro and alkali basalts of the Little River Formation in contact with the felsic volcanic rocks of the Nepisiguit Falls Formation, and the Brunswick horizon. Rock units of Flat Landing Brook Formation and Miramichi Group show, in general, very weak reflectivity. Correlation with the geological cross-section B–B′ (see Figs. 2 and 4) further supports this interpretation of alternating reflective and transparent zones. Isolated, but long high-amplitude reflections within the transparent zones (such as R1 and R2 on Figs. 7 and 11), are likely to be generated by gabbroic intrusions or perhaps basaltic rocks that forms part of the Flat Landing Brook Formation (see Fig. 10). The best example is probably R1 which projects to the surface at the location of a gabbroic dyke and near a fault zone observed on the geological map (Fig. 11). There are no known surface features related to R3 and R4; but, based on repetition of formations observed on the geological map (Fig. 2), they could be related to the Brunswick horizon. Surface geological observations indicate an unconformity at the contact between Miramichi Group rocks and felsic tuffs of the Nepisiguit Falls Formation. The unconformity is not distinguishable in the seismic image as it is out-of-the-plane of the profile. It is possible that the hanging-wall of P1 and P2 reflective zones mark two thrust faults that extend to depths greater than 6–7 km (see also Fig. 9). A careful

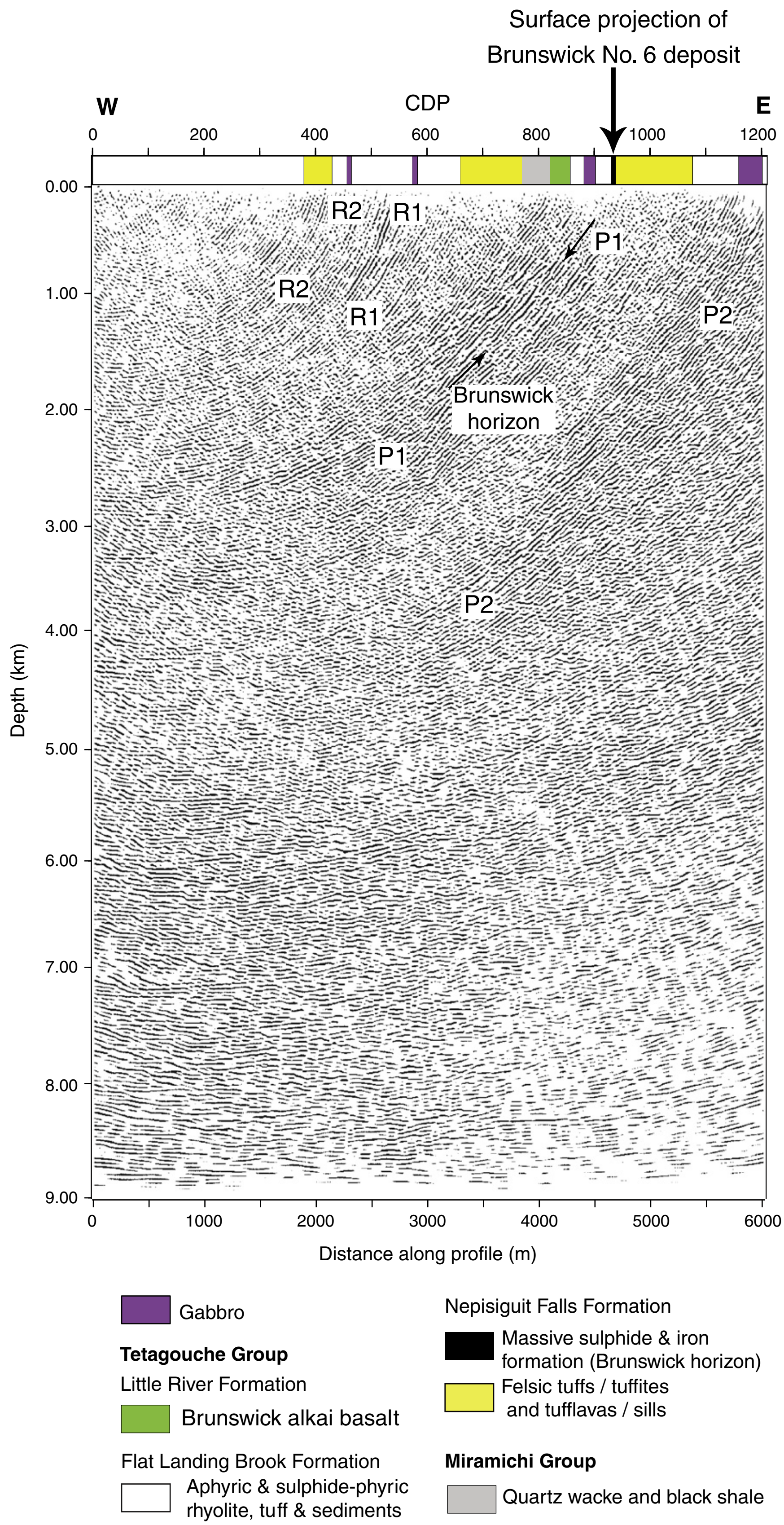

Fig. 11. Migrated section of profile BRN991001. See text for interpretation of P1, P2, R1, and R2.

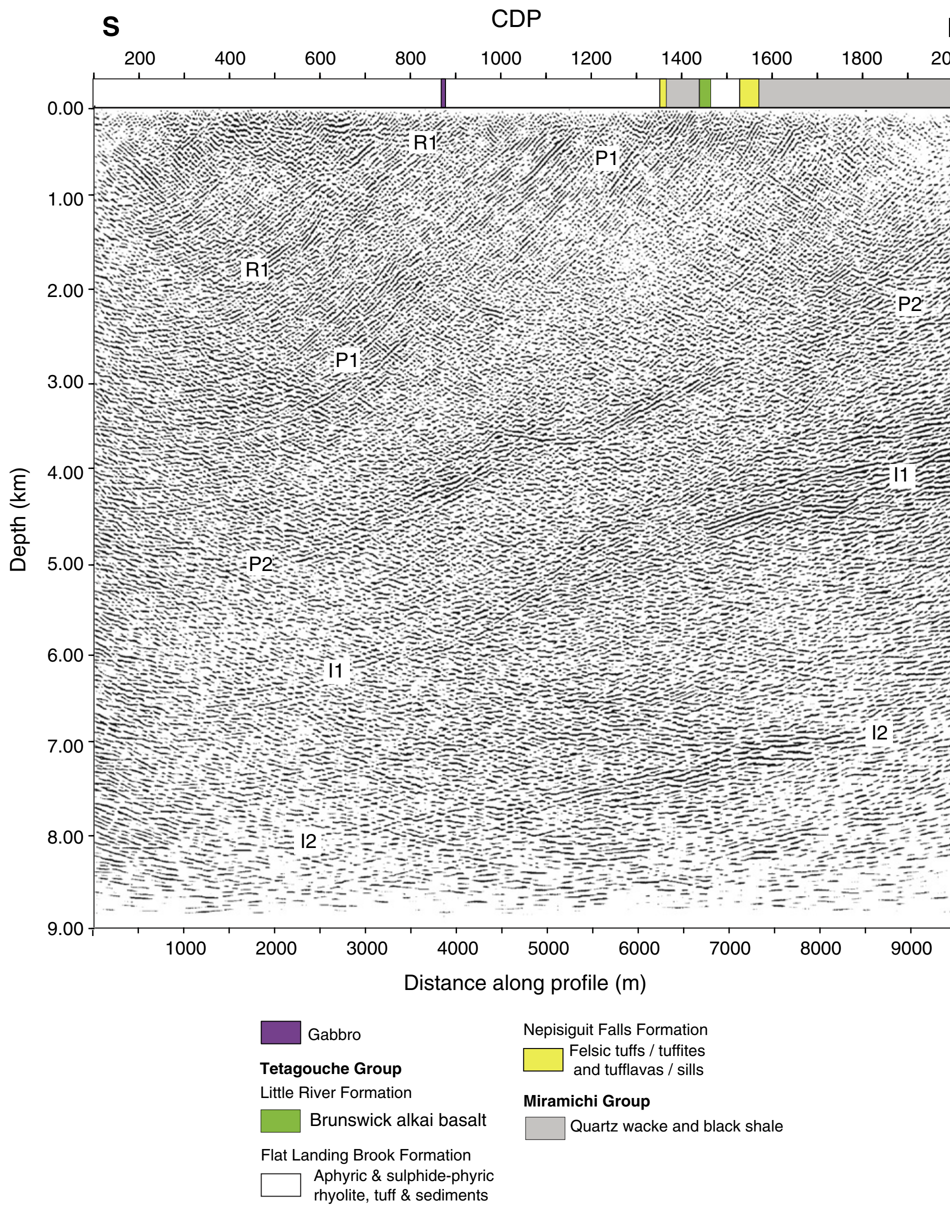

Fig. 12. Migrated section of profile BRN991002. See text for interpretation of I1, I2, P1, P2, and R1.

inspection of the stacked section suggests that a strong reflection observed within the P1 reflective zone could correspond to the Brunswick horizon (c.f., Fig. 10).

Reflections at greater depths are generally short and discontinuous (arrows on Fig. 7). They show a general west-dipping trend similar to the trend in the Ordovician sequences observed at surface and suggests the presence of more nappes at depth. A short sub-horizontal reflection at approximately 2.75 s (Fig. 7) marks a change in the structural style that could indicate the lower limit of the Brunswick belt.

7.2. Profile BRN991002

This north–south directed profile is almost perpendicular to profile BRN991001. When compared with profile BRN991001, the stacked section of BRN991002 (Fig. 8) shows a different reflectivity pattern. Shallow reflections appear more isolated and are much shorter. The only long reflection with a clear tie with surface geological observations is P1 that extends down to 3 km (see Figs. 8 and 15). P1 is generated from the contacts between the alkali basalts of Little River Formation, the Miramichi sediments and felsic volcanic rocks of Nepisiguit Falls Formation. Similar to the results observed for BRN991001, structures associated with the Flat Landing Brook Formation and the Miramichi Group rocks are relatively transparent. A few high-amplitude, short reflections observed within the Flat Landing Brook Formation may be originated from gabbroic/basaltic intrusions that are observed on the geological map of the Brunswick No. 6 area (e.g., R1 on Figs. 8).

The most prominent reflections are P2, I1 and I2, which occur at greater depths within a relatively transparent zone. I1 and I2 correlate with reflections observed on profile BRN991003 (see also Figs. 9 and 15). P2 and I1 are sub-parallel and dip to the south on this profile. They are not defined by a single reflection, but are rather zones comprising a series of reflections. This characteristic is similar to the reflection package P1 on BRN991001 (see also Fig. 10). The surface projection of P2 and I1 is located within the sedimentary rocks of the Miramichi Group that are intersected in the northern

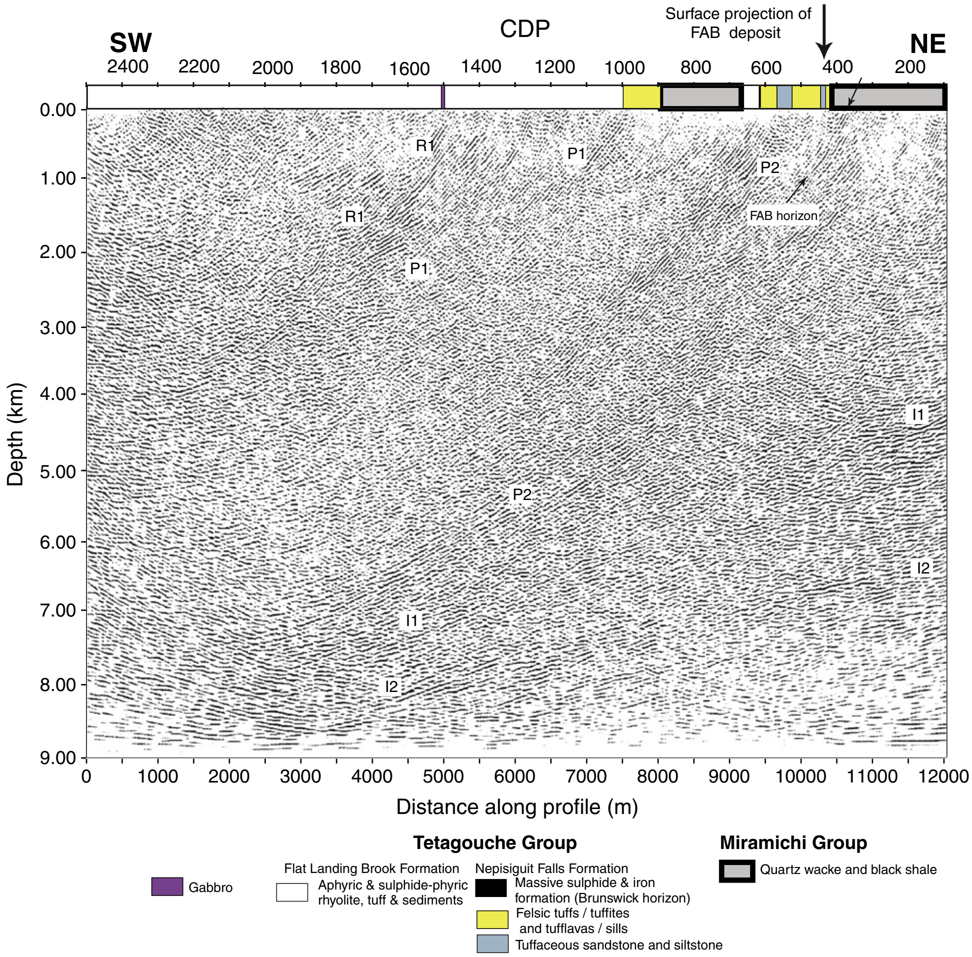

Fig. 13. Migrated section of profile BRN991003. See text for interpretation of I1, I2, P1, P2, and R1.

part of the profile. The significant lateral extent of P2 and I1 suggests that they are important regional structures. They may indirectly be associated with regional detachment planes in a similar way that reflections within P1 on BRN991001 may indirectly indicate the presence of thrust faults. If so, then these reflections suggest the presence of an additional nappe of thrusted rocks at depth on the eastern margin of the mining camp. The intersection between BRN991001 and BRN991002 in Fig. 15 shows a good tie for P2 in the stacked sections. Small mis-tie can be due to projection of the midpoint to the straight-line geometry used during data processing. As we explained for BRN991001, the P2 reflective zone can be originated at the contact between the rock units of Nepisiguit Falls Formation and alkali basalts of Little River Formation. A similar tie for P1 reflective zone can also be seen on Fig. 15; it is possible to track this reflection in all three profiles.

Reflector I2 is located at greater depths and is also a well-defined reflection requiring a strong acoustic impedance contrast to explain it. The gentle dip of this reflection suggests a possible contact between rocks of the Brunswick belt and potentially mafic/ultramafic dominated ophiolitic slab beneath it. This follows a geological interpretation of van Staal et al. (2003) suggesting that rocks of the Bathurst mining camp overlie oceanic crustal rocks (see Fig. 3). Deeper regional seismic data would be required to further confirm this hypothesis.

7.3. Profile BRN991003

This longest profile in the Brunswick No. 6 area crosses the FAB sub-economical VHMS deposit (main zone) in the northeastern part of the profile (Fig. 2). The FAB main zone is located within the Nepisiguit Falls Formation of the Tetagouche Group, just above the contact with the sedimentary rocks of the Miramichi Group. The FAB main zone consists of small massive or disseminated pyrite-pyrrhotite bodies forming a zone approximately 1675 m long, 9 m thick and 400 m deep. The contact between the Tetagouche and Miramichi Groups produces a clear continuous reflection extending down to approximately 0.5 s (approximately 1.5 km, assuming a 6000 m/s average velocity), indicating the continuation of the rocks hosting the FAB main zone at depth (see Fig. 9). This reflection extends down to depths greater than 0.5 s in the stacked section (it is shallower in migrated section, see Fig. 13) but is not as clear as it is in the shallow part of the profile. The FAB zone is too shallow (mostly above 200 m) and too thin to be properly imaged with the acquisition geometry used for this survey.

The direction of profile BRN199003 is approximately 20° from the axis of the Pabineau synform (Fig. 2). This suggests that some reflections could originate out-of-the-plane of the seismic profile, from lithological units dipping toward the synform axis. This could explain the few northeast-dipping reflections observed at shallow depths between CDP 400 and 1000 (Fig. 9). Other northeast-dipping reflections at the south end of the profile are in general agreement with the dip of the contact between rocks from the Little River and Flat Landing Brook Formations. Intersection of the seismic profile with BRN991002 (see Fig. 14) suggests that P2 can be followed in both profiles. Although the P2 reflection does not reach the surface in BRN991002, Fig. 14 shows that it can be correlated with the same formations (P2) observed in BRN991003 in Fig. 9.

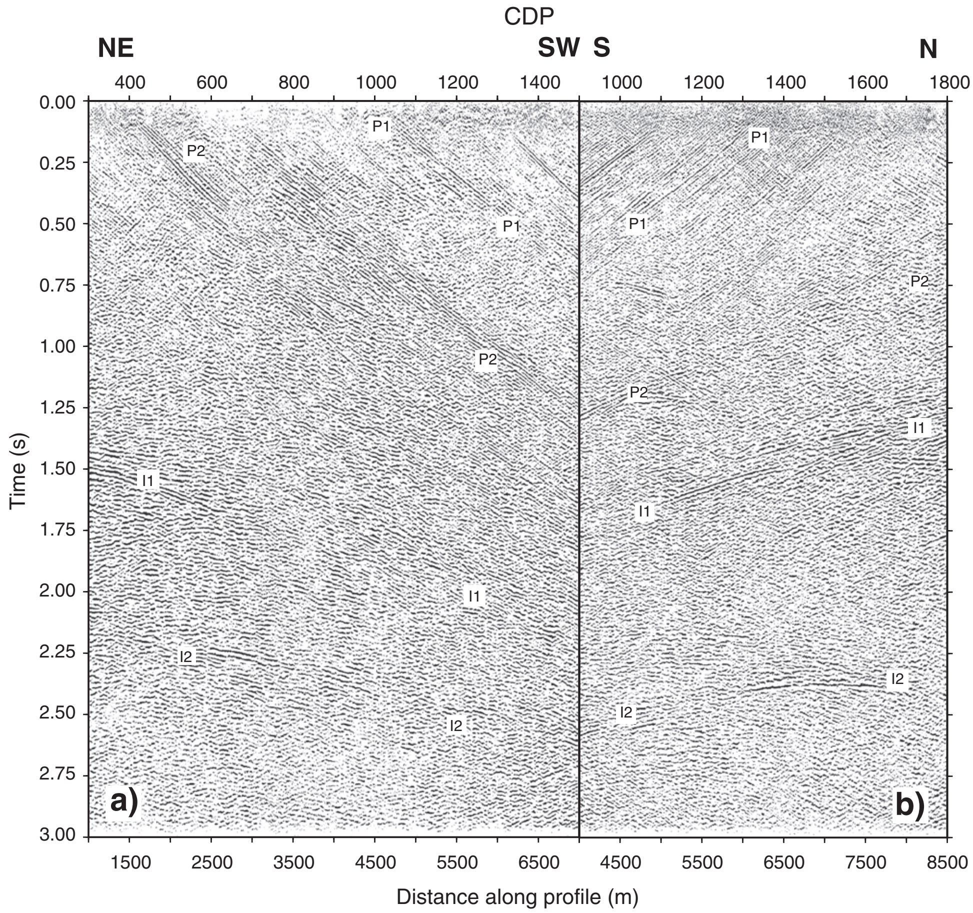

Fig. 14. Parts of profiles (a) BRN991003 and (b) BRN991002, showing intersection between the profiles, viewed from the northeast. See text for detailed interpretations of I1, I2, P1, and P2.

Other key reflections almost reaching the surface represent the contact between Flat Landing Brook Formation and Nepisiguit Falls Formation (e.g., P1 reflection on Fig. 13). P1 can be tracked in both intersection points with the other profiles (see Figs. 14 and 15). R1 and a series of parallel reflections between CDPs 1300–1500 are partially correlated with the gabbroic intrusion also observed in BRN991001. At greater depths, I1 and I2 generally dip to the southwest and are interpreted as thrusted nappes and suggest mafic/ultramafic dominated ophiolitic slab beneath the Miramichi Group rocks. This interpretation is consistent in all the three profiles (Figs. 14 and 15).

8. Discussion

The Brunswick No. 6 seismic data are of excellent quality and provide reliable seismic images of the upper crust. The seismic data in combination with surface geological observations and petrophysical measurements have allowed interpretation of major geological structures down to about 9 km depth. In general, the main geological structures dip to the southwest and west. A three-dimensional view of main lithological units at shallow depths constrained by surface geological observations and borehole data, and the migrated seismic data is shown in Fig. 16. The main lithological units from the geological model clearly correlate with the seismic reflections. The sequence of reflective-transparent packages observed clearly on BRN991001 (Fig. 16) suggests a stack thrust sequence; this pattern can also be observed in the other two profiles (see Figs. 8 and 9). The thrust faults are indirectly interpreted on the seismic profiles in the study area. The stratigraphic repetition of the main lithological units also suggests repeated occurrences of the Brunswick horizon at different depths.

Small fold systems observed on the geological map of the study area and the 3D model (Fig. 16) are not observed on the seismic sections. This is further supported by the synthetic data shown in Fig. 10. The only exception may be in Profile BRN99003 where the P2 reflection indicates a large but tight fold with its hinge occurring at a depth of more than 2 s in the stacked section (Fig. 9). However, such a tight and steep fold is difficult to preserve after migration (see Fig. 13).

Petrophysical studies show no differences between the expected amplitude of the Brunswick horizon and mafic intrusions (see Fig. 10). Therefore, high-amplitude seismic signals cannot be drilled based upon their amplitude characteristic alone. However, the Brunswick horizon occurs within reflective zones which can be used to distinguish areas of low potential for mineralization (transparent zones) from areas with the higher potential (reflective zones). A strong seismic signal at the location of the FAB deposit (see Fig. 9) needs to be further investigated in order to explain its origin.

The two sets of deep but high-amplitude and gently dipping reflections observed clearly on BRN991002 and BRN991003 (I1 and I2 in Fig. 13) provide insights on the deep structural framework of the Bathurst Mining Camp. Theses reflections correlate well with each other on the two profiles and can be seen as weak events on BRN991001 (specified by arrows on Fig. 7). The geometry of these deep reflections may indicate the presence of additional thrusted nappes (or mafic/ultramafic dominated ophiolitic slab) at depth, which could indicate an extension of the Brunswick rocks to the east, beneath the Carboniferous

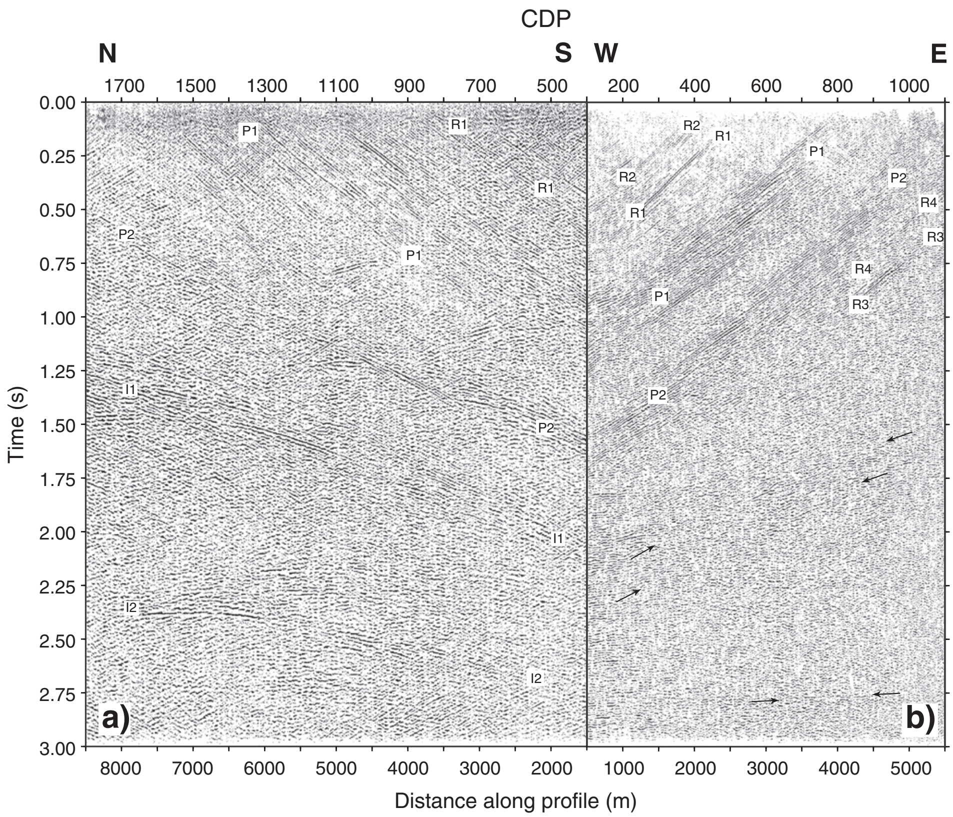

Fig. 15. Parts of profiles (a) BRN991002 and (b) BRN991001, showing intersection the profiles, viewed from the north. See text for detailed interpretations of I1, I2, P1, P2, R1, and R2.

sedimentary rocks exposed at surface east of the mining camp. If this interpretation is valid, then the deepest reflection observed on the profiles (I2) indicates the top of the oceanic crust assumed to underlie the Bathurst Mining Camp. Presence of such high-density materials is also implicated by gravity studies in the study area. Further deep crustal scale seismic studies are suggested to help unravel the puzzling tectonic history of the Bathurst Mining Camp.

9. Conclusion

In this study, we recovered, processed and interpreted seismic reflection data acquired in the Brunswick No. 6 deposit along three crossing profiles. The data quality is high and allows imaging of major geological structures down to about 9 km depth. Processing steps included refraction static corrections and coherent and random noise removal, shear-wave attenuation, velocity analysis, NMO and DMO corrections, residual statics, stacking and migration. Although the geology is complex, the processing results have enabled us to follow some of the steeply dipping reflections to the surface allowing correlation with surface geological observations.

Petrophysical studies of seismic wave velocity and density from a nearly 570 m deep borehole in conjunction with petrological observations suggest that the Brunswick horizon and gabbroic intrusions produce strong reflected seismic signals. Although the Brunswick horizon has a high acoustic impedance contrast on the borehole logging data, it is not possible to link all high-amplitude reflections to the Brunswick horizon. Finite-difference modeling results conducted in this study supports these interpretations. The modeling results further suggest that it is not possible to image tight and very small folding systems observed in this area. The Brunswick horizon occurs within a reflective package that extends down to at least 6–7 km depth. The recognition that the Brunswick horizon occurs within a reflective package helps to distinguish areas of no or weak reflectivity from areas of high reflectivity for further deep mineral exploration.

The observed reflections in both stacked and migrated sections and intersection of profiles have helped us to map the upper crustal architecture of the Bathurst Mining Camp. Reflectivity patterns can be divided into two groups, either reflective or transparent. We interpret the sequence of reflective-transparent packages to represent thrust faults. Two sets of deep, but long high-amplitude reflections observed clearly in all the three profiles are interpreted to represent deep thrusted nappes suggesting a possible repetition of the Ordovician rocks beneath the Carboniferous sedimentary rocks exposed at surface east of the Bathurst Mining Camp. The bottom most reflection may represent the top of a mafic/ultramafic dominated ophiolitic slab underlying the Tetagouche and Miramichi Groups. This interpretation is solely based on the seismic reflection data; thus, it is ambiguous and requires further geological and geophysical investigations.

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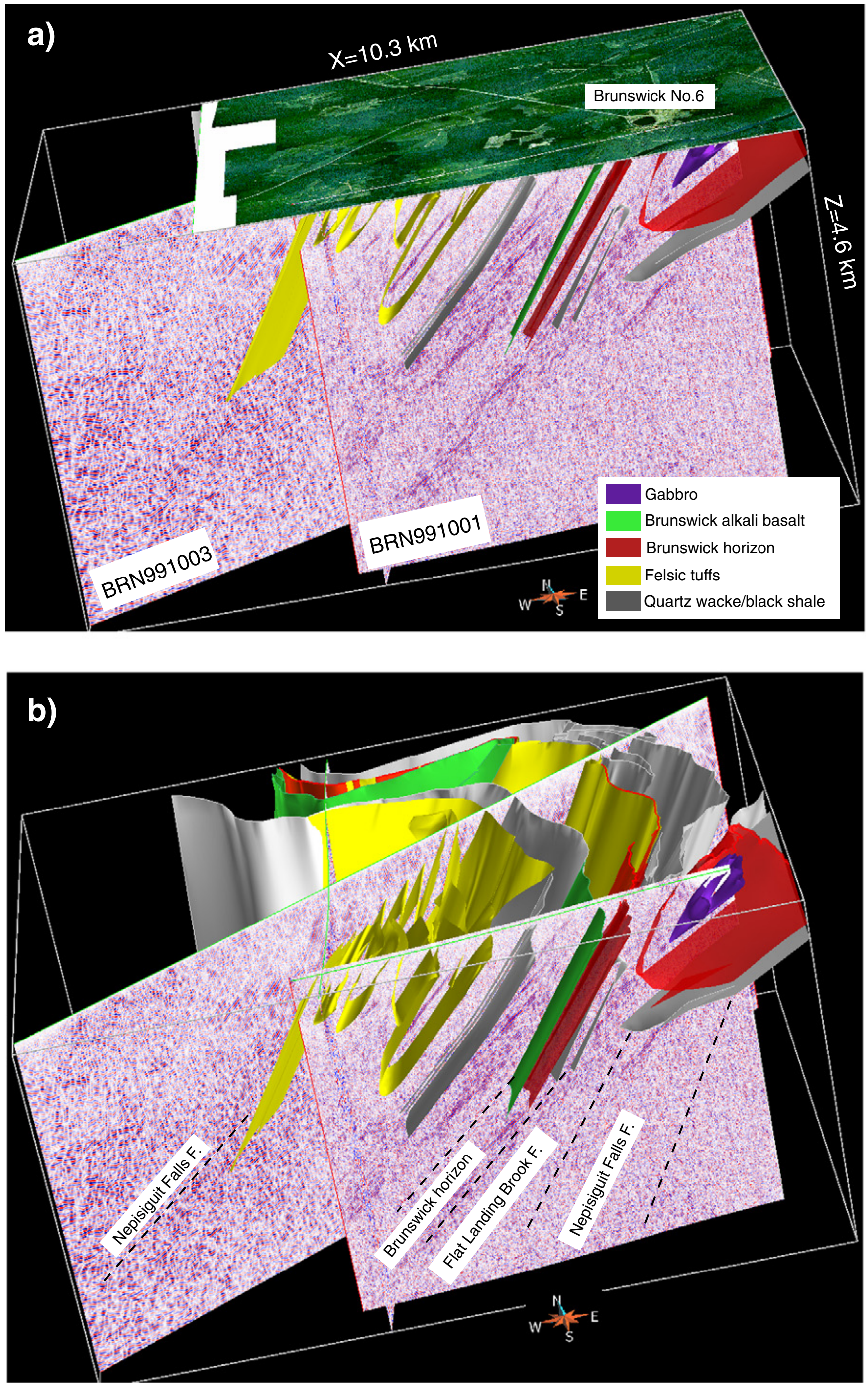

Fig. 16. (a) and (b) three-dimensional integration of the migrated seismic sections with the available 3D geologic model of the Brunswick No. 6 area (courtesy of Xstrata Zinc). The Brunswick horizon is shown in red color only for presentation purpose.

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